Crop Production Science in Horticulture series

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Tropical Fruits, 2nd Edition, Volume 1

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Contents

PREFACE

The monoaxial banana, pineapple and papaya and polyaxial mango are the most well-known tropical fruits worldwide. Avocado is better known for production in subtropical areas, but considerably more production occurs in the tropical zone. Banana, pineapple and avocado are extensively grown by large companies. Banana, along with plantain, is the largest fruit crop in the tropics, with only a small fraction entering international commerce. Many other tropical fruits, already well known in the tropics, are now appearing in larger temperate city markets.

The first edition of this book was started by Dr Henry Nakasone after he retired from the University of Hawaii at Manoa in 1981. His work on the book was prolonged because of his extensive volunteer and consulting activities from his retirement to 6 months before his death in 1995. The extensive research carried out by Henry in preparing some draft chapters laid the foundation for the 1998 first edition. Henry understood the need for a book that melded equally the genetics, physiology and cultural practices with postharvest handling of each fruit crop as an interrelated whole.

This second edition has been completely revised and new chapters added. A colleague, Dr Odilo Duarte, formerly Professor from Escuela Agrícola Panamericana – El Zamorano, Honduras, and now Professor and Lead Scientist in Agribusiness, CENTRUM Católica Business School, Pontificia Universidad Católica del Perú, Lima, Perú, joined me in this revision. It was decided to make this a general tropical fruit production textbook and only cover the major tropical crops in Volume 1. The other tropical fruits have been moved to Volume 2, which should appear next year.

The first five chapters deal with the general aspects of the tropical climate, fruit production techniques, tree management and postharvest handling. Subsequent chapters deal with the principal tropical fruit crops that are common in temperate city markets. The information in each fruit chapter deals with taxonomy, varieties, propagation and orchard management, biotic and abiotic problems, variety development and postharvest handling. The information contained should be of use to all readers and students interested in an introductory text on tropical fruit production.

Many have contributed to the first edition and to this edition. Encouragement and help to Henry in this passion came from many, and they were acknowledged in the first edition. Others must be mentioned who provided help and encouragement since the first edition, including Skip Bittenbender, Victor Galán Saúco, Ying Kwok Chan, George Wilson, Ken Rohrbach, Duane Bartholomew, Francis Zee, Ken Love and Chun Ruey Yen. Their numerous comments and suggestions have been incorporated in most cases. All errors and omissions are our responsibility. The illustrations of each crop were done by Susan Monden, and her perseverance and skill were greatly appreciated. Thanks are also due to the Commissioning Editor, Sarah Hulbert, for her assistance and patience during the book's development.

We would greatly appreciate receiving all comments and suggestions on this text. We can be reached at the addresses given on the title page or via e-mail at paull@hawaii.edu or odiloduarte@yahoo.com

In closing, we both acknowledge the continued support, assistance and love of our wives, Nancy and Carla, and our children, which enabled us to complete this undertaking.

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2010

1

INTRODUCTION

INTRODUCTION

The tropics, with its warm climate and little temperature variation, occupies approximately 40% of the earth's land surface. The region also has half the world's population. The majority of the world's biodiversity is also found in the tropics, biodiversity being the total of all living organisms on earth. These endemic animals and plants are adapted to the diverse tropical environments, which range from wet tropical rainforests to deserts and snow-covered, high mountains.

The tropics can be divided into three major zones. The zone most recognized is that with year-round rainfall and lies on the equator (Amazon, Central America, Central Africa, Indonesia, New Guinea) and is ~8% of the world's land surface. As one moves away from the equator, the rainfall becomes more seasonal, and this zone occupies 16% of the land area (Central America, north and south Amazon, West Africa, India, South-east Asia, northern Australia). The last is the dry tropics, which makes up 16% of the land area and ranges from deserts to large areas with long dry seasons of 9 months or more. Examples would be the Sahara, Bolivian El Chaco lowlands, central India and northern central Australia.

About half of the plant families are tropical, and the tropical region contains 15 of the 25 world biodiversity 'hot spots' (Crane and Lidgard, 1989; Meyer *et al.*, 2000). The 'hot spots' are regarded as centres for agricultural origins, and it is thought that crop domestication took place in or near these 'hot spots'. This domestication reflects the role of hunter–gatherers and early farmers, and their dependence on these crops for their daily subsistence. The abundance of species with different life cycles, adaptations and useful products in these 'hot spots' would facilitate their selection by hunter–gatherers and early farmers. Examples of these centres include half of the southern part of Mexico and the northern half of Central America, Ecuador, western and central Brazil, the Indo-Burma region, South-east Asia, the Indonesian and Philippine archipelagos, the East Melanesian Islands and Pacific Micronesia.

TROPICAL FRUITS

Most botanical families have at least one species of tropical fruit (Table 1.1). In tropical America, more than 1000 fruit species are described, though only 100 are found in local markets. Asia has about 500 tropical fruit species, the Indian subcontinent about 300, with about 1200 in Africa. Of these fruits only a few are found in local markets and fewer are exported. Ninety per cent of the export market is made up of citrus, banana and plantain, mango and pineapples (Table 1.2). A further 5% is made up of papaya, avocado and dates. The remainder is made up of more than 20 species, ranging from breadfruit and litchi to mangosteen, passion fruit and coconut. More than 90–95% of tropical fruits are not exported from the producing country but are consumed locally.

The most common tropical fruits in trade come from three major areas: Central and South America (papaya, avocado, pineapple, guava), Asia (most citrus fruits, litchi), and South and South-east Asia (banana, mango, mangosteen, durian) (Gepts, 2008). Only one important tropical fruit is native to Africa and that is the date, though the continent has many other tropical fruits. Fruit species were selected by man and distributed widely throughout the world, based upon various factors, which included the crop's adaptability to different environments, the fruit's seed storage life, ease of plant propagation (seed, cuttings, plants), the size and shape of the plant, a multiplicity of uses other than as a fresh fruit (cloth, medicinal, wood) and having an agreeable taste. Many tropical seeds are recalcitrant and cannot be dried and must be transported as cuttings or plants to be introduced to new areas.

As people migrated, often the crops with which they were familiar were taken along. The spread to areas surrounding that of their origin probably began early. For example, the mango, a native of the Indo-Burma region, had spread to all of South-east Asia by the end of the fourth century CE. Arabs traders in the Indian Ocean probably took mangoes to the east coast of Africa around 700 CE. The orange was also moved, most likely by Arab traders, to the Mediterranean and southern Europe. Opportunities probably also existed to move some tropical fruits (e.g. pineapple) around the warmer areas of Central and South America. The European discovery of America led to a rapid exchange of tropical fruit crops between the Old and New Worlds. Bananas were carried to Santo Domingo from the Canary Islands in 1516. The Portuguese spread tropical fruits from their colony in Brazil around the Cape of Good Hope to Goa in India, Malacca in Malaysia, China and Japan. The Spanish had a regular galleon service from Mexico to the Philippines between 1565 and 1815. The Dutch, British and French ships also spread tropical fruits around the globe.

Table 1.1. Taxonomy and primary centre of diversity and probable centre of origin of the major tropical fruits (Gepts, 2008).

	Order	Family (subfamily)	Crop(s), taxa	Centre of origin
Magnoliid complex	Laurales	Lauraceae	Avocado, *Persea americana*	Tropical Central America
	Magnoliales	Annonaceae	*Annona* spp., cherimoya, ilama, soursop, sweetsop, atemoya; *Rollinia pulchrinervis,* biriba	Tropical South America
Monocots	Arecales		Coconut, *Cocos nucifera*	South-east Asia
			Date, *Phoenix dactylifera*	N. Africa, Middle East
	Poales	Bromeliaceae	Pineapple, *Ananas comosus*	South America
	Zingiberales	Musaceae	Banana and plantain, *Musa* spp.	South-east Asia
Eudicots	Caryophyllales	Cactaceae	Pitaya	Tropical America
	Oxalidales	Oxalidaceae	Carambola, *Averrhoa carambola*	South-east Asia
	Malpighiales	Malpighiaceae	Barbados cherry, *Malpighia glabra*	West Indies, South America
		Clusiaceae (Guttiferae)	Mangosteen, *Garcinia mangostana*	South-east Asia
		Passifloraceae	Passion fruit, *Passiflora* spp.	Tropical America
	Rosales	Moraceae	Breadfruit, chempedak, jackfruit, etc., *Artocarpus* spp.	Polynesia
	Myrtales	Myrtaceae	Surinam cherry, *Eugenia* spp.	Tropical America
			Jaboticaba, *Myrciaria cauliflora*	Brazil
			Guava, *Psidium guajava*	Tropical America
	Brassicales	Caricaceae	Papaya, *Carica papaya*	Central America
	Malvales	Malvaceae	Durian, *Durio zibethinus*	South-east Asia
	Sapindales	Sapindaceae	Longan, *Dimocarpus longan*; litchi, *Litchi chinensis*; and rambutan, *Nephelium lappaceum*	South-east Asia
		Rutaceae	Citrus, *Citrus* spp.	South-east Asia
		Anacardiaceae	Cashew, *Anacardium occidentale*	Tropical America
			Mango, *Mangifera indica*	India, South-east Asia
			Hog plum, mombins, *Spondias* spp.	Tropics
	Ericales	Sapotaceae	Caimito, *Chrysophyllum cainito*	South America
			Sapodilla, *Manilkara zapota*	Central America
			Mamey sapote, *Pouteria sapota*	Mexico, Central America

Table 1.2. World production and acreage of major tropical fruits in 2007, from FAO Statistics Division (FAO, 2009).

Fruit		Production (1000 of t)	Acreage harvested (1000 × ha)	Important producing countries
Avocado		3,569	407	Mexico, United States, Dominican Republic, Brazil, Colombia, Chile, South Africa, Indonesia, Israel, Spain
Banana	Dessert	85,856	5,109	Burundi, Nigeria, Costa Rica, Mexico, Colombia, Ecuador, Brazil, India, Indonesia, Philippines, Papua New Guinea, Spain, Central America
	Plantain	33,925	5,375	Colombia, Ecuador, Peru, Venezuela, Ivory Coast, Cameroon, Sri Lanka, Myanmar
Citrus	Oranges	7,104	1,071	Brazil, United States, India, Mexico, Spain, China, Italy, Egypt, Pakistan, Greece, South Africa
	Tangerines and Mandarins	27,865	2,052	Brazil, United States, India, Mexico, Spain, China, Italy, Egypt, Pakistan, Greece, South Africa, Japan
Coconut		61,504	11,106	Indonesia, Philippines, India, Sri Lanka, Brazil, Thailand, Mexico, Vietnam, Malaysia, Papua New Guinea
Mango		33,446	4,610	India, Pakistan, Indonesia, Philippines, Thailand, Mexico, Haiti, Brazil, Nigeria
Papaya		7,208	378	Nigeria, Mexico, Brazil, China, India, Indonesia, Thailand, Sri Lanka
Pineapple		20,911	2,378	Philippines, Thailand, India, Indonesia, China, Brazil, United States, Mexico, Nigeria, Vietnam

TROPICAL FRUIT CHARACTERISTICS

Tropical fruits are harvested from woody plants (avocado, mango, orange) but also from herbaceous plants (banana, papaya) and vines (passion fruit). The evolution of fruit in the early Tertiary period was a major advance that increased the efficiency of angiosperm seed dispersal. Climate change, radiation of birds and animals, and changes in plant community habitats are all potential evolutionary forces that led to the appearance of a range of fruit types. The fleshy fruits, with their mutually beneficial interaction of providing nutrition to animals and improving seed dispersal, have arisen independently in different families, have disappeared and reappeared, are not evolutionarily conserved, and show no clear association with phylogeny. The fossil and morphological evidence indicates that multiple fruit types have evolved directly from a dry follicle-bearing ancestor (Fig. 1.1).

The follicle is seen as the archetypical progenitor fruit, with a single fused carpel that splits along a single seam (dehiscent zone). The fused carpel appeared about 97 million years ago (Mya), in the middle Cretaceous. The abscission (separation) zones are found much earlier in the fossil record (400 Mya) in early vascular plants. In fruit, the biochemical processes in the dehiscence zones and during ripening are thought to have co-opted systems that evolved for the abscission of sporangia, leaves, petals and stamens. The fruits that are consumed have soft and juicy arils (rambutan, litchi, longan), pedicel (cashew), floral and accessory tissue (pineapple, annonas), mesocarp

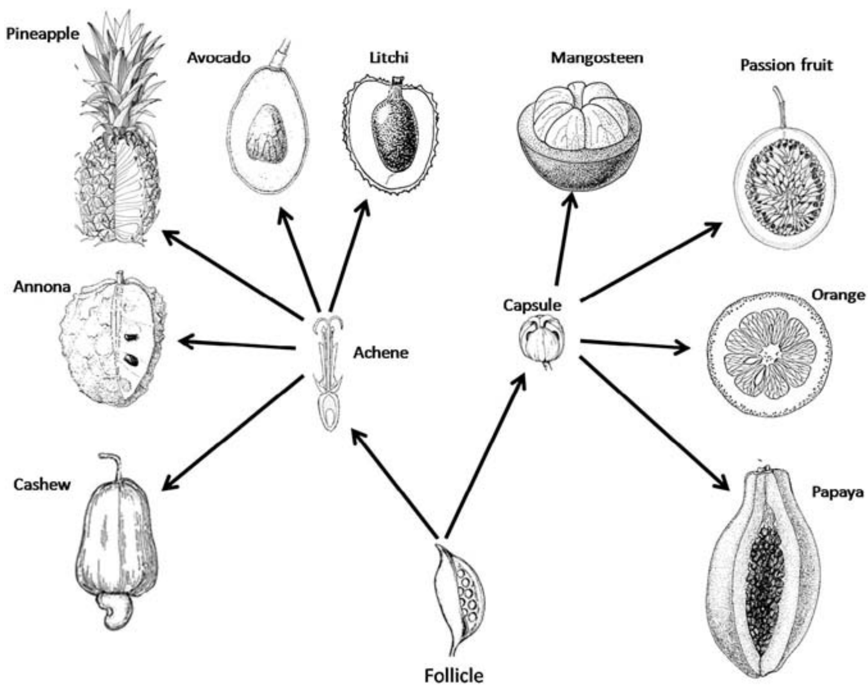

Fig. 1.1. Types and structures of tropical fruits and their evolutionary development from dehiscent and non-dehiscent dry fruits (redrawn from figures in Nakasone and Paull, 1998).

(papaya, avocado) and endocarp (citrus). A few species are in the magnoliid complex (annonas, avocado) and monocots (banana, coconut, pineapple); the most important species are all eudicots. The floral parts of the magnoliid complex occur in whorls of three (trimerous); the pollen has one pore and they usually have branching-veined leaves and are regarded as basal or more ‘primitive’ angiosperms.

Tropical fruits, in most cases, are sold fresh, and off-grade fruit is processed. The exception to this would be coconut, which is grown principally for other products (copra, oil, coir) with a small acreage, often of special varieties, that are grown for fresh consumption. Cashew is grown mainly for its nut, with the fleshy pedicel being eaten fresh, processed and made into juice. Most tropical fruits are highly perishable, and significant development has taken place to process selected fruits into dried products, juices and purees. Bananas such as plantains are also often used as a starch staple in Africa, Asia and Latin America and not as a dessert fruit.

NUTRITIONAL VALUE

Nutrient contents of tropical fruits found in food composition tables are used for nutritional assessment, research linking diet to health, nutritional policy, food labelling, and consumer education. Accurate data are needed in order to predict dietary energy intake and undernourishment. For tropical fruit, this is important, as they are often regarded as significant sources of minerals, vitamins and carbohydrates (Favier *et al.*, 1993).

Natural variation occurs in the nutrient content of fruits. This variability is due to soil and climatic conditions, variety grown, the stage of maturity at harvest and physiological state when eaten. Traditionally, food composition tables for most foods are presented as mean values, ignoring the natural biological variability. It is probably more useful to know the range of values found and the standard error or deviation.

Most food composition tables present data as nutrient values per 100 g of edible food. Tropical fruits have low to moderate energy content and provide about 200 to 300 kJ (FAO, 2003). Some tropical fruits, such as bananas (380 kJ), avocado (572 kJ) and durians (536 kJ), are higher and others less energy-dense, such as the carambola (121 kJ). The protein content of most fruits, including tropical fruits, is low (<1 g/100 g), though avocado (1.8 g) and durians (2.6 g) are higher. Fat contents are also low, except for avocado (14.2 g) and durians (2–5 g). The carbohydrate content is presented as monosaccharide equivalents with fibre excluded, and contents normally range from 10 to 15 g, which is the range that most consumers regard as sweet. Higher carbohydrate contents are found in bananas (~20 g), atemoya (~21 g) and durians (~26 g). Dietary fibre is reported to range from 1 to 2 g in tropical fruits, though different analytical methods are used that give different values in the same fruit.

Tropical fruits are low to moderate sources of macronutrients and good sources of micronutrients. For example, while most fruits have 10–20 mg of calcium, mango only has ~1.2 mg. Iron ranges from 0.2 to 0.4 mg. Banana and durian are good sources of potassium, having 100–200 mg. Some fruits are good sources of folate, and most are high sources of vitamin C (>20 mg). The beta-carotene in fruit varies widely, depending upon the content of the different carotenes present. The different varieties of mangoes can vary in beta-carotene from 350 to 13,000 mcg. Other components present in tropical fruits include antioxidants and other phytochemicals that have potential health-promoting effects, with various claims being made.

Nutrient and health claims are frequently made for tropical fruits. *Codex Alimentarius* (2001) has set standards for health-claim labelling. Using these standards, some nutrient claims can be made for tropical fruit (Table 1.3). For example, for a product to be low in fat it must have less than 3 g/100 g; for a tropical fruit to be a 'source' of a particular nutrient it must contain 15% and a 'high source' 30% of the *Codex Alimentarius* (2001) reference nutrient value.

SIGNIFICANT TRENDS – PRODUCTION AND MARKETING

The production and world trade in fresh tropical fruits is expected to expand (Sarris, 2003). Most of the production occurs in developing countries (98%), while developed countries are the major importers (80%). Citrus and bananas are traded worldwide, followed by mango, pineapple, papaya and avocado.

Table 1.3. Potential nutrient claims that can be made for fresh tropical fruits using standards from Codex Alimentarius (2001).

	Nutrient claim				
Fruit	Energy	Fat	Vitamin A	Folate	Vitamin C
Avocado				Source	Source
Banana		Low			Source
Carambola	Low	Low			High
Durian		Low			High
Guava	Low	Low			High
Lime	Low	Low			High
Litchi		Low		High	High
Longan		Low		Source	High
Mango		Low	High	Source	High
Papaya	Low	Low	Source	Source	High
Passion fruit		Low			High
Pineapple		Low			High
Rambutan		Low			High

Litchi, durian, rambutan, guava and passion fruit are produced and traded in smaller volumes, with their market shares expanding rapidly in recent years.

The projections made by the FAO assume normal weather patterns and the continuation of past trends in area planted, yield, income growth and population for mango, pineapple, papaya and avocado (Table 1.2). World production is expected to reach 62 million tonnes by 2010, an increase of 15.4 million tonnes over the 1998–2000 period, with developing countries continuing to account for 98% of the global production. This is a compounded growth rate of 2.6% per year. The Asia and Pacific region accounts for 56% of production, followed by Latin America and the Caribbean (32%) and Africa (11%). The production increase has come from additional planted acreage intended for export. The growth has occurred mainly in Latin America and the Caribbean region, with their more accessible trade route to the major importing regions, the United States and Europe.

Demand for fresh tropical fruits has increased and imports are at about 4.3 million tonnes for mango, pineapple, papaya and avocado, with 87% going to developed country markets. Europe is the world's largest import market, followed by the United States, accounting for 70% of import demand. In Europe, France is a major importer, and the Netherlands is the major trans-shipment point.

TROPICAL FRUIT AND CONSUMERS

In most markets, consumers are demanding higher quality. This quality is no longer judged solely by size and appearance; aroma, flavour and nutrient value are now increasing in importance. This can be seen in the larger range of commodities on the retail shelves, the number of varieties of each commodity now offered, and reduction in seasonality of supply in developing country markets. The traditional term, quality, implies excellence or suitability for use and means different things to different groups. Suitability for use includes freedom from microbial and chemical contaminants. Understanding of consumer behaviour is related to how it will be accepted in the marketplace (Sabbe *et al.*, 2009).

Consumer satisfaction is related to their view as to what constitutes quality, and this varies widely in different markets and is decided by familiarity, economic status and marketing. For many minor tropical fruits, familiarity in many temperate markets is a major limitation to expanding the market for tropical fruits, coupled to a consumer willingness to try new fruits (Fig. 1.2).

INTERNATIONAL FORUMS

Numerous national and international groups are dedicated to specific tropical fruits or groups of closely related fruits. The International Society

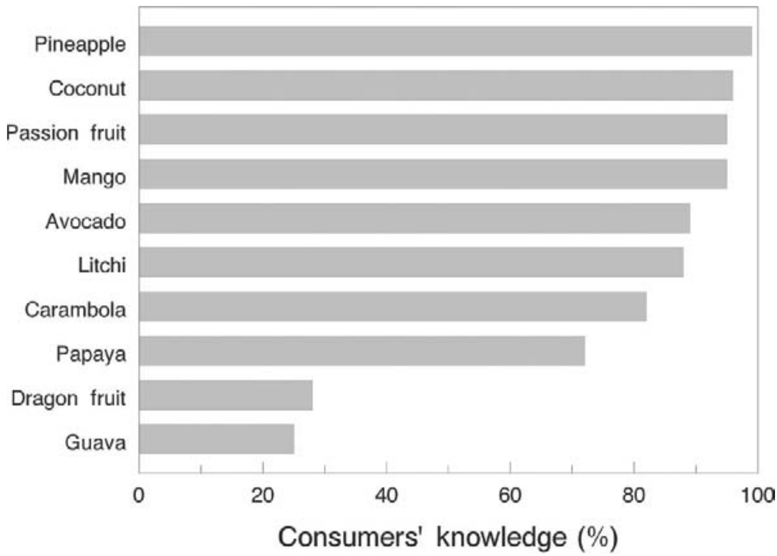

Fig. 1.2. European consumers' knowledge of different fresh tropical fruits (redrawn from Sabbe *et al.*, 2009).

of Horticultural Science (ISHS) has established a Commission of Tropical and Subtropical Horticulture, with working groups in specific tropical and subtropical fruits. The various working groups meet at regular intervals, and meeting times and places are posted on the ISHS web site (http://www.ishs.org/calendar/). The calendar posted at this site is the most extensive that deals with horticulture conferences. The International Tropical Fruit Network (TFNet) (http://www.itfnet.org/) is an excellent source of tropical fruit knowledge. TFNet is an independent global network that serves as a depository of tropical fruit production, postharvest, processing, marketing and consumption information. For Latin America, an InterAmerican Society of Tropical Horticulture (formerly Tropical Region of the American Society of Horticultural Science) was active until 2006. Annual meetings were held in different Latin American countries. Their web site is at (http://www.ashs.org/isth/index.html) (accessed 19 January 2010), and this site lists the many volumes published from 1951 to 2004, which are available in some libraries and were abstracted in *Horticulture Abstracts* until 1998, and are now available by subscription through CAB Direct (http://www.cabdirect.org/).

TROPICAL HORTICULTURE

Tropical agriculture, including fruit production, has a number of limitations. In the next chapter we will consider the constraints associated with temperature, rainfall amount and distribution, evapotranspiration and soil moisture. These climate factors have had, and continue to have, a significant impact on abiotic and biotic factors that affect fruit production, which will be discussed in the individual fruit chapters.

Frequently tropical soils are highly leached and acid, with aluminium toxicity occurring. Nitrogen levels are frequently low, due to high rainfall. The continual high temperature in the tropics means that organic matter turnover is high, compounded by low nitrogen availability and poor soil structure. Leached soils are high in iron and low in phosphorus, and show micronutrient deficiencies (Zn, Mn, S).

Pests and diseases are more prolific in the tropics, with year-round development in the absence of a cold winter (no frost, snow or ice) to reduce inoculum and pest levels. This biotic stress carries over to the postharvest stage and contributes to high postharvest losses. Integrated pest management (IPM) is now being widely applied in the tropics, where it can be successful. Ongoing research will lead to wider application by reducing pest populations below levels that cause economic injury.

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2

THE TROPICS, ITS SOILS AND HORTICULTURE

INTRODUCTION

Climate is defined as the general temperature and atmospheric conditions of an area over an extended period of time. Atmospheric conditions include rainfall, humidity, sunshine, wind and other factors. Climates are subject to modification by various factors, such as latitude, elevation and whether or not the land mass is continental, coastal or oceanic, direction of wind and ocean currents, proximity to large bodies of water and mountain ranges, and cloudiness.

The tropical region is a belt around the earth between the Tropic of Cancer at 23° 30′ latitude north of the equator and the Tropic of Capricorn 23° 30′ latitude south of the equator (Fig. 2.1). The term 'tropics' has its origins in astronomy and comes from the Greek meaning 'a turning'. In astronomy, it defines the farthest southern- and northernmost latitudes where the sun shines overhead. The Tropics of Cancer and Capricorn are rather rigid boundaries and do not take into consideration the presence of areas that do not meet the various climatic characteristics generally established to describe the tropics. Some climatologists have extended the region to 30° N and S of the equator, based upon surface temperatures and precipitation, or use the 18°C isotherm of the coolest month (Fig. 2.1). This increases the land mass in the tropics substantially, from ~40% to ~50%, especially on the continents of Africa, China, South America and India, and would include approximately two-thirds of Australia's land mass.

CHARACTERISTICS OF THE TROPICS

The tropical zone is generally described as possessing the following characteristics:

1. An equable warm temperature throughout the year, having no cold season at lower elevations. The average annual temperature of the true tropics is

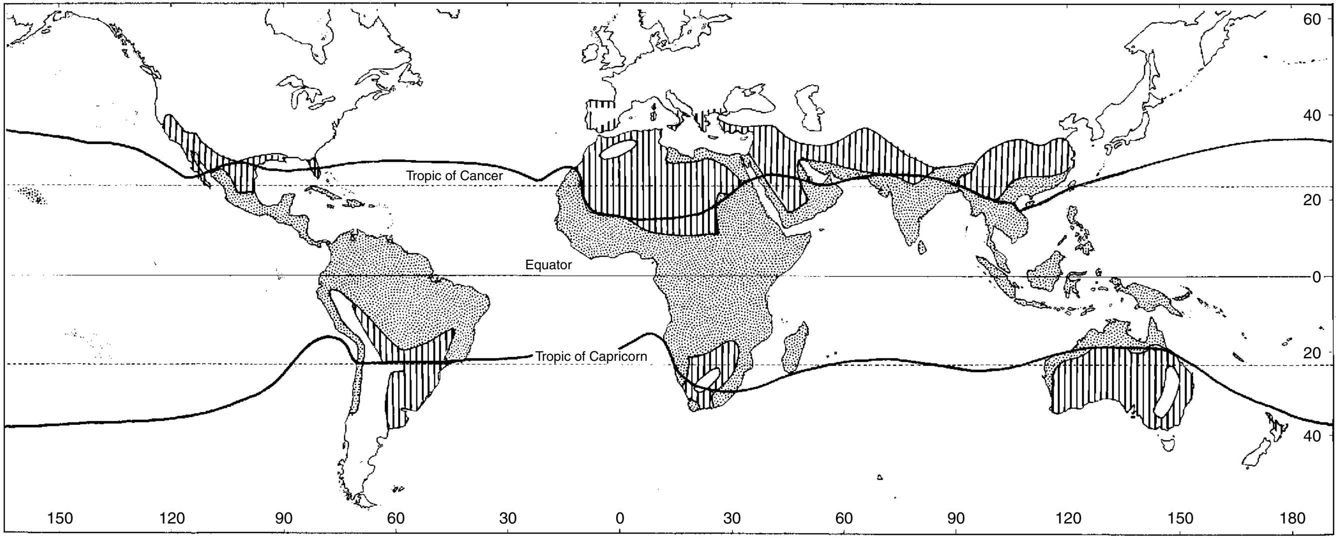

Fig. 2.1. Distribution of tropical and subtropical regions of the world and the position of the 18°C sea-level isotherm for the coolest month as the boundary of the tropics. The white area indicates where frost can occur; the vertical hatching indicates the subtropical areas, while the mottled areas are regarded as tropical.

generally greater than 25°C, with no month having an average less than 18°C. Others have described the tropics as areas with a mean temperature of not lower than 21°C and where the mean annual range of temperature equals the daily range of temperature. The latter boundary is very much influenced by continentality. Another boundary is the isotherm where the mean sea-level temperature in the coldest months is not below 18°C; though it can include certain errors, these are relatively small on a world scale and reliable data are available for its computation (Fig. 2.1). In the tropics, diurnal temperature variation is greater than the seasonal change.

2. Rainfall is usually abundant, seldom less than the semi-arid 750 mm to as high as 4300 mm, indicating considerable variation (Fig. 2.2). The heaviest rainfall occurs near the equator. Seasonality in rainfall increases with distance from the equator. Where rainfall is marginal for agriculture, its variability takes on greater significance.

3. Photoperiod varies little throughout the year; at the equator day length is about 12 h (Table 2.1).

4. The position of the sun is more directly overhead, giving a year-round growing season (Fig. 2.3).

5. Rainfall, temperature, and solar radiation lead to higher potential evapotranspiration.

These characteristics describe the true tropics, on and near the equator, with latitudinal changes toward the poles producing a variety of subclimates. Even near the equator, mountain ranges and other geographical factors can produce various subclimates. Since temperature, solar radiation and photoperiod are fairly constant in the tropics, the variety of subclimates and vegetation are frequently dependent upon rainfall.

A continuous succession of climates starts with a long season of well-distributed precipitation and a short dry season close to the wet tropics. As you move away from the equator and the latitude increases, there is a gradual change to a short season of relatively low rainfall with a long dry season. Some seasonal variation in mean daily temperature becomes apparent, with cool temperatures increasing with increasing distance from the equator.

Table 2.1. Day length extremes in hours and minutes at various latitudes in the tropics and subtropics.

Latitude °	0	10	20	30	40
Longest day	12:07	12:35	13:13	13:56	14:51
Shortest day	12:07	11:25	10:47	10:04	9:09

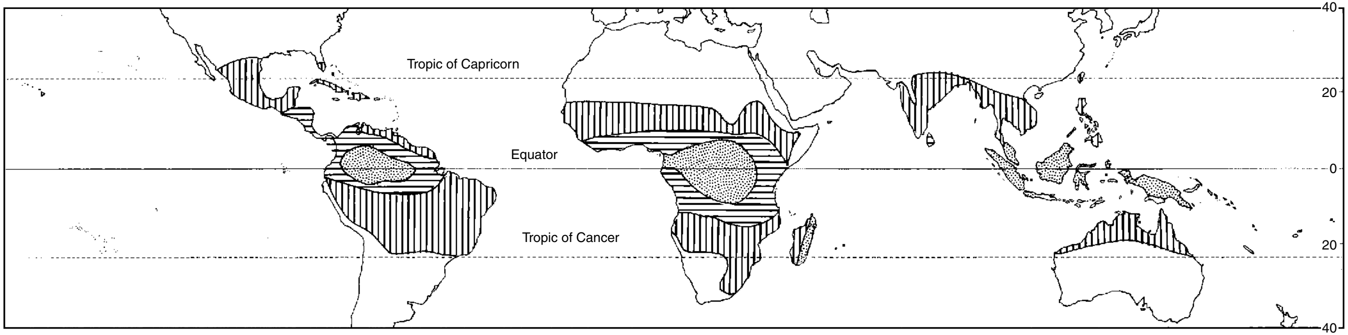

Fig. 2.2. Seasonal rainfall distribution in the tropics (after Bluthgen, 1966). The mottled areas are those that receive rain throughout the year. The horizontal hatching indicates the wet and dry tropics with seasonal rainfall. The vertical hatching indicates the dry tropics and monsoon areas with long dry periods.

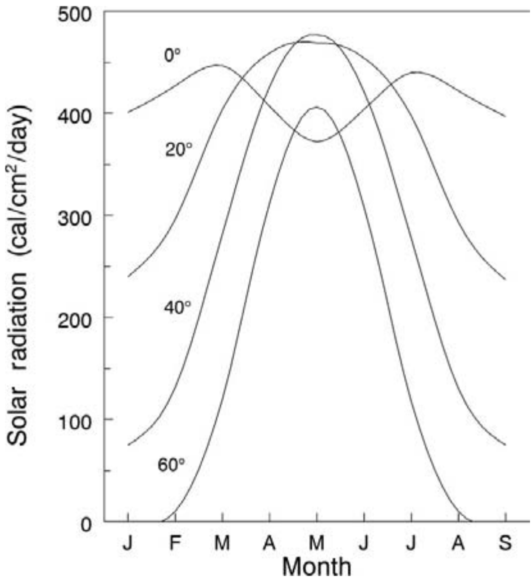

Fig. 2.3. Solar radiation received at the earth surface at different latitudes and an atmospheric coefficient of 0.6 (Gates, 1966). Solar radiation changes significantly between the summer and winter periods as you move away from the equator. The data in the figure are for the northern hemisphere.

MAJOR TROPICAL CLIMATE TYPES

Many geographers and climatologists have classified climates into zones by temperatures (tropical, temperate and frigid zones), by vegetation or crop requirements, precipitation, altitude, soils, human responses, or by combining these factors. A well-recognized classification system is the Köppen system, named after the Austrian botanist and geographer, Wladimir Köppen. This classification is based on temperature, rainfall, seasonal characteristics and the region's natural vegetation and was developed from 1870 to his death in 1940. The newer systems have most often been built upon the 1918 scheme of the world climactic regions (Table 2.2). Another well-known modification is that of C.W. Thornthwaite (1948), who based his classification on distribution of effective precipitation (P/E (precipitation/evaporation) ratio), temperature efficiency and evapotranspiration. This led to nine moisture and nine temperature regions. Numerous other classifications have been published based upon similar criteria (Oliver and Hidore, 1984; Schultz, 2005).

The classification systems of Köppen, Thornthwaite and others are focused on the major factors (temperature, precipitation and evaporation) that limit vegetation growth and hence horticultural production. The 18°C

Table 2.2. Köppen's major climates based upon four major temperature regimes, derived from monthly mean temperatures, monthly precipitation and mean annual temperature: one tropical, two mid-latitudes and one polar. The second division is based on moisture availability. The system does not completely agree with natural vegetation and climate, and frequently the boundaries are rigidly interpreted.

	Principal climatic types	Temperature (°C)	Rainfall
Tropical	Rainy	Coolest month > 18	>600 mm driest month, range 2000 to 4000 mm per year
	Wet and dry		<600 mm driest month, range 500 to 1500 mm per year
	Seasonal rainfall		
Dry	Steppe		Evaporation > precipitation, 100 to 500 mm per year
	Desert		
Mid-latitudes	Mediterranean	Coolest month < 18	3 × more precipitation in winter than summer
Mild winter	Wet and dry	> −3	10 × more precipitation in summer than winter
	Rainy		≥ 30 mm per month
Mid-latitudes	Wet and dry	Coolest month < −3	
Cold winter	Rainy	Warmest month > 10	
Polar	Tundra	Average warmest month 0 to 10	
	Ice cap	Average warmest month < 0	

boundary of Köppen recognizes the dramatic slowing of tropical plant growth and development at lower temperature. At temperatures less than 10–12°C and above freezing, most plants that evolved in the tropics stop growing and are injured, depending upon length of exposure and species; this response is called chilling injury. Precipitation and evaporation significantly impact natural vegetation and subsistence agriculture, although irrigation does allow horticultural production to proceed.

Several major tropical climatic types have been described:

1. *Wet tropics*: The wet equatorial or humid tropics, equatorial zone or tropical rainforest occurs within 5–10° of the equator. It is characterized by constantly high rainfall, humidity and heat. Rainfall is well distributed and may range from 2000 to 5000 mm or more annually. Solar radiation is reduced due to cloudiness. Vegetation is luxuriant on very weathered soils. Undisturbed, the soil supports natural vegetation very well, but under cultivation the soils lose their organic matter and porosity rapidly. Much of the land in the wet tropics is undeveloped and in some areas unpopulated. Attempts have been made to improve productivity, but past attempts by private industries and government agencies have often not succeeded.

This wet tropics climatic type is common in parts of Africa within the 10° N and S latitudes and includes the Congo Basin, Gulf of Guinea in West Africa, parts of Kenya and Tanzania in East Africa; in South America the Amazon Basin of Brazil and countries bordering the basin, such as French Guiana, Guyana, Surinam and Venezuela; and in South-east Asia most of Malaysia, Indonesia, Papua New Guinea, the Philippines and some Pacific islands. The wet tropics are not limited to the above areas and are also widespread in countries bordering the equator.

2. *Wet and dry tropics*: This is also known as the monsoon rainforest, with marked seasonal rainfall between 5 and 15° N and S of the equator and as far north as 25° in parts of tropical Asia (Fig. 2.2). Walter (1973) extended this zone from about 10° N and S to about 30° N and S latitudes. Maximum rainfall occurs in the summer when the sun is directly overhead, with the dry season in the cooler months. A tropical fruit horticulturist will probably spend most of their time in this climatic zone.

This wet and dry tropical climate is found in a wide region of Africa, Asia, the Americas, Australia and the Pacific tropics. Many tropical fruit species are well adapted to wet–dry climatic conditions. For fruit production, some form of irrigation is necessary, especially in areas where the wet season is relatively short. A dry period in winter may substitute for cool temperatures in crops requiring some stress prior to flowering. However, irrigation is desirable once flowering begins and during fruit development.

3. *Dry tropics*: Also called the tropical savannah, occurs to the north and south of the monsoon climate zone along the Tropics of Cancer and Capricorn, between 15° and 20° N and S latitudes. It is characterized by hot, dry desert conditions where crop production cannot succeed without irrigation. This climate is found in North Africa, bordering the Tropic of Cancer, north-east India, Australia and parts of the Pacific coast of South America. The coast of Peru has arid plains and foothills and fertile river valleys. For example, average annual rainfall for the town of Piura on the north-western coast is 51 mm, and average minimum and maximum temperatures are 17.6°C and 30.5°C, respectively. Thousands of hectares of land remained unproductive due to lack of irrigation until large dams were built to produce hydroelectric power as well as to provide irrigation.

ALTITUDINAL CLIMATES

Climates change with altitude at the same latitude, and the change is related to temperature. The environment can be divided into three temperature zones at the equator: the hot zone, from sea level to 1000 m; the temperate zone, from 1000 to 2000 m; and the cool zone, above 2000 m, with frost occurring at approximately 5000 m at the equator. Temperatures in these zones differ with changes in latitude, prevailing wind patterns, precipitation and other factors.

In the Selva region of eastern Peru with large rivers, principally the Amazon, two subclimates are recognized in terms of altitude and rainfall. The low jungle or humid tropics extends from sea level to 800 m and has rainfall throughout the year. The high jungle or central Selva, located between 800 and 1500 m above sea level, has a wet and dry climate, with about 6 to 7 months of wet season and the remainder with little or no rain. In the low jungle, subsistence agriculture prevails, with crops such as coffee, cacao, banana, mango, papaya, pineapple, soursop, citrus, black pepper, cassava and poma rosa (*Syzygium malaccensis*). Under large-scale commercial cultivation, some of the traditional crops, such as mango, papaya, pineapple and citrus, would do better at latitudes somewhat removed from the equatorial region, having better soils and reduced disease problems associated with high rainfall. The high jungle (wet and dry tropics) in the central Selva area of Peru is better developed, with farms of large commercial size. Citrus (Valencias, mandarins and limes) and coffee have done well.

SUBTROPICS

Strict separation of tropical, subtropical and temperate climates is not practical because of the many factors that influence climate. Even within the geographical limits of the tropics, there are areas that are subtropical and temperate, or even frigid, because of altitude, topography, ocean and air currents. The subtropics occur between the two tropics and about 40° latitude, with summers being hotter and winters cooler than in the tropics. Humidity is generally lower in this region, and the difference in day length becomes greater with higher latitude (Table 2.1). The limit for the subtropics is the isotherm of 10°C average temperature for the coldest month. This 10°C isotherm excludes the large land masses whose climates are temperate and includes almost half of China, three-quarters of Japan, all of South Korea, the southern half of the United States, all of the southern half of Australia, the North Island of New Zealand and more than half of Argentina and Chile between 23° 30′ and 40° latitude.

Horticulturists who have spent their professional careers in regions where the temperatures during the coldest month at sea level are rarely lower than 15–18°C find it difficult to accept the tropical classification of regions with winter temperatures down to 4–7°C and frost potential.

CLIMACTERIC FACTORS

Day length

The day length at the equator is about 12 h. At low latitudes in the tropics, the increase in difference between the longest and shortest days is about 7 min per degree (Table 2.1), increasing to 28 min per degree at latitudes between 50 and 60°. The difference in photoperiod (Table 2.1) is associated with the earth being inclined on its axis by approximately 23° 30′; hence the solar equator moves about 47° as the earth moves around the sun. The extremes are the Tropic of Cancer (23° 30′ N) to the Tropic of Capricorn (23° 30′ S); within this belt the sun's rays are perpendicular at some time during the year. At the spring and autumn equinoxes, the lengths of the day and night are equal everywhere over the earth.

Fruit trees such as mango, papaya, bananas, the annonas, avocado, acerola and guava show no response to photoperiod and are capable of flowering at any season of the year. In equatorial Colombia, with approximately 12-h day length, it is common to find mango trees flowering during February–March and again in August. In the subtropics, flowering is more precise, occurring in the spring as a function of lower temperature and moisture availability limiting growth. For guava, seedlings grown under 15-h day length from germination to 140 days and field transplanted produced fruit within 376 days from sowing; the control seedlings under 10-h day length did not flower. This result with guava reflects the longer period available each day for photosynthesis and not photoperiodism. Guava can also be forced to flower by pruning.

Pineapple can flower naturally at any time of the year, depending upon the size of the planting material, though it is a quantitative, but not an obligatory, short-day plant. Interruption of the dark period by illumination suppresses flowering. Though pineapple does not require low temperatures or diurnal variations in temperature to flower, there is an interaction with temperature. Temperatures lower than 17°C during short days can induce considerable flowering, even in small plants. No flowers are produced on yellow passion fruit (*Passiflora edulis* f. *flavicarpa*) vines under artificially induced short days (8 h). Long days promote passion fruit vine growth and flowering, while short days promote vine growth only. This observation, however, could be due to the amount of solar radiation received and not photoperiod.

Radiation

When compared to higher latitudes, the tropical latitudes have small seasonal variation in solar radiation along with high intensity. The longer summer day length at the higher latitudes means that these latitudes exceed the daily amounts of solar radiation received in the tropics. The highest annual energy input on the earth's surface, 12 MJ/m^2/day, occurs in the more cloud-free subtropical dry belt of 20–30° (Fig. 2.3). In the tropics, solar radiation received is reduced by clouds and water vapour in the air, through reflection and absorption, to a minimum of ~7 MJ/m^2/day at the equator. Over a large portion of the tropics the average is 9 MJ/m^2/day ± 20%.

In the tropics, atmospheric radiation transmissivity varies from 0.4 to 0.7, due largely to clouds and seasonal variation. The maximum recorded irradiance under cloudless skies at noon in the tropics is 1.1 kW/m^2, with a daily total received of from 7 to 12 MJ/m^2. About 50% of this energy is in the 0.4–0.7 μm waveband, which is known as photosynthetically active radiation (PAR). In full sunlight, C_3 plants, including all fruit crops discussed in this book except pineapple, which is a CAM plant, are 'light' saturated. This saturation is due to ambient CO_2 availability limiting the rate of photosynthesis.

High shade (3–5 MJ/m^2/day) does not influence litchi flowering, though it does increase early fruit drop. Flowering in passion fruit is reduced once irradiance falls below full sun. Irradiance is normally not a factor limiting plant growth in the tropics except during heavy mist and cloud, and in shade from other vegetation and mountains.

Temperature

Near the earth's surface, temperature is controlled by incoming and outgoing radiation. Surface temperatures are modified spatially and temporally throughout the year by local factors more than radiation. The main factors are continentality, the presence of large inland waterbodies, elevation modified by prevailing topography, and cloudiness. Highest diurnal temperatures occur in dry continental areas, at higher elevations and in cloud-free areas. The rate of decrease in temperature with elevation (adiabatic lapse rate) varies with cloudiness, hence season, and between night and day. The normal rate is about 5°C per 1000 m under cloudy conditions and can range from 3.1 to 9°C per 1000 m.

The human sensitivity to temperature is modified by the rate of evaporation. Evaporation from human skin is primarily influenced by humidity, wind speed and response to sunshine. A human can endure high temperature if the humidity is low; hence the discomfort felt in the humid tropics is associated with high temperatures and humidity (>25°C and >80% R.H.). These conditions are also favorable to growth of microorganisms and insects. The problem of controlling plant diseases and insect pests in the tropics is compounded by the absence of a cold winter and aridity to limit their adult development.

Tropical fruit crops such as mango, guava, acerola, papaya, pineapple, some annonas and others originated in the warm, lowland tropics. Others such as the litchi, Mexican and Guatemalan races of avocado, cherimoya and purple passion fruit are subtropical fruits by virtue of their origin in the subtropics or at higher elevations in the tropics. Man, in his attempt to commercialize tropical fruit crops, has extended production into subtropical regions beyond the Tropics of Cancer and Capricorn and has generated considerable knowledge on the range of temperature adaptability of these crops. Data on threshold temperatures and durations of exposure for various stages of plant development of tropical fruit trees are often unavailable; minimum temperatures in the coolest month that support survival, commercial or best production have been approximated (Table 2.3). The minimum temperature criterion takes into account differences in elevation and latitude. In regions subjected to marginal winter temperatures, site selection becomes a paramount consideration, such as southern-facing slopes in the northern hemisphere and northern-facing slopes in the southern hemisphere. Young plant growth may also be inhibited when soil temperature exceeds 35°C, a common condition in the tropics. Leaf temperature can exceed air temperatures by 20°C; for example, pineapple fruit and leaf temperature have been recorded in excess of 50°C in the field. Hence, maximum temperatures in the orchard microclimate need to be considered in site selection. Three crops (mango, litchi and avocado) illustrate this temperature adaptability and the varietal and race adaptation at various stages of development. Mature mango trees have been found to withstand temperatures as low as −16°C for a few hours with some injury to leaves. Flowers and small fruits may be killed when temperatures less than 4.5°C occur for a few hours during the night. Mango varietal differences for cold resistance have not been observed. Mango responds to cool night temperatures (10–14°C) with profuse flowering. Ideally, day temperatures during this period should be warm (21–27°C). When winter night temperatures are mild (16–18°C), flowering is more erratic.

Table 2.3. Guidelines for survival, commercial and best production of tropical fruit based upon mean minimum temperature in the coldest month (after Watson and Moncur, 1985).

		Mean minimum temperature (°C) for coolest month		
Crop	Botanical name	Survival	Commercial	Best
Acerola	*Malpighia glabra*	10–12	>12	>14
Banana	*Musa* spp.	6–8	>8	>16
Breadfruit	*Artocarpus altilis*	14–16	>16	>16
Carambola	*Averrhoa carambola*	6–8	>8	>14
Chempedak	*Artocarpus polyphema*	12–14	>14	>16
Cherimoya	*Annona cherimoya*	4–6?	5–12?	6–10?
Durian	*Durio zibethinus*	14–16	>18	>18
Duku and langsat	*Lansium domesticum*	12–14	>14	>18
Guava	*Psidium guajava*	4–8	>8	>14
Jackfruit	*Artocarpus heterophyllus*	6–10	>10	>14
Longan	*Dimocarpus longan*	4–8	8–18	8–14
Litchi	*Litchi chinensis*	4–8	>14	>16
Mango	*Mangifera indica*	6–8	>8	>12
Mangosteen	*Garcinia mangostana*	10–14	>14	>16
Papaya	*Carica papaya*	6–8	>8	>14
Pineapple	*Ananas comosus*	6–8	>8	>10
Rambutan	*Nephelium lappaceum*	8–12	>12	>14
Sapodilla	*Manilkara zapota*	6–10	>10	>14
Soursop	*Annona muricata*	6–10	>10	>16

Vegetative and flowering behaviour of litchi is very similar to mango, except that it is adapted to even lower minimum temperatures than mango. The total duration of relatively low temperatures seems to be the determining factor rather than the frequency or time of occurrence during a critical period. There are considerable cultivar differences in the temperature exposure necessary to induce flowers, e.g. 'Brewster' litchi flowers better in seasons with 200 or more h of temperature below 7.2°C. Other cultivars flower profusely when night temperatures of 14–15°C occur.

The three races of avocado originated under different ecological conditions. The West Indian race is best adapted to humid, warm climates, with the optimum around 25–28°C. It is susceptible to frost, and the minimum temperature tolerated by the foliage is recorded at 1.5°C. Mature trees of the Mexican race have shown tolerance to as low as –4 to –5°C without damage to foliage, although flowers are damaged. The Guatemalan race is adapted to a cool tropical climate but is less tolerant of low temperatures than cultivars of the Mexican race. The leaves of the Guatemalan cultivars have shown tolerance of light frost down to –2°C, with flower damage by even light frost. The Mexican–Guatemalan hybrids, such as 'Fuerte' have shown wider tolerance of cold than the Guatemalan cultivars. Temperatures of 12–13°C during flowering can prevent growth of pollen tubes and embryos, leading to production of unfertilized, underdeveloped fruits.

Rainfall

Temperature determines agricultural activity in the temperate regions of the mid-latitudes, while rainfall is the crucial factor in the tropics. The seasonal and diurnal distribution, intensity, duration and frequency of rainy days vary widely in the tropics, both in space and in time (Fig. 2.2). The maximum rainfall occurs near the equator, with no dry season. Surrounding this equatorial zone in Africa and South America are areas with two rainy seasons alternating with two dry seasons; rarely are the seasons of the same duration or intensity. Further from the equator is a region of minimum rainfall at 20–30° latitude, associated with the subtropical high pressure area, with one rainy season, frequently due to the monsoons. Topography can significantly modify the generalized rainfall pattern; examples include the western coast of India and Borneo, and the coastal areas of Sierra Leone, where monsoonal winds are forced to rise because of mountain ranges. Trade winds can bring considerable rainfall and are subjected to the forced rise by topographical features. Other factors influencing rainfall include changing and slowing down of wind speed as it approaches the equator and continentality, such as in south-west and central Asia. The above factors lead to complicated rainfall patterns, with broad generalization possible while remembering that there is considerable variation (Fig. 2.2).

Tropical fruit production is normally limited by available soil moisture. The stage of growth or development at which water stress occurs greatly affects the final yield and quality. Many factors influence the amount of rainfall available to plants, including evaporation and transpiration rates, surface runoff, soil water-holding capacity and percolation through the soil profile beyond the rooting area. Using the average tropical daily net radiation of 9 MJ/m^2 and the latent heat of vaporization for water (2.45 MJ/kg), an evaporation rate of *ca* 4 mm per day can be calculated. This evaporation rate is similar to that in a temperate summer. Higher rates of 10–15 mm per day occur for irrigated crops in the semi-arid tropics due to the advection of hot, dry air. Rainfall and irrigation need to make up this evaporative loss, and a mean monthly rainfall of 120 mm (~4 mm per day) would be required.

Excessive rainfall causes major problems with flowering, pests, diseases and fruit quality. Many trees, such as mango and litchi, require a dry (or cold) period to stop vegetative growth and induce flowering. Mango and litchi originated in areas with a monsoon climate that provides distinct wet and dry seasons.

Dry conditions, preferably accompanied by cool temperatures during the pre-flowering period, promote flowering, while cool, wet conditions reduce flowering in both crops. When mango flower buds begin to emerge, some soil moisture is needed, preferably from irrigation rather than from rainfall. Light rain during mango flowering leads to severe anthracnose (*Colletotrichum* spp.), which can destroy most of the inflorescences. Too much rain during litchi anthesis also reduces flower opening and/or the insect activities needed for pollination.

Total rainfall is frequently less important than its distribution throughout the year. In Loma Bonita and Acayucan, Mexico, two large pineapple-producing areas, mean rainfall over a 5-year period was 1600 mm and 1500 mm, respectively. These approximate the upper limits of the optimal range for pineapple; however, periods of serious drought are encountered, as 89 and 82%, respectively, of the rainfall occurs from June to November. In a tropical rainforest, 85% of a 1 mm shower may be intercepted by plants, but only 12% of a 20 mm rainfall, indicating that fall intensity, duration and frequency are significant factors. The interception by plants is significantly influenced by species; pineapple with its upright leaves funnels water to the centre. Plant density similarly affects rainfall interception.

Orchards located on flat lowland areas can experience flooding during the rainy season, particularly if drainage is poor. This is important for avocado, papaya, litchi and pineapple, for which waterlogging causes severe root-rot problems. Mango is slightly flood-tolerant, as indicated by reductions in leaf gas exchange, vegetative growth and variations in tree mortality. Mangosteen, by contrast, grows well under conditions of flooding and high water table. A high water table may prevent mangosteen trees from experiencing the moisture stress needed to induce flowering.

Water deficit, and therefore irrigation demand, is determined by evaluating rainfall, evaporation and soil water storage. The two most common approaches are the water balance (rainfall, evapotranspiration, water storage, change in the root range, surface runoff) and actual soil moisture measurement. The crop needs, along with the soil type, determine frequency of irrigation; this determination should be made on at least a weekly basis for fruit crops. The use of drip (trickle) and micro-sprinkler irrigation enables a grower to match the needs of the crop to irrigation needs at different stages of growth and development, avoiding the need to rely on rainfall. These irrigation methods allow precise placement of the water, reduce surface evaporation and seepage, and increase water-use efficiency. Other irrigation methods used are basin, furrow, overhead sprinklers and cannons.

Strong winds, frost and hail

In the equatorial zone, strong winds are associated with localized thunderstorms (diameter <25 km) having greater intensity than those in the middle and upper latitudes and lasting from 1 to 2 h. Most occur outside the 0–10°

latitude zone (Fig. 2.4) and are convectional in origin and associated with intense solar heating. Other strong winds can be due to sea or land breezes and unstable warm and humid air masses. Hail occurs rarely in the tropics except in the highlands, though it is known to damage tea in Kenya and tobacco in Zimbabwe.

Tropical cyclones (hurricanes, typhoons) are an almost circular storm system, ranging in diameter from 160 to 650 km and winds from 120 to 200 km/h, originating over water in the warm summer season. Most develop within latitudes 20° N and S of the equatorial belt and may turn north-east in the northern hemisphere or south-west in the southern hemisphere to 30–35° latitude (Fig. 2.4). These systems bring violent winds and heavy rains. The Philippines are very prone to such systems. Crop damage, especially to trees, can be very severe due to the high winds.

Monsoon depression is a less intense weather phenomenon. It brings 80% or more of the precipitation to the Indian subcontinent, with considerable year-to-year variation. It occurs when there is at least a 120° directional shift in prevailing wind direction between January and July. It is a characteristic of the wet and dry tropics and spreads from Asia to Africa. The intensity of rainfall can lead to considerable flooding.

In the subtropics, frost is a major limiting factor to tropical horticultural production. In isolated tropical high mountainous areas, frosts can occur frequently. Frost in the subtropics is associated with incursions of cold air masses (advection frost), while on tropical mountains it is mainly due to rapid cooling on clear nights (radiation frost).

Trees have inherent differences in the degree of resistance to winds, but all fruit species benefit from wind protection. Mango, acerola and guava exhibit greater resistance than other tropical tree crops such as banana, to the extent that they survive strong gusts of wind without losing limbs or being blown down. Leaves, flowers and fruits are often completely blown away. Pineapple, by virtue of being low growing, gives the appearance of resistance, but wind can damage leaves, and during the fruiting period the peduncles may be broken, resulting in loss of fruit. However, windbreaks are almost never found on pineapple plantations. The annona species, avocado and litchi are known for their brittle branches and show limb splitting even under moderate gusts of 65–80 km/h. Limb braces are occasionally used to prevent splitting of large limbs, forming 'Y' crotches on litchi trees. Guava trees propagated by grafting have tap roots that provide substantial anchorage. However, guava trees propagated by rooting cuttings or by air-layering are subject to uprooting during the first 3 years, probably due to faster top growth than root growth. Papaya plants and passion fruit vines are vulnerable to even moderate winds. Papaya trees are easily blown over, especially if the soil is softened by heavy rains. Passion fruit vines on trellises can be tangled and broken, or the entire trellis may be blown down. Developing carambola fruit is easily bruised and marked by rubbing on branches and adjacent fruits due to wind, reducing fruit

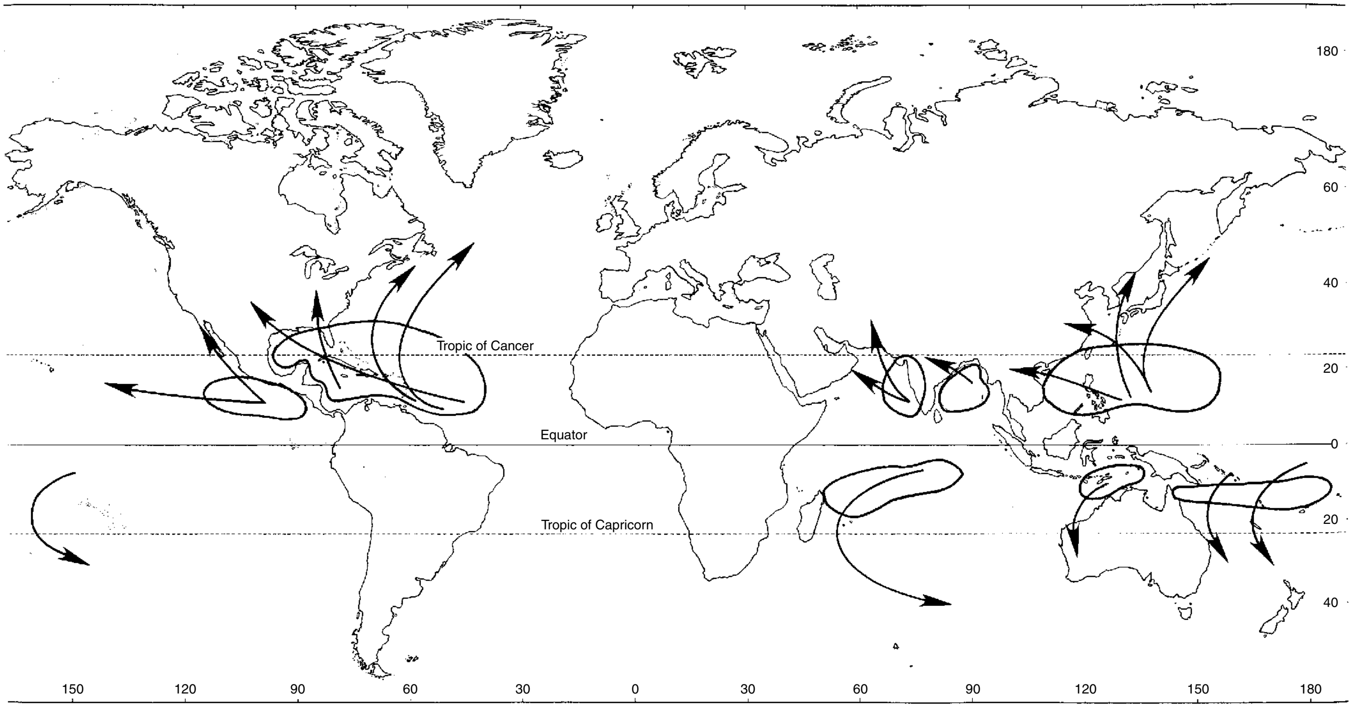

Fig. 2.4. Areas of tropical storm development, which can significantly influence fruit production in the tropics (after Gray, 1968). Tropical storms can uproot trees, break limbs and snap the top of the trees. For plants with large leaves, such as papaya and banana, the leaves can be shredded, with significant loss in photosynthetic capacity.

appearance and grade. Mangosteen trees may also require protection from full sun during early establishment as well as from wind. Windbreaks for these crops are standard practice (see Chapter 3).

Soils

Using the US classification system, soils are separated into ten groups, based on parent material, soil age and the climatic and vegetative regime during formation. Tropical soils are diverse, having formed from different parent material and climatic conditions (Fig. 2.5). These soils have formed in areas where the soil temperature at 50 cm differs less than 5°C between the warm and cool season. The parent rock materials are as different in the temperate zone as in tropics; erosion and deposition are similar; soil formation can have been from recent volcanic or alluvial flood plains to 1 million years old. The differences in temperate regions lie in soil-forming factors such as glaciation and movement of loess, which have not occurred in the tropics (Sanchez and Buol, 1975).

The majority of tropical soils are found in US soil orders oxisols, aridisols, alfisols, ultisols and vertisols and are spread widely throughout the tropics (Fig. 2.5). The soil orders are separated on the presence or absence of diagnostic horizons or features that indicate the degree and kind of the dominant soil-forming process. It is very difficult to make generalizations about tropical soils other than they have less silt than temperate soils and that surface erosion and deposition have been more significant. There are greater volcanic deposits in the tropics and a larger proportion of younger soils than in the temperate region. Only a small proportion (2–15%) of the tropics has so-called lateritic soils (oxisols and ultisols), defined as soils that have high sesquioxide content and harden on exposure (Table 2.4). The red colour of tropical soils does not mean that they have low organic matter. For example, the average organic carbon content in the top 1 m of a black North American mollisol is 1.11%, while red, highly weathered tropical oxisols may have 1.05%, the reddish temperate ultisols 0.4% and tropical ultisols 0.66%.

The more intensively farmed, fertile soils of the tropics cover about 18% of the area and are alfisols, vertisols, mollisols, and some entisols and inceptisols (Table 2.4). These soils generally developed from alluvium and sediment and are high in calcium, magnesium and potassium (Table 2.5). This gives them a high base status with no acidity problem. Phosphorus deficiency can be readily corrected. Larger groups of tropical soils (oxisols, ultisols and others) are of low base status, highly leached and cover 51% of the tropics (Table 2.4). Phosphorus deficiency can be significant as it is fixed by the iron and aluminium oxide in these soils, which also often have aluminium toxicity problems, with sulfur and micronutrient deficiencies (Zn, B, Mo, S). However, they have good physical properties. The high-base soils (aridisols) in tropical

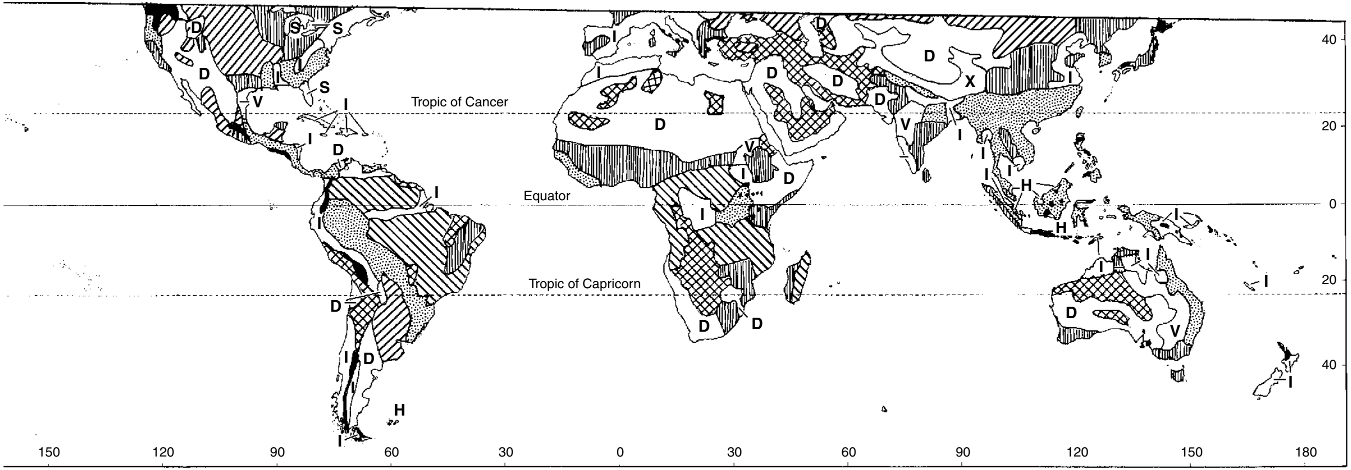

Fig. 2.5. Soil-type distribution in the tropics (after Kalpage, 1976; Sanchez, 1976). Tropical soils are diverse, having formed from different parent material and under different climatic conditions. Key: vertical lines – aridisols; cross-hatched – entisols; rising diagonal lines – mollisols; declining diagonal lines – oxisols; and speckled – ultisols. D – aridisol; I – inceptisol; S – spodosol; V – vertisols and X – mountain areas.

Table 2.4. Distribution of major soils in the tropics (after Sanchez, 1976; Sanchez and Salinas, 1981).

	Humid tropics[a] (%)	Seasonal (%)	Dry and arid (%)	Tropics (%)
Highly weathered, leached, red or yellow soils – (oxisols, ultisols, alfisols)	36	61	2	51
Dry sands and shallow soils – (entisol–psamments and lithic group)	10	33	58	17
Light-coloured, base-rich soils – (aridisols and aridic groups)	0	15	85	14
Alluvial soils – (inceptisol–aquepts, entisol–fluvents)	40	52	8	8
Dark-coloured, base-rich soils – (vertisols, mollisols)	8	60	32	6
Moderately weathered and leached soils – (inceptisol–andepts and tropepts)	7	59	34	4
% of tropics	24	49	27	100

[a] Classified on number of rainy months: humid tropics, 9.5–12 months; seasonal, 4.5–9.5 months; dry and arid, 0–4.5 months.

deserts (14%) can be very productive with irrigation. Nitrogen deficiency and sometimes salinity can be problems. The 17% covered by dry sands and shallow soils are greatly limited in agricultural productivity. The most important aspect is the development of management strategies for the different tropical soils, taking into consideration their unique properties. Management practices developed in temperate regions may not be directly transferrable.

Soil physical characteristics are of primary concern for tropical fruit production, with soil nutrients being secondary because they can normally be readily corrected. Soil texture and structure, soil water storage and drainage are crucial. Deficiencies in these characteristics are major constraints to production because they are difficult and expensive to correct. Under natural conditions, most soils considered for fruit crops in the tropics have a good topsoil structure. This includes the highly weathered oxisols and ultisols (Table 2.5). Loss of organic matter may lead to loss of structure and crusting of these soils after heavy rains. Some soils, however, do not favour root development due to a dense subsoil layer that needs to be broken during soil preparation to avoid shallow root systems. Heavy machinery may also cause the formation of a compact subsurface layer in medium-textured oxisols with low iron and in fine-textured oxisols. Low calcium and phosphorus and high aluminium contents in the subsoils can also restrict root growth.

Tropical fruit crops have shown a wide range of soil adaptability and have been observed to grow and produce well in a wide variety of soil types,

Table 2.5. Soil classification and main characteristics of tropical soils and orders.

Order	Characteristic	Agricultural productivity
Entisol	Recent alluvium, also on barren sands and near deserts. Lacks significant profile	Some very productive alluvial soils
Vertisol	Swelling clay. Cracks in dry weather	Productive, difficult to till
Inceptisol	Horizons forming, little accumulation of Al or Fe oxides. Tropic with long, wet season, acid	Very prone to erosion, good if well drained
Aridisol	Deserts, little organic matter, $CaCO_3$, $CaSO_4$ and soluble salts	Need irrigation to be agriculturally productive
Mollisols	Granular or crumbly soils. High in silt and organic matter	Most productive worldwide
Alfisol	Humid regions soil with grey or brown upper horizon and silicate clay below	Good soils, prone to erosion, easily compacted
Ultisol	Highly weathered, acidic in moist, warm tropical areas, moderate fertility	Very productive, easily compacted, prone to erosion, needs fertilizer
Oxisol	Highly weathered, in hot, heavy rainfall areas, deep clay of hydrous oxides of Al and Fe, can be very acidic, leached	Needs nutrients to be productive, susceptible to erosion if left bare
Andisols	Surface deposits of volcanic ash, free draining, low bulk density	Erosion serious problem, high P fixation, high Al and Fe fixation, excellent structure, productive

provided other factors are favourable. In some cases considerable management skill is required to maintain the crops in good growth and production. Soil pH can be corrected by liming during field preparation, with most trees preferring pH 5.5–6.5. Papaya is one of the few fruit crops that is adapted to a wide range of soil pH, growing and producing well in soil pH ranging from 5.0 to well into the alkaline range. Deficiencies in phosphorus associated with adsorption and excess aluminium need to be addressed in the oxisols, ultisols and some inceptisols. Soil organic matter can be maintained by use of manure, ground cover crops and mulches to preserve soil moisture and structure, and improve the rhizosphere. Magnesium, zinc and boron deficiencies may also be encountered in some tropical soils, but these are relatively easy to correct in a management programme. Saline and alkaline soils, along with deep peat soils, should be avoided for fruit production because of their difficult nature. Acid sulfate soils require specialized management strategies, such as raised beds, to be productive.

A prime soil requirement for all crops is good drainage to prevent waterlogging, which leads to root diseases. Drainage is crucial for crops that are susceptible to *Phytophthora* root rot, such as avocado, papaya, passion fruit and pineapple. Mango and avocado have been observed to show branch dieback in parts of fields in western Mexico with a water table around 50–60 cm below the soil surface.

CLIMATE CHANGE

Climate change is regarded as the most important threat facing the environment that will have a significant effect on society and agriculture. For the tropics, climate change is predicted to expand the tropical region, with significant changes in temperature (2–5°C increase) and rainfall (more variable). The predictions are made for large regions and the expectation is that there will be less rainfall near the equator and more rainfall, with greater variability, further away from the equator, in the current drier tropical zones (Easterling and Apps, 2005; Cerri *et al.*, 2007; Ingram *et al.*, 2008).

The predicted direct environmental changes include freshwater availability, carbon and nitrogen cycling, land cover and soils. All these changes will directly impact biodiversity and agricultural, including horticultural, productivity. It is expected that the induced biodiversity changes will lead to new pest and disease pressures and greater weed problems (Sutherst *et al.*, 2007). For example, aphids are expected to become an increasing pest because of their low development temperature threshold, short generation time and high dispersal ability. Pathogens may have higher growth rates and more generations per growth season. Weeds, with their more rapid growth and development, may be more favoured in comparison to crops.

SUMMARY

Whereas temperature is the major limitation to plant growth in temperate areas, in the tropics rainfall plays that role. There is considerable variation in tropical climates due to altitude, continentality and the presence of large bodies of water. Disease and insect problems are more severe in high-rainfall areas. Year-round plant growth is generally only limited in the tropics by moisture availability. Good soils are available in the tropics, and the high value of horticultural crops means that they can command the use of more favoured areas.

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3

Cultivation

Growing tropical fruit trees is a long-term investment, with harvesting not beginning for several years. The exceptions are the herbaceous fruit crops, banana, plantain and papaya, which will start producing marketable yields in less than 2 years. Perennial and herbaceous fruit crops involve large initial investment costs for site selection, land preparation, varietal selection, planting establishment, fertilization, irrigation, pest control, pruning and your own management costs. For perennial trees these costs will continue for several years before the trees come into full production. After the trees start to produce marketable volumes of fruit, the largest cost is for labour, and this is during harvesting. It is therefore very important to provide the best management possible so that the trees start fruiting as soon as possible and are in the best possible condition to maximize yield and fruit quality at the lowest costs.

MARKET ANALYSIS

Market analysis is the crucial first step in establishing a new orchard. This analysis will determine where the demand is for the products you plan to grow, how big the demand is and who are your competitors, and can the market be expanded. This analysis will enable you to decide if you will be able to sell the product at prices that will leave you with a profit. The most efficient production methods and the best varieties will not make up for an inability to sell your product. This detailed market analysis has to be done before venturing into this activity. Additional components in this analysis include knowledge regarding the best time of year for fruits to arrive in the markets for higher prices and what the market desires with regard to varieties and fruit quality. New or different varieties that have different quality characteristics (colour, texture, aroma, taste) can increase demand for a fruit and expand the current export markets and should be considered. Export markets are very competitive and the quality, including fruit safety requirements, is much more rigorous than for most local markets. Export windows when a fruit may command a premium price are becoming narrower. For many products, export markets have variety-specific quality requirements, with only one or a few varieties being in demand. Export markets will also require you to meet certification requirements with respect to how a product is grown and managed, working conditions and environmental stewardship. An example of a certification system is the European GlobalGap. All of these factors have to be carefully analysed before starting this business.

LAND SELECTION

The ideal land for a fruit orchard should normally be fairly flat with a deep soil of medium texture and good water percolation to enhance root growth. Soils with poor drainage are prone to be waterlogged during heavy rains, which can limit root growth and increase root diseases. Other soil chemical and physical properties must also be evaluated before starting an orchard. Investing a large amount of money in land that is not suited for the species to be grown will normally mean reduced yields and increased production costs. Many times the savings in purchasing cheap land with poor soil quality will be offset by the negative economic returns. For an annual crop, if a mistake is made in land selection and the wrong soil type is chosen, this will become obvious at the end of the first cycle, while for perennial fruit tree crops with a long juvenile stage it may take a number of years before the mistake is apparent. This mistake will be felt every year, resulting in large investment of money spent, not returned, or both. Careful land selection is therefore essential, and if you are not familiar with the area, the opinion of an expert will help. A number of key questions need to be answered (Fig. 3.1) before making a selection. A simple decision tree (Fig. 3.1) ensures that you evaluate the more important factors that can potentially impact production and economic return.

In many instances there is a tendency by farmers to plant fruit crops in the worst areas of their property. Producing fruit is normally a long-term investment and has large upfront costs of land acquisition, preparation, planting, establishment and management, and the expectation is for high returns. The best land available should be used for fruit crops in order to obtain the best possible economic return. In some cases marginal lands that are normally only suited for forestry or grazing can be used for fruit trees, but there is no reason to expect optimal profits. Irrigation systems using drip and micro-sprinkler with fertigation can provide water and nutrients to the plants, reducing the differences in orchard productivity between good and marginal soil types. The soil, in some situations, has become a place for the roots to establish themselves and the plants get water and fertilizers from the irrigation system, but these production technologies cannot correct the problems associated with poor soils that are saline, have poor structure and water percolation, frequently are waterlogged or have toxic levels of nutrients.

Land too steep	Yes →	Discard
No ↓		
Soil extremely heavy	Yes →	Discard
No ↓		
Irrigation impossible, long dry season	Yes →	Discard
No ↓		
Irrigation possible, long dry season	Yes →	Irrigate if economic
No ↓		
Soil too shallow	Yes →	Discard or prepare mounds
No ↓		
Very poor soil structure	Yes →	Discard
No ↓		
Poor soil drainage	Yes →	Drainage or subsoil if economic
No ↓		
Very high water table	Yes →	Drainage if economic
No ↓		
Too many salts in soil	Yes →	Leach if economic
No ↓		
Soil too acid	Yes →	Raise pH with lime
No ↓		
Soil very alkaline	Yes →	Lower pH with sulfur
No ↓		
Saline sodic soil	Yes →	Normally discard
No ↓		
Hardpan or plough pan	Yes →	Subsoil adequately
No ↓		
Soil poor in macronutrients	Yes →	Add macronutrient before planting
No ↓		
Soil poor in organic matter	Yes →	Add organic matter, green manure
No ↓		
Previous crop was the same	Yes →	Make sure no negative effects for new crop, otherwise discard
No ↓		
Previous crop heavily root diseased	Yes →	Avoid susceptible species, otherwise discard
No ↓		
Persistent weeds	Yes →	Choose clean land if possible
No ↓		
Heavy nematode infestation	Yes →	Add organic matter heavily, use non-host crop or discard
No↓		
USE LAND		

Fig. 3.1. The major steps in deciding whether land is suitable for a tropical fruit orchard are set out as a decision tree. Going through the questions allows a decision to be made as to suitability.

Soil evaluation

The soil on the selected site should be appropriate for the species you plan to grow to improve the chances of success. Soil preparation and management, including liming to change the pH, provide some flexibility with a soil that has a good structure. If the soil is improperly treated it will not provide the best conditions for plant growth and production will not be the ideal.

The results from the physical analysis of the soil will determine its texture and structure, water retention and drainage. These characteristics, if unfavourable, can be very serious production constraints and are difficult and expensive to modify. Most soils considered for tropical fruit crops have good topsoil and subsoil structures. Since fruit trees often have deep root systems, poor subsoil conditions, such as a perched water table, will not allow root growth below it. Other subsoil problems, in addition to a high water table, are associated with the existence of rocks or hard soil layers. The presence of a heavy soil layer above a sandy layer or the opposite can lead to difficulties for water drainage. An easy way to determine this is to dig three or four trenches to 2–3 m scattered over the planned site to evaluate the soil profile.

Soil chemical analysis will tell you the soil's nutrient content, pH, salinity and alkalinity levels, organic matter content and the presence of elements that could be toxic. Soils with undesirably low pH (<4.5) are frequent in the humid tropics. This acidity is corrected by incorporating lime during land preparation and often during the life cycle of the crop. Liming should raise the pH to adequate levels of around 5.5–6.5. Some crops can do well in a wide range of pH values while others need a narrower range. A frequent problem in tropical soils is low calcium and phosphorus levels and high aluminium availability, in addition to magnesium, zinc and boron deficiencies. These deficiencies can be corrected by an appropriate fertilization programme and liming. In arid tropical zones, soils with high pH and low phosphorus availability, with deficiencies in iron, copper, manganese and zinc due to the nutrient being in a non-soluble, unavailable form, are common and most can be corrected by fertilization. Soils with high salinity or alkalinity should be avoided since they can be very costly to correct. The soil organic matter content should also be adequate and be maintained or increased if necessary by the incorporation of manure or green manure crops. Soil organic matter improves moisture and nutrient retention, maintains soil structure and enhances biological life in the root zone (see Chapter 2 for more information).

Irrigation water

The potential irrigation water's quality needs to be determined. The salinity and sodium level in relation to calcium and magnesium (sodium adsorption ratio or SAR) are evaluated, as these parameters can cause problems with perennial crops in arid zones (Table 3.1). The data will enable a decision to be made on usage, as species and varieties vary in their salt tolerance, with some crops being very susceptible to salt injury (Table 3.2).

Previous land usage

A replant problem can exist with some fruit crops. Peach trees are probably one of the best examples in a deciduous fruit crop; replanting into old peach orchard areas often leads to failure due to chemical substances left by the initial crop that can affect the growth of the replanted crop (allelopathy) (Rice, 1974). This is sometimes referred to as soil fatigue. Another cause of replant problems can be due to fungi, bacteria or nematodes that were hosted by the former crop. Plants of the *Solanaceae* family are very prone to being infected by root fungal diseases, bacteria and nematodes, and therefore it is recommended not to plant a species of this family right after another. Citrus are also known to show this problem. In many cases, the only solution to this soil fatigue is crop rotation, which can last as much as 10 years using different species, including grasses, before planting the same crop again. The alternative is to plant a crop that will not be affected by the above factors.

Planning

The collection of all the above data before land preparation allows you to plan and cost out the project before starting. Potential problems can be avoided by in-depth planning and making decisions on species and variety, rootstock, soil management practices, irrigation system and fertilization practices. The analysis could also lead to the possibility of rejecting a particular field or farm because the soil or water is not suitable for the fruit species to be grown. If the grower lacks the proper background knowledge about these matters, a soil specialist should be consulted to assist in making the right decisions to avoid unnecessary expenses and future problems. Most tropical fruit crops have a

Table 3.1. Irrigation water quality for tropical fruit trees.

Water quality	Conductivity (dS/m)	TDS (total dissolved salts) ppm
No detrimental effects	0.25	175
Sensitive crops could be affected	0.25–0.75	175–525
May have adverse effects	0.75–2.0	525–1400
Salt-tolerant plants only	2.0–3.0	1400–2100
Unsuitable	>3.0	>2100

Table 3.2. Salt tolerance of different fruiting trees. Adapted from Campbell and Goldweber (1985) and Maxwell and Maxwell (1985).

Good	Moderate	Fair	Poor
Carissa (Natal plum)	Akee	Atemoya	Ambarella
Coconut	Bignay	Barbados cherry (Acerola)	Avocado
Tamarind	Black sapote	Cherimoya	Banana
Date palm	Canistel (egg fruit)	Cherry of Rio Grande	Caimito (star apple)
	Cattley (strawberry)	Citrus (rootstock dependent)	Carambola
	Guava	Custard apple	Cashew
	Fig	Grumichama	Jaboticaba
	Governor's plum	Illama	Longan
	Imbu (*Spondias tuberosa*)	Imbe	Lychee
	Indian jujube	Kei apple	Macadamia
	Jackfruit	Kumquat	Mango
	Jelly palm	Mamey sapote	Papaya
	Key lime	Miracle fruit	Passion fruit
	Loquat	Mulberry	Strawberry tree
	Mayan breadnut	Otaheite gooseberry	
	Monstera	Persimmon	
	Pineapple guava	Pineapple	
	Pomegranate	Pitomba	
	Prickly pear	Soursop	
	Pummelo	Sugar apple	
	Purple mombin	Surinam cherry	
	Rose apple	Wampi	
	Sapodilla	White sapote	
	Spanish lime		
	Tangerine/mandarin		
	Wax jambu		

fairly broad range of adaptability and are grown in a wide variety of soil types, provided other factors are favourable. Ideally the best soils and irrigation waters should be used and, as with other crops, proper management is always important to obtain an efficient and sustainable production.

It is normally assumed that fruit trees need a soil profile that is at least 0.5 m, and ideally more than 1 m, deep, so that roots can grow down to that depth. This is not always the case since many tropical fruit trees are shallow-rooted. In instances where the soils are much shallower, either because parent rock is near the surface or because the water table is close to the surface, good profitable production can be obtained. Fields with a shallow water table can be drained or fragile parent rock can be cracked by ripping. Soils with a 'caliche', a natural hard, crusted layer of calcium carbonate found in arid zones, can be ripped or a hole bored through to allow root penetration.

Weeds in some areas can be very difficult to control. Areas heavily infested with aggressive and persistent weeds like nut sedge (*Cyperus* spp.), Johnson grass (*Sorghum halepensis*), Bermuda grass (*Cynodon dactylon*), star grass (*Cynodon nlemfuensis*) and others are best avoided. They can be eliminated but it will take time, effort and money.

Mountainous land

Fruit orchards are commonly located on fairly flat land, as steep and mountainous land is more expensive to prepare and carry out field management. The advantage of mountainous land is that it is often cheaper and usually has not been used for any fruit crops previously and is more likely to be free of many parasites, weeds and chemical residues common in other areas. Mountain soils need to have good soil texture and depth to allow for good root establishment and growth. Erosion can be a problem on steep hillsides, so care has to be taken not to eliminate the low vegetation and to plant on the contour to minimize erosion. Terraces built along the contours often have deep soils, though these terraces are expensive to build and maintain. Individual terraces for each tree are also used. Drainage will normally not be a problem under these conditions.

Irrigation of steep hillsides can be difficult, especially in the arid tropics or tropics with a long dry season. An expensive irrigation infrastructure is needed, which includes tanks to store water at the highest elevation and pumps to fill the tanks. In older orchards, contour irrigation systems are seen, with newer orchards using drip irrigation and micro-sprinklers. The flexibility of drip and sprinkler systems is that they are not limited to flat land and can be used very easily on steep hillsides and on stony or poorer soils. Once the water is pumped to the tank at the highest part of the orchard, gravity can be used with pressure compensation drippers. Pressure-compensated drippers emit equal amounts of liquid along the system, with a range of supply pressure.

LAND PREPARATION

In virgin areas, land preparation for fruit crops can be as simple as just removing the trees and other vegetation before digging a planting hole. This approach was used by the companies for banana plantations in Central America. In mountainous areas, land preparation is normally by hand or with small motorized equipment; larger machinery normally cannot be used. Large trees and bushes are removed with the low vegetation left, and individual holes are dug for each tree. This could include making a small terrace with the planting hole at the centre.

A hard layer or hardpan can be present in previously cultivated land (Fig. 3.2). These layers can develop in soils that have been cultivated with heavy equipment when the soil was too wet or where the plough passed many times at the same depth (plough pan). This hard layer (Fig. 3.2b) is eliminated by subsoiling or ripping of the soil deeper than the hard layer (Fig. 3.2c). This disruption of the hard layer (Fig. 3.2a and b) will allow better root penetration into the subsoil. Subsoiling involves using a heavy tractor or bulldozer pulling subsoiling hooks or rippers that are set to rip to 50–200 cm (Fig. 3.2c), with a second pass done at a 45° angle to the first pass (Fig. 3.2d). Some other subsoiling techniques use a torpedo-shaped device that is pulled with a cable and leaves an underground passage that improves water and air circulation. This operation should normally be done when the soil is dry in order to be effective.

Subsoiling and ploughing can be used to incorporate any fertilizer or amendment to the soil. Typical amendments include manure to increase organic matter, sulfur to lower the pH or lime to raise it, or any element that will be in big demand can be incorporated at this time, when it is easier than after planting. Phosphorus and other elements can also be incorporated deeper into the soil and will be more effective, since mobility when applied on the surface is very poor. If there are different soil layers, then subsoiling will also help to mix and homogenize the layers, with large pieces of roots from the previous crop normally being removed. When a very hard underground 'caliche' layer is present, subsoiling is not normally practised but a hole is made through the layer using an auger or pointed steel rods to allow roots to penetrate further

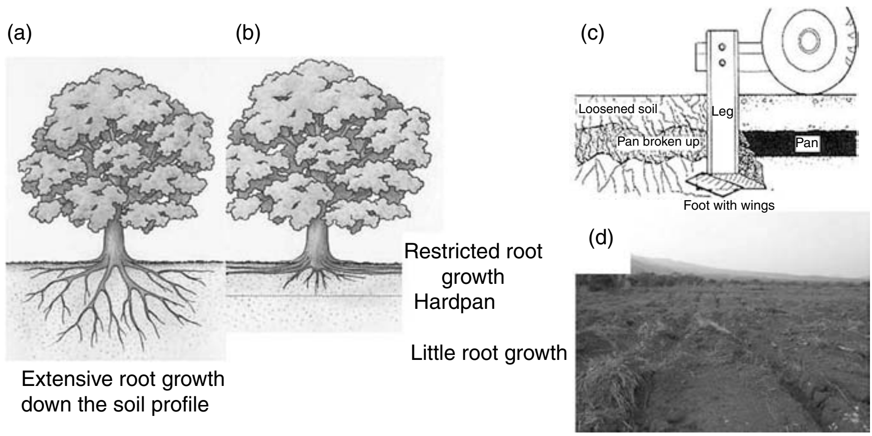

Fig. 3.2. Root development of tree crops mainly occurs in the top metre of the soil profile (a); a hardpan can restrict root growth (b) and the hardpan needs to be broken by a subsoiler (c). The tine of the subsoiler rips through the hardpan and allows roots to penetrate. Subsoiling should be done with two passes of the field at about 45° to each other.

down the soil profile and for water to drain to the subsoil. Dynamite has been used to crack superficial rocky soils, especially if the rocks are of coralline origin or calcareous; this was done in large areas in Cuba. A small hole the size of the dynamite piece is bored into the rock and then exploded to crack the rock and leave a passageway for water and roots to penetrate.

Stones can be another problem during land preparation, though not as much as with annual crops. Ideally all rocks and stones should be removed, especially from the soil surface, in order to ensure that the machinery will have no problems in moving around and will not be damaged. In very stony areas, removal is uneconomic and only large and medium stones on the surface are taken from the field so vehicles can move freely in the orchard and mowing can be carried out. Stone removal should preferably be done after subsoiling and ploughing, so that most large stones will be on the surface. Often the stones are used to build boundary fences. Alternatively, the stones are used to fill depressions, holes or ditches in the field or throughout the farm. The next step is ploughing the whole field, sometimes in two directions, with large stones again being removed. Ploughing is followed by discing to break up the larger clods and make the field ready for planting. Land levelling is sometimes performed, especially if furrow irrigation is to be used; with drip or micro-sprinklers this will not be necessary. If surface flood or furrow irrigation is used, the furrows need to be cut at this time, along with soil fumigation, if required, and planting holes made.

DRAINAGE

Drainage is needed for most orchards, especially when the land is flat and the soil has a low water percolation rate. Failure to provide drainage can mean waterlogging and standing water remains in the field for more than a few hours. Standing water in flooded fields means that the soil atmosphere will soon become depleted of oxygen and become anaerobic. Anaerobic conditions cause stress to most tropical fruit tree roots, limit nutrient uptake and make the roots less able to resist soil-borne pathogens such as root rots due to *Phytophthora* and other fungal pathogens.

Drainage is accomplished with ditches and sometimes with interconnected subsurface drainage pipes. This can be an expensive investment. On gently sloped land, plant rows are normally oriented to follow the maximum incline so that the excess water flows downhill. This orientation is possible if the slope does not exceed 10%. When the slope is greater than 10% transverse ditches will be needed to slow down the water speed, and these transverse ditches are connected to the main drainage ditches. In mountainous areas, tree rows normally follow the contour, so as not to create an erosion problem when it rains. Swales along the contour or ‘French drains’, which consist of a system of ditches filled sequentially with stones and gravel and sometimes covered with soil, are used. These drains slow the rate of water flow and allow the water to infiltrate into the soil. In most cases, swales are left open and they carry the water to a main ditch or creek. In heavy rains, these shallow swales are overloaded and can lead to significant erosion.

Raised beds are recommended when root rot-susceptible crops such as papaya, passion fruit, avocado and pineapple are grown on level land (Fig. 3.3). The deep furrows created between the beds drain away the excess water (Fig. 3.3a). These furrows can be used for irrigation during the dry months. In fields with depressions or under wet or in heavy soils, planting the tree on a mound reduces the problems due to waterlogging (Fig. 3.3b). The mound height depends upon the magnitude of the flooding problem, with around 25 cm being common. Taller mounds increase the orchard layout costs and consideration should be given to field-levelling grading, leaving only a gentle slope. Levelling or land shaping is practised in some pineapple-growing areas. The shaping is done with heavy machinery by making a successive series of wide and not very steep mounds so that the excess rainwater runs into their lower parts, to be drained from the fields. This shaping maybe done in addition to the use of raised beds that are oriented so that their furrows conduct water to the lower parts of the field.

The banana industry is very sophisticated in its drainage infrastructure in the wet tropics. Bananas do not tolerate a high water table or long periods of soil saturation. A successive series of parallel, open drains 1.2–2.5 m deep every 40–60 m, referred to as tertiary drains, are dug. These drains are designed to keep the water table at the desired depth and also to collect runoff that is not absorbed by the soil. Shallow drains (quaternary drains) are dug

(a) (b)

Fig. 3.3. Drainage is a major concern for tropical tree fruit production in areas with high water tables or heavy rains. Trees are grown on raised beds (a) and planted on mounds (b).

with shovels to the tertiary drains after a heavy rain to drain areas where water accumulates in the field, so that the excess flows into the tertiary drains. Tertiary drains conduct the water to 2.5–4.0-m-deep secondary drains, which in turn will drain the water into a river or creek or a primary drain that can be 2.5–6.0 m deep.

PLANTATION LAYOUT

A contour or 'Google' map of the farmland is ideal to start layout planning. The map should ideally include the location of buildings, farm boundaries, roads, fences, irrigation water supply and drainage ditches. Decisions are then made on the direction and length of the tree rows, the number of plants, the need for additional interior roads for transporting materials or products to and from the field, and location of additional structures such as storage and machinery sheds and packing facilities.

The length of the rows will depend on the type of soil and irrigation; if irrigation is by furrows or basin, rows that are about 60–80 m long in light soils and 120–180 m in heavy soils would be a starting point. Rows that are too short are not convenient for efficient machinery movement. The direction of the rows should take into account the water movement from both irrigation and runoff.

Using the layout map the easiest way to start in the field is to confirm that the direction chosen for the tree rows on the layout map is the best and make appropriate corrections in the field. Use a long string or rope stretched to follow the direction chosen and then stake each end. These stakes serve to establish a 90° angle at each end to start the geometric layout pattern. At each of the ends use a measuring tape with the 0 m mark at the stake and mark the point on the rope 3 m from the stake, then mark another point with a stake 4 m in a perpendicular direction to the rope, adjust the position of this stake so it is 4 m from the end stake and 5 m from the 3 m mark on the rope. The 5 m line is the hypotenuse of your triangle and a 90° angle is formed at the stake. At the other end of the rope repeat the same procedure, so you have two parallel lines. Measure on both parallel lines an equal distance to confirm that the distance between these two points is the same as the distance between the first two stakes. If the same, then you have parallel lines, if not you will need to recheck the two triangles so that a square or rectangle is formed. Then all four corners are staked and new stakes are put in or the spots marked with gypsum or lime at the distances the trees or rows will be and repeat on the other side. Then a rope or wire is pulled between the matching stakes of the opposite sides and at the perpendicular lines the same is done. Where the ropes or wires cross a stake or a lime mark is left, which will indicate the location to dig a planting hole.

Orchards are usually planted following geometrical arrangements (Avilán *et al.*, 1989), depending on the land condition, the species, variety, plant shape, planned pruning and need for machinery. Planting layouts between trees can be square (Fig. 3.4a), rectangular (Fig. 3.4b), an equilateral triangle or hexagonal system (Fig. 3.4c) or some other combination, including extra or temporary plants to increase returns during the initial juvenile years (Fig. 3.4d, e and f). If a rectangle layout is used (Fig. 3.4b), the trees will form this geometric figure; the longer side will correspond with the distance between tree rows and the shorter side will be the distance between trees in the row. In the square arrangement (Fig. 3.4a), the distances in both directions will be the same, and in the equilateral triangle normally a plant will be planted in each angle, forming triangles or a hexagon that has a plant in its centre (Fig 3.4c), and this gives 15% more plants per area than the square system while leaving the same distance between trees.

The rectangular layout is used when bulky machinery has to enter the field, although in the square layout this can also be done in the initial years also. Sometimes a square pattern can be used and every few rows a wider row is included in the layout. The wider row is left to allow movement of machinery. The location of the wider row will depend upon the length of hoses or how far the sprayers can reach and the distance you need to move harvest bins or boxes to facilitate fruit collection. Between-plant distances are shorter for plantains, bananas and papayas, and in hilly conditions where heavy or bulky machinery will not be used, normally a square or, better, a triangular arrangement should be used. The distance between trees will be the same in the square and equilateral triangle arrangement, with the latter resulting in more plants per unit area.

To maximize early income, the quincunx (Fig. 3.4d) and other systems are used. The quincunx consists of a square arrangement with a temporary or extra plant at the centre of each square. This arrangement almost doubles the number of plants per unit area and allows higher production during the initial years. Another intensive initial planting system consists of planting a temporary plant in the space between the permanent plants in the row (Fig. 3.4e); this will duplicate the initial number of plants. An even more intensive initial planting system consists of planting three temporary plants for each permanent plant. This intensive planting has an extra row of temporary plants between two permanent plant rows and an extra temporary plant in all the spaces between the plants in the rows, even in the temporary rows (Fig. 3.4f). As the trees start maturing and yield increases, the extra trees are pruned and later removed. This system is not recommended for all crops or all growers.

PLANTING DISTANCES

Planting distances will be determined by many factors, the most important being the species. Tree size and shape can vary from large trees like mango to small plants like papaya or banana. The variety can play a significant role,

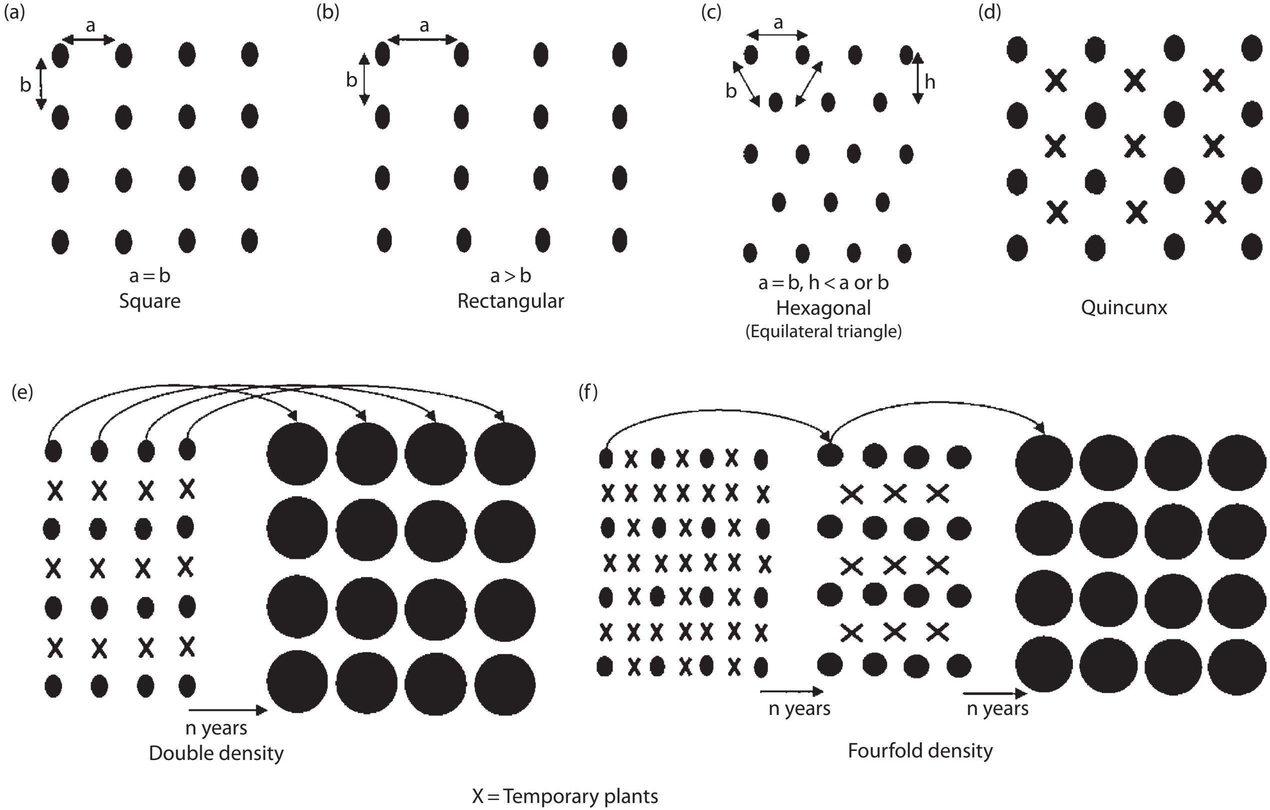

Fig. 3.4. Field layouts can be as a square (a), rectangle (b), hexagonal (c) or quincunx (d). In denser planting for the early orchard years, a double planting (e) or a fourfold density (f) can be used – the plants indicated by 'X' being removed after a number of years to avoid overcrowding. On steep land the layout may need to be modified with trees planted on the contour.

with different growth vigour and habits. Varieties can be compact compared to the traditional size, or their canopy shape can vary from wide to narrow. Rootstocks will also play a vital role in tree vigour, varying from very vigorous to dwarfing rootstocks. Sexually propagated plants are normally larger than their asexually propagated counterparts. Another factor that can modify distances is how large the tree will be allowed to grow and the pruning and shaping carried out during initial growth. For example, a tree pruned into a vase shape will be wider than a tree left with a central leader, while a tree trained in a palmette system will be wide only in one direction. The severity of pruning also plays a role.

Soil quality influences final tree size, with trees grown in poorer soils being smaller. Rainfall pattern and its amount in non-irrigated areas can also reduce tree size. Sometimes the harvest practices, irrigation or the spraying system can modify certain distances or at least make it necessary to leave some broader spaces among certain tree rows. The exact distance will be difficult to establish if the crop has never been grown in that area. An approximate distance can be established, sometimes with the help of an expert (Table 3.3).

In the middle of the last century, orchards were planted at densities of less than 250 trees per hectare; today, tree density ranges from 200 to 2000 plus trees per hectare. In the past, tree spaces were based upon the distances required for the adult trees; this meant a lot of wasted space before the ground area was covered by the canopies. This practice led to a higher cost of weed control and spraying and increased harvest cost, as tall trees (>3 m) are more expensive to collect fruit, requiring ladders and mechanical platforms. This adult-form concept has now changed, with a more pressing need to recover your initial investment as soon as possible and reduce your overall management cost associated with large, tall trees. One system being used is to plant at much shorter distances, and as the trees become larger, the so-called temporary or filler trees are pruned so as to reduce interference with the growth of the permanent trees. Finally, the temporary trees are removed completely to avoid further competition. A second thinning of the remaining trees is sometimes performed once they have grown larger, in order to leave the final number of trees per area. This system will require larger early investments in trees and maintenance, which will need to be balanced against the larger returns and income during this early orchard development period. In some situations, this practice may not be worth the extra cost and alternatives such as short-cycle vegetable crops or even widely spaced banana or papaya may be alternatives.

PLANTING

In a good soil with irrigation and which has been properly prepared, a planting hole slightly larger than the container holding the root-ball can be used. This is normally a 30 by 30 cm or a 50 by 50 cm hole made using shovels or augers.

Table 3.3. Some examples of recommended between-tree and row spacings in tropical orchards for some fruit crops.

Crop	With fillers (m)	Trees/ha	Permanent spacing (m)	Trees/ha
Acerola	2.7 × 5.5	673	5.5 × 5.5	332
			4.6 × 5.5	395
Atemoya	4.5 × 9.0	247	9.0 × 9.0	124
			8.0 × 12.0	104
Avocado	4.5 × 6.0	370	9.0 × 12.0	93
	6.0 × 7.5	222	12.0 × 15.0	56
Fuerte	7.5 × 7.5	177	15.0 × 15.0	44
Hass	7.0 × 7.0	204	14.0 × 14.0	51
Cherimoya			5.0 × 6.0	333
			5.0 × 7.6	263
Durian			10.0 × 10.0	100
Guava	3.1 × 7.6	424	6.2 × 7.6	212
			4.6 × 7.6	286
Litchi	5.0 × 5.0	200	10.0 × 10.0	100
	6.0 × 12.0	139	12.0 × 12.0	69
Mango	5.0 × 10.0	200	10.0 × 10.0	100
	12.0 × 12.0 (+ one tree in centre)	138	12.0 × 12.0	69
Papaya			2.4 × 3.1	1344
Passion fruit			3.3 × 4.0	1324
Sapodilla			6.6 × 6.6	400
Soursop	3.7 × 7.6	356	7.4 × 7.6	178
			6.0 × 9.0	185

A large hole may be used in poor-quality soils or in good-quality soils with no supplementary irrigation that depend only on seasonal rainfall. A hole of 80 by 80 cm or 100 by 100 cm is filled with a good substrate so that during the initial years the plant will grow vigorously before the roots reach the poor or dry soil area.

When the hole is dug, keep the topsoil in one mound and the subsoil in a separated mound since they normally differ in quality, with the topsoil being better. Before planting, mix the topsoil with organic matter such as matured moist manure or decomposed coffee pulp or any composted product and fill to the 40–50 cm mark of the 80–100 cm depth, then topsoil is added to about 30 cm from the soil surface and compacted by stepping on the materials in the hole. The topsoil without manure is placed next to the root-ball since fresh manure can burn the roots as it starts decomposing if in direct contact. Manure can burn the roots either by the elevated temperature produced by decomposition or by the salts that it releases. If the manure is well decomposed or a composted organic matter is used, then it is not necessary to separate the material and the hole can be filled with the mixture of topsoil and decomposed manure.

The root-ball can be set in place with a 20-cm-wide ring of topsoil around it. The remaining part of the hole is then filled with topsoil, or ideally with the mixture of topsoil and composted organic matter, and compacted so the plant stays firmly in position, and the root-ball is in close contact with the surrounding soil medium. This will allow new roots to grow rapidly into the surrounding soil without problems. If the subsoil is of poor quality, topsoil from neighbouring areas can be used and then these areas can be backfilled with the subsoil from the hole. It should be remembered that most of the feeder root activity occurs in the upper 50 cm of the soil. Large holes provide much better growing conditions than a normal hole. When establishment is dependent upon seasonal rainfall and irrigation is not available, planting should occur just prior to the wet season. It may be necessary to water the plants under these circumstances using buckets during the first 2–3 years to give the plant a much better start.

PLANTING MATERIAL

Often new growers will purchase planting material that is not of the highest quality or the best variety. This practice leads to poor tree establishment, poor yield or poor fruit quality. Having to replant an orchard is expensive and it should be avoided. Plant quality is determined by several criteria.

Plant identity

Most tropical fruit trees are a combination of a varietal scion and a rootstock. Alternatively, cuttings, air layers or vegetative organs like suckers and runners are used. For herbaceous fruit trees such as papaya, seeds are used. It is necessary to ensure the plants are the variety that you want. In grafted or budded plants the identity of the scion has to be known, and in many cases it is also very important to know what rootstock was used. Rootstock choice is crucial for some fruit species, and it has to be a very specific variety or type in order to allow the tree to grow well under determined soil conditions in the presence of certain plant pests and diseases and to produce good-size plants. For some species, choice of rootstock is not so crucial, as it serves only to propagate the desired variety by grafting or budding.

Plant health

The plant needs to be free of the most important diseases so that it does not contaminate the fields with new pests (disease, insect or nematode). Occasionally, new weeds can be introduced via the substrate the plants were grown in.

Anatomical and physical aspect

It is best to use plants that are anatomically well formed with a straight and strong main stem (Fig. 3.5a). The plants should be healthy and vigorous and be inspected to make sure they have a good root system and a straight stem with a good caliper. There should be no pronounced bends in the 'neck' – the zone that separates the root from the stem – which indicate an improper seed or embryo position at sowing time. The bends in the neck are due to chance or bad sowing position plus a lack of proper sorting of the seedlings when transplanted to the containers, These seedlings should be discarded at the time of the first transplant in the nursery or at the time of purchase. The bent condition is more of a problem in seedlings from polyembryonic seeds like citrus and mangoes of the Indochina–Philippine group. The mangoes of this group form many embryos, which compete for the space that is normally for one embryo, resulting in abnormal growth and entanglement and bending.

Plants with bends in the main roots at the bottom of the root-ball or with a mesh of roots around it indicate they have stayed far too long in the container (Fig. 3.5b). Ideally plants with these problems should be discarded. If needed or because of scarcity of planting material they can be used, but the peripheral roots have to be pruned away and the root mesh disrupted by making several longitudinal cuts in this layer with a sharp knife. The objective is to ensure that this abnormal growth pattern does not continue and that new roots will emerge from the root-ball and grow outwards. When the primary root at the bottom of the root-ball has a bend, it should be cut above the bend to eliminate this abnormal growth pattern. This root pruning will result in root loss and a plant with reduced water and nutrient absorption capacity. The recommendation is to defoliate the plant to reduce potential transpiration and balance the root absorption with leaf transpiration. Failure to defoliate can lead to plant dehydration and death. This defoliation and root pruning will retard plant growth and therefore all plants with manipulated roots should be planted together in one area of the field so that they can be given additional care. Their growth will be initially slightly behind the other transplants that have intact roots. Similar procedures should be used if the root-ball cracks or breaks during transplanting, or if too damaged then discard.

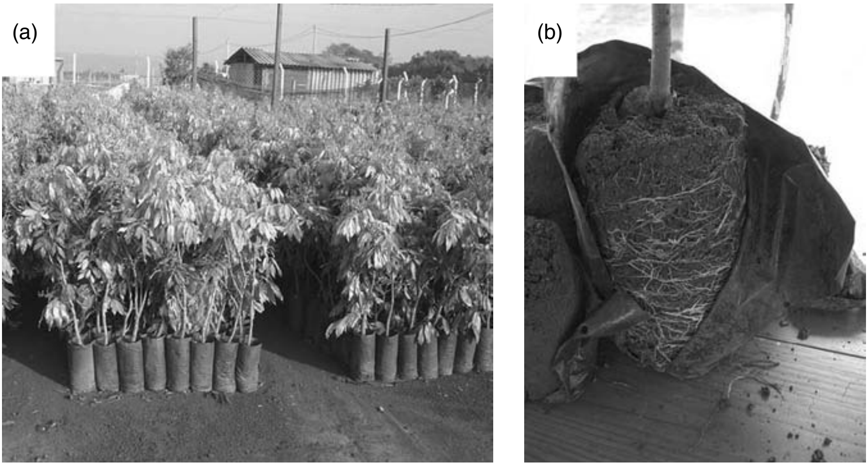

Fig. 3.5. Nursery production of planting material is crucial for the successful development of an orchard. Black plastic bags are frequently used (a). It is important to ensure that the plants are not allowed to stay too long in the bag or they become root-bound (b), with the roots growing around the outside of the medium against the inside of the bag.

ASSOCIATED CROPS OR INTERCROPS

After or before planting the trees, an associate crop can be started, in order to maximize the use of land and, hopefully, get extra income during the first years, which are the most difficult economically. This could be any annual crop, including vegetables or a short-cycle fruit crop such as pineapple, cocona (*Solanum hyporrhodium*) and naranjilla (*Solanum quitoense*). In some areas intercropping in orchards with vegetables, leguminous crops and cucurbits is a common practice. In Mexico, fruit orchards have been observed with excellent intercrops of beans (*Phaseolus vulgaris*), watermelons (*Citrullus vulgaris*), cantaloups (*Cucumis melo* var. *reticulatus*) and chilli (*Capsicum annuum*). Good weed control is obtained under these intercropping systems.

In the second and third years, intercropping can be repeated, but the soil should only be worked between rows at an increased distance from the fruit trees each year. This reduction in cultivated distance is required to avoid root damage, which can weaken the plants or become an entry point for harmful organisms. It is normally recommended that after 3 or 4 years no soil disturbance by heavy machinery should occur except for the pass of mowers or brush cutters and the equipment for spraying and harvesting. An alternative is to kill off the ground cover with herbicide and transplant the intercrop directly without soil disturbance.

Short-lived fruit crops such as yellow passion fruit or papaya (Fig. 3.6) can be planted between rows, and after 2 or 3 years they will normally be at the end of their production cycle. Plantain and banana could be also used, making sure their shade does not affect the small trees; after a reasonable time they can be eliminated and the propagating material taken to another location. Care has to be taken during the first years not to allow any large plants to grow close to the young fruit trees since they may check their growth and these trees are your long-term priority. Pasture can be started, and the shadow of the trees as they increase in size will eventually eliminate the pasture from the more shaded areas under the canopy. This pasture, generally a legume, will show little damage from this shade and can be used as a weed control crop. The other alternative, discussed above under plant spacing, is to increase the number of trees planted twofold to fourfold to increase early production with no room left for an associated crop. All of these alternatives help the farmer to increase his early returns. It is necessary to estimate the extra costs associated with these alternatives against the extra income that could be expected, which could be negative.

Ideally the best approach is to start the orchard with an associated crop almost simultaneously, so that the initial land preparation serves both crops. This approach can leave the soil undisturbed except for sowing the cover crop at a later time, if needed. The associated crop should not host enemies that could attack the fruit trees and should not produce substances that may inhibit the tree growth. The fruit trees and the associated crop need a degree of compatibility with respect to water needs or frequency of irrigation. An associated crop can also complicate field practices such as spraying and hence are not recommended after the third or fourth year.

(a) (b)

Fig. 3.6. Short-lived crops such as beans planted between rows of young avocado trees (a) and papaya and banana planted between rows of the future crop of rambutan (b) provide income during the juvenile period of the main crop.

ORCHARD FLOOR MANAGEMENT

The physical and chemical properties of the orchard's soil need to be maintained in a good condition to ensure that root growth occurs without difficulty. However, weeds need to be controlled, people and machinery need to move around in the orchard, and irrigation needs to reach all of the trees. No single system can be used for all soil types as all have their advantages and shortcomings. Rainfall, soil characteristics, irrigation system, water availability, type of weeds, and the species and age of the trees should be taken into account when deciding upon orchard management, without forgetting costs and returns. The main orchard floor management systems used are mechanical cultivation, cover crops, mulching and keeping the soil bare with herbicides, as used on the coralline sandy soils of Florida.

Cultivation with machinery is very effective with annual weeds and it helps break the crust that sometimes forms and allows incorporation of fertilizers and organic matter. Its shortcomings are that, after the orchard is 3–4 years old, disturbing the soil between tree rows is normally not recommended due to the danger of damaging the root system and the entrance of some pathogen through the wounded roots. The destruction of irrigation ditches or furrows can be another problem with mechanical cultivation. The presence of pipes and hoses limits the use of cultivation, and the multiplication of weeds with underground structures (nutgrass) can be another problem. Shallow and careful cultivation avoiding under the tree canopy should be done with offset discs or equipment that scratches the soil. As the trees grow, the soil should be worked at increasing distances from the tree canopy line (Razeto, 1993).

Temporary or permanent cover crops are an alternative, especially if there is good moisture in the soil throughout the year (Table 3.4). These crops help maintain good soil structure, increase water penetration, prevent erosion from wind and rain, and keep soil temperature lower. In the humid tropics, a legume such as kudzu or other suited legume species can be used, with the additional benefits that they fix nitrogen. Kudzu can be an invasive weed because of its rapid growth and habit of climbing up and over trees. Extra management is necessary to periodically cut the climbing shoots with a machete and change the vines' growth direction with the hands or a long stick.

Growing sod as a cover crop requires ample water and nitrogen in order not to affect tree production (Fig. 3.7a). Mowing or grazing is needed with sod, with the extra advantage of allowing machinery to get into the field sooner after rain and irrigation. On steep land, the presence of a cover will prevent soil erosion during heavy rains. Aesthetically, sod is a good approach, but there is strong competition for water and nutrients with the crop. In areas with a dry season, the transpiration from the sod can be very high and it will also need fertilizer, so care must be taken to irrigate and fertilize taking this additional need into account. In the absence of irrigation, competition for water can be a

Table 3.4. Some tropical ground covers and green manures.

Name	Main characteristics
Arachis pintoi	Forage or perennial groundnut. Good coverage. Permanent. Non-climber. Will revegetate after dry period. Shade tolerant.
Cajanus cajan	
Calapogonium mucunoides	
Calapogonium caeruleum	
Canavallia ensiformis	Jack bean Toxic seeds. Green manure and ground cover. Very drought resistant, shade tolerant and good for poor soils. Does not tolerate excess water.
Canavallia gladiata	Sword bean Uncooked seeds are toxic. Drought resistant. Green manure
Centrosema pubescens	
Clitoria ternatea	Butterfly pea Green manure. Very drought resistant. Small leaves will not cover well.
Crotalaria juncea	For fibre extraction. Fairly toxic to cattle. Some drought tolerance.
Crotalaria ochroleuca	Sunn hemp Green manure. Non-toxic cattle feed except seeds. Upright. Fairly drought resistant.
Desmanthus virgatus	Wild tantan Green manure or fodder. Drought resistant. Bushy plant grows back quickly.
Desmodium adscendens	
Desmodium ovalifolium	Shade tolerant. Climber.
Dolichos lablab or *Lablab purpureus*	Lablab bean Similar to velvet bean but for more fertile soils. Drought resistant. Green manure and cattle feed.
Indigofera hirsuta	Hairy indigo Nematode suppressant. Annual, will reseed itself. Ground cover or green manure. For well-drained soils.
Medicago hispida	Garrotilla
Mucuna pruriens	Velvet bean Green manure. Very palatable. Aggressive climber. Tolerates drought and low soil fertility. Bushy growth.
Phaseolus cocineus	Scarlet runner
Psophocarpus tetragonolobus	Winged bean Edible. Climbing. Does best in hot, humid areas. Drought and sandy soil sensitive.
Pueraria phaseoloides	Tropical kudzu Green manure cover or pasture crop. Tolerates high water levels, acid soils and dry season. Grows well under trees. Not to be confused with the weedy *Pueraria lobata*.
Vigna unguiculata	Forage cowpea Green manure/cover crop. Drought tolerant but for well-drained soils. Bushy.

problem. Mulching can be an alternative, but it is normally expensive to spread out in the orchard. Straw, hay, dried grass, wood shavings or any cheap and easily obtained organic material can be used (Fig. 3.7a). Care has to be taken to not let the mulch come in close contact with the trunks to avoid excess moisture and collar rot occurring. Mulch will prevent weeds from growing and at the same time will allow roots to grow near the surface, where the soil is of better quality. One problem with mulch if allowed to dry out is a possible risk of fires and it can harbour rodent pests. Plastic mulches can be used, especially in short-lived crops like papaya or pineapple, and their use will be determined by the economic convenience (Fig. 3.7b). Normally only the plant rows are mulched, and sometimes just a piece of black polyethylene about 1 m square is placed around the tree pole to avoid the initial direct weed competition.

No vegetation on the orchard floor fits better in orchards located in arid zones like the Peruvian coast or the Florida coralline sands. In desert areas, there is very little to do to control weeds if drip irrigation is used. In Florida, herbicides are used after rains to control weeds (see next section). The no-vegetation approach means no competition with the crop for water or nutrients. It also allows easier incorporation of manure or cover crops into the soil.

WEED CONTROL

Weeds, as well as associated crops, compete with the fruit trees for water and nutrients, and in certain circumstances can be an important factor in lowering

(a) (b)

Fig. 3.7. Weed control can be achieved by placing organic mulch under the trees (a), or plastic mulch (b) is also used on shorter-cycle crops or during tree establishment.

crop yields. For example, neglect of weeding results in a 20–40% decrease in pineapple yields. In situations with adequate moisture in the soils, weeds are not a factor in competing with the crop for water. Some weeds can also cause sanitary problems that can affect the crop, this in addition to the negative aesthetic aspect. Weeds are an important problem in climates where there are year-round crop-growing temperatures that favour continuous growth. This weed problem is especially acute in tropical and subtropical climates, except for subtropics with cooler winters, or the arid tropics and subtropics. Weed control is particularly troublesome during the first 2–3 years of orchard establishment, when the trees have not yet developed substantial canopies to shade weed growth.

In arid areas with drip irrigation and little or no rainfall, weed problems are not very difficult to solve, since weeds will only be found in wet areas around a dripper and these can be eliminated mechanically or chemically. However, if sprinkler, furrow or basin irrigation is used, weeds will be widespread and control measures will have to be used frequently. Weeds can be controlled by non-chemical and chemical means. Both approaches have advantages and disadvantages, but if done properly can produce similar results. The approaches can also be combined. The non-chemical control involves either weed elimination or cutting weeds back to reduce competition. Annual weeds are controlled by the use of hoes, pulling them manually, flooding the land, the use of mulches, and mechanical tilling or discing the soil. Mechanical cultivation should be avoided, though very effective, due to the damage it causes to the superficial feeder roots. Weed height reduction is achieved by periodically cutting the weeds back with a machete and with mowers or many types of brush cutters.

The chemical approach relies on herbicides or weed killers, which can belong to different chemical groups. Herbicides can be selective and non-selective; in both categories some are for foliar application and others for soil application: The chemicals can work by contact or can be translocated to other parts of the plant (systemic). Contact herbicides kill only the tissue that they contact, while the systemic herbicides applied to the soil or the foliage will be absorbed by the roots or aerial parts and move into the plant, reaching the places where they will have their lethal effect. Some herbicides are applied to the soil before the weed seeds germinate and thus are called pre-emergence, while the post-emergence herbicides are applied once the plant has germinated. Pre-emergence application, either before or immediately after planting, is effective, the least costly and a desirable management practice.

Some of the techniques used for chemical weed control consist of using a contact herbicide for annual weeds and a systemic herbicide for perennial weeds. Sometimes a pre-emergence herbicide can be used before the start of the rainy season. Several herbicides are on the market and different approaches for their use can be taken. An analysis should be made to be sure about the most convenient application procedure. Annual weeds should be eliminated when they are succulent and before they shed their seeds; the same is true for biennial weeds. With perennial weeds the approach has to be different, and normally they will be much harder to control. Chemicals are applied with spray apparatus, which ranges from simple knapsack sprayers to the more sophisticated boom-type sprayers, and some products are incorporated in dry form into the soil.

In young orchards care has to be taken not to use certain herbicidal products that can check tree growth by being absorbed through the root system. In other cases, the small trees have to be protected from receiving the chemical spray or drift, which can be absorbed by the green stem, branches and leaves or cause severe burns in these young tissues, while in large trees this is not normally a problem because of their woody bark. For young seedlings and newly transplanted orchards, glyphosate, a systemic herbicide, may be applied by rope wick or weed wipers saturated with a more concentrated herbicide solution and wiped on the weed leaves. These applicators eliminate spray drift and can be used close to the stem. Application of herbicides through the irrigation system, known as herbigation, has been shown to be effective. An important aspect with many herbicides is to know the time needed after application for them to be absorbed; in many cases if it rains too soon after application, the product will not have had a chance to be absorbed and it might be lost. Often morning applications are done to avoid the afternoon and evening rains.

There are restrictions on herbicide use imposed by manufacturers and government agencies, and all applicators must know the proper uses. Growers who intend to export fruit should become acquainted with regulations of the consuming countries governing the use of registered chemicals, residue levels and other precautions. In organic production, no chemical herbicides are normally allowed and only mechanical or cultural practices like cover crops or mulching can be used.

The use of herbicides can be expensive, so a cost comparison has to be made between spraying them over the whole surface and the system of mowing between rows and cutting weeds back in the row with a machete or the use of a hoe, or the mixed chemical–mechanical approach of applying a herbicide in the rows and mowing between them. The mixed approach keeps tree rows free of weeds using mulches or herbicides, or weed growth is kept in check by hoeing or keeping weeds low with a machete or mowers. In the humid tropics, the area between rows has either a legume or grass that is mowed periodically. The approach used is a financial decision and will depend on the orchard size and financial status of the grower. Weeding is an important production cost component in orchard maintenance.

WIND BARRIERS

Wind can have several effects on fruit crops. Gentle winds help ventilate the orchard and create a healthier atmosphere around the trees. They will also favour wind pollination and fecundation. However, strong winds can produce mechanical damage and, depending on velocity, can have severe, sometimes even fatal, effects on crops, resulting in uprooting the whole tree, broken main trunks, broken scaffold branches or dehydrated and burnt leaves to completely defoliated trees. Hurricanes or cyclones during flowering and fruiting periods can cause a severe flower and fruit drop in many species. Bananas and plantains are some of the most susceptible crops to wind damage. In Central America, bananas and plantains are sometimes subjected to blow down caused by gusts of wind that unexpectedly hit certain areas and break all tall pseudostems, and a whole year's production is lost until the ratoon pseudostem grows and harvesting can resume. Windbreaks are especially helpful when normal prevailing winds become gusty with velocities exceeding 65 km/h. Occasional high-velocity winds are damaging to orchard trees, but equally harmful in the long run are the mild prevailing winds of 40–50 km/h. Trees exposed constantly to such prevailing winds gradually develop a deformed, lopsided shape, with all branches growing away from the winds.

Winds can also affect sprinkler irrigation and spraying operations, causing uneven water distribution of herbicides and other chemicals, which can drift on to other plants. It is necessary to protect the plantation with a barrier that should be effective ideally from planting. Wind barriers will reduce water loss from the soil and leaves, produce a more uniform temperature in the orchard and reduce wind erosion (Wilkinson and Elevitch, 2000). The windbreak can reduce crop evaporation on the leeward side to 40% within twice the height of the windbreak, being more effective at higher wind speeds (Fig. 3.8a). The reduction in evaporation allows the trees in the orchard to develop the higher humidity in the canopy that is important for crops such as rambutan, mangosteen and durian. Sometimes a partial solution can be to plant the tree rows following the same direction of the main winds, so that the first trees in the rows protect the rest of the row.

Two types of barriers are used: natural (Fig. 3.8b) and artificial (Fig. 3.8c). Both should filter, not stop, the wind and have about 50% permeability. The windbreaks are perpendicular to the prevailing wind direction and extend beyond the width of the orchard so that no wind enters from the sides. Natural barriers consist of two or three rows of trees. The effectiveness of the windbreak depends upon the height and lateral extent of the barrier, its permeability and the angle of incidence of the wind to the barrier. Wind velocity is reduced to 35% within a distance of four times the height of the windbreak (Fig. 3.8a).

Many different species are used as windbreaks, which complement each other in size, growth form and canopy height. Sometimes a single species is used. All trees used as a windbreak should compete as little as possible with the crop; therefore deep-rooted and well-anchored, flexible trees are preferred. The trees should be adapted to the zone and should not harbour enemies of the crop (Table 3.5). Ideally the barrier should be planted before the crop so

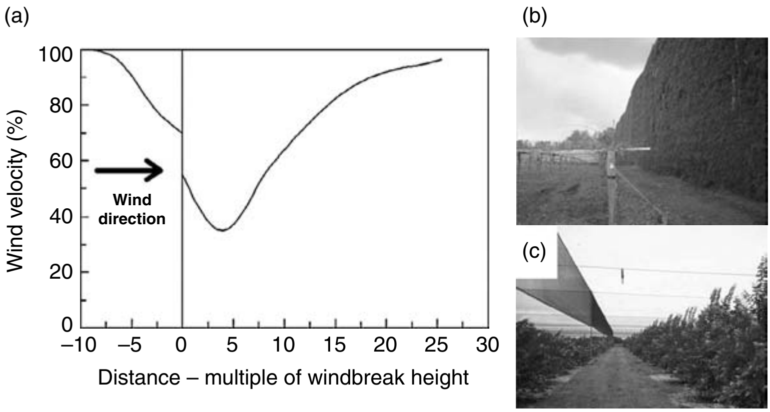

Fig. 3.8. Windbreaks reduce tree damage by reducing the wind velocity on both sides of the barrier (a), with a significant reduction on the leeward side up to ten times the height of the windbreak. Trees can be hedged (b), as in this kiwi orchard, or an artificial barrier can be made with plastic netting (c), as in this carambola orchard.

that it starts protecting it from the beginning. Barriers have to be maintained, and yearly pruning is usually performed to avoid too much compactness; also subsoiling hook should be passed 3 m away from the barrier to avoid excessive root competition with the crop. Barriers of trees that produce fruit instead of timber or firewood can be used. The main disadvantages of natural barriers are that they take time to be effective, use up land and compete with the crop for light, water and nutrients. They also need maintenance and can harbour crop enemies.

Few windbreak trees can provide crop protection under hurricane (typhoon) wind velocities. One of the most substantial windbreak trees is *Garcinia spicata*, called ‘Fukugi’ in Okinawa, Japan. Windbreaks composed of this species have been observed to withstand hurricane winds of approximately 210 km/h in northern Okinawa, providing crop protection without itself being damaged. This species is related to mangosteen and grows well in subtropical and tropical climates. Its only drawback is the very slow growth rate.

Artificial barriers are usually plastic fabric with 30–70% permeability to wind (Fig. 3.8c). They should be resistant to ultraviolet rays as well as to sun and rain, and resist deformation. Good barrier materials should last 10–15 years. The main advantage is that they can be installed and start functioning immediately. Additional advantages include that the permeability can be chosen and it will remain the same over the lifetime; they do not use much space or compete with the crop and do not harbour plant enemies; they can be moved to another location if necessary, and they do not need any maintenance. Their main disadvantage is the high initial installation cost.

Table 3.5. Some trees for windbreaks. Adapted from Wilkinson and Elevitch (2000).

< 6 m		
Annona muricata	*Acacia koaia*	*Averrhoa carambola*
Bixa orellana	*Cassia spectabilis*	*Casuarina equisetifolia*
Citrus reticulata	*Coccoloba uvifera*	*Eugenia uniflora*
Gliricidia sepium	*Leucaena leucocephala*	*Morus nigra*
Myrciaria cauliflora	*Parkinsonia aculeata*	*Pimenta dioica*
Psidium guajava	*Psidium cattleyanum*	*Sesbania sesban*
Thepesia populnea		
6–15 m		
Anacardium occidentale	*Acacia confusa*	*Albizzia lebbeck*
Artocarpus integer	*Azadirachta indica*	*Bambusa oldhamii*
Casimiroa edulis	*Cassia (Senna) siamea*	*Casuarina cuninghamiana*
Cedrella odorata	*Chrysophyllum cainito*	*Cojoba arborea*
Cordia subcordata	*Cordia egalantha*	*Dalbergia glomerata*
Dimocarpus longan	*Erythrina berteroana*	*Erythrina poeppingiana*
Grevillea robusta	*Ilex tectonica*	*Intsia bijuga*
Khaya ivorensis	*Macadamia integrifolia*	*Mammea americana*
Manilkara zapota	*Melia azedarach*	*Musa balbisiana*
Pandanus odoratissimus	*Pithecellobium dulce*	*Pouteria campechiana*
Schinus molle	*Syzygium aromaticum*	*Syzygium malaccense*
Tabebuia pentaphylla	*Tamarindus indica*	*Terminalia superba*
>16 m		
Acacia auriculiformis	*Acacia koa*	*Acacia mangium*
Acrocarpus fraxinifolius	*Aleurites moluccana*	*Artocarpus heterophyllus*
Artocarpus altilis	*Azadirachta excelsa*	*Calophyllum inophyllum*
Cocos nucifera	*Dendrocalamus asper*	*Eucalyptus dunnii*
Eucalyptus microcorys	*Guadua angustifolia*	*Litchi chinensis*
Mangifera indica	*Pinus caribaea*	*Prosopis pallida*
Pterocarpus indicus	*Sandoricum koetjape*	*Swietenia macrophylla*
Syzygium jambos	*Terminalia catappa*	*Tristania conferta*

PEST BARRIERS

In some tropical areas, birds and fruit bats can cause extensive losses of fruit near harvest. Numerous bird species, from solitary species to large flocks of parrots, will eat fruit. Various approaches are used to reduce these losses, including propane-fired cannons to scare the birds and permanent net enclosures (Fig. 3.9). The propane-fired cannons produce loud, unexpected blasts at random intervals, which are generally not less than 3 min apart. The noise keeps the birds nervous, while they will become accustomed to cannons that are always located in the same spot in a field, if the firings occur at regular intervals or fire very rapidly. Other electronic devices produce electronic synthetic sounds to repel birds by reproducing distress calls that mimic individual bird species. Visual repellents, such as balloons, streamers and flashing lights, are not as effective as acoustical devices. Bird netting is available that is lightweight and draped over the tree and, once over, harvesting is possible, to heavier, ultraviolet-resistant protective materials fastened to an overhead structure that totally encloses the orchard. The overhead structure has a very high initial cost. Netting comes as rigid or stretch materials in different widths and mesh sizes. The material chosen depends upon the crop and layout, expected material life and the equipment available for installation and removal.

In Asia, structures are built and covered with fine nylon mesh to exclude aphids that carry viral diseases. An example would be a mesh structure in which papaya is grown to protect it from ringspot virus. These structures cover hectares of land and are rather light in structure and frequently suffer considerable damage from hurricanes (typhoons) during the warm season.

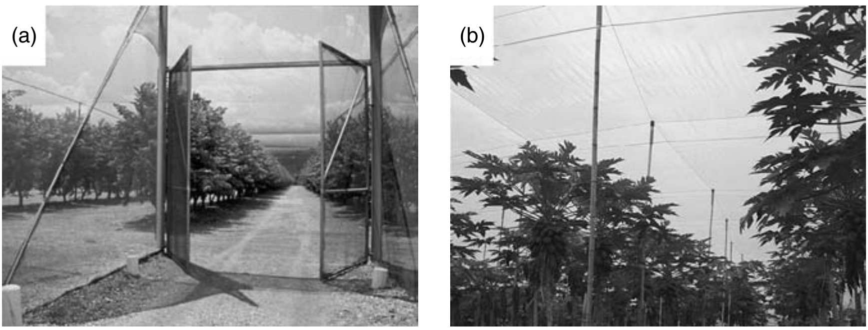

Fig. 3.9. Birds and fruit bats cause significant damage to fruit and may require the use of a protected shelter to protect the crop (a). Protective shelters are also used to protect papaya and other crops from insect-borne viruses (b); these lightweight shelters are made of very fine mesh nylon.

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4

TREE MANAGEMENT

INTRODUCTION

Tree management plays a key role in the economic success of an orchard. The soil and climate conditions chosen for the species and the variety to be grown set the foundation for an orchard. The infrastructure and associated logistics, such as packing and storage facilities, coupled to adequate transportation, energy availability, and water quality and supply, will aid in continued success. Tree management can compensate for less than ideal soil or climate conditions and the opposite is also true; improper tree management can render the best soil and climate conditions of little value.

Tree management includes, firstly, the choice of propagation material that is of the highest quality. Other components of tree management are irrigation, pruning, fertilization, pest and disease control, pollination, flower and fruit thinning, fruit bagging and the use of plant growth regulators. All these components together will result in a proper-functioning tree that will produce good yields and fruit quality.

A frequent problem is that some growers will attempt to apply very sophisticated management practices without being aware of their advantages and limitations. Some management practices apply only to certain varieties or only under specific conditions. Other growers will use plant growth regulators without having adequate irrigation or fertilization procedures. It is crucial to solve these basic management practices before attempting more refined practices. We have seen a number of cases when prospective growers will spend a lot of money in preparing the land and installing an expensive irrigation system and then buy poor-quality plants for their orchard. Other problems are experienced with the purchase of a bad piece of land just because it is cheap and then believing that you will get maximum yields, or hiring poorly trained field supervisors and/or failing to provide adequate supervision and training of labour while sophisticated practices are being applied. These decisions are short-sighted and frequently lead to poor fruit yields and quality.

PROPAGATION

Probably most fruits sold and consumed a few centuries ago would have been rated as poor in quality by present standards. Fruit size, colour, flavour, appearance and postharvest handling have dramatically improved, while the levels of defects, disease and pest damage have declined, especially in the last half-century. Commercial production a few centuries ago, when most people lived in rural areas, was based upon backyard or small orchard production, frequently of plant material that had received limited selection. Initially, the seed from a selection of the best type was planted, which frequently did not ensure the maintenance of the desired selected characters, though it is an easy approach. Large orchards cannot rely on highly variable plant material if they want high yield and consistent fruit quality. Higher quality was achieved by selecting superior wild trees or chance seedlings, and these genotypes were propagated, often as vegetative materials. The use of vegetative material meant that the genetic characteristics of these desired plants were retained and led to the creation of varieties or cultivars. At the same time, especially in the temperate zones, growers, nurserymen and hobbyists were finding new types of plants that arose either as chance seedlings or as mutations, which they selected and evaluated. Later, fruit-growing specialists and entire institutions started breeding programmes that initially consisted of sowing numerous seeds to see if some of the seedlings were better than their parents. In many cases, nurseries or growers found mutants that were superior or had a special characteristic. Superior plants known to exist elsewhere were asexually propagated. Examples include the ‘Fuerte’ avocado, which was brought to California as scions from Mexico; the ‘Washington’ navel orange, discovered as a mutation in Brazil and its buds taken to the USA, where it was popularized and later spread all over the world; the ‘Smooth Cayenne’ pineapple, discovered in South America and taken to Hawaii; and the ‘Solo’ type of papaya, discovered in Barbados and also taken to Hawaii. Many tropical fruit breeding programmes that use modern techniques, such as mutation induction and hybridization, to obtain superior varieties exist around the world.

Propagation of new selected cultivars is more sophisticated and relies mainly on asexually propagating certified varieties. The pineapple canning industry relies especially on selection out of the ‘Smooth Cayenne’ variety, while the pineapple fresh fruit export industry is dominated by the ‘Smooth Cayenne’ low-acid hybrids. Five or six major mango varieties are the backbone of the export trade, and the avocado varieties in international trade are ‘Hass’ and ‘Fuerte’. The international trade in bananas is based on one variety, ‘Grand Nain’, in the Cavendish group.

Many fruit trees need a rootstock that is adapted to adverse soil conditions and has resistance to certain diseases, nematodes and insects. The rootstock can also be required to attain a certain plant vigour, to achieve this the variety will have to be budded or grafted onto the desired type. The rootstock may have different vigour or simply will provide a root for a species or variety that is difficult to root by cuttings or air layers.

Certified planting material is meant to ensure that the desired variety is being obtained and it is free of specific diseases. Care needs to be taken that the planting material purchased is free of pests, nematodes and diseases that could contaminate areas where these problems do not exist.

Main propagation methods

Sexual or seed propagation

Propagation by seed is regarded as the most 'natural', but frequently the new plants are not identical to the mother plant and thus variability occurs. The only seed-propagated plants that are identical to their mother plants are those that have been self-fertilized for several generations so that the genetic arrangement has become uniform (homozygous), and they are called pure lines, such as rice or wheat varieties. This seldom happens with fruit trees, which are mostly cross-pollinated and show variability when propagated by seeds.

In some species, the seed is exactly the same as the mother plant. The condition is called apomixes, where an embryo develops in the absence of fertilization by pollen. Apomictic seeds occur in mangosteen, achachairu and jaboticaba, with vegetative embryos and no sexual embryo being present in the seed. Mango varieties of the Indochina–Philippine group (see Fig. 10.5) and most citrus species' seeds also have a sexual embryo, and several embryos can arise from the nucellar tissue of the ovary that surrounds the embryo sac. Where you have embryos from nucellar tissue, often the sexual embryo is suppressed by these surrounding asexual embryos. These propagation methods are considered clonal, with seeds being used.

Seeds are used commercially to propagate herbaceous, short-lived crops such as papaya, cocona, naranjilla, tree tomato, yellow and purple passion fruit, giant passion fruit, sweet granadilla, banana passion fruit, cape gooseberry and some others, such as coconut and pejibaye palm (*Bactris gassipaes*). Variability is very low since the crops are very homogeneous and the best fruits are selected to obtain seed. In the case of papaya, hybrids, a cross between two selected parents or a selected variety like 'Maradol' and 'Kapoho' are used. For selected varieties, hermaphrodite plants are self-fertilized to obtain the same variety.

The other important use of seeds in fruit crop production is to obtain rootstocks on to which the commercial varieties will be budded or grafted. Normally seeds for rootstocks are highly variable, leading to the propagation of rootstocks by cuttings or layers so that they are genetically identical and there is no variability in the orchard. Rootstocks derived from apomictic embryos are genetically identical to the mother plants.

For many lesser-known tropical fruit trees, seed is used for propagation because they do not have a high commercial value and little information exists about asexual propagation. The consequence is that fruits are very variable in quality and are not easily marketed. If the quality of these fruit is to be improved, methods to propagate them vegetatively are needed.

Asexual or vegetative propagation

When a new plant is regenerated or propagated from a piece or part of a mother plant, it is called clonal or vegetative propagation. Plants can be vegetatively propagated using many different tissues from roots (breadfruit) (Fig. 4.1a), stem cuttings (guava), apices (banana) and buds (citrus) (Table 4.1).

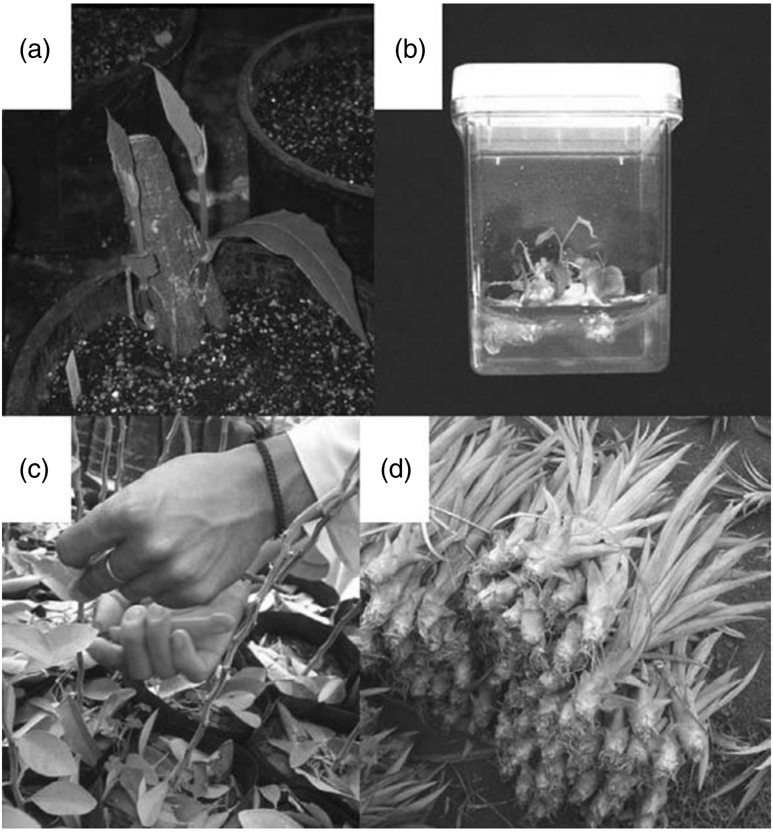

Fig. 4.1. Asexual propagation includes the use of root cuttings for breadfruit (a), tissue culture (b), budding (c) and the use of suckers for pineapple (d).

Table 4.1. Propagation methods commonly used for selected tropical fruit crops (Garner and Chaudhri, 1976).

Crop	Seed	Suckers Stooling	Layering (Marcotting)	Cuttings	Grafting Budding
Annona			Air layers	Stem	Budded, grafted
Avocado					Grafting
Banana		Corm			
Breadfruit				Root	
Carambola					Budded
Durian	Seed		Air layers	Stem	Budded
Guava			Air layers	Stem and root	Budded
Jackfruit			Air layers	Stem	Budded
Lanson, duku, langsat	Seed				Budded
Litchi and longan			Air layers		Budded
Mango	Polyembryony		Air layers	Stem	Budded
Mangosteen	Apomixis			Stem	Grafting
Papaya	Seed			Stem	Cleft grafting
Passion fruit	Seed		Air layers	Stem	
Pineapple		Crown and shoot		Leaf and bud	
Rambutan			Air layers		Budded
Sapodilla			Air layers	Stem	Budded approach

Cuttings

A leafy cutting is normally the terminal or subterminal part of a shoot with leaves left. A terminal cutting comprises the tip of a shoot, while the subterminal comprises the portion just below the tip of a branch; the upper leaves are left on and the basal leaves removed. These cuttings are held under conditions that prevent water loss (hermetic polyethylene chambers or a mist bed) in some porous medium with good drainage and moisture-holding capacity. Cuttings can be used for many tropical fruits, including guava, cashew, acerola, jaboticaba, golden spoon, litchi and passion fruits. When propagating hardwood or semi-hardwood cuttings, all the leaves are removed or absent, as for *Spondias*.

Most stem cuttings are treated with compounds that have auxin-like activity, such as naphthalene acetic acid (NAA) and/or indole butyric acid (IBA), to improve rooting percentage, accelerate the rooting process or to obtain more roots per cutting. The rooting products are applied to the basal cut end as prepared powders or in liquid form (50% alcohol/50% water) at concentrations of 1000 to 10,000 ppm, depending on the species, variety and type of cutting.

Tissue culture

This approach (*in vitro* propagation) uses micro-cuttings, which can be meristems or portions of cells from different parts of the plant (Fig. 4.1b). The process involves two phenomena: dedifferentiation from its original tissue condition to callus, followed by redifferentiation to generate all the tissues of a whole plant, which involves somatic embryogenesis. In many crops and under certain tissue culture protocols, somaclonal variations can be a problem. Somaclonal variation is thought to be due to DNA changes in the cell nucleus caused by tissue culture stress in the presence of plant growth regulators such as auxin and cytokinin.

This *in vitro* approach is used for rapid and consistent reproduction of elite or difficult-to-propagate genotypes. Since the tissues are so small and tender, they are very prone to rot or infection, and therefore they are first surface-sterilized then handled under sterile conditions in special growth chambers. During the last three or four decades, several species have been propagated by this system to ensure freedom of diseases and true-to-type plants. The cost per plant is normally higher than asexually propagated plants, but many plants can be generated quickly from one elite mother plant.

Until now, soft-tissue plants like pineapple, papaya, banana and plantain have been commercially produced, while with trees some success has been obtained with avocado, mango, *Annona*s and jackfruit. This propagation method is essential if molecular biology gene transfer approaches are to be used for tropical fruit tree improvement.

Layering

In layering a portion of a branch relatively close to the tip and still attached to the tree is put in contact with a moist substrate and the stem below the substrate is cinctured. New roots emerge into the medium, then the branch portion with the new roots is separated from the mother plant, cutting below the roots, and a new plant is obtained.

The most popular layering system for tropical fruit trees is air-layering or marcottage. The leaves are removed from a portion of a branch located about 30–60 cm from the tip and a 3 cm ring of bark peeled off. The girdled area and part of the stem with bark remaining are covered with a ball of moist sawdust or peat moss. The ball is wrapped tightly with plastic sheet or aluminium foil. Sometimes auxins can improve the rooting of these air layers. After 1–3 months, when the roots are visible and have turned from a white to cream colour, the air layer can be harvested by cutting below the new rooted area. The wrap is removed and the ball with roots transplanted into a pot or bag with a substrate and held under medium shade. When this new plant shows signs of growth, the bag or pot can be taken into full sun for some months until an adequate size is attained for transplanting to the field. Air-layered plants lack a tap root and can be more easily blown over by strong winds, the same as plants propagated by cuttings, but this is not a problem under normal field conditions.

Grafting or budding

Grafting is a system where a piece of stem containing two to six buds, called a scion, is used, while in budding just a single, detached bud is joined with the stem of a plant that provides the root system (Fig. 4.1c). The plant that provides the root system is called the rootstock. The bud or stem piece with the buds (scion) is of the variety that will become the tree canopy.

The most common methods of grafting are cleft, splice (whip), side and saddle graft, while the main budding methods are 'T' or shield, patch, chip and veneer. In some cases, branches of different trees are brought in contact to form a union, and this is called approach grafting. For grafting or budding to be successful, the cambium layers of both components have to be in intimate contact to regenerate the union with all needed parts: xylem, phloem and cambium. Many tropical fruits are, or can be, propagated by this system, and most of them will do well with different grafting or budding methods. Some species are more difficult and a specific type of grafting or budding has to be used. The skill and experience of the grafter plays a very important role as to which method is best for certain species, while in other species several methods will produce satisfactory results.

Every grafted or budded plant has two genotypes, that of the root system (rootstock or stock) and that of the canopy (variety or scion). The orchard canopies should be genetically identical because the buds are taken from a tree or trees of the same variety, so they are cloned on different root systems. The ideal would be for the roots to be from a single clone, which occurs when they are from vegetatively propagated plants or come from seeds with nucellar embryos because of their asexual origin (apomixis). In most other fruit trees, the seedlings used for rootstocks are of sexual origin so they vary among themselves. Since the rootstock can significantly influence the canopy growth and development, any variation can show up once planted in the field. The root and canopy maintain their original genetic make-up and do not exchange genes, except in the few cells around the graft union.

Natural propagative structures

Plants produce organs or structures that are used for its propagation (Table 4.1). Examples of these structures would include runners in strawberry and suckers in date palms. Some tropical fruits do produce suckers. Banana or plantain suckers have a solid base called a corm. This corm is the normal propagation material for these species. The sucker arises from the corm of the mother plant and can be transplanted whole or with most of the pseudostem removed, leaving the base and the corm. This piece is buried ~10 cm deep. Pineapple suckers arise on top of the fruit (crown sucker), at the base of the fruit (slips) and at the base of the plant (basal sucker) (Fig. 4.1d). The preferred propagation material is the sucker at the base of the fruit, but they are not produced all year round by the plants. These suckers are detached from the mother plant and left to dry for a few days so that the wound forms its scar, and after that they can be used for a new pineapple planting.

Differences between sexually and asexually propagated fruit trees

Trees originating from seeds tend to be vigorous since they are in a juvenile state that does not produce flowers and fruits. After these plants reach a certain age and become adults, they are able to flower and fruit. For some fruit trees the juvenile period can last 8–10 years. During this juvenile period, the plant will grow vigorously and become very large unless subjected to modern tree management practices. Additionally, trees from sexual seeds are normally genetically different from their mothers and among themselves, and potentially have different growth patterns and have fruit of different quality characteristics, making marketing more difficult.

Asexually propagated trees are clones of their mother plants and bear the same type of fruit. Additionally, the material used for asexual propagation is normally obtained from a plant in the adult phase, not in the juvenile phase. This adult material will have already fruited and its quality can be evaluated. The trees obtained from adult plants will flower and fruit upon receiving the external signal that induces flower development and will not have a juvenile phase such as a plant from seed. If no external stimulus is required, they will flower immediately. This earlier flowering results in smaller trees. In the case of grafting or budding, the existence of a graft or bud union can restrict the internal xylem and phloem transport and additionally influence tree size reduction and precocity. Dwarfing rootstocks are being sought for species that normally grow very large.

NURSERY TREE MANAGEMENT AND PLANTING

Tree management starts in the nursery, since many problems in fruit production can be avoided by just taking care of this phase of development.

Seedlings

At this stage many trees will show twisted or malformed roots or stems due to the position of the embryo at sowing time. In some species this can be controlled or reduced by sowing the seed in the correct position. This is unpractical with some species because of the small seed size, and when the seeds are polyembryonic (citrus, mango) the orientation of some of the embryos, relative to the correct position of the seed at sowing, is not normal, and there will be a number of seedlings that come out with a swan-neck-shaped stem base or root. Seedlings with this condition should be discarded since they do not become good plants or rootstocks. Only seedlings with straight stems and roots should be transplanted to the nursery pots or bags.

Plants in nursery containers

Plants left too long in nursery pots or bags normally have deformed root systems. The main root will reach the bottom of the container and will not be able to grow through so it will bend and start growing horizontally in a circular fashion, following the lower rim form of the container. The lateral roots, upon reaching the walls of the container, will grow around the root ball and form a sort of peripheral basket or root mesh (see Fig. 3.5b). This condition is also referred to as root-bound. When transplanted, the root-ball prevents the development of a good root structure; the plants remain stunted and are poorly anchored in the soil. Therefore only plants that are not root-bound or have not stayed in the container too long should be selected and planted.

Transplanting in the nursery into larger or taller containers that allow the roots more time before they become deformed is preferable. If planting material of the desired variety is in short supply, then the deformed plants can be used. Remove the deformed plant from the container and cut the main root above the point where it started to bend at the bottom. The lateral roots should also be cut to disrupt the peripheral root basket, if present, by making several vertical cuts on the outer part of the root-ball.

Planting

Planting in warm climates can be done almost any time of the year. If the weather is too cool, planting can be delayed. If no irrigation is available, planting should be done at the beginning of the rainy season. Some people recommend adding 20–50 g triple superphosphate in the bottom of the hole, separated by a 3–5 cm layer of soil from the root-ball.

PRUNING

Pruning fruit trees involves training the tree to the desired shape. The shape of the trees will depend upon the species and the specific management objective. Several models that are based upon developmental fate of the apices, the configuration of the branching points and plagiotropy (horizontal growth) and orthotropy (vertical growth) of tree axes exist. The growth of the trunk can be monopodial, rhythmic and indeterminate.

The models of tree growth habits provide a basis for comparing pruning and training protocols for different tropical fruit trees. Pruning to shape a tree aims to control the number, orientation, size and angle of branches and thereby improve the trees' structural strength to carry a fruit load, reduce wind damage, increase light penetration, improve air circulation, stimulate flower-shoot development and enhance fruit yield and quality. Too much pruning can delay flowering and lead to vegetative growth. Pruning is not practised in monoaxial crops with short life cycles (banana, plantain, pineapple and papaya), except that excess suckers are removed in bananas and plantains; in papayas normally short lateral branches arising from the main stem are removed. Broken, weak, drooping and diseased branches and leaves should be removed. Pruning of many tropical trees may reduce yields during the following season (mango, litchi), but some form of tree size control is necessary to maintain a manageable tree size and structure. The trend is to maintain the trees at a 3–5 m height by yearly or more frequent pruning for ease of flower cycling, pruning and harvesting.

Avocados, mango and litchi have monopodial rhythmic growth (Table 4.2). In avocado, the branches are morphologically identical to the main trunk, with flowers borne laterally with only minor effects on the vegetative shoot. In the case of guava, mango and rambutan, the rhythmic flushing of vegetative growth and flowering influences when and how pruning is carried out. Flowers develop on shoots that are not flushing, and the objective of pruning should be to increase the number of shoots that can flower simultaneously. Carambola can be extensively pruned to remove overlapping branches and topped to maintain 2–4 m height without significantly reducing yield, and it can also be trellised.

In the past, it was said that only deciduous fruit trees had to be pruned; nowadays most of the evergreen tropical trees are being pruned in modern orchards. Normally there has to be a formation pruning at the beginning of the plantation, and later production and sanitary pruning has to be performed.

Formation pruning

This practice is of major importance in deciduous fruit trees, where it takes several cycles to achieve the desired form. Most tropical fruit species have a natural tendency to develop a desired form, but often they need to be helped to achieve well-balanced and anatomically proportioned canopies. This canopy should be not too tall, without structural faults that might cause the trees or main branches to break easily with a full fruit load. The object is to prune the trees to achieve the right form and avoid overcrowding of branches in the canopy. The main pruning actions eliminate all shoots arising below the graft union. Shoots below the graft union can lead to a loss of a grafted canopy as

Table 4.2. Tropical seedling fruit tree growth is normally continuous and the trees develop different growth phenomenon and branching habits. Flowering then either becomes synchronized to vegetative growth or is more responsive to the environment (Verheij, 1986).

Branching	Vegetative growth and flowering		Example	Growth characteristics
Single-stemmed (monoaxial)	Continuous	Concurrent	Papaya, coconut	Constant growth and concurrent floral development, stable number of leaves thus a constant top to root ratio. Improvement via altered growing techniques (nutrients, water) to maintain high growth rate.
		Terminal	Banana, pineapple	Supported by current photosynthesis. Suboptimal growing conditions postpone flowering. Improvement via altered growing techniques (nutrients, water) to maintain high growth rate. Equidistant planting patterns frequently used in single or double row.
Branched (polyaxial)	Flushes	Concurrent	Passionflower	Rapid, continuous shoot growth and concurrent flowering, rectangular planting patterns.
		Separate in loci	Avocado, durian, mango, *Annona* spp., soursop, jackfruit, abiu, lanson	Rhythmic growth. Major competition between intermittent vegetative growth and flowering. Synchronous vegetative growth with almost simultaneous flowering and fruiting, feedback control between top and roots to maintain balance. External stimulus for flowering and growth rhythm. Improvement by manipulation of tree (juvenility reduction, pruning, fruit thinning, girdling, defoliation) before growing conditions (nutrients, water) have favourable response.
		Separate in time	Atemoya, avocado, mango, mangosteen, litchi, carambola, rambutan, guava, longan, chiku	Feedback control between top and root growth. Improvement in yield via manipulation of the tree using pruning, fertilization and irrigation. Improvement as for separate in loci category above.

these shoots can grow taller and more vigorously than the grafted canopy. Another objective is to eliminate all excessive primary branches and all water sprouts that are very vigorous and succulent shoots in a juvenile stage that will take time to become adult branches.

The modern tendency is to have canopies close to the ground. In the case of trees that tend to have a main stem with vigorous upright growth, they are tipped at about 80–90 cm in order to induce lateral branching that starts below that point and close to the ground (Fig. 4.2a). If the branching starts higher on the main stem, as in non-pruned trees, the canopy will leave too much empty space between the canopy and the ground. This space is wasted and results in a higher tree, and it is more difficult to carry out spraying, fertilization, pruning and harvesting.

Once the tree has been tipped, several lateral branches will develop. Three to four of these lateral branches are retained to become the main scaffolds of the tree (Fig. 4.2b). The lateral branches are selected so as to form a glass shape, with a 120 or 90° angle between the third and fourth branches (Fig. 4.2c). The branches should not arise too close to each other on the main stem, with 20–30 cm between them or between at least of one of them and the other two branches. If all the main lateral branches come out too close together on the main stem, too much of the canopy weight will be concentrated at one point. This concentration of weight can become a problem in later years when the trees are large, and they often break at this junction or form a water pocket that accumulates water, which is undesirable.

If a primary branch grows too fast in relation to the others, it should be checked by tipping or bending, in order to promote a balanced growth of all the primary branches. In some species these primary branches have to be cut back to about 60 cm, in order to induce them to form secondary branches (Fig. 4.2d), and this is followed by further pinching (Fig. 4.2e) to form a canopy closer to the ground. A more open growth angle of the primary branches is achieved by pulling them with strings attached to the ground or with strings that have a weight hanging at the other end or by putting pieces of twigs or bamboo between the branches in order to open their growth angles. Sometimes the inner part of used tyres is put between the branches so that the insertion angle to the stem is wider.

Formation pruning can start in the nursery or at planting time if the plants are large or already show unwanted growth proportions, or after they have achieved a certain size in the field. During the first years of growth in the orchard, every 3 or 4 months the plants should be inspected and any water sprout or sprout coming from below the graft union removed. If this is done frequently, it can be done with the hands and no tools are needed. Longer intervals will require pruning shears. The shoots should be cut at their base, to prevent re-sprouting of more than one shoot.

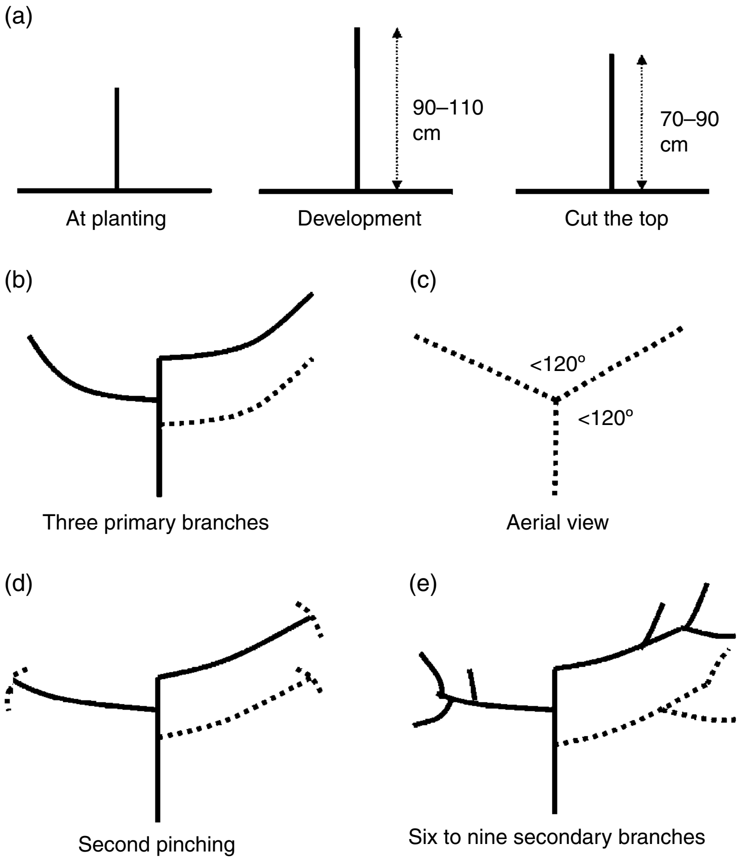

Fig. 4.2. Formation pruning, which can start in the nursery or soon after planting, develops a central pole cut to 70–90 cm from 100 cm, retaining only three evenly spaced lateral branches that form the basic framework of the tree and develop from the lateral buds, ensuring that these lateral branches arise at different positions on the pole. Additional pinching of the apical buds induces additional secondary branches; pinching of the apical buds may be done a number of times.

Production pruning

There is a growing tendency to prune adult evergreen fruit trees periodically to manage their size. Tree size of less than 3–4 m is needed in order to facilitate all management operations being carried out from the ground, such as spraying and harvesting. The canopy should also not be overcrowded with branches, which limits good light penetration and ventilation. The aim of production pruning is to improve tree health, plant growth and flower bud formation and so improve fruit yields and often fruit quality (Fig. 4.3a).

Maintaining the trees at less than 3–4 m can be achieved by topping trees either with large machine pruners or by hand, using different cutting devices such as machetes, chain saws or pruning shears. This pruning becomes a periodic or yearly operation and is often carried out immediately after fruit harvesting in order to allow the trees plenty of time to regenerate their productive structures. This pruning has resulted in significant increases in yields and fruit quality, and in disease reduction.

Another technique used, in species like mango, is a peripheral pruning after harvest, eliminating the outer 30–40 cm of the canopy in order to stimulate a uniform re-growth so that all new shoots have the same age, in order to induce uniform flowering (Fig. 4.3b). This includes eliminating all fruit stalks left from the former harvest since they have been shown to have an inhibitory effect on production.

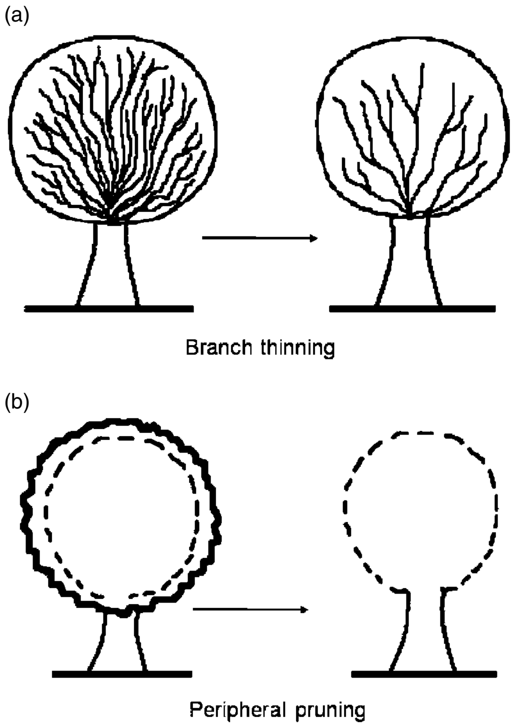

Fig. 4.3. Production pruning begins after the formation pruning and the induction of subbranches. The most common practice is to remove branches inside the canopy, especially those that are diseased and crossing other branches; this will also maintain tree height. Peripheral pruning is also practised to maintain canopy size and tree height.

Guavas are forced to produce year round, and normally the actively growing shoots are tipped once they become too large. This tipping forces regrowth and new flowers to be induced, to keep production high and constant. In guava cycling, as soon as the harvest is finished, a peripheral pruning of the canopy is performed, in order to force new shoots that will bear flowers. Cherimoya and atemoya are also tipped to remove last season's growth and force new shoots to arise below this cut. The new shoots lead to adequate and more uniform flowering since new flowers arise from these new shoots. If the climate permits, this pruning can be done at shorter than yearly intervals, as soon as the previous growth and leaves start to mature. This shortened period can lead to fruit harvests every 7 to 9 months. In orchards where the trees in a row are closely spaced and are starting to touch and shade each other, they can be pruned as a hedge, by pruning the trees on both sides and leaving a flat surface where the hedge is a bit wider at the bottom than at the top. This is achieved by pruning at a 20° angle. The top of the hedge would also be trimmed horizontally at this time.

In banana and plantain all but one of the suckers taller than 1 m are eliminated, leaving one replacement sucker or son that will be the next to flower; the smaller suckers (grandchildren) are not cut. This practice is done every 6–8 weeks.

Sanitary and maintenance pruning

Sanitary pruning is done to eliminate any growth that has been damaged by diseases or by insects. It also includes branches that are broken or growing in the wrong direction or interfering with neighbouring branches. Branches growing towards the ground and interfering with fertilization or weeding practices should be also eliminated. Any structure left from the former harvest should also be eliminated. The person doing this pruning needs training in order to make the correct decision as to what growth to eliminate. This could include old, diseased or broken leaves in the case of papaya, plantain or banana.

Structural regeneration pruning

This is performed to induce the regeneration of the productive structures and, in the case of large plants, to reduce their size to facilitate field operations and avoid overcrowding. In yellow passion fruit, the plants are pruned after about 3–4 years, when they start to decline, and the decision has to be made between replanting the whole field or rejuvenating the old vines. If rejuvenated, pruning is performed so as to leave the main stem and the primary branches, which are cut back too about a metre, and all secondary branches are cut to leave a short cane. This pruning will force new vigorous growth. Coffee plants are cut back to 30–40 cm and they will start to regenerate their canopies, and in this way they will be rejuvenated and return to a more manageable size and be more productive. Regeneration pruning can also be done in old and large trees of several species where size has reached unmanageable proportions and there is a need to reduce it.

Pruning to change a variety

A grower can change the variety of an orchard that is mature but still healthy and vigorous. The mature trees are pruned to leave the bases of the three or four scaffold branches (Fig. 4.4). Scions or bud-wood can be grafted on to the stubs of the scaffold branches directly or on to the shoots coming from them. This operation reduces the time for the orchard to come back into full production, as compared to starting with new plants from the nursery.

When large scaffold branches are cut back and left without shade from the canopy, care has to be taken to avoid sunburn. Normally the whole trunk and the remaining portions of the scaffold branches are protected with whitewash prepared at the farm or with white latex paint. The wounds have to be disinfected and protected; in some cases aluminum foil is used to cover them. An alternative to this could be to cut one or two of the branches and graft them, while the others are left intact and will provide protection and keep the normal sap flow within the plant; the next year the remaining part of the plant will be cut back and grafted (Razeto, 1993).

Pruning cuts and tools

Pruning cuts, if smaller than 1 cm in diameter, are normally not treated, but larger cuts are treated with a paste containing copper, such as copper sulfate or other fungicide, and sometimes insecticide, to avoid the entrance of some pathogens or insects. Under very wet situations and if certain diseases are present, almost any cut has to be disinfected; sometimes it is best is to wait for a dry spell to prune.

Pruning tools include pruning shears, pruning saws, chainsaws and even machetes. Machetes are not recommended, but they are used to prune trees that have a soft wood. Tools should be disinfected before pruning the next tree, in order to avoid transmission of diseases from one tree to another. In some cases, such as with fire blight, tools should be disinfected between each cut (Harris, 1983). Disinfection is of the utmost importance with some tree species or when disease is present, to protect the rest of the grove from becoming infected. In banana plantations, the machetes used for eliminating suckers are disinfected after each cut is made, to avoid the spread of 'Moko',

Fig. 4.4. To regenerate an old orchard and change the variety, growers cut back the old tree to the main lateral branches (stag-horning) and graft the new variety scions on to the old branches.

the bacterial wilt disease. Disinfection products include an iodine-containing odophor such as the commercial product 'Vanodine', sodium hypochlorite (bleach) at a 10% diluted solution or denatured methyl alcohol (shellac thinner). Bleach can be very corrosive on equipment, so it should be used with care.

IRRIGATION

In some parts of the tropics with abundant rainfall, such as the Atlantic coast of Costa Rica, which receives ~4000 mm/year, irrigation is not necessary, even for bananas; drainage is the main concern, to remove the excess rainwater. In tropical areas with high rainfall, most have a dry season of a couple of months, when irrigation is needed. Installation of irrigation will depend on an economic analysis of the situation as to whether artificial irrigation will improve fruit size, production and quality. The analysis should take into consideration the species, trees' growth phase, temperature, wind and relative humidity during the dry months. If the dry season occurs during the cool season, when little wind occurs or high relative humidity is present, irrigation needs are less than if the dry season is hot and windy and the relative humidity is low. A problem arises in abnormal years with a longer than usual dry period, when productivity can fall significantly. Two or three dry months under the tropical heat can have detrimental effects on yields of some species not adapted to long dry spells and it can be wise to irrigate during the dry season.

Many fruit crops that originated in the monsoon areas need a dry period to restrict tree growth, mature the foliage and induce flowering. The mango is an example of a tree that evolved in a monsoon environment and flowers better if subjected to cool weather and dry soils. In many places, mango is grown with only rainfall, though yield may be reduced. Some fruit trees are subjected to a water stress even when irrigation is available, with irrigation resulting in heavier and more uniform flowering. A number of tropical species, such as many *Spondias*, have evolved mechanisms to withstand the dry season by shedding their leaves to minimize water loss.

Tropical fruit trees should be irrigated or receive adequate rainfall in order to yield their maximum. Most modern orchards install an irrigation system even if the rainfall is adequate to keep the plants growing; irrigation under these circumstances will provide extra water in case of mild stress or when the rainfall pattern changes.

Irrigation systems

The irrigation system installed will depend on many factors: amount and cost of water, availability of money, steepness of the land, and the technical level of the farmer. Several systems are used in tropical fruit orchards.

Surface irrigation

Surface irrigation includes furrow and basin irrigation, with furrow irrigation being the most popular. The land needs to be fairly level or to have been levelled during preparation (Avilan *et al.*, 1989). Land levelling can be a costly operation, but once it is done, furrow and flood irrigation will be cheap though very inefficient in water usage. Furrows are more suited to flat or almost flat land where the slope is 0.5–1.0%. The furrows can be made to follow the contour, with the same slope of 0.1–1.0%. Higher slopes can lead to erosion, which will destroy the irrigation ditches and the furrows will become excessively deep.

In furrow irrigation, water is conducted along the tree rows and around the trees. For young plants, one furrow is often sufficient, later increased to two furrows, one at each side of the trees, and this could be increased to four furrows in older orchards. Furrows can also be dug around the trunk or have a side furrow that directs water under the canopy. Furrows should be no longer than 120–180 m in loamy soils and 60–80 m in very permeable soils. If a furrow is excessively long, the time for the water to reach the end will allow for excessive infiltration at the start beyond the root zone and waste water and fertilizers. Short furrows have the opposite effect of insufficient penetration and faster onset of water stress.

In the basin system, around each canopy drip line a 25–30 cm mound of soil is prepared to retain the water and allow flooding of the canopy area till the soil becomes saturated. This system has 35–40% water-use efficiency and is used where water is abundant and cheap or free.

Furrow and basin irrigation are less efficient in water usage because of the excessive infiltration at the start of the furrow and the loss of water in transporting to the field. Care is taken to ensure no flooding or excess irrigation water comes in contact with the base of the trunk, as this can lead to serious trunk diseases and even tree death.

Low-pressure irrigation

Drip and micro-sprinkler irrigation are low-volume, low-pressure systems (Fig. 4.5a, b). These systems can be used on steep and uneven land, and require no land levelling. Pressure compensation built into emitters and sprinkler heads means that all points receive similar amounts of water. Water is applied only where needed to the plant roots, and these systems are the most efficient for reducing water wastage. The distribution of the water in pipes and hoses results in very little evaporative loss, saving 30–40% of the water in relation to conventional surface systems.

Drip irrigation consists of having hoses running along the tree rows (Fig. 4.5a), and these hoses will have several drippers, normally three or four under the canopy drip line, with one or two hoses on each side of the trees along the rows. In sandy soils, lateral movement of water is poor, so more drippers will have to be used or the frequency of irrigation increased. Sometimes micro-sprinklers are a better alternative in sandy soils. Normally with micro-sprinklers (Fig. 4.5b), there will be one per tree to keep the soil under the canopy moist. Some large banana companies use sprinklers that hang from cables. Watering is more frequent and a lower volume applied each time, so

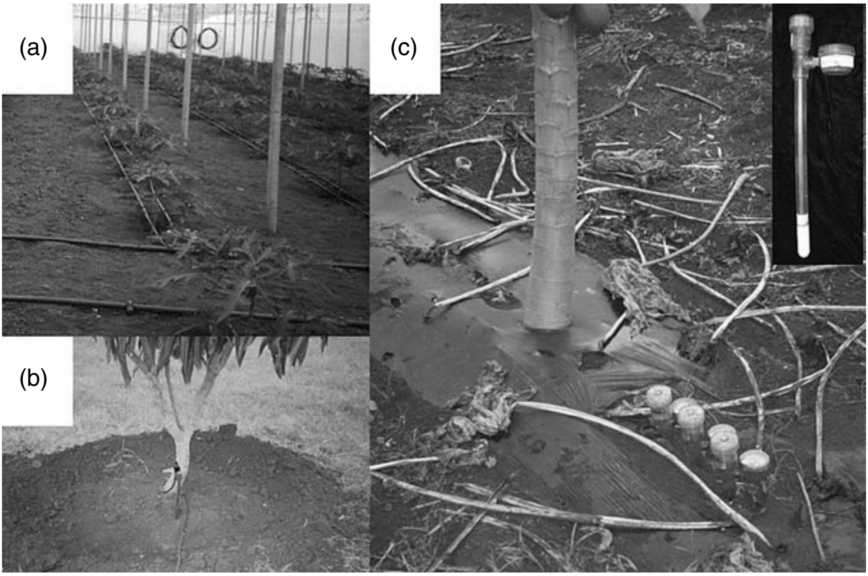

Fig. 4.5. Irrigation of orchards has moved away from furrow and flood irrigation to the use of drip tubes (a) and micro-sprinklers (b). To determine water needs a simple system is the use of tensiometers at different depths (c). Electrical tensiometers are also available.

that the plants do not become water-stressed, resulting in improved yields (Baldini, 1992). The systems represent a higher initial investment, and skilled labour is needed to install and maintain, with the benefits of lower water usage and greater efficiency of application. In many parts of the world, these systems lend themselves to 'fertigation' or 'ferti-irrigation', a combination of irrigation and fertilization. A calibrated mixer injects a fixed amount of a concentrated liquid fertilizer stock solution into the main irrigation supply line. The amount injected is determined by knowing the amount of water to be applied, flow rate and the amount of concentrated fertilizer to meet the plant's needs.

Sprinkler irrigation

Sprinkler irrigation is still quite popular for fruit trees. Permanent and semi-permanent or portable sprinkler systems are used. Sprinkler irrigation can be over or under the tree canopy (Fig. 4.5b). The above-canopy system washes pesticides off the leaves and can contribute to disease spread because of the humidity and splashing the droplet causes. In the case of banana and plantain, under-canopy irrigation is used. Mini-sprinklers that cover a circle with a diameter of about 12–14 m are installed every 10–11 m in a square arrangement. Under-canopy irrigation avoids the disadvantages of the big sprinklers used in the past, which covered almost 1 ha. In very few situations, especially with small trees like guavas that are pruned, travelling sprinkler systems can be used successfully. Sprinkler irrigation does not require level land, uses little labour and improves soil structure; water volumes can be regulated; it wastes less water than surface irrigation, but it requires more pump power, and it is more expensive to install than furrow or basin irrigation. Sprinkler systems sometimes interfere with farm machinery operations.

Sub-irrigation

Sub-irrigation can be used in very permeable soils like the coralline soils of Florida. Water is pumped into the drainage system and this makes the water table rise, so that the root zone becomes saturated.

Irrigation control

An excess of water or drought affects plant functions and thus tree yields. Drought will reduce water availability and consequently nutrient uptake; the stomata will close and less carbon dioxide is available for photosynthesis. With fewer sugars produced by photosynthesis, translocation of carbohydrates will be reduced, as well as hormonal transport from the roots to the canopy. Excess water will create a shortage of oxygen in the soil, leading to anaerobic conditions, which are toxic and reduce root activity and growth, often leading to root death. Root death results in reduced water absorption and hormone production by the roots and more pathogenic activity, which can cause root rot and finally tree death.

Irrigation has to meet the plant's needs, which depend on the species, the tree size and age, foliar density and the climatic conditions. Any irrigation plan has to take into account the water retention of the soil, the rate of water penetration, the distribution and depth of the root system and the amount of water the crop uses. The amount of water to apply will depend on soil structure and texture, and depth of the root system. Irrigation must take into account the depth that water should reach in the soil profile, and this is based upon root distribution and where the majority of roots are active. During tree growth, root distribution shifts from the roots being concentrated near the surface to becoming deeper in distribution. If irrigation is too shallow, the root system will also remain shallow, forcing more frequent irrigation. If irrigation is too abundant, water will pass below the main root zone and take with it many nutrients needed for plant growth.

After heavy rain or irrigation, the soil is saturated and begins to drain under gravity, and it reaches a point called field capacity (FC) about 24 h later; that water is held by the soil against gravity. The potential (force) that this water is held at is about 7 kPa (7 cbars, ~0.07 atmospheres) and it is readily available for the plants. At FC, there is more water in a heavy than in a light soil. If no further water is received by the soil, it will start to dry out, until it reaches the so-called permanent wilting point (PWP), where most plants are no longer able to extract water from the soil and the water potential is too strong. At PWP, plants start to wilt, irrespective of the time of day. Water at PWP is retained by the soil with a force of 1500 kPa (15 bars, ~15 atmospheres).

Several methods are available to determine plant needs and the amount of irrigation that must be applied. Simple approaches involve digging a small hole with a shovel to see if there is moisture at a certain depth or checking whether the annual weeds in the orchard are wilting. In some cases, growers use rain gauges (pluviometers) to determine the amount of rain and calculate how much irrigation water to apply knowing the crop's total water needs on a weekly basis. Total crop water needs depend upon the surface area covered by the crop canopy and the potential evaporation. In certain banana-growing areas in Honduras, irrigation needs are estimated based on research data showing that the plants need about 2000 mm of water falling on the ground, ~40 mm/week, supplied with three applications of 13 mm each time. The amount applied is reduced by the amount of rainfall recorded in the rain gauge in 2-day periods. For example, if it rained 6 mm they would only irrigate to apply 7 mm.

A more accurate method is to use tensiometers (Fig. 4.5c). Tensiometers are pieces of pipe with a porous tip where water can flow in and out. The pipe is filled with water and at the other end there is a manometer, which will measure the tension by which water is retained by the soil. The manometer is calibrated in centibars (cbars) or hundredths of a bar, a bar being equivalent to 1 atmosphere. In a saturated soil, there will be practically no tension and the manometer should indicate 0 cbars; at 10–25 cbars there is a good amount of water available, while at >25 cbars, water is becoming more difficult for the plant to extract and at 75–80 cbars irrigation is essential.

Tensiometers are usually installed at a number of locations spread throughout the orchard and at different depths to represent the root-zone conditions. If the tensiometer with the porous tip 30 cm deep shows high tension, irrigation is necessary, while if the one with the tip at 60 cm shows tension it means more water has to be applied to reach that depth. The 30 cm depth indicates when and the 60 cm tip indicates the amount of water required. For avocados, irrigation should be carried out at 40–50 cbars tension. In basin or furrows irrigation, 50–60 cbars would indicate the need to irrigate, and with drip irrigation 10–15 cbars would be the threshold.

In the last few years more sophisticated remote indicators or sensors have become available. Some sensors measure the electrical resistance of gypsum or other blocks whose resistance varies according to the soil water content. Other instruments measure the time an electromagnetic impulse takes to travel through the soil (TDR – time domain reflectometry), and that varies according to soil moisture content, and the neutron emitter that receives the reflected emissions, which also vary according to soil moisture.

A more accurate calculation of a crop's water needs is the crop's consumptive water usage, which combines leaf transpiration and water evaporated by the soil and the leaf surfaces. These losses are affected by temperature, relative humidity, wind speed and radiation, and their combined value is called evapotranspiration. A type 'A' evaporimeter, which is a circular tank 1.20 m in diameter and 25 cm deep filled with water, is used in meteorology; daily measurements are made to establish how much evaporation occurred and it is expressed in mm/day. This value multiplied by a location factor and the crop coefficient (Kc) (ground area covered by the crop) will give the daily evapotranspiration or consumptive water use and is used to calculate how much and when to irrigate according to what is evaporating.

FERTILIZATION

Fertilizer needs and dosages

A number of mineral elements are required for plant growth and development and are classified, according to the amounts needed, into macronutrients and micronutrients. Macronutrients are needed in higher amounts and include nitrogen, phosphorus, potassium, sulfur, calcium and magnesium. The micronutrients are needed by plants in lesser amounts and include iron, zinc, boron, manganese, copper, molybdenum and cobalt. Both groups are equally important; when plants do not have enough of any one of the macro- or micronutrients, they are unable to complete their life cycle. In an orchard, a shortage or deficiency is overcome by the application of fertilizer.

The amount of fertilizer to apply can be established in many ways. In some tropical regions the nearest university or agricultural extension office can provide a fairly good estimate as to the amount of fertilizer to apply for specific crops; published information can be a useful initial orientation as to a specific crop plant's needs, and some neighbouring farmers' fertilizer practices can help as a starting point. A more technical approach is to determine the amount needed to replace that 'exported' by the harvest. This estimate needs to be adjusted for the amount of nutrients lost through pruning and efficiency of nutrient uptake and the amount unavailable to the plant roots. Another system is to establish trials using different dosages of fertilizers for a given species or variety under your climatic and soil conditions. These trials can take a long time, and often the answer is needed sooner than the results are obtained. The other approach is to carry out soil and plant tissue chemical analysis.

Soil analysis

Soil samples are collected before planting from a soil depth of between 10 and 30 cm with a shovel or auger. It may also be necessary to sample the subsoil. In fairly uniform soils, soil is sampled at various points, following a 'W' pattern across the field. The soil samples are mixed for analysis. If the soils appear to vary in a field, each different area should be sampled and analysed separately. The analysis results will provide the soil's pH and an estimate of the available macronutrients and, when data are available, a recommendation as to the fertilizer needs. For nitrogen content, the results will not be as exact. Any deficiencies noted at this time should be corrected. It is important to remember that the soil analysis indicates what is present but not necessarily available for the plants; sometimes an extreme pH can block the availability of some nutrients. So the soil's analysis has to be complemented by the plant analysis. The soil analysis can be repeated every 2 or 3 years to detect any significant changes.

Plant analysis

Plant or foliar analysis indicates the level of a particular element present in the plant. The amount is compared with a standard table, which have been developed for many species after long field studies. This analysis makes it possible to know if the level found in the tissue is normal, deficient or excessive. For leaf analysis, it is important to know how the standards were developed, as the type, number and age of leaf, what type of shoot (with or without fruit) and at what time of the year samples were taken can change the standard values. The samples taken will need to duplicate this sampling protocol carefully in order to have comparative results. In banana, leaf or petiole pieces are used instead of whole leaves. The sampling has to be performed by trained personnel and the samples analysed by a certified and trusted laboratory. The analysis results will indicate what nutrients are insufficient for the plant's growth or what is in excess. A decision can then be made to correct a nutrient that is limiting growth by applying more or less of that nutrient in your fertilizer programme (Table 4.3).

Dosages will initially follow recommendations from other growing areas until reliable local or your own information is available. The nutrients most commonly deficient are nitrogen, phosphorus and potassium, and sometimes magnesium, and these are included in a regular fertilization programme. Roughly, in the adult stage plants need around 100 kg of nitrogen, 50 kg of phosphorus (P_2O_5) and 100 kg of potassium (K_2O) per hectare per year. These very broad referential numbers vary significantly with species, soil type and plant growth stages. Banana, plantain and pineapple normally need much more nitrogen and potassium than other tree crops. A common problem

Table 4.3. Nutrient levels that are sufficient for growth for various selected tropical fruit crops (after Reuter and Robinson, 1986; Jones *et al.*, 1991).

		Nutrient levels adequate for growth (%)					
	Tissue	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium	Sulfur
Annona spp.	Leaves	2.5–3.0	0.16–0.2	1.0–1.5	0.6–1.0	0.35–0.5	
Avocado	Leaves	1.6–2.0	0.08–0.25	0.75–2.0	1.0–3.0	0.25–0.8	0.2–0.6
Banana	Leaves	3.5–4.5	0.2–0.4	3.5–5.0	0.8–1.5	0.25–0.8	0.25–0.8
Guava	Leaves	1.3–1.6	0.14–0.16	1.3–1.6	0.9–1.5	0.25–0.4	
Litchi	Leaves	1.3–1.5	0.15–0.2	0.8–1.2	0.56	0.21	0.1–0.16
Mango	Leaves	1.0–1.5	0.08–0.25	0.4–0.9	2.0–5.0	0.2–0.5	
Papaya	Petioles	1.01–2.5	0.22–0.4	3.3–5.5	1.0–3.0	0.4–1.2	
Passion fruit	Leaves	4.75–5.25	0.25–0.35	2.0–2.5	0.5–1.5	0.25–0.35	0.2–0.4
Pineapple	Leaves	1.5–1.7	< 0.1	2.2–3.0	0.8–1.2	< 0.3	

is a tendency to use an excess of nitrogen on most crops, which can lead to excessive vegetative growth and environmental contamination, besides being a waste of fertilizer and increasing production costs.

Timing of application

Nitrogen, if applied conventionally, should be applied three or four times a year in equal amounts, with the first application before flowering or the main growth flush. The next applications will follow at 3- or 4-month intervals. If there is no irrigation, the first application should be done as soon as the rains start, and the other two or three divided so that the last is made 2 weeks before the rains stop. Potassium can be split into two or three equal fractions and applied with the second and third, and eventually the fourth, nitrogen application, if nitrogen is applied four times a year. Magnesium can also be split into two or three applications. Phosphorus, since it is readily immobilized in the soil, can be applied all at once for the whole year, normally with the first application of nitrogen. Nitrogen should not be applied close to harvest, as this results in fruits that are more succulent, mature later and are not as sweet and tasty. Nitrogen is preferably applied right after harvest

Fertilizer application

Solid application

When low-volume or sprinkler irrigation systems are not installed, conventional soil fertilizer application systems are used. This application of dry fertilizers to the soil is made by broadcasting the fertilizer on to the soil surface over the outer half or third to the canopy drip line. There is no need to apply fertilizer near the tree trunks, as the old roots have little nutrient-absorption ability. Small banana growers apply dry nitrogen and potassium fertilizer four times a year, while phosphorus is normally applied once a year; these applications are done by applying the fertilizer in a semicircle about 60 cm long and 30 cm wide in front of the ratoon sucker, about 30 cm from its base.

When the plants are closely spaced, fertilizer can be broadcast uniformly in the space between rows, as it is assumed that this area is filled with roots. Alternatively, a shallow semicircular furrow about 40 cm long and 5 cm deep is excavated with the edge of a hoe or square shovel 30–40 cm from the main stem; the fertilizer is put in the furrow and covered. Sometimes fertilizers are applied following the irrigation furrows or in the basins, which ideally should be wet. Fertilizers such as urea should not be left exposed but covered with a rake or irrigated into the soil to avoid volatilization of the active components. The fertilizer should be applied when the soil is wet and moved from the surface into the soil by irrigation or rainfall. When irrigation facilities are not available, the farmer should wait for a day when he is certain that there will be rain and fertilize just before it rains. Fertilizer applied during the dry season will not be available to the plants until it rains, unless an irrigation system is available.

In many orchards, a wide and 10–15 cm deep furrow is made that follows the drip line of the canopy, and the fertilizer is placed in that furrow and buried to avoid losses. Four to six holes about 30–40 cm deep can be made in the vicinity of the drip line in a square or a hexagon layout, and the fertilizers, sometimes including manure, are buried.

Dilute application

Large banana companies used to fertilize every 2–3 months with nitrogen and potassium, using ‘cannons’ or large sprinklers that covered a circle of about a hectare. They first irrigated with water containing no fertilizer until the soil was wet, then injected the soluble fertilizer into the water until the calculated amount had been applied to the field and ended the process with plain water. The last phase of irrigation without fertilizer ensured that the fertilizer had been taken into the soil and that leaves and metallic structures in the field were washed, so that fertilizer residues, especially urea, did not burn the leaves or corrode the metals. This approach applied a large amount fertilizer a few times a year. When sprinklers, micro-sprinklers and drippers are used, smaller amounts of fertilizer are applied with each irrigation. The advantage of using smaller amounts at more regular intervals is that the fertilizer is placed near the root zone and less fertilizer is lost because of leaching. Small, regular, almost continuous application ensures that most of the fertilizer is used by the plants, reduces plant nutrient stress and the application rate can be readily adjusted to the stage of plant development. Nitrogen applications near harvest time have to be reduced or eliminated to avoid delayed fruit maturation, excessive fruit succulence and to achieve a better-flavoured fruit. The reduction in nutrient stress associated with almost continuous application of fertilizer results in higher yields and allows growers to recover the investment made in the irrigation infrastructure, in addition to significant reduction in fertilizer and water usage.

Foliar fertilization

Although the roots are the main organs that the plants use to absorb needed nutrients, foliar applications can be made to correct certain deficiencies. Foliar fertilization is normally used to apply micronutrients and in exceptional cases to supplement for a deficiency of a major element, especially nitrogen in the form of urea. Because of the large plant needs for major elements and the low concentrations tolerated by the leaves, especially urea, it is almost impossible to fill the needs through the leaves. Microelements are also normally taken up by the roots, but in situations with low micronutrient availability or the root inability to absorb them, foliar sprays provide a very rapid response, and after 2–3 weeks improvement can be noticed. Pineapple in Hawaii is sprayed at regular intervals with an iron solution to correct a deficiency; even though the soils are high in iron, most is unavailable to the plant.

Many fertilizer preparations contain microelements that are sprayed on to the foliage from one to four times a year. Spray application frequency is dependent on the micronutrient, the species and the deficiency severity. Foliar fertilizations should not be performed at flowering time or when the fruits are very small. Some micronutrients are applied as sulfates, such as zinc sulfate, but since this is an acid product, it has to be mixed with lime to avoid leaf damage. Urea, which has a high biuret content, can also cause severe burns. Soluble forms of single essential micronutrients and mixtures of a number of micronutrients, as their sulfates, nitrates and chlorides and complexed with chelating compounds (EDTA), are available commercially. These products can be tried and used if satisfactory results are obtained.

For best results, foliar fertilization by spraying young leaves will make it easier for the product to be absorbed, since the leaf cuticle is thinner. If the spray drop size is small, repeat applications at lower concentrations enhance uptake. Since a liquid is applied to the foliage, the more foliage it covers and the longer it stays as a liquid the more nutrients will be absorbed by the plant. Application during cooler, high-moisture and calm air conditions is the best to obtain maximum benefits, with early-morning sprays being recommended. Covering both sides of the leaves, especially the underside, with the greater number of hairs and pores and less wax, aids in foliar nutrient uptake. The addition of a spreader sticker to the foliage fertilizer mix can also increase uptake. Some foliage spraying can be done in combination with disease and insecticide sprays after checking for compatibility. Phosphates are not compatible with salts of copper, manganese, zinc and iron; copper fungicides should not be mixed with sulfates, nitrates or chlorides. If a new product or procedure is being used, test the mixture on some plants before spraying the whole field.

CROP PROTECTION

Fruit crops can be affected by insects, mites and nematodes, and diseases caused by bacteria, fungi, viruses and similar organisms. Vertebrate enemies such as rats, squirrels, monkeys, birds and bats can also be a problem. Since fruits are expected to be without blemishes, and more so if they are for export, the tolerance is zero for damage. It is not possible to obtain blemish-free-quality fruit without using pesticides. For many tropical fruit crops, there are few approved pesticides, and the residues tolerance is low, and varies with market.

Insects

Insect pests are a major problem in agriculture, including tropical fruit production. Most insects are harmful because they chew plant parts or suck their fluids. Some insects are borers that damage the branches or stems. Additionally, some sucking insects can transmit viruses, viroids and mycoplasmas that cause diseases if they come from an infected plant. There are also beneficial insects such as honey bees, silk worms, those involved in pollination, predators that eat harmful insects and parasites that lay their eggs into the insect pest; the parasite eggs hatch and the larvae consumes the pest larvae or pupae.

Insect control using integrated pest management (IPM) requires knowledge of the insect life cycle and habits. Questions asked include: Where do they lay their eggs? How much time does it take to become larvae? How long are the larvae active before becoming pupae? Where do they stay during these stages? What are their feeding habits? What species and what part of the plant do they attack? What are their migratory habits? Knowing this information allows the IPM person to design a strategy for controlling them.

A major pest such as fruit flies requires a preventative approach for its control, since once the flies lay their eggs, the fruits are difficult to market unless subject to a kill or sterilization treatment. Frequent preharvest sprays and traps can be used for fruit fly control, though costly. Fortunately, fruit flies do not generally lay their eggs into unripe fruit, therefore harvesting at early-ripening stages avoids major fruit fly injury. Fruit flies are a significant insect problem in fruit export, since the USA, Japan and others have very stringent quarantine regulations and in many cases require the fruit to be treated before entry.

Insect traps in the field (Fig. 4.6a) give an indication about the insect species present and their population size, and this is used to decide if spraying is necessary. Some traps used have light as an attractant and have either a pan filled with soapy water to reduce surface tension so that the insect sinks into the water, or kerosene or water with a contact insecticide is used to kill them. Other traps use a lure, which can be a pheromone or a particular scent that will make the insect go to the trap and be killed in similar ways. Another way is the use of attractive plastic sheets with a sticky substance in the nursery (Fig. 4.6b) and in the field (Fig. 4.6c), which will immobilize and thus kill the insect.

Among the exclusion methods used are barriers and tall plant fences, which will not keep insects out but will reduce the number of insects visiting the field. Anti-insect fabrics exclude insects completely but they are expensive, although they are used to exclude aphids from papaya trees in some areas (see Fig. 3.9b). Another exclusion method is bagging the fruit (Fig. 4.6d), which is very effective in preventing fruit fly and other insects from laying eggs.

Fig. 4.6. To protect the trees and fruit, various approaches can be used to reduce the insect pest levels by use of traps (a), which may include a lure or sticky traps in the nursery (b) and in the orchard on the trunk (c), and protecting the fruit by bagging (d).

Cultural practices can be used, such as ploughing or discing to kill insects present in the soil, weed control to remove shelter and an alternative place to reproduce, and pruning damaged parts and burning them. In the case of fruit flies, all fallen fruit should be buried at least 40–50 cm deep so that if the larvae evolve into pupae there will be no chance for the flies to reach the surface. High-pressure water sprays can also be used for control, and in other cases, hand collection of the leaves with larvae that have hatched from eggs or of larvae shaken from the plants.

Biological control includes the use of predators' parasites as well as bacterial and fungal enemies. In many cases insect damage can be solved by releasing predators or parasites that can be acquired commercially and released in the orchard. This approach provides a very effective long-term biological control. Examples include the effective control of many scales and aphid insects in different parts of the world. The bacterium *Bacillus thuringensis* is used widely to control many leaf-eating larvae and the fungus *Beauveria* to control a number of pests such as whitefly and different beetles.

Chemical control is obtained by using insecticides. Insecticides act by poisoning the insects that ingest the sprayed plant. The ingestion of the insecticide can occur by direct contact, inhalation of the toxic vapours or when systemic products are used that get into the plant sap through either the leaves or the roots, and as the insect sucks this poisoned sap, it is killed. There are also repellent substances that keep the insects from attacking the plants; in some cases they are plants. For chewing insects, products that act through ingestion or contact are used. For insects in older stems, trunks, roots and seeds, control is obtained either by fumigation or with a contact insecticide. For insects sucking aerial or root parts, a contact and a systemic insecticide can be used.

Most newer insecticides are less harmful to the environment, the farmers and the consumers. The new products are very specific and short-lived in the field, so that their poisoning effect is not as long-lasting as it used to be with the old insecticide compounds. The grower should always make sure what the best product is for controlling an insect and if it has been approved by the government or the importer for that species, especially in case of an export product. For field safety, the requirements as to how soon after spraying people can re-enter a field and what is the minimum time before harvest that the insecticide can be applied should be determined. Some friendlier products include pure soap, oils and plant extracts, which can be very effective for some insects.

Mites

Mites belong to a different group and are related to spiders. They normally rasp the underside of the leaves and feed on the sap, damaging the plant and its ability to photosynthesize. Mites can become more of a problem when the plants have a shortage of water or fertilizer. Normally they are on the underside of the leaves, making it more difficult for sprays to reach them. Their control should start with feeding and watering the plants. Biological control measures include the use of predatory mites. The chemical approach includes the use of some fungicides such as sulfur and some dithiocarbamate fungicides. Specific acaricides are based on pyrethroids, and in recent years many new compounds have been developed, most of them interfering with mitochondrial activity. For best control, it is often necessary to apply another product 5 days later to kill the new adults that emerge from the eggs. Rotating products avoids the build-up of resistance. During spraying it is essential to cover the underside of the leaf where mites are found.

Diseases

Diseases are caused by bacteria, fungi, viruses and other organisms, such as mycoplasmas and viroids.

Bacteria

These organisms are the cause of moist foul-smelling wounds, necrosis, galls and wilting, because they can infect the vascular system and clog it. Bacteria can be controlled with antibiotics such as streptomycin, but these products are fairly expensive. The measures to reduce their appearance and progress are to select propagating material that is clean and avoid excess moisture. Disinfecting any tool before using it on another plant and destroying any diseased material by burning are other simple techniques.

Fungi

Fungi are the most common cause of plant diseases. For a fungal attack to be successful it will depend on the status of the plant; the presence of mechanical breaks in the cuticle, the plant's susceptibility to the fungal strain, the plant's stage of development; the fungal development stage and the environmental conditions. Relative humidity of 90–100% is optimal for fungal development, with dew sometimes creating favourable conditions.

All fungi need a certain combination of temperature and relative humidity to become a problem; hence many fungal diseases can be a serious problem in some situations and seasons but not in other conditions. Fungal diseases can be avoided through resistance in a few cases. Well-fertilized plantings with a good drainage system and careful irrigation to avoid excess of water will reduce the risk of root diseases. Disinfection of pruning and other wounds, control of host weeds and spraying with specific fungicides all help in controlling diseases. Preventive applications of fungicides are often used with some crops, such as papaya against anthracnose, where all stages of fruit development are present versus application only at certain stages, such as during mango flowering.

Fungicides act via contact or systemically, with many products being available in the market. In most cases, fungicides have to be rotated to avoid resistance development; this is especially acute for postharvest use. It is important to check the toxicity of the product and the waiting time before harvest. Fungicides in general are less toxic than insecticides, and in the last years several new products have been developed that are more effective and also friendlier to the environment. Several older products are still available that are cheap and effective. Examples include copper sulfate, copper oxide, Bordeaux mixture (a copper derivate), sulfur and some oils.

Virus and viroids

Viruses are very simple microscopic agents that possess either RNA or DNA that is encapsulated in a protein coat. They are capable of replicating themselves inside the plant using the plant cell's own metabolism. Viroids differ from viruses in being composed of only a single strand of ribonucleic acid but are not protected by a protein coat. Virus diseases are normally transmitted by contaminated propagation material, such as seeds, cuttings, layers, budwood or entire plants, hands or tools that are contaminated or by insect transmission. Insect transmission is probably the most important way viral diseases are spread, and aphids are one of the most important vectors, as well as some other insects such as thrips.

Once a plant is infected with a virus, it is not possible to cure that plant. Sanitation is by removal of the diseased plants and using plants that serve as host vectors for the virus and insect. Careful disinfection of hands and tools such as grafting knives, pruning shears or saws is a must. Seed disinfection can also be effective with some plants of the *Solanaceae* family. If an economic analysis can justify its use, an anti-aphid screen or fabric can be used, as is done in some papaya fields.

Viruses can kill a plant or reduce production and quality of fruit. Some cause different types of leaf spots such as mosaics, while others can cause leaf yellowing, stunting and curled leaves. Some species will show no obvious visible symptoms but are still infected. Clean material can be obtained by meristem culture combined with thermotherapy, micro-grafting, ovule and nucellar embryo culture. Some viral diseases are not seed-transmitted and the seeds act as filters. Care has to be taken with the plant material taken to the farm and to keep it as clean as possible. At country level, strict quarantine is important to avoid the importation of new viruses carried unknowingly by people.

Nematodes

Nematodes are non-vertebrate animals that can be plant parasites. Most of them attack the roots, causing galls, wounds, tumours and lesions. Their feeding reduces plant vigour and yields. Several genera of nematodes – *Meloidogyne* (knot nematode), *Ditylenchus, Tylenchus* and *Radopholus* – cause plant diseases, and the last two are parasites of citrus roots.

Nematodes are more common in sandy soils and their control, till now, has been by the use of fumigants. Fumigants are very poisonous and the results obtained from their use have been mixed. Once you start on a fumigation programme you have to continue. Post-plant nematicides are also available. Other approaches are rotations that involve trap crops, organic matter addition and soil solarization, which can be used with short-cycle crops such as pineapple and banana.

Vertebrate enemies

Birds, bats, squirrels, rats, monkeys, pigs and other animals, including elephants, can become a real problem in orchards. These animals cause damage to the tree trunk and eat the fruit. Birds can devastate a whole crop, with several methods having been tried and discussed in Chapter 3.

For rodents, metallic plates around the trunks can be used to prevent them from climbing to the tops or to prevent damage to the bark of the base of the tree. Poisoned baits or paraffin blocks containing an attractant and a poison that are fairly weatherproof are also a good solution. The use of repellents or trunk protectors can sometimes be useful.

Other less important miscellaneous problems include algae, mosses and parasite plants. Algae can be controlled with copper.

Integrated pest management (IPM)

This approach involves the use of many of the above procedures and practices in combination to obtain the best control with the least environmental impact. A careful analysis of the crop and pests' development cycles need to be established to develop a strategy to combat the problem at its most susceptible phase. Computer systems can assist by analysing the environmental conditions and predicting the development of certain problems. IPM potentially can save money, protect the environment and allow the orchardist to market a product with fewer pesticide residues. For tropical fruit the market demands products that are of the highest quality, and without blemishes or insect and disease damage, making it difficult to avoid the use of some chemicals (Penman *et al.*, 2003).

GIRDLING AND SCORING

Girdling consists of taking off a ring of bark, 4 mm to 3 cm wide, from the main trunk (Fig. 4.7a), scaffold branches or smaller branches to stop the movement of sugars in the phloem, especially from the canopy to the roots. This procedure is usually done with two knives or blades that are joined or welded together to cut through the bark and phloem, which are removed once the cuts have gone around the whole stem. Sometimes spiral girdling is used, and semi-girdles of two Cs in opposite positions but at different heights of the branch are used to avoid a complete blocking of the flow.

Scoring is a mini-girdle by which the bark of the trunk or branch is cut in a circumscribing form with a saw blade or a knife. This wound is very narrow and will take about 3 weeks to heal, while a normal girdle will take about 3–4 months. Scoring is made by orchardists to manage fruit tree size and to improve yield. However, scoring has variable effects on vegetative growth,

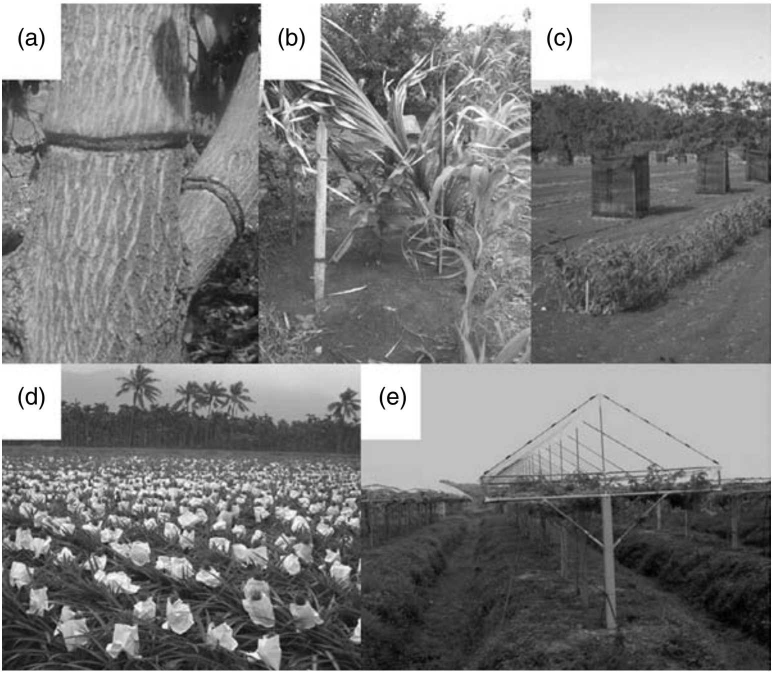

Fig. 4.7. Girdling is used to aid in inducing flowering (a). To protect young trees that are susceptible to full sunlight, simple structures such as palm fronds are used (b), to plastic shade structures (c) and wrapping pineapple fruit with paper to reduce sunburn (d). Some crops may need to be protected from rainfall (e) during flowering and fruit development, with rain shelters built over the crop in the field.

possibly due to imprecision that is inherent in cutting a tree with a saw or knife blade.

Girdling and scoring are used in some fruit trees for different purposes. In the case of layers or air layers (marcotts or gootees), a 3 cm-wide ring of bark is removed at the point just below the zone where new roots are expected to arise; the interruption of the phloem flow stimulates adventitious root formation above the girdle. Sometimes the branch from which grafting or budding material is to be obtained is girdled below these buds 2 or 3 weeks before material is to be removed. The objective is to induce bud swelling, which results in higher grafting and budding success rates.

Another objective of girdling is to stimulate flowering. In very hot areas with no cool or dry period to induce mango flowering, a 3-cm girdle is done on a primary branch to induce flowering. The problem is that 5% of the branches often die. The girdling technique is also used on avocados, macadamias and litchis, in order to improve flowering, fruit set or fruit size. For better fruit set, girdling or scoring should be done at petal fall, while for larger fruit size girdling is done at the end of the initial small fruit drop. Girdling has been used to improve avocado fruit size, especially 'Hass' (McNeil, 2001). A longer-term objective is the elimination or modification of biennial bearing in some tropical and subtropical fruit trees. Litchi girdling is done before flush initiation, around September in the northern hemisphere, to induce more flowering and increase fruit yield. Only one of the three or four main branches should be girdled, in order to avoid the danger of killing the tree. Girdling should be preceded by a heavy irrigation and fertilization for better results. Normally if there was a poor crop the previous year, girdling will work, while if there was a heavy crop, no girdling should be done. It is recommended that girdling or scoring be done for no more than 3 years in a row. Girdling is not a standard practice and, in many cases, growers will use it when they have marginal yields and will forget about this practice when good yields are being obtained.

DEFOLIATION

Most tropical fruit trees are evergreen and usually do not shed their leaves. An exception is some *Spondias* species that lose their leaves during the dry season as a drought-protection mechanism. The trees begin flowering while completely bare. Some other trees, such as avocados in the subtropics, might have a heavy loss of leaves just before flowering time. Artificial defoliation is practised in difficult-to-graft trees, where the portion of the branch from which bud-wood is going to be taken is defoliated 2 or 3 weeks prior to collecting the scions. This defoliation stimulates the lateral buds to start swelling and become more active, and ensures better budding or grafting success.

Cherimoya and atemoya, being more subtropical, are sometimes classified as semi-deciduous. The lateral buds of these species are covered by the leaf petioles (see Fig. 6.1) and are not at the leaf axils, as in most plants. Thus the leaves have to fall or be removed for the bud to burst. Defoliation is done to induce uniform sprouting of these buds just before the new growth is about to start and natural defoliation has not been complete. This is achieved by hand-stripping or with the application of urea or other defoliants, at the time of pruning, to induce a new cycle of flowering and fruiting.

PLANT GROWTH REGULATORS AND OTHER STIMULANTS

Plant regulators have been studied for many years and some practical uses have been developed. Among the most common uses of plant regulators is the improvement of rooting of cuttings or air layers with auxin-like compounds such as indole butyric acid (IBA) or naphthalene acetic acid (NAA). These auxins improve rooting percentage, accelerate adventitious root emergence and increase the number of roots a layer or cutting will form.

Some trials have been made to enhance fruit set in cherimoyas and atemoyas. Auxins will reduce fruit drop while gibberellins will improve fruit set and growth rates. In some trials seedless fruits of atemoya have been obtained, but repeated sprays have to be done during the first 2 months and fruit size is smaller and flavour is poorer. Similar results have been obtained with cherimoya and sweetsop. None of these practices are commercially used. In guava, trials have been done to reduce the number of seeds with auxins and gibberellic acid; the latter has reduced the number of seeds and enhanced soluble solids but is not used commercially.

In commercial pineapple production, flower induction is carried out to obtain more uniform flowering. The plants are sprayed, once they achieve the right size, with ethylene gas dissolved in water or ethephon (2-chloro-ethyl phosphonic acid), an ethylene-releasing compound. Also, acetylene generated from calcium carbide reacting with water can induce flowering; this product can be applied dissolved in water as a spray or by putting a little amount of it in the cup formed by the leaves in the centre of the plant. Since ethylene is the ripening hormone that plants and fruits produce naturally, many fruits are treated with ethylene gas or ethephon to hasten and to obtain uniform ripening. This is done commercially with bananas. For citrus, it helps achieve better rind colour.

Some growth retardants, such as pachlobutrazol and uniconazole, which act as gibberellin antagonists, are used commercially to prevent mango shoots from re-sprouting too soon. This treatment allows the shoot to achieve a minimum age, so that when it does sprout it is a flower panicle instead of a vegetative shoot. These products have not been approved by the US government but are used outside of the USA.

Potassium nitrate or ammonium nitrate is used to induce flowering in mango. This foliar application treatment is more successful if the shoots have achieved certain age and are mature. This treatment is more successful in the tropics than the subtropics. In the case of longan, potassium chlorate can be applied to the soil to induce flowering. Dinitro-orto-cresol (DNOC) has been used to burn mango inflorescences in order to force a second flowering a few weeks later, when climate or market conditions are more suited.

POLLINATION

Some fruit species have self-sterility problems and will not produce good yields in single-variety planting. The species can be completely or partially self-sterile or the plants can have different sexes or because of dichogamy, when there is no coincidence of the maturation time of the female and male organs of the flowers. Often more than one genotype has to be present in the field or artificial pollination has to be done. In other cases, a certain number of male plants have to be inter-planted among female plants. For avocados that have A and

B flowering habits, there has to be a combination of both types in the orchard to get proper pollination, fruit set and yields. Macadamia or carambola require two or three varieties in the orchard to achieve higher yields, since most varieties are partially self-incompatible and intercrossing results in higher yields. In carambola, sometimes a branch of the rootstock is left on the tree to ensure better fruit set. Date palms are dioecious and wind pollinated, and one male plant is planted for every 10–14 female plants, distributed uniformly throughout the orchard. Male date inflorescences can be shaken in front of female inflorescences to achieve better fruit set, and sometimes pure pollen is obtained and applied to the female flowers with dust blowers.

The dichogamy in cherimoya, atemoya, soursop and other *Annonas* makes it necessary to hand-pollinate either by collecting pollen of flowers that opened the day before in glass jars or by collecting pollen from flowers in the field in the male stage to apply it to flowers in the female stage. This can be done with a No. 4 fine paint brush made with camel hair or with a hand mist blower (see Fig. 6.4) using pollen dissolved in *Lycopodium* spores to be able to pollinate more flowers. In soursop, which has moist pollen and large flowers, this can be done with the fingers.

Yellow passion fruit is self-sterile and carpenter bees (*Xylocopa*) have to be present to get proper fruit set. When bees are absent, hand-pollination has to be carried out using cloth gloves to collect the pollen from flowers in the contiguous plant row to ensure that it comes from a different genotype, since plants come from seed. This is done in the afternoon since flowers open at noon.

The presence of bees, carpenter bees or common flies is a great help in achieving better yields. For bee pollinatation, four to six bee hives per hectare should be in the field at flowering. In some places, mango trees in flower are sprayed with a solution of manure to attract as many domestic flies as possible to the orchard to improve pollination.

TEMPORARY SHADE, SHELTER AND BAGGING

Some tropical fruit species that originated in forests may benefit from being under partial shade during their first years in the field. This is the case for mangosteen, durian, jackfruit, acahachairu and other species. Semi-shade is provided by planting certain bushy plants, such as pigeon peas, castor beans, bananas or small fast-growing trees, around the planting hole or making a tent-like structure with palm leaves (Fig. 4.7b), branches with leaves or shade cloth (Fig. 4.7c). This shade will avoid sunburn damage and provide the plants with less-stressful growing conditions. Some fruits, such as pineapple, are also susceptible to sunburn and are protected by tying the leaves together over the fruit, placing straw around the fruit and the use of plastic or paper wrappings (Fig. 4.7d).

Rain shelters are sometimes constructed to protect a fruit crop from incessant light rain showers (Fig 4.7e). This can be seen when grapes are grown in the tropics and mango in Okinawa, to protect the fruit from disease and for pollination, respectively.

To harvest high-quality, blemish-free fruit, bagging when the fruits are young is often practised (Fig. 4.7d). Often the fruits are sprayed with a fungicide, thinned and the remaining selected fruits bagged. The thinning allows a grower to ensure that each remaining fruit has sufficient leaves on the stem for fruit growth and development. Though there is a cost associated with this bagging operation, the harvested fruits are blemish free, without disease and insect damage, and more than 90% are marketable. For fruits that are not bagged, 50–70% of the harvested fruit maybe marketable and a smaller percentage will be of the highest grade. Another advantage of bagging is that it evens out labour needs by moving some of labour requirements from harvesting to thinning and bagging and thereby offers more continuous work for good workers whom you wish to retain.

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5

Postharvest Technology

INTRODUCTION

Postharvest handling refers to all the steps that take place at harvest and from harvest through to when the consumer receives the fruit (Fig. 5.1). The goal of postharvest handling is to maintain quality. Quality is defined as the absence of defects or degree of excellence and includes appearance, colour, shape, injuries, flavour, taste, aroma, nutritional value and being safe for the consumer (Abbott, 1999; Shewfelt, 1999). Fruit qualities when consumed are decided in large measure before harvest and depend upon variety grown, crop management (fertilization, irrigation, etc.), environment (climate, soil) and other preharvest factors. The objective of postharvest handling is to maintain quality by preventing mechanical injury, water loss and disease development, limiting unwanted physiological changes and preventing chemical and microbial contamination (Cook, 1999).

Farmers, packers, shippers, wholesalers, retailers and consumers frequently have different perspectives with regard to quality and often place different emphasis on the different components of quality. In research, quality is related to some intrinsic character(s) (appearance, colour, acids, sugars, etc.) and how these characters change during handling. The research data give us information as to how a product should be handled postharvest. The data need to be complemented with simulated shipping studies and the evaluation of the product from initial commercial shipments.

POSTHARVEST LOSSES

During postharvest handling, losses frequently occur, referred to as shrink in the commercial and retail trade. These losses mean a complete loss of all the resources that went into production. Estimates of tropical fruit postharvest losses in both developed and developing countries vary widely from 10 to 80%. The losses given in published reports highlight the total postharvest

Harvested by hand – maturity
– grade
↓
Placed into shoulder bag
↓
Poured into field bin or lug box
↓
Transported to packing house
↓
Water- or hand-unloaded
↓
Culling
↓
Disinfestation treatment
↓
Sprayed with wax and fungicide
↓
Culling
↓
Weight/colour sorting
↓
Hand packed into cartons
↓
Cooled to 10–12 °C
↓
Loaded into shipping container
↓
Air or sea transport to market

Fig. 5.1. Generalized fruit-handling scheme for tropical fruit.

losses of products but do not consider the loss of quality or nutritional value and the downgrading that may reduce the price received. Losses may be due to mechanical injury, physiological damage or pathogens. Once a tree comes into production, the most expensive cost is the cost of labour to harvest and to prepare the fruit for market; that in developed countries ranges from ~30 to 80% of the total operating costs for the year. The reduction of losses in a systematic way requires a knowledge of postharvest physiology, its applied technical aspect, handling and the appreciation of its biological limitation, represented as storage potential (Paull *et al.*, 1997).

GENERAL CHARACTERISTICS OF TROPICAL FRUIT

Like all fresh fruit and vegetables, tropical fruits have four general characteristics that need to be understood and considered during postharvest handling. These characteristics are the reason why postharvest technology is needed. The characteristics are:

1. All fresh fruits after harvest are still living and respiring.
2. All fresh fruits have a high water content (~90%), and after harvest it is no longer being replaced from the plant yet they continue to lose water.
3. All fresh fruits are subject to pathogen attack before and after harvest.
4. All fresh fruits are made up of diverse morphological structures, with the edible tissues varying between different fruits, and hence they have different composition and physiology.

The edible fruit tissues in tropical fruits are derived from many tissues, such as the floral receptacle in strawberry and cashew, the fused clustered flowers in pineapple, the entire pericarp in tomato, the exocarp and mesocarp in apple and peach, the mesocarp only in papaya, the endocarp in citrus, the aril tissue arising from the funicle in litchi and durian, and the seed coat in rambutan (Fig. 1.1). This diversity needs to be understood as it influences how a fruit will respond to postharvest handling treatments.

The objective of postharvest handling is to minimize adverse changes in these characteristics, especially respiration, dehydration and pathogen attack. Losses postharvest are tied directly to these adverse changes, often associated with poor storage environment and mechanical injury. Mechanical injury, besides causing unsightly scarring, also increases water loss and susceptibility to pathogens. The component of the storage environment over which we have the greatest control postharvest is temperature. Proper storage temperature and avoiding mechanical injury are the two most important variables in postharvest handling.

POSTHARVEST PHYSIOLOGY

Tropical fruit physiology does not differ from the basic knowledge gained from studies of temperate and subtropical fruits. Differences occur between fruits in the major substrates involved in ripening, the rate of ripening and senescence, and in some cases variation in the order in which various components of ripening occur. The aspects of tropical fruit physiology that make these fruits unique are:

- their chilling sensitivity;
- the generally more rapid ripening of climacteric tropical fruits when compared to temperate fruits; and

- the frequent need in postharvest handling to expose them to high temperatures or other stresses during insect disinfestation prior to export.

Respiration is the conversion of sugars such as glucose into carbon dioxide, water, chemical energy and heat. The chemical energy (ATP, NADH) is used to synthesize the molecules needed to keep the cells alive and to grow. The heat represents the inability of the cell to capture fully all the potential energy in the sugar. The simple overall equation for glucose respiration highlights the relationship between storage environment and respiration, which is directly related to postharvest storage life.

$$\text{Glucose} + \text{Oxygen} \rightarrow \text{Carbon dioxide} + \text{Water} + \text{Chemical energy} + \text{Heat}$$

The respiration rate is decided by the amount of the substrate, in this equation glucose but it can be starch or fats, and oxygen. The rate of conversion, indicated by the arrow, is determined by temperature. Lower storage temperatures lead to a slower rate of respiration and a greater storage life; the higher the temperature the higher the rate of respiration and the shorter the storage life. Storage life includes all the time spent in the various marketing steps from harvest to the consumer.

The initial use of cold to preserve or extend the shelf-life of fresh commodities in many cultures is lost in antiquity. Examples of the use of cold for storage of fresh produce range across the use of clamps, cellars, basements, caves and ice houses. Industries developed around the harvesting of ice in the winter for use in the summer. The limitations of cold for tropical plants were well recognized by the 18th century; for example, the Palace of Versailles' greenhouse was designed to keep tropical plants alive during winter. An understanding of the range of suitable temperatures for fruits and vegetables followed the development of reliable calibrated thermometers in the 1700s by the Dutch instrument maker Gabriel Fahrenheit and the Swedish astronomer Anders Celsius. The choice and acceptance of common fixed temperature points (freezing and boiling points of pure water) led to standardization of temperature scales.

Climacteric and non-climacteric

Like temperate fruits, tropical fruits can be divided into climacteric and non-climacteric (Table 5.1). This division is based on the respiratory pattern after harvest. In climacteric fruits such as banana and papaya, there is generally a dramatic and rapid change in respiration, ethylene and other quality characteristics during ripening. In commercial handling, ethylene can lead to earlier ripening of climacteric fruit but not of non-climacteric fruit. Non-climacteric fruit such as pineapple and citrus should be already ripe and ready to eat when harvested since they show little change in respiration and quality characteristics after harvest.

Table 5.1. Classification of selected tropical fleshy fruits according to their respiratory pattern.

Climacteric	Non-climacteric
Avocado (*Persea americana* Mill.)	Carambola (*Averrhoa carambola* L.)
Banana/plantain (*Musa* spp.)	Litchi (*Litchi chinensis* Sonn.)
Breadfruit (*Artocarpus altilis* Parkins Fosb.)	Mangosteen (*Garcinia mangostana* L.)
Cherimoya (*Annona cherimoya* Mill.)	Mountain apple (*Syzygium malaccense* (L.) Merril & Perry)
Durian (*Durio zibethinus* J. Murr.)	Pineapple (*Ananas comosus* (L.) Merrill)
Guava (*Psidium guajava* L.)	Rambutan (*Nephelium lappaceum* L.)
Mango (*Mangifera indica* L.)	Rose apple (*Syzygium jambos* (L.) Alston)
Papaya (*Carica papaya* L.)	Star apple (*Chrysophyllum cainito* L.)
Passion fruit (*Passiflora edulis* Sims)	Surinam cherry (*Eugenia uniflora* L.)
Sapote (*Casimiroa edulis* Llave.)	
Soursop (*Annona muricata* L.)	
Chiku (*Achras sapota* L.)	

Respiration and ethylene

Tropical fruits vary widely in their respiration rate and ethylene production (Table 5.2). The rate and production depend upon the stage of ripeness as well as variety, preharvest environment and culture. Respiration rates also vary with type and maturity of the fruit and the presence or absence of the plant growth regulator ethylene.

Respiration varies from <35 mg/kg/h for pineapples to nearly 300 mg/kg/h for ripening avocados and ripe bananas (Table 5.2). Green bananas have a much lower respiration rate of about 50 mg/kg/h. Knowledge of the rate of respiration of different fruits is essential in determining the potential heat loads in refrigerated cold rooms and containers. The ethylene production rate is also essential information, as its presence can lead to premature ripening and senescence of fresh commodities. In mixed storage, where fruits and vegetables are held in the same room or shipping container, the ethylene released from ripening fruit can lead to rapid yellowing of leafy vegetables.

Respiration rate and storage life are related (Fig. 5.2). Fruits with high respiration rates have shorter postharvest lives, hence the need to reduce respiration and thereby increase postharvest life. Temperature management is the major method of controlling respiration rate, although it is limited in most tropical fruits by their chilling sensitivity, which leads to injury.

Table 5.2. Respiration and ethylene production rate of selected tropical fruits at 20°C.

	Respiration		Ethylene	
Class	Range mg/kg/h	Commodity	Range µl/kg/h	Commodity
Very low	<35	Pineapple, carambola		
Low	35–70	Banana (green), litchi, papaya, jackfruit, passion fruit, mangosteen	0.1–1.0	Pineapple, carambola
Moderate	70–150	Mango, rambutan, chiku, guava, durian, lanzone	1.0–10.0	Banana, guava, mango, plantain, mangosteen, litchi, breadfruit, sugar apple, durian, rambutan
High	150–300	Avocado, banana (ripe), sugar apple, atemoya	10–100	Avocado, papaya, atemoya, chiku
Very high	>300	Soursop	>100	Cherimoya, passion fruit, sapote, soursop

Vital heat: kJ/tonne/h = mg CO_2/kg/h × 11. BTU/tonne/h = mg CO_2/kg/h × 10.4

Chilling injury

The ability to use temperature to extend the postharvest life of tropical fruits is limited by chilling injury. For example, temperate fruits such as apples and pears can be stored at 0°C for months, while the maximum storage life for papaya is about 21 days at 10°C (Fig. 5.3). Papaya, when held at less than 10°C, has reduced storage life due to chilling injury (Chen and Paull, 1986). The symptoms of chilling injury are similar for most commodities and include pitting, skin darkening, failure to ripen completely and increased susceptibility to decay. Carambola and the subtropical fruits longan and litchi are crops that are somewhat resistant to chilling injury, requiring a considerable time (>14 days) at 1°C before injury occurs.

In any discussion of chilling injury, two aspects must be considered: the storage temperature and the duration or exposure at that temperature. Although there is not an exact, fruit-specific, reciprocal relationship between temperature and time, it takes a longer time at a higher temperature to develop injury than at a lower temperature. As storage temperature is lowered from 30°C, the duration of storage life increases and the limitation is fruit ripening and senescence. Storage life reaches a maximum at 15°C for Brazilian

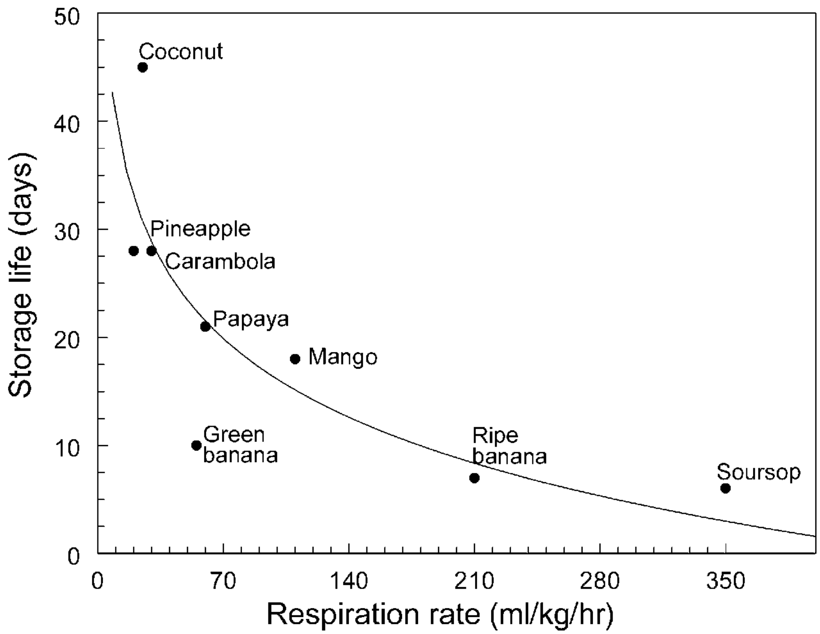

Fig. 5.2. Relationship between respiration rate and postharvest life of tropical fruits held at their optimum storage conditions (Paull, 1994).

banana, 10–12°C for papaya, 8°C for rambutan and 5°C for carambola (Fig. 5.3). Lowering the temperature further leads to a shorter storage life, but the limitation changes from being fruit ripening to the development of chilling injury, as ripening is completely inhibited. Recommendations for optimum storage of most tropical fruits are just inside the chilling range (8–12°C), as this allows ripening to be controlled, and, if removed before the chilling stress threshold is exceeded, the fruit still has a number of days of useful marketing life as it ripens. Unfortunately, similar data are not available or are fragmentary for many other tropical fruits. The actual relationship between storage temperature and duration can vary with cultivar, preharvest conditions, the stage of ripeness and postharvest treatments.

Moisture loss

Frequently, injury induced by water loss is confused with chilling injury. Water loss by tropical fruit postharvest is dependent upon the commodity, cultivar, preharvest conditions, vapour pressure deficit, wounds, postharvest heat treatments and the presence of coatings or wraps. Tropical fruits can be grouped as to water moisture loss rate, from low (coconut) to medium

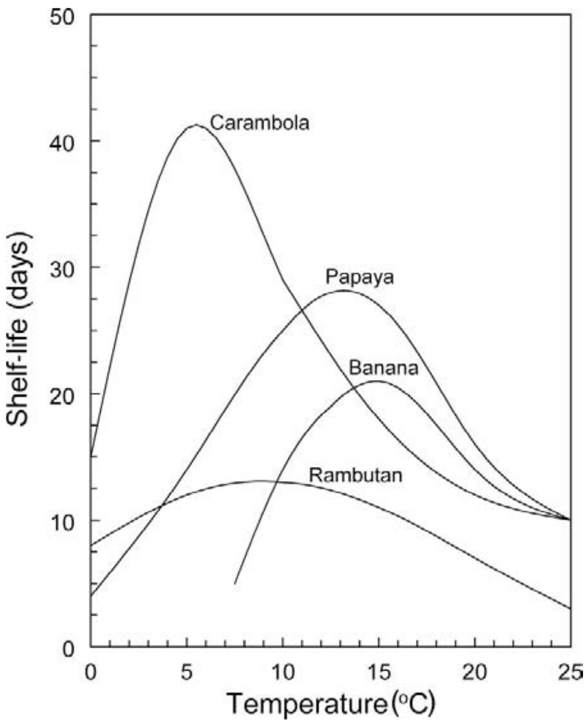

Fig. 5.3. The shelf-life at various storage temperatures for carambola, rambutan, Brazilian banana and papaya fruit (O'Hare, 1993, 1995; Paull, 1994).

(avocado, banana, pummelo) to high (guava, litchi, mango, papaya, pineapple, rambutan). On a per unit area basis, the stem scar is frequently the site of highest water loss, although most water is lost through lenticels, stomata and skin cuticle. Tropical fruits have water loss rates between about 0.1 and 0.3%/day/mbar WVPD (water vapour pressure deficit) (Table 5.3). Fruit having lost 6–8% of their fully turgid initial weight begin to show signs of mass loss. Usually the initial sign is skin wrinkling, although skin discoloration is the first symptom in some fruits. Loss of moisture, besides affecting overall appearance, is also an economic loss if fruit is sold by weight.

Nutritional attributes

Composition is a significant quality attribute, and storage temperature can influence vitamins and other nutrients in many fruits and vegetables. Ninety per cent of the vitamin C in the US diet is derived from fresh fruits and vegetables. Loss of vitamin C is generally more rapid at higher storage

Table 5.3. Comparison of water loss from different tropical fruits.

	Water loss	
Tropical fruit	% loss/day	% loss/day/mbar WVPD
Avocado	0.5–1.0	
Banana	0.4	0.3
Guava		0.3
Mango		0.1
Papaya Sunset		0.08
Plantain	0.5	
Rambutan		0.32
Chiku		0.3

temperatures and slower in acid fruit (pineapple) than more neutral fruit (avocado, papaya). A 40% loss of vitamin C occurs in tangerines at a higher storage temperature (7–13°C) for more than 8 weeks, while a negligible loss is found in lemon at 13°C, although it is significant at 24°C, and no significant loss in grapefruit held at 8°C and 12°C, with an increase in concentration following 2-month storage at both temperatures. Vitamin C loss can be significant during fruit ripening, and the impact of temperature is not regarded as nutritionally significant.

Flavour and aroma attributes

Flavour is determined largely by the sugar to acid ratios. Changes in these two components can vary independently and so alter flavour. Storage temperature can influence the rate and direction of change. Both soluble solids (mainly sugars) and acidity decline more in grapefruit held at 8°C than at 12°C, while guavas show no dramatic change during storage at temperatures between 10 and 15°C. The stage of maturity at harvest has a significant effect on changes during storage.

Improper storage temperature can lead to significant alteration in the volatiles produced during ripening. Jonathan apples stored at ~10°C lose the volatiles butyl, isopentyl and hexyl acetates and alcohols. The rate of loss is reduced up to 6000-fold when stored at 0°C (Wills and McGlasson, 1970, 1971). Soursop aroma develops during ripening and is lost if the fruit is stored at 10°C for 2 days. Off-flavours due to ethanol and acetaldehyde in citrus fruits are frequently associated with chilling injury or long-term storage of tangerines and grapefruit (Cohen *et al.*, 1990).

STORAGE POTENTIAL

Storage potential is normally defined as the postharvest life of a commodity held at its optimum storage temperature. This potential is dependent upon cultivar, preharvest environment and culture, maturity at harvest and storage conditions. Postharvest life is terminated because of physiological, mechanical and pathological stress, with associated symptoms such as excessive water loss, bruising, skin scald, failure to ripen and decay.

The commercial postharvest storage potential for most fresh fruits and vegetables are given in numerous publications. The values given for storage life (Table 5.4) should be regarded as the maximum, as they are based upon laboratory studies using appearance criteria and may not allow for loss of the other quality criteria, such as texture, nutritional value and flavour. The range in storage life for each fruit indicates the variability in the information available, different criteria probably being used to evaluate the end of storage life, and differences associated with stationary or transport storage. Often simulated laboratory studies used do not allow for the vagaries of commercial handling and storage. An important aspect of this variation is associated with the retailing phase, where proper temperature maintenance is frequently lost for various reasons.

Storage temperature

Low temperature has been used to extend the shelf-life of fruits and vegetables since antiquity (Qi, 1982; Paull, 1993, 1999). The additional benefit of low-temperature storage is in protecting non-appearance quality attributes, such as texture, nutrition, aroma and flavour. Time of day when harvest is performed can influence storage life. In addition, delays in cooling after harvest can reduce fruit storage life and quality. In commercial handling, shelf-life of commodities may vary greatly from laboratory studies. The distribution chain rarely has the facilities to store each commodity under ideal conditions and requires handlers to make compromises as to the choice of temperature and relative humidity (RH). These choices can lead to physiological stress and loss of storage life and quality. This limitation, especially late in the handling chain during retailing, requires all participants in the distribution chain to increase their understanding of the need to improve management of handling, temperature and RH, to limit losses in quality.

If cooling is delayed after harvest, storage life can be significantly reduced. Simple shading, if there is a delay, can limit loss of quality. An unshaded commodity directly exposed to the sun can rapidly warm to 10°C higher than the ambient air. A 2-h delay after harvest can mean a loss of marketable strawberries of about 93–80%, and 6 h leads to an increased loss of ascorbic acid, soluble solids, fructose, glucose and sucrose, and titratable acidity and

Table 5.4. Recommended storage temperature and storage potential as postharvest life of selected tropical fruits. Data extracted from commercial publications.

Fruit		Optimum storage temperature (°C)	Relative humidity (%)	Postharvest life at optimum temperature (days)
Acerola		0	85–90	50–58
Atemoya		13	85–90	28–42
Avocado	Mexican	5	85–90	14–28
	West Indian	10	85–90	14–28
Banana		14	90–95	7–28
Breadfruit		13	90–95	14–40
Carambola		1	90–95	21–28
Cherimoya		13	85–90	14–28
Durian		4	85–90	42–56
Guava		10	90–95	14–21
Jackfruit		13	90–95	14–45
Langsat		11	90–95	10–15
Litchi		1	90–95	21–35
Longan		2	90–95	21–35
Mango		10–12	85–90	14–25
Mangosteen		13	85–90	14–25
Papaya		8–12	85–90	7–21
Passion fruit		12	85–90	14–21
Pineapple		10	90–95	14–36
Rambutan		12	90–95	7–21
Sweetsop		7	85–90	28

firmness. Most tropical fruits do not show as rapid change in quality, but delays in cooling should be kept to a minimum. Apples that have a long postharvest life and lower rate of respiration should be cooled within 3 days of harvest, to prevent loss of apple firmness and acidity during storage for 7.5 months at ~3°C. For most climacteric tropical commodities, the delay in cooling allows continued ripening and overall loss of storage potential. This is a problem, especially for commodities such as papaya and atemoya, which have a short shelf-life (10–14 days). In general, the higher the metabolic rate (respiration) the shorter the overall shelf-life, the greater the impact of delayed cooling on preserving quality (Fig. 5.2).

Fresh fruits and vegetables probably receive the greatest temperature abuse at the retail level (LeBlanc *et al.*, 1996). Mean temperatures of display cases used for fruits and vegetable are *ca.* 8°C. The majority of those commodities that should have been stored at <4°C are above the recommended temperature range. The same percentage is found for commodities that should have been held >12°C.

Storage relative humidity

Relative humidity is the percentage that air is saturated with water vapour at a particular temperature and pressure. At low temperatures such as 0°C, the amount of water vapour required to saturate the air is fivefold less than at 25°C (Gaffrey, 1978). This difference in amount of water vapour at lower temperatures means that condensation is a greater problem on fruit when small changes in temperature occur. Relative humidity is used as a handy measure of water vapour pressure (WVP) in air relative to standard pressure. Psychrometric charts give a graphical representation of the relationship between temperature, RH and WVP in moist air. The water vapour pressure deficit (WVPD) is the difference between actual vapour pressure and the saturated vapour pressure and determines the rate of evaporation from a fresh commodity at the same temperature (Paull, 1999).

Relative humidity in storage rooms is dependent upon the surface area of the refrigeration evaporator coil and the temperature difference between the coil and the air, along with air exchange rates, temperature distribution in the room, commodity and packing material used. Practical difficulties are encountered in maintaining RH in large storage rooms within a narrow range at high relative humidity. To illustrate the difficulty, to maintain 95% RH at 0°C, the mean temperature differential between the air and the evaporator must be ~0.5°C. A measurable and controllable temperature difference of ~1°C is available at 90% RH. These small differences test the limits of sensitivity needed to measure temperatures to this degree of accuracy. At high RH, a small fluctuation in temperature (<0.5°C) can result in condensation on cool surfaces. Poor air distribution could mean that air at 0°C, 95% RH from the coil would be 70% RH in an area at 5°C. Fibreboard and wood absorb water and may decrease RH in a room. A fibreboard box held at 50% RH has a moisture content of 7% (dry mass basis); at 90% RH, the moisture content would be 16%. High RH will not prevent moisture loss if the product temperature is not near the air temperature. Newer refrigeration controls, more rugged humidity detectors and humidification technologies have increased the ability to vary both temperature and RH and reduce energy consumption.

The nature of the commodity evaporative surface is determined by commodity type and cultivar, and both have a major influence on the rate of evaporation. Surface area to volume ratios are a significant commodity factor influencing evaporation (Ben-Yehoshua, 1987). The ratio varies widely for different commodities: individual edible leaves have 50–100 cm^2/cm^3, strawberries 2–5 cm^2/cm^3 and bananas 0.5–1.5 cm^2/cm^3. In order to compare fresh commodities, it is necessary to incorporate these factors into loss units such as %/day/mPa WVPD (Table 5.3). This enables the time needed to reach a permissible water loss as a percentage of the original mass at which a commodity becomes unmarketable or has to be sold for a lower price to be calculated.

Recommendations on RH have been made for most commodities (Table 5.4), with variation in the recommendations from different sources. These differences in recommendations may reflect general conclusions for a particular commodity group or specific observations. There is fairly good agreement as to the degree of water (or mass) loss from initial field condition before a commodity shows wilting symptoms (Robinson *et al.*, 1975; Sastry *et al.*, 1978). The wilting symptoms most often reported are less gloss, wrinkling or flaccidness. Maximum permissible losses can vary from ~10% for onions, ~7% for papayas and other tropical fruit to ~3% for lettuce. The corresponding loss rates are 0.02% initial mass/day/mbar WVPD: 3.6, 0.5 and 7.5, respectively (Table 5.3). This loss can be modified by postharvest handling practices such as packaging, waxing and wax removal during washing. This loss criterion occurs at about double the loss required for the first visible symptoms to appear and integrates the overall loss rate, which normally declines with storage. Mass loss is linear and related to WVPD; hence loss can be reduced by lowering the WVPD via reducing air temperature, increasing humidity or creating a barrier to water loss. High air flow may be necessary during cooling; once cool, RH is crucial in determining rate of moisture loss.

Moisture loss from pre-climacteric avocado, mango, banana, plantains and pear fruit hastens ripening (Fig. 5.4). There is a linear negative relationship between water loss and green life of avocado, banana and mango (Fig. 5.4). For example, the green life of bananas is about 22 days at 20°C with 95% RH and ~16 days at 13% RH. There is also about a 50% reduction in the postharvest life of custard apple at low RH and 65% reduction for plantains.

There are numerous studies relating reduced chilling injury symptom development in sensitive tropical commodities to high RH. Lemon chilling injury symptoms in the peel are reduced at high RH, though RH had no impact on flesh chilling injury symptoms.

Mechanical injury

Mechanical injury causes unsightly blemishes and favours decay by breaking the cuticle, which also favours water loss. Three types of mechanical injury are recognized as occurring preharvest, at harvest and during handling; they are impact, compression and abrasion. Often personnel handling fruit do not recognize that they are causing injury as the symptoms do not become obvious until the fruit ripens. Examples of this would be abrasion injury to green bananas, which turn black as the fruit ripens, and in papaya, which appears as sunken green areas. Impact and compression injury is sometimes not visible on the skin but is recognized as water-soaked areas in the flesh. The water-soaked areas are often only on one side of the fruit and are caused by the kinetic energy of the impact being dissipated in the fruit cells, which rupture.

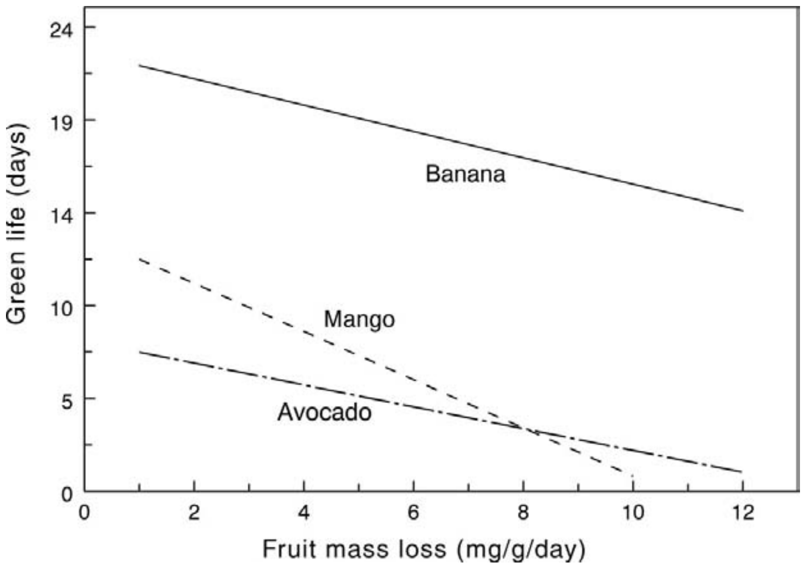

Fig. 5.4. Relationship between water loss and green-life of tropical fruits.

Careful handling is the most effective method of limiting injury. This involves careful harvesting practices, placing fruit in buckets or boxes, ensuring that the bags and buckets are clean and free of dirt and grit that can abrade the skin.

Controlled and modified atmosphere storage

During respiration, the other substrate besides sugars is oxygen, while the major product is carbon dioxide. Controlled and modified atmosphere storage methods normally reduce the oxygen levels to slow respiration and increase carbon dioxide levels to slow conversion of substrates. Controlled atmosphere (CA) storage is a more controlled, active regulation of oxygen and carbon dioxide levels, while modified atmosphere (MA) storage is more passive and relies on gas exchange. Both CA and MA methods are supplements to good temperature management and do not replace temperature management (Kader, 1993; Yahia, 1998).

Generally oxygen levels are reduced to 3–4% (Table 5.5); below 3%, frequently the fruit may become anaerobic and off-flavours will develop and alcohol production occurs. Carbon dioxide is increased to 4–10%, though greater care is needed as off-odours and flavours frequently develop. The potential benefits of MA and CA for tropical crops depend on the type of crop, pre- and postharvest handling methods and length of shipping period. Frequently, exported tropical fruits have a number of additional postharvest

Table 5.5. Conclusions and recommendations on the use of MA/CA for some tropical fruit crops.

Fruit	Intended use	Atmosphere %O_2	Atmosphere %CO_2	Degree of benefits
Avocado	Transport, MAP	2–5	3–10	Good
Banana	Transport, MAP, storage	2.5	2.5	Excellent
Cherimoya	Transport, storage	2–5	3–10	Good
Durian	Transport	3–5	10–20	Fair
Lanzon	Transport	5	0	Fair
Litchi	Packaging, transport	5	20	Good
Mango	Transport	3–5	5–10	Good
Mangosteen	Transport	2	10	Fair
Papaya	Transport	2–5	5–8	Fair
Pineapple	Transport	2–5	5–10	Not determined
Sapodilla	Not determined	5	10	Fair
Sweetsop	Not determined	5	10	Fair

constraints such as chilling sensitivity, short postharvest life, and disease and insect infestations.

It is essential to assure a sufficiently long postharvest life for tropical fruits to be able to be distributed in distant markets. The minimum times required for sea freight from eastern Australia to South-east Asia, Japan and North America, and Europe are 3, 4 and 6 weeks, respectively. Minimum shipping periods from Mexico to Europe and Japan are about 18 and 21 days, respectively. In addition to better postharvest handling systems (i.e. optimum harvesting time, control of insects and diseases, and the use of proper postharvest temperature management), MA and CA can be of major benefit to preserve quality and to prolong postharvest life.

For example, MA has been used for more than 30 years during banana transport from Central America to the rest of the world. Advances in MA/CA technology during transport have been implemented, and the technology is much more promising for tropical fruits. Atmospheres for transport have been developed that are passive (MA), semi-active or active (CA). The semi-active systems are those in which a selected atmosphere is created in the container immediately after loading, after which the container is closed and no further control of oxygen and carbon dioxide levels is carried out. Atmospheres are created by an oxygen sensor telling a valve to open or close to allow more air to enter the container to increase the oxygen level, or nitrogen to reduce oxygen levels. Carbon dioxide can also be monitored and a valve controls the amount of air entering to prevent the carbon dioxide from getting higher than the desired level.

The major question is whether the additional costs of applying the MA or CA treatments are recovered in the increased storage life and quality maintenance. Shipping containers with atmosphere-monitoring capabilities are in service, providing greater opportunities for CA storage of tropical commodities when the cost can be justified.

POSTHARVEST HANDLING

Most fresh fruits and vegetables are harvested by hand, sometimes with mechanical aids. Hand-harvesting is accurate, causes minimum damage, allows flexible use of labour and requires minimal capital investment in equipment. When fruit is hand-harvested, the supervision of field labour is greater, to ensure that the correct fruit maturity is harvested and diseased and contaminated fruits are not collected (Thompson, 1996). The trend in tropical fruit production is to maintain tree height to less than 3 m so that all field operation, including harvesting, can be done from the ground. When mechanical harvesting aids are used in the field, such as ladders and moving harvest platforms, harvest rate is slower and has a higher potential for worker injury and hence liability. Mechanical harvesting is used for fruit that is destined for processing as it is more rapid and requires less management, though it causes more mechanical injury.

During collection in the field and transport to the packing area, fruit should be protected from mechanical injury and high temperatures due to direct exposure to the sun. Upon arrival at the packing area, the fruits are normally washed, cleaned and graded, and unsuitable fruit culled; sometimes fruits are coated with waxes or other barrier compounds to reduce water loss and improve appearance, and the fruit is treated for disease control, often in the coating materials, before being packed into shipping cartons. The washing is done to remove dust and other contaminants. Potable water should be used, with chlorine or another sanitizer added to reduce cross-contamination of fruit. Chlorine is the most common sanitizer, available in a number of formulations, and requires 100–150 ppm of chlorine ion at pH 6–7.5 and a contact time of 1–2 min. Fruit should be rinsed with potable water upon removal from the chlorine solution.

National, international and commercial grade standards are used to cull fruit that does not meet the standards. The standard used will depend upon the market requirement. The grade standards include a description of maturity, skin colour, firmness, shape and size, and freedom from decay, defects, mechanical injury and physiological disorders. The standards also include percentage of off-grade fruit allowed in a batch of fruit. Skin colour charts are published for many fruits, such as banana, pineapple and papaya.

Packing into cartons or other containers (clamshell) is done to aid in marketing. The package needs to meet the following requirements: protect the fruit from injury, allow temperature management, protect the fruit from water loss and facilitate special treatments. Most tropical fruits are hand-packed either by weight or by a fixed number per container.

Postharvest cooling is carried out to reduce the rate of respiration and ethylene effects. Cooling also reduces water loss from the fruit, rot organism growth and the development of mechanical injury symptoms. The most common method used is room cooling, where fruits are placed in a refrigerated room that is above the chilling injury threshold for the fruit. Room cooling is slow and, if the cartons are stacked on a pallet, can take days to reach the room temperature setting. Forced air cooling draws refrigerated cold air through the cartons themselves and thereby increases the rate of cooling. Another less frequently used method for tropical fruit is hydro-cooling, where cold water is used as the coolant instead of air and is faster.

POSTHARVEST INSECT DISINFESTATION

Postharvest treatments are required to disinfest economically important host fruit, vegetables, dried fruits and vegetables, nuts, flowers and ornamentals of insect pests before they are moved through marketing channels to areas where the pests do not occur (Paull and Armstrong, 1994). Examples of these pests are various tephritid fruit flies and mango seed weevil. Alternatively, the importing country has a 'zero tolerance' for all live insects, whether or not they are economically important. While there are many insects and arthropods of quarantine importance, fruit flies represents a major group of destructive pests that attack a wide range of fruit, including most tropical fruit. Disinfestation treatment technologies and strategies include pest-free zones, non-host status, fumigation, irradiation, insecticides, heat and cold treatments, controlled or modified atmospheres, and combinations of these treatment methods. Inspection by regulatory personnel is required to ensure quarantine treatment procedures and regulations, including handling requirements to preclude reinfestation after treatment, are followed.

Many of these disinfestation treatments cause damage to the commodity that limits postharvest life and reduces quality (Paull and Chen, 2000). Research efforts are directed to the use of physical disinfestation treatments, such as heat, cold and irradiation. Such physical disinfestation treatments are non-polluting and they leave no toxic residues. No single quarantine treatment or system can be expected to work equally against all insects or for all host fruits, and the response to any treatment can vary greatly between commodities.

POSTHARVEST DISEASE

During growth and development fruits are continually being attacked by pathogens. However, disease is only seen when the fruit is injured and the right environmental conditions exist (Snowdon, 1990). Some infections, such as anthracnose, are called latent infections, as the initial infection occurs with little pathogen growth while the fruit is green and only becomes visible as the fruit ripens and the fruit's natural resistance mechanisms are breaking down. The major factors that determine whether a pathogen attack will be successful in germinating and colonizing the fruit are the cuticle, which acts as a morphological barrier, the presence of stomata and lenticels as a pathway for entry, and the broken peduncle. Other factors postharvest are the physiological state of the fruit such as having been subject to chilling temperatures, the presence of inhibitors that frequently decline during ripening and the storage temperature. As with respiration, lower temperature reduces pathogen growth and limits disease development.

Control methods include preharvest and postharvest disease control using fungicides. The loss of postharvest fungicides has led to renewed interest and the use of alternative methods to control disease postharvest. The approaches have included heat treatments such as the 49°C for 20 min hot water dip for papaya and the use of natural biostatic compounds and chemicals such as sodium bicarbonate. These approaches are often not as effective as some fungicides and need to be used in a systems approach that includes more effective sanitation.

FOOD SAFETY

Since fresh fruits and vegetables are raw agricultural products grown in fields, they can be expected to be in contact with a wide range of microorganisms (Brackett, 1999; Zagory, 1999). Many are plant pathogens and other microorganisms, but human pathogens at low levels can also be expected. Recent food safety outbreaks have raised concerns about human pathogen survival and proliferation on fresh produce. The increase in outbreaks could reflect better reporting, more complex handling systems, multiple sources, greater opportunities for contamination and wide distribution of potentially contaminated products. The US Centers for Disease Control reported that, from 1983 to 1992, only 3% of traceable outbreaks of food-borne diseases were associated with source and supply. Most were associated with postharvest handling (77%) and the home (20%). These incidents occurred primarily during the warmer summer months. Poor sanitation and improper hygiene were the major source.

The management of temperature and relative humidity (RH) used during shipping and storage is a critical component in maintaining a safe food supply. Temperature and relative humidity are two major criteria used to define critical limits in monitoring programmes associated with the hazard analysis and critical control point (HACCP) system. HACCP is a preventive quality-assurance system and is required so that safety programmes can be properly implemented. The HACCP system involves an evaluation of every step in the handling chain by the different individuals handling a commodity from harvest to the consumer. The critical points where contamination could occur are identified and procedures developed to ensure that safety is maintained. The procedures are called standard operating procedures (SOP), and responsibility is assigned to someone in authority to ensure that these SOPs are carried out. Such safety programmes involve a number of principles, including developing a plan to carry out inspections, good record-keeping and steps to ensure safety throughout handling, shipping and storage, and monitoring to ensure that procedures are being implemented, and, most importantly, assignment of responsibility.

In the USA, major retailers and food service chains are putting restrictions on and demanding compliance by suppliers to avoid food microbial contamination. These require self- and third-party audits, as the buyers set the terms. The objective is to verify use of good agricultural practices (GAP) and good manufacturing practices (GMP). Voluntary guidelines have been issued by the US Food and Drug Administration (FDA). The document *Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables* can be found on the FDA web site (www.foodsafety.gov/~dms/prodguid.html). Third-party audits are performed by private companies, and some of their web sites contain information as to how audits are carried out and the postharvest practices that are evaluated. In Europe, GlobalGAP (http://www.globalgap.org/cms/front_content.php?client=1&changelang=1&parent=&subid=&idcat=9) has been developed by large retailers and includes social and environmental aspects. Most of the guidelines are common sense, and are possibly already being done but not being monitored and recorded. A comprehensive food safety programme based upon risk assessment includes employee training, audits, food safety record-keeping and a senior manager in charge of the programme.

The goal of all food safety programmes is the prevention of contamination. The harvest considerations to prevent contamination are only picking dry fruit, leaving fruit that has bird droppings on them, use of clean bags or buckets for collection, training workers on the importance of hand-washing and cooling the product quickly. Further steps to reduce contamination are excluding animals from the orchards and packing facilities and the use of potable and chlorinated water to prevent cross-contamination. Clean bins and containers should be used to transport fruit.

FRUIT RIPENING

Ethylene gas, which is a natural plant growth regulator, is used postharvest to ripen fruit. Fruit ripening is carried out with ethylene (~1000 ppm) under controlled temperature and relative humidity conditions. The objective of ripening with ethylene is to place fruit on the retail shelf at the desired stage of ripeness for the consumer. Banana is most commonly ripened in this way at terminal markets or by wholesalers. Another fruit that is sometimes ripened with ethylene is avocado. Pineapple, a non-climacteric fruit, is treated with an ethylene-generating compound about 6 days before harvest or postharvest, to enhance the degreening of the skin; the treatment has little effect on other aspects of fruit quality. Papaya can be induced to ripen faster with ethylene treatment, but it is not practised commercially as it leaves little time for retailing.

In the absence of ethylene gas, acetylene can be used at a slightly higher dose. Calcium carbide, which in the presence of water releases acetylene, is widely used in developing countries. Fruit can also be ripened by adding an already-ripening fruit, such as passion fruit or avocado, which generates higher amounts of ethylene. Crushed leaves of some species also generate a lot of ethylene and these are used for fruit ripening.

ORGANIC TROPICAL FRUIT

Organic standards place additional requirements on those in the postharvest chain handling organic fruit. The requirements relate specifically to what chemicals can come into contact with the organic commodity. There are limitations on the use of chlorine in the wash water to prevent cross-contamination and the types of chemicals that can be used as cleaners and sanitizers. Synthetic fungicides and many wax coating materials are not allowed and alternative natural products are used. Care is also needed during shipping and storage to ensure that organic products are clearly marked and no direct contact occurs with conventional products.

LOGISTICS

During the movement of fresh products to market (Fig. 5.1), wholesalers and retailers frequently do not have enough facilities set to the optimum conditions for each commodity. Inventory management and marketing largely determines how a product will be handled (Prussia, 2000). These limitations are especially true for specialty commodities, such as minor tropical fruits, handled in small quantities.

A major logistical issue is to maintain quality while integrating improvement in technology into the supply chain (Prussia and Shewfelt, 1993; Thompson, 1996; Hewett, 2003). The integration needs to manage the available resources at all steps in the chain (Epperson and Estes, 1999). The most important resource is the human capital, who can jeopardize safety and quality and who manage the chain so as to reduce losses (shrink). This requires an understanding that the value of a commodity increases as the product moves through the chain to the consumer and that money and information should move freely back from the consumer to the producer. Between the extremes of farmers' markets and street stalls in developing countries and almost vertical-integration producers/shipper/supermarkets, information and money flow must occur. Frequent disruption of this communication flow can occur when there are numerous suppliers and buyers separated by wholesale and spot markets.

In addition to information flow, the reduction in seasonality of many commodities by global sourcing and new production technologies has heightened the need to manage inventories. No longer is a first-in-first-out credo sufficient. Supermarkets strive to set quality standards, delivery schedules and minimize inventory at both the distribution warehouse and the individual outlets. This is achieved, in part, by forward contracts, so that inventory and quality can be managed, storage costs minimized and in-store losses reduced.

The management's practices used at all the steps from harvest to the consumer (Fig. 5.4) play a crucial role in maintaining quality and safety of tropical fruit. The requirements to maintain quality and safety are the same in developed and developing markets. In most cases, application of current knowledge will bring the handling system to a high level of quality and safety assurance. A major limitation for small-scale operations is often lack of resources, infrastructure, marketing systems and the availability and understanding of the tropical fruits' handling requirements. These limitations can be overcome by consolidation, using marketing companies, associations and cooperatives.

In all logistic chains, and particularly for tropical fruit handling, managers play a central role. This role is equally as important in developing markets, where labour costs maybe much lower than in developed markets. Effective supervisor and worker training, and retraining, as to their role in maintaining fruit quality and safety, is crucial. The role and the responsibilities of supervisors and workers must be stressed to maintain quality and safety, and worker productivity and development of problem-solving skills. Frequent fruit-handling logistics problems are seen when supervisors do not have problem-solving skills or the authority for implementation of changes. Often supervisors must ask permission from the owner or a few owner-trusted persons to make changes in the postharvest handling of a specific shipment, thus reducing worker productivity.

CONCLUSIONS

The quality of fruit sold to consumers and the measure of postharvest success depends upon five factors. The five factors are the initial fruit quality at harvest, which is set by how it is grown; the maturity of the harvested fruit; careful handling to avoid injury; proper storage environment (temperature, relative humidity, atmosphere); and sanitation to prevent disease and human pathogen contamination. Prevention of mechanical injury, temperature maintenance and sanitation are crucial.

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6

Annonas: Cherimoya, Atemoya and Sweetsop

Three *Annona* species will be covered in this chapter. One species is thought to have originated in Central America (sweetsop or sugar apple, *Annona squamosa*), while cherimoya (*Annona cherimola*) origins are the highland plateaus of the Andes. The third is not a species but a cross between sweetsop and cherimoya and called atemoya (*A. squamosa* × *A. cherimola*), the 'ate' from the Brazilian word for sweetsop and 'moya' from cherimoya. All three are found cultivated or naturalized throughout the tropics. Cherimoya is better adapted to cooler, drier and subtropical climates, and sweetsop in moist, tropical climates and in drier, subtropical climates.

BOTANY

Family

Annonaceae, in the Order Magnoliales, commonly referred to as the custard apple family, consists of about 75 genera, widely distributed. The family is in the basal group of the dicots. Some are grown as ornamentals, while only four genera produce edible fruit. This chapter will focus on the three *Annona* species widely grown for fruit.

Important genera and species

The genus *Annona* is the most important, being the second largest genera in the family, and among its 100 or more species, seven species and one hybrid are grown commercially. All are native to the American tropics. Leaves are alternate, simple and entire, and flowers may be solitary or in clusters, with two series of three thick and fleshy petals. The other closely related genus with some commercial fruit is *Rollinia*.

The important commercial species are:

A. cherimola Mill.	Cherimoya (English); chirimoya (Spanish); cherimolier (French); anona (Mexican); noina ostrelia (Thai); chirimoya (German)
A. squamosa L.	Sugar apple, sweetsop (English); anon, riñón (Spanish); noina (Thai); nona seri kaya (Malay); custard apple (Indian)
A. squamosa × *A. cherimola*	Atemoya, custard apple (English); atemoya (Spanish)
Annona diversifolia Saff.	Ilama (English, Spanish)
Annona glabra L.	Pond apple (English); mamon (Philippine)
Annona montana Magfady	Mountain soursop (English); guanábana cimarrona (Spanish)
Annona muricata L.	Soursop (English); guanabana, atio (Philippines); guanábana, catoche (Spanish); durian belanda, nona sri kaya (Malay); nangka belanda (Indonesian); thurian-khaak (Thai); sitaphal (Indian); fruta de conde, graviola (Brazilian); zapote agrio, catoche (Mexican); corossol épineux (French)
Annona reticulata L.	Custard apple, bullock's heart (English); anon, anona, corazón (Spanish)
Rollinia orthopetala R.DC.	Biriba (Brazilian).

Area of origin and distribution

Cherimoya (*A. cherimola* Mill) is thought to have originated in the highlands of Ecuador and Peru. The antiquity of the fruit is attested to by ancient artifacts shaped in the form of the fruit in Peru. Distribution through Central America and Mexico probably occurred at an early date, as it has become naturalized in the cool highland areas. Distribution continued from Mexico to the Caribbean islands and then to the African coast and the Mediterranean. Introduction to Africa and the Far East is attributed to early Spanish navigators.

The cherimoya is considered the best of the *Annonas* and is cultivated in subtropical regions and in the tropical highlands. In most areas, it is grown as a garden tree or as part of a subsistence farming system. Commercial production occurs in Spain, Bolivia, Chile, Peru and New Zealand (George and Paull, 2008). Experience has shown that the California coastal regions are more conducive to cherimoya production, having higher relative humidity (RH) (70–80%) in spring and summer than in the interior valleys, where the RH can drop to less than 40% during the hotter part of the day in summer.

The tree grows to about 7.3 m; it is vigorous when young but tends to decline in growth with age. New buds cannot sprout until the leaves have been shed, as the leaf bases grow over the axillary buds, as in sweetsop and atemoya (Fig. 6.1). Leaves are 10–25.4 cm long, light green and arranged alternately. Leaves tend to fall before spring, and many people call it a semi-deciduous plant.

The sweetsop (*A. squamosa* L.), also called sugar apple, probably originated in the Caribbean region and is the most widely distributed and also the most commonly grown *Annona* species in the tropical regions of the Americas, Africa, Asia and the Pacific. It is less tolerant of cold temperatures than the cherimoya but more tolerant than the soursop, as it is found thriving in subtropical areas, such as the coastal areas of south Florida. The fruit is frequently found in village markets but has not shown any potential for large commercial cultivation, due to the small fruit size, frequent cracking at maturity and poor shelf-life. It is intensively cultivated in Taiwan, where about 5000 ha are planted, producing around 50,000 tonnes; the peak harvest is between July and March

The tree is normally smaller than the cherimoya, attaining heights of 3.0–4.6 m, with slender branches. The leaves are oblong–lanceolate, narrower than those of the cherimoya and 10–15 cm long (Fig. 6.1). All leaves are shed before new shoots appear. Flowers are axillary, in clusters of two to four on leafy shoots (Fig. 6.1). Fruit set is better than in the cherimoya.

The fruit is more nearly heart-shaped, 5–10 cm in diameter. It is yellowish-green in colour, but a purple-fruited variant is also known. The exterior parts of adjacent carpels are not completely fused, and these rounded protuberances

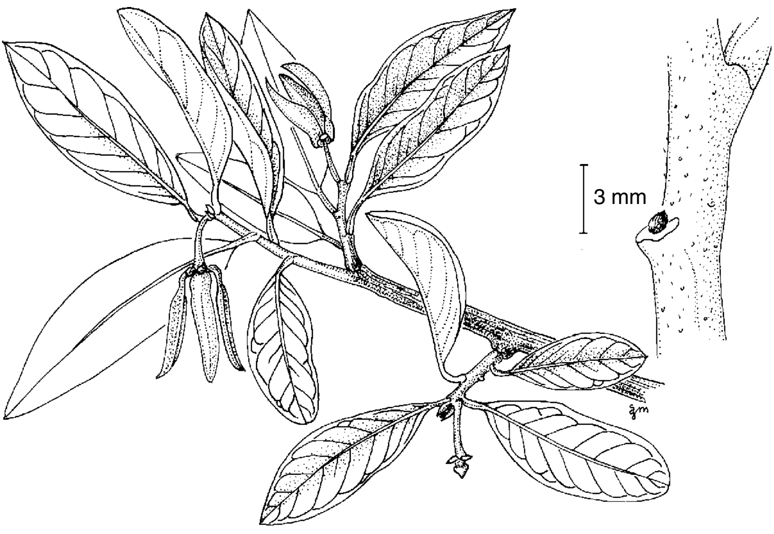

Fig. 6.1. Leaves, axillary buds and flower of sweetsop. The figure shows the buried nature of axillary buds, which can be vegetative or a mixed flower and vegetative bud. The leaf must abscise before the bud can develop, the same as in atemoya and cherimoya.

frequently separate, exposing the white flesh upon ripening (Fig. 6.2). The fruit matures during the summer although production can extend for several months.

Atemoya is a hybrid between *A. squamosa* and *A. cherimola*; P.J. Wester of Florida produced the first hybrids in 1908 and called it the 'atemoya', using the Brazilian name 'ate' for sweetsop and 'moya' from cherimoya. In 1927, hybrids were also developed in Poona, India. Numerous cultivars have been selected in Israel (Gazit and Eistenstein, 1985). There is considerable variation among seedlings. Leaves are glabrous and larger than those of the parents, with flowering and fruiting seasons resembling those of *A. squamosa*. Seedlings also differ widely in the external and internal structure of the fruit. Favourable characteristics inherited from the cherimoya parent include many seedless carpels and carpels that adhere together instead of breaking apart into individual tubercles, as in the sweetsop (Fig. 6.2). The atemoya is more tropical in its requirements than cherimoya. While young trees require some protection from frost, older trees have shown tolerance in Australia. The atemoya is currently grown commercially in Israel, Australia, California, Florida and Hawaii and in other countries for domestic consumption.

A. glabra L. (pond apple) has greater potential as a rootstock than for fruit. It grows wild in southern Florida around lakes and rivers and is widely distributed in the lowlands of tropical America. It is a vigorous grower, reaching heights of 12 m and grows well in swampy areas. The flower is fragrant, creamy-yellow and reddish inside. The fruit is about the size of the sweetsop and heart-shaped; its yellow pulp is described as insipid.

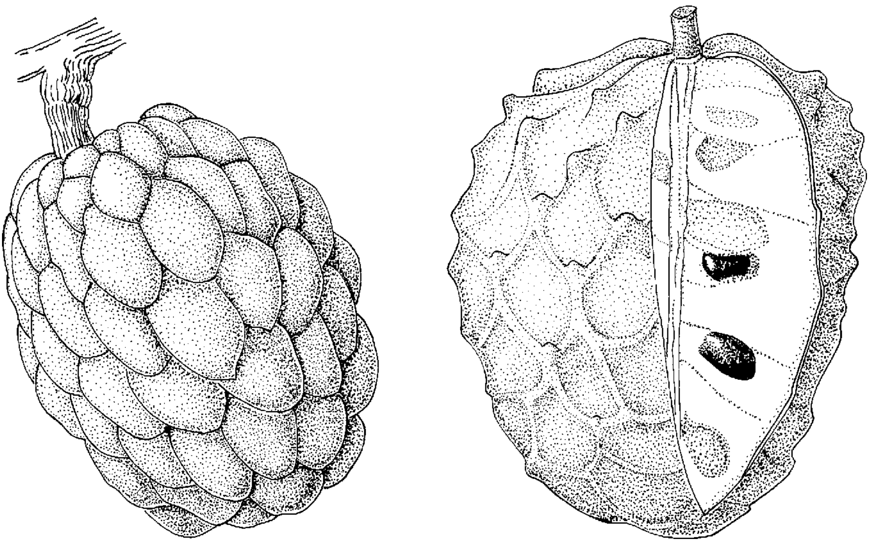

Fig. 6.2. Fruit of sweetsop and atemoya.

ECOLOGY

Soil

All species are capable of growing in a wide range of soil types, from sandy soil to clay loams. Nevertheless, they differ in their soil preferences. Higher yields occur on well-drained sandy to sandy loam soils, except in the case of *A. glabra*, which can succeed in shallow ponds. Drainage is essential to avoid root-rot diseases; hence the interest in *A. glabra* as a rootstock, related to its tolerance of wet soils. Cherimoyas and atemoyas prefer sandy or sandy loam soils with uniform moisture but with a good drainage to avoid root rots, and a dry period at the end of winter at the time of leaf fall will enhance flowering uniformity. Sweetsop is capable of growing in a wide range of soil types, but its shallow root system does not allow for flooded or waterlogged soils. It will do best if good drainage exists and if soil pH is around 5.8–6.6.

Rainfall

In cherimoya and atemoya, rainfall and high humidity during the peak flowering season greatly enhance fruit production by preventing desiccation of stigmas, prolonging their receptive period and increasing fruit set and early fruit growth. Similar conditions are also ideal for other *Annonas*. The sweetsop is probably the most drought-tolerant species and it grows and produces poorly where rains are frequent. For example, sweetsop does much better in northern Malaysia, where dry periods occur, than in the southern part, which has year-round high moisture. For cherimoya and atemoya, a dry period at the coldest time of the year enhances leaf fall and flowering at the end of spring and early summer. This dry period is not required for sweetsop.

Temperature

Temperature is the limiting factor, with frost killing young trees, especially sweetsop, but older trees showing some tolerance. Cherimoya (7–18°C mean minimum) is more tolerant to low temperatures (Fig. 6.3), followed by atemoya (10–20°C mean minimum). Cherimoya can initiate vegetative growth at ~7°C, while atemoya starts at ~10°C. Except for cherimoya, the annonas do not require chilling periods and do well under lowland conditions (George and Nissen, 1987b). Cherimoya is susceptible to high temperatures, with a growing temperature range of 21–30°C (George and Nissen, 1986b). Both cherimoya and atemoya are semi-deciduous, and growth declines at

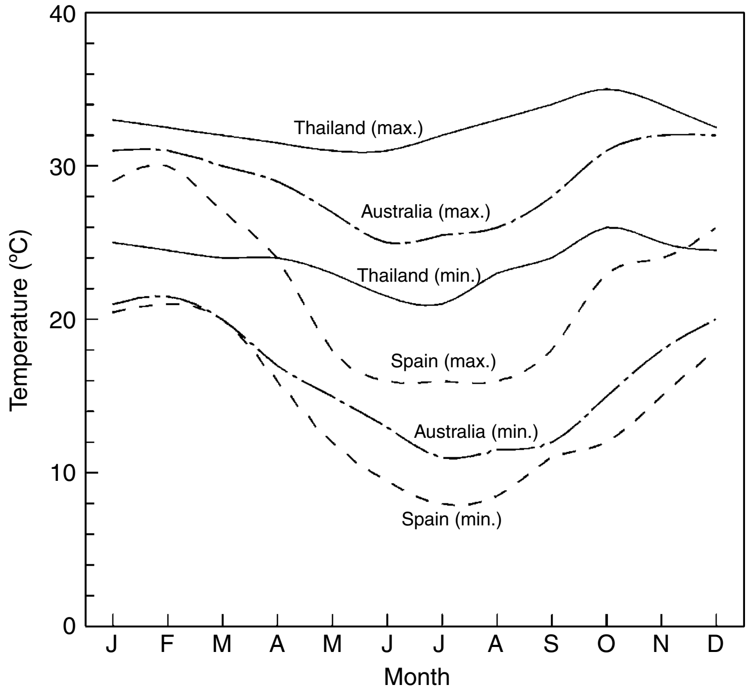

Fig. 6.3. Seasonal changes in mean monthly minimum temperature for areas suited to sweetsop (Bangkok, Thailand), atemoya (Mareeba, Australia) and cherimoya (Malaga, Spain) in southern-hemisphere equivalents (after Marler *et al.*, 1994).

the end of winter and the beginning of spring, during which many leaves fall, followed by flowering by the end of spring. In areas with year-round good growing temperatures and no dry period, atemoyas can be forced to complete their flowering and fruit cycle in 8 months. An 8-month fruit cycle allows for three harvests in 2 years. To achieve three cycles in 2 years requires careful management of irrigation, fertilization, pruning and defoliation.

Poor pollination is a frequent problem with all three species and occurs under high temperature (30°C) and low humidity (30% RH). Lower temperature (25°C) and high humidity (80% RH) greatly improves pollination. Hand-pollination is recommended for cherimoya and atemoya to achieve more uniform fruit shape (Fig. 6.4). Sweetsop exposed to >30°C and relative humidity <60% leads to poor pollination, even if hand-pollinated. At 25°C and a relative humidity >80% sweetsop pollination is greatly improved, with too high RH and rain negatively affecting anther dehiscence. High temperatures will induce strong vegetative growth in atemoya and cherimoya. A temperature of 22–28°C is ideal for fruit set in atemoya, while cherimoya needs slightly lower temperatures for fruit set.

Fig. 6.4. Hand-pollination of atemoya using a hand-blower to disperse the pollen collected the day before on to the open flower (courtesy of R. Manshardt).

Light and photoperiod

Light penetration to the base of vigorous atemoya trees with a dense canopy in close spacing can be 2% of full sunlight, and there is very little fruit set. Pruning practices and spacing need to be adjusted for this shading effect on growth. No photoperiod responses have been reported. All three species need some sort of pruning to obtain better light penetration into the canopy.

Wind

The soft wood of the trees makes them susceptible to wind damage and limb breakage. Tree shaking may also be partially responsible for the penetration of collar-rot organisms. The fruit skin is easily damaged by rubbing and exposure to drying winds, leaving black scars. *Annona* leaf stomata are very sensitive to changes in RH and rapidly close in response to declining RH (Marler *et al.*, 1994). Productivity can be improved by windbreaks and under-tree sprinkling to raise the RH above 60%.

GENERAL CHARACTERISTICS

Flowers

The flowers of *Annona* species are hermaphroditic and are produced singly or in small clusters in a compound inflorescence on an enlarged receptacle. Flowers arise on the current season's growth and occasionally on old wood. Cherimoya and atemoya flowers are fragrant and are solitary or in groups of two or three on short, hairy stalks. The flowers are multi-staminate and multi-pistilate. New flowers continue to appear towards the apex of the shoot as flowers produced earlier at the basal portions mature (Fig. 6.5). Defoliation of cherimoya or atemoya manually or by using ethephon spray promotes lateral branch growth and induces additional flower formation, since it exposes the buds covered by the petiole base.

Annona species generally require 27–35 days for flower-bud development from initiation to anthesis. Differences in floral behaviour in the various areas may be attributed to both genetic variability and climatic differences (Kshirsaga *et al.*, 1976). Flowering can extend from 3 to 6 months or even longer, with heavy peaks. In sweetsop, two major flowering periods occur after periods of vegetative flushes, with the second peak coinciding with the onset of the monsoon in India (Kumar *et al.*, 1977). Atemoyas in Australia produce the

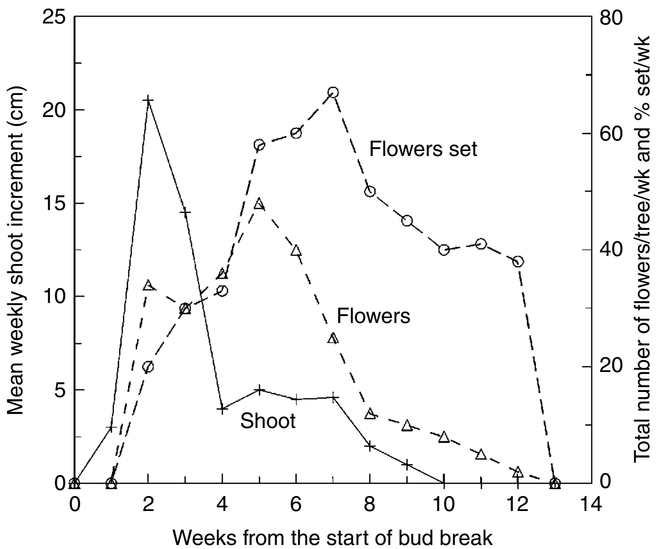

Fig. 6.5. Atemoya: newly emerging vegetative-flush shoot increment, total number of flowers produced per week and percentage flowers set per week. Peak fruit set occurs after completion of vegetative flush (after George and Nissen, 1988).

first flowers during spring and have a second flowering during the summer, the latter being the more productive (Sanewski, 1991).

Pollination and fruit set

Natural pollination

The flowers exhibit both dichogamy and a protogynous nature. This poses a serious problem in obtaining high yields. The flowering seasons of *A. squamosa* and *A. cherimola* coincide. When sweetsop pollen is shed at about 2 a.m., cherimoya flowers are receptive, opening around 7–9 a.m. and, when cherimoya pollen is shed at 3–6 p.m., sweetsop flowers are receptive. This flower synchrony, together with complementary functional sexes, favours cross-pollination, leading to natural hybridization. This is attested to by the frequent appearance of hybrid seedlings under the trees of sweetsop and cherimoya when grown in close proximity. Sweetsop is a more effective pollen source than cherimoya in cross-combination studies.

The atemoya female parts are receptive between 4 p.m. and 8 a.m. and appear moist and sticky (Thakur and Singh, 1964). Atemoya pollen is discharged in the afternoon of the same day from 3 to 6 p.m., if the RH is above 80% and the temperature >22°C. At lower temperatures, pollen is released on the afternoon of the second day. The pollen sacs turn a greyish colour as pollen is discharged. Pollen grains from flowers that appear early in a flowering season have thick walls, are high in starch, germinate poorly and give poor fruit set. Pollen of later flowers shows a high proportion of individual pollen grains without starch grains, which germinate well. Upon opening, flowers are receptive for about 24 h. It has also been shown that spraying the flowers with water or putting a drop into the flower can significantly increase fruit set, probably because of the increased humidity slowing the drying of the stigma and pollen grains. Night-time irrigation with micro-sprinklers or late afternoon rains also increases fruit set.

Nitidulid beetles (*Carpophilus* and *Uroporus* spp.) are the important pollinators of *Annona* flowers, with wind- and self-pollination being low (1.5%). Fruit set of 'African Pride' atemoya increases linearly with increasing numbers of nitidulid beetles per flower. Three or more beetles per flower increased fruit set to nearly 25%. Studies also show that these beetles breed rapidly in rotting fruit media and that their populations can be increased by maintaining a rotting-fruit attractant.

Hand-pollination is frequently practised to ensure pollination and good fruit shape. Pollen must be collected in the evening from fully open flowers, when the sacs have turned from white to cream. The flowers are held in a paper bag, not a closed container, and should discharge that afternoon. The flowers are shaken over a shallow tray or paper to collect the pollen, which is transferred to a small container and held in the refrigerator for use the next morning. Twenty to 30 flowers can give enough pollen to pollinate 50–60 flowers. Pollination is done daily, using a small (No. 4) organic hair brush, so that pollen adheres better to it, or a puffer (Fig. 6.4). Pollen diluted with *Lycopodium* spores (1:1 dilution) allows pollination of more flowers. About 150 flowers can be pollinated in 1 h, with a success rate of 80–100% being achieved.

Hand-pollination is less successful when carried out on very humid, overcast days and on young vigorous trees. In Honduras, hand-pollinatation of 'Gefner' atemoya was better when done between 4.00 and 6.00 p.m. than between 6.30 and 8.30 a.m. when the day temperatures were ~30°C and relative humidity was low (Duarte *et al.*, 1997). A fruit set of ~47% was obtained against ~12% for morning pollination. This result was probably obtained because of the lower night temperatures and higher humidity and the use of pollen collected in the field and applied immediately. When the Peruvian 'Cumbe' cherimoya was grown in Honduras, better fruit set was obtained using pollen from a different variety ('Bronceada' from Chile) and afternoon pollination rather than pollination in the morning (Duarte and Escobar, 1994).

Growth regulators for fruit setting

Hand-pollination in commercial orchards is tedious, time-consuming and a costly practice. Attempts have been made to use growth regulators, with considerable variation in the results obtained. Auxin-induced (indole acetic acid (IAA), naphthalene acetic acid (NAA)) fruit grow very slowly with less fruit drop, while gibberellic acid (GA_3) promotes fruit set and growth; however, it does not aid in early fruit retention (Duarte *et al.*, 1974a; Yang, 1988). Application of the two substances separately at appropriate times has produced seedless fruit of 200–300 g (Saavedra, 1979). Gibberellin (1000 ppm) is more effective than hand-pollination and produced seedless fruit in atemoya cultivars 'African Pride' and 'Gefner'. Repeated spraying is necessary to prevent fruit abscission during the first 2 months. Seedless fruit are smaller, with less flavour and less fruit splitting than occurs in the seedy fruit that result from pollination (Yang, 1988). Similar results have been obtained for cherimoya and sweetsop. GA spraying is not recommended as a general management practice for atemoya, because of variable results, although it could be used in areas with poor natural pollination.

Fruit

Fruits of cherimoya, atemoya and sweetsop are compound fruits, generally conical or roundish or heart-shaped. Cherimoyas can weigh up to 1000 g, with an average of about 150–500 g, while atemoyas and sweetsops are smaller. The skin can be smooth with fingerprint-like markings or can be covered with conical or rounded protuberances. The mature fruit is soft and can easily be opened to show its white, juicy flesh, of pleasing aroma and subacid flavour, containing numerous – sometimes few – brown or black, hard and glossy, bean-like seeds. Atemoya has smaller seeds, while sweetsop has the largest seed number.

Fruit growth shows the typical sigmoidal curve, with maturation occurring in 16–24 weeks, depending upon species and growing conditions (Fig. 6.6). Low humidity (<60% RH) and temperature (<13°C) near fruit maturity can increase the severity of fruit skin russeting, as well as delaying fruit maturation. High temperature can cause premature fruit ripening and fermentation of the fruit.

CULTIVAR DEVELOPMENT

Genetics, cytogenetics and breeding

The chromosome numbers of *A. cherimola*, *A. reticulata*, *A. squamosa* and atemoya are 2n = 14. *A. glabra* has been shown to be a tetraploid (2n = 28),

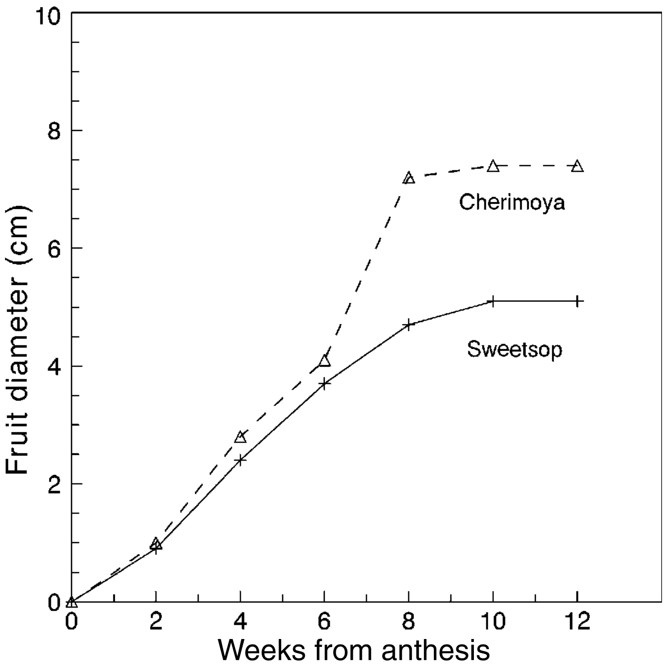

Fig. 6.6. Increase in fruit diameter from anthesis for sweetsop and cherimoyas (after Thakur and Singh, 1965).

and the occurrence of high chiasma frequency and the absence of multivalents during meiosis suggest that it is of amphidiploid origin.

Cross-pollination between species is conducted primarily to determine compatibility for increasing fruit set. Atemoya is the only hybrid that has gained importance and it has inherited the glabrate leaf character of *A. squamosa* and a leaf size almost as large as that of *A. cherimola*. Flowering and fruiting seasons are similar to those of sweetsop. Skin, pulp and seed characters of both parents are inherited in varying degrees by each plant. A desirable hybrid would be between the cherimoya and soursop that combines the larger fruit size and acidity of the soursop and the cherimoya's sweetness, flavour and texture. Attempts to cross the soursop with cherimoya, ilama, bullock's heart or sweetsop have not been successful and may reflect a considerable genetic distance of soursop from the other species (Samuel *et al.*, 1991).

Problems in breeding

The long reproductive cycles, higher levels of heterozygosity and the costs associated with evaluating large populations of crosses limits breeding programmes. Existing commercial cultivars show considerable variation in growth, fruit set, fruit size and quality. No single variety has all the desirable characteristics. The length of the juvenile period varies, with earliest production occurring in 2 years and full production in 5–6 years. This juvenile period is extremely variable with scions on seedling rootstocks. The seedling rootstocks are derived from extremely heterogeneous, open-pollinated seeds; hence it is difficult to fix specific characters in a short period. Breeding programmes have focused on selections from seedling populations. Early maturity, better fruit appearance and, in the subtropics, greater cold tolerance are the most frequent objectives.

Cultivar development

Except for cherimoya and atemoya, very few named clonal cultivars have been developed among the *Annonas* (Table 6.1). Most of the plantings have been of seedlings. In California, some old cultivars of cherimoya include 'McPherson', 'Deliciosa' and 'Bays'. Considerable work has been done in Peru on the development of cultivars, but they are not widely known outside Peru; one of them, 'Cumbe', is considered exceptional, because of size, surface smoothness, flavour and very few seeds. Chile, Spain and New Zealand grow the cherimoya, as it is more tolerant of cold temperatures, with more successful self-pollination than the atemoya. New Zealand's principal cultivars are 'Reretai', 'Burton's Wonder' and 'Burton's Favourite'. Chilean cultivars 'Bronceada' and 'Concha Lisa' have also performed well in Australia, the former having been reported to

Table 6.1. Selected cultivars of cherimoya and atemoya.

Cherimoya		Atemoya	
Name	Origin	Name	Origin
Andrews	Australia	African Pride	Southern Africa or Israel
Bays	USA – California	Bradley	USA – Florida
Booth	USA – California	Gefner	Israel
Bronceada	Chile	Island Gem	Australia
Burton's Wonder	New Zealand	Kabri	Israel
Campa	Spain	Malalai	Israel
Concha Lisa	Chile	Nielsen	Australia
Cristalino	Spain	Page	USA – Florida
Cumbe	Peru	Pink's Mammoth	Australia
E-8	Ecuador		
Fino de Jete	Spain		
Kempsey	Australia		
Libby	USA – California		
Lisa	USA – California		
Mossman	Australia		
Negrito	Spain		
Reretai	New Zealand		
White	USA – California		

possess a postharvest cold-storage life of 3 weeks. Pascual *et al.* (1993) report seven cherimoya cultivars in Spain, of which 'Fino de Jete' and 'Campa' are the most extensively cultivated, due to their superior yield and quality. Isozyme studies indicated that these two cultivars showed identical banding patterns for 15 enzymes, indicating that they were most probably the same cultivar. A cluster analysis of isozyme patterns showed that Spanish cherimoya cultivars were distinctly different from cultivars in California (Pascual *et al.*, 1993) and atemoya (Ellstrand and Lee, 1987). Spain has focused its programme on germplasm collection and *in situ* evaluation. Similar programmes are taking place in Mexico and Chile. In Spain polymorphic molecular markers are being developed for cherimoya, most of which can be transferred to other *Annonas*.

Six atemoya cultivars have been described in Australia (Sanewski, 1991). 'Pink's Mammoth' is reported to have been introduced from British Guiana to Australia. It takes 6–7 years to begin producing commercial-size yields of fruit, which are large, weighing from 800 g to as much as 2 kg, and it is a less precocious bearer than 'African Pride'. 'African Pride' was probably introduced into Australia from South Africa, although its origin may have been Israel.

It produces good yields of small to medium-sized fruit. 'Bullock's Heart' (an atemoya) is similar to 'Pink's Mammoth'. 'Island Gem' is an early-maturing, small-fruited, heavy yielder. Two new cultivars developed in Australia are 'Maroochy Gold' and 'KJ Pinks', which have superseded the old, above-mentioned cultivars (George and Paull, 2008). In Florida they developed the cultivars 'Bradley' and 'Page'. The former produces small-sized fruit with relatively smooth and thin skin. The latter produces medium-sized, well-shaped fruit with prominent skin segments. 'Gefner', an Israeli cultivar, is the main cultivar grown in Florida and Hawaii; it produces small to medium-sized fruit resembling 'Page'.

In order to develop cultivars adapted to cooler environments, Australia has concentrated on self-progenies and interspecific crosses of *A. cherimola* with *A. reticulata* and *A. diversifolia*. Progenies of *A. cherimoya*–*A. reticulata* crosses are late-maturing, showing flowering and fruiting characteristics of *A. reticulata*, which flowers in the autumn and has mature fruit in late spring. Selections possessing most of the fruit qualities of commercial cultivars have been established in various areas for evaluation.

India and Taiwan have produced a few named cultivars of *A. squamosa* that are propagated vegetatively. The main Taiwan cultivars are 'Ruan-zhi', 'Cu-lin', 'Da-mu', 'Tainung no. 1' and 'Xi-lin'. Indian cultivars include 'Arka Sahan', 'Barbadose Seedling', 'Washington', 'Red Sitaphal', 'Balanagar', 'Mammoth', 'Purandhar' and 'Arka'. Thailand has developed 'Fai Kaew', 'Fai Krung', 'Nang Kaew', 'Nang Sir Krung' and 'Nang Thong'. In Florida they selected 'Lessard', 'Kampong Mauve' and 'Red Sugar', and they also plant 'Cuban Seedless', a cultivar developed in Cuba that is seedless with medium-sized fruit; there is another Cuban cultivar that is low in fibre content. Seedling populations have been established in Taiwan to select superior lines with better yield, quality, early maturity and higher edible flesh ratio and better postharvest behaviour (Chen and Paull, 2008).

CULTURAL PRACTICES

Propagation

The *Annonas*, except for the cherimoya and atemoya, are usually propagated by seed (George and Nissen, 1987b). There is a rapid loss of seed viability (6 months), and seeds should be planted as soon as possible after removal from the fruit. Cherimoya seeds can take up to 30 days to germinate, and GA treatment (10,000 ppm) can significantly increase germination and enhance seedling growth (Duarte *et al.*, 1974b). Seedlings require at least 3–4 years to bear fruit (Sanewski, 1991). In some seed lots, germination occurs quickly, while in other lots it can take several months; therefore ideally it is better to use fresh seeds in all *Annonas*.

Clonal propagation by cuttings, layering, inarching, grafting and budding have been tried (Table 6.2). Inconsistent results have been obtained with cherimoya when 1-year-old cuttings are treated with rooting hormones, and cuttings from mature trees have been difficult to root (Duarte *et al.*, 1974b). Atemoya, as a hybrid, has to be propagated asexually by cuttings from selected trees or grafting or budding. There are cultivar differences in the rooting ability of atemoya, with 'African Pride' having a higher rooting response (60–80%) than 'Pink's Mammoth' and cherimoya (<20%). Atemoya tip cuttings are superior to stem cuttings, with rooting percentages between 50 and 60%, as compared with about 25% for stem cuttings (Sanewski, 1991). Time of cutting removal is crucial for success, cuttings taken at the end of the cool season showing the greater success. Roots should occur in 8–12 weeks and the cuttings are ready to pot in 16–20 weeks. Air-layering can be used with some cultivars, although cherimoya is not propagated easily. A modification where the new shoot is clamped and only the shoot tip is exposed is successful. Inarching of *A. squamosa*, *A. cherimola*, *A. glabra* and atemoya to *A. reticulata* rootstock has been successful, with only *A. glabra* giving less than 70% success. Although inarching has given good results, it is time-consuming and costly for large-scale propagation (George and Nissen, 1987b).

Cherimoyas are normally grafted or budded. Grafting is superior to budding in percentage takes and subsequent growth, with side-whip graft and cleft-graft techniques giving the best results (Duarte *et al.*, 1974b). The branches should be defoliated 1–2 weeks before scion wood is cut to induce bud swelling. T-budding and chip-budding methods are successful. There are considerable graft incompatibilities among *Annona* (Table 6.3) and *Rollinia* species and types. Cherimoya has been found to be a vigorous rootstock for 'Pink's Mammoth' (atemoya), although atemoya is not compatible with *A. glabra*, *A. montana*,

Table 6.2. Propagation methods and success for *Annona* spp. (after George and Nissen, 1987b). Root-cutting success rate is unknown.

Method	Species		
	Atemoya	Sweetsop	Cherimoya
Seedling			
Genetically	Variable	Uniform	Variable
Use	Not recommended	Good	Rootstock
Tip and stem cutting	Some cvs only	Some cvs only	Not successful
Micropropagation	Possibly high	Unknown	Unknown
Layering	Unknown	High if modified techniques used	Unknown
Air-layering	<5%	<8.3%	<5%
Budding	>70%	>70%	>70%
Grafting	>70%	>70%	>70%

Table 6.3. Rootstock and scion compatibility of different *Annonas* (after Sanewski, 1991).

	Scion							
Rootstock	Atemoya	Gefner	Pink's Mammoth	Page/Bradley	*A. cherimola*	*A. glabra*	*A. muricata*	*A. squamosa*
Atemoya	C				C	–	–	C
Gefner		C						
Pink's Mammoth			C					
Page/Bradley				C				
A. cherimola	C		C		C	C	–	C
A. glabra	N				–	C	C	–
A. muricata	N				–	C	C	N
A. palustris	–				–	–	–	N
A. reticulata	N	P	C		C	P	–	C
A. squamosa	C				C	–	–	C

C, compatible; P, partial; N, not compatible; –, unknown.

A. muricata and *A. reticulata* as rootstocks (Sanewski, 1991). This is complicated by cultivar differences in compatibility with common rootstocks. Atemoya cultivars ‘Bradley’ and ‘Page’ are compatible with custard-apple rootstocks, but ‘Gefner’ shows partial incompatibility with the same rootstock (Table 6.3).

Sweetsop is usually seed-propagated. The seeds should be sown within a week after extraction from the fruit. Inarching can be done to *A. reticulata*, with 70% success (George and Nissen, 1987b). The same success is obtained for grafting and budding. Rooting of tips has been successful in some cases, as well as air layers, but they are more costly.

Rootstocks

There are several possible combinations and incompatibilities among *Annona* and *Rollinia* species. Cherimoya rootstocks normally include seedlings of cherimoya and, in some cases, soursop and sweetsop. For atemoya, cherimoya and atemoya are normally used as rootstocks and also *A. squamosa*, but it is susceptible to bacterial wilt caused by *Pseudomonas solanacearum*. Sweetsop is normally not grafted or budded, but it could be done with seedlings of sweetsop, cherimoya or *A. glabra* (Table 6.3). *A. muricata* or *Annona palustris* are not good rootstocks for sweetsop.

Field preparation

A soil sample should be taken 4–6 months before planting to determine lime requirements and soil nutrient levels. Soil phosphorus can also be adjusted at this time or in the planting hole. Minimal tillage can be achieved with a 2-m-wide band cultivated where the trees are to be planted. Drainage should be installed at this time to avoid flooding, with either contour or subsurface drains. Windbreaks should be established prior to transplanting. Napier or Buffalo or Bana grass (*Pennisetum purpureum* Schumacher) can be used when shelter is required in the first 12 months.

Transplanting and spacing

Transplanting should be done at the beginning of the wet season if there are seasonal dry periods and no irrigation facilities. In the subtropics, planting should not occur if there is a risk of frost. Plants should have attained a height of 30–50 cm at transplanting time, with the union of grafted or budded plants placed 15 cm or so above the ground. Trees should be irrigated as soon as possible after transplanting, with wind and sun guards sometimes required.

Transplanting distance depends upon the species of *Annona*. The periodically pruned small sweetsop can be spaced at 3.7 m × 4.6 m. In dry areas with less luxuriant growth, closer within-row spacing than 3.7 m can be considered. Closer spacing would increase humidity and benefit the longevity of stigma receptivity. For machine operations, wider spacing of 5.0–5.5 m × 6.0–6.5 m can be used.

Cherimoya can be planted at 5 m × 6 m within and between rows, with appropriate pruning practices. Row spacing of 5–10 m and between rows 7–12 m are recommended for atemoya in Australia, depending on cultivar, rootstock and pruning to an open goblet. Narrower spacing is used for 'African Pride' on *A. squamosa* rootstock, and the widest spacing is for 'Pink's Mammoth' on *A. cherimola*. In Florida, narrow plant spacing of 4–6 m and row spacing of 6–7 m are used (Campbell, 1985). A triangular layout is recommended whatever planting distance is selected, with the rows running north–south to avoid shading. In Chile, narrow spacing (4 m × 2 m) has been tried for cherimoyas, and there are some commercial plantings that use 5 m × 1.5 m (Gardiazabal and Rosenberg, 1993). Some experimental trellis plantings also exist.

Irrigation practices

The *Annonas* are grown in many areas without irrigation when rainfall is well distributed. Except for pond apple (*A. glabra*), most *Annonas* can stand periods of drought and prefer rather dry conditions. There must be adequate soil moisture to encourage vegetative growth, since flowering occurs on new growth. Bearing atemoya trees may need up to 1440 l/tree every 4 weeks during the low-growth phase and from 500 to 750 l/tree every 3–5 days during flowering, fruit set and fruit growth (Sanewski, 1991). Reducing irrigation in late winter to force atemoya and cherimoya trees into dormancy for 1–2 months in spring is recommended in Australia and California, respectively. The amount and frequency of irrigation must be determined by experience in any particular location and soil type. Water stress should be prevented during flowering, fruit set and fruit development, as fruits are more sensitive than leaves to water stress (Fig. 6.7).

High soil moisture to increase humidity during the flowering season may prolong stigma receptivity and fruit set and growth. The use of low-rise sprinklers under the tree canopy during flowering increases the canopy humidity. The stomata of *Annona* respond to RH, not water stress, and will continue to lose water if the humidity is greater than 80%, making it crucial to maintain soil moisture content (Marler *et al.*, 1994).

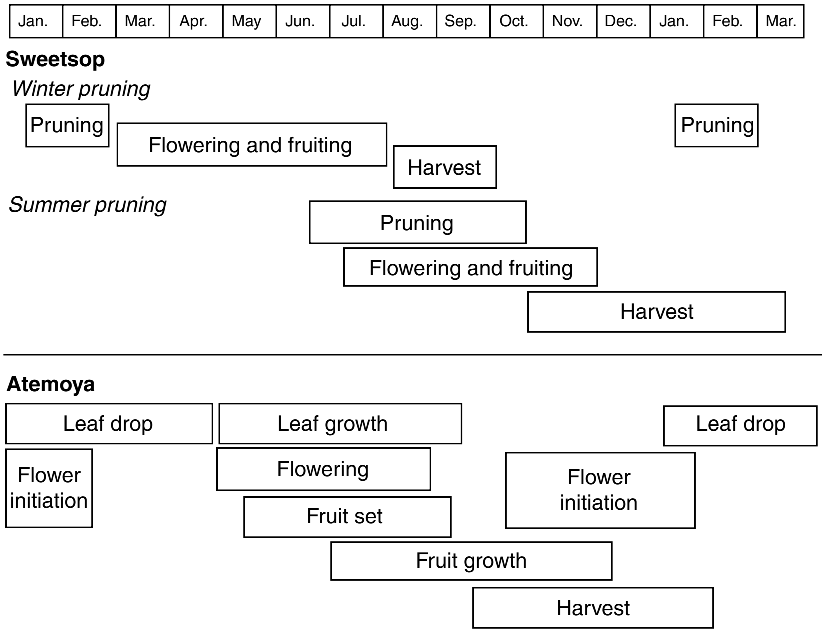

Fig. 6.7. Growth and management practices for sweetsop grown in Taiwan (Anon., 1995) and atemoya (Sanewski, 1991). In Taiwan, normal sweetsop pruning occurs in January and February, and there are extended periods of pruning of selected trees in summer. The atemoya cycle has been converted to northern-hemisphere seasons for comparison purposes.

Pruning

Training of trees should begin in the nursery, and pruning should continue after transplanting. It is desirable to train the tree to a single trunk up to a height of about 90 cm and then it should be headed back to produce lateral branches. The lateral branches should be spaced 15–25 cm above each other and be allowed to grow in different directions to develop a good scaffold. After about 2 m, they can be left to natural growth. Pruning is carried out when the trees are dormant and, in heavy trees, involves removal of lower limbs touching the ground and branches in the centre that may be rubbing against each other. The objective is to allow sunlight access to the centre of the tree (George and Nissen, 1986a).

All lateral buds can have up to two vegetative buds and three flower buds. The lateral buds of atemoya, cherimoya and sweetsop are normally 'buried' (subpetiolar) in the base of the swollen leaf petiole (Fig. 6.1). Leaf shed must occur prior to the elongation of 'buried' buds (George and Nissen, 1987a). Removal of leaves mechanically by stripping or chemically with urea or ethephon releases these buds. The buds in 'Pink's Mammoth' and 'African Pride' are more suppressed and may require leaf stripping in the summer. Adventitious buds can arise at any point on a trunk.

Atemoya produces the first flowers of a season and the most flowers on 1-year-old wood. The second and third flushes of flowers occur on new growth and produce most of the crop (Fig. 6.5). The flowers of the first flush may be removed, as they show poor fruit set and have greater problems with fruit splitting upon ripening. In south-east Queensland, each year the 1-year-old fruiting wood is shortened to about 10–15 cm, with four to six buds (Sanewski, 1991). These pruned laterals are retained after producing fruit and allowed to become part of the framework, thus extending the canopy by 30–50 cm each year. However, dense shading within the canopy is a major problem. The open-goblet system is used to produce an open, spreading tree that will produce fruit early and avoid dense shading. The strategy is to produce one or two fruits on each shortened, 1-year-old lateral. These laterals are removed completely after 2–3 years and replaced by new growth closer to the leader. The ideal seasonal growth of laterals producing fruit is about 60 cm long and about 10 mm in diameter at the base. Annual lateral growth more than 100 cm is considered excessive for mature fruiting trees. This system allows the development of fruiting laterals along all the main limbs, with a moderately open centre, although trees under this system rapidly grow tall. Pruning is normally carried out in spring before large amounts of bud growth have occurred, with a moderate summer pruning. Defoliation during the cool season to allow early development of the buried buds and more uniform flowering is sometimes carried out with an ethephon–urea mixture (Sanewski, 1991). Rejuvenation by heavy pruning is occasionally needed.

Summer pruning of cherimoya was tried in Chile by removing the shoot tips, leaving six or ten buds, after artificial pollination had been performed. In some cases, girdling or scoring were used in combination. The best treatment was to cut the shoots at ten buds combined with girdling the trunk during flowering time, with an increase of 22% in fruit yield and 25% in fruit weight (Razeto and Diaz de Valdes, 2001).

Sweetsop is pruned so that 1-year-old branches are cut back to 10 cm. The pruning left 120–150 branches per tree, with root pruning not being recommended. Flower initiation begins at the basal end of the growing branch (Lo, 1987). In Taiwan, normal pruning occurs in January/February, with fruit harvest from July to September (Fig. 6.7). A summer pruning with fruit thinning (June–October) of selected trees can lead to harvesting fruit from October to the next March (Yang, 1987). Highest winter fruiting occurs when summer growth is pruned, compared with pruning non-fruiting shoots or pruning in late May.

Fertilization

The *Annonas* have an indeterminate growth habit (axillary flowering), and applying nitrogen (N) in somewhat excessive amounts does not interfere greatly with floral initiation, as is the case with plants having determinate growth habit. However, excessive tree vigour is usually associated with reduced flowering and yields in many tree crops and the atemoyas are no exception (George *et al.*, 1989).

In Australia, continued research and field observations on atemoya nutrition have led to greater refinements in terms of quantity of fertilizer and times of incremental applications during the annual growth and fruiting cycles (Table 6.4). The use of foliar nutrient analysis has become a useful management tool in determining atemoya fertilizer programmes (Sanewski, 1991). Sampling for foliar analysis consists of obtaining the most recently matured leaf – the fourth or fifth leaf below the growing point. Leaves are selected from non-bearing shoots without a leaf flush during late summer or early autumn (Table 6.5). After 10 years of age, the annual amounts of N, phosphorus (P) and potassium (K) remain the same, as tree size is kept relatively constant by annual pruning and by competition from adjacent trees. The annual requirements of N and K are split into four increments (Table 6.4). In the cool subtropical areas, greatest vegetative growth takes place during the warmer months, from spring to autumn. Reduction in N during the winter minimizes new vegetative growth in young trees that are vulnerable to cold temperatures. This adjustment is not necessary in the warm tropics. P is given once per year during the early-autumn application.

Table 6.4. A guide to annual application of NPK for 'Pink's Mammoth' atemoya trees of different ages using straight fertilizers (g/tree/year) and percentage distribution of application of annual amounts (Sanewski, 1991).

Tree age (years)	Urea (g/tree/year)	Superphosphate (g/tree/year)	Potassium chloride (g/tree/year)	
2	400	500	360	
4	860	550	930	
6	1300	780	1170	
8	1600	880	1500	
10	1750	880	1650	
Fertilizer	**Early spring**	**Early summer**	**Early autumn**	**Late autumn**
Urea	20%	30%	40%	10%
Superphosphate			100%	
Potassium chloride	10%	30%	40%	20%

Table 6.5. Tentative leaf nutrient standards for atemoya (Pink's Mammoth) in Queensland, Australia, presented as a guide (Sanewski, 1991).

Nutrient	Acceptable range
Nitrogen	2.5–3.0%
Phosphorus	0.16–0.2%
Potassium	1.0–1.5%
Calcium	0.6–1.0%
Magnesium	0.35–0.5%
Sodium	< 0.02%
Chloride	< 0.3%
Manganese	30–90 ppm
Copper	10–20 ppm
Zinc	15–30 ppm
Iron	50–70 ppm
Boron	15–40 ppm

The primary sink for K in the atemoya is the fruit, rather than the leaves, and thus there is a high requirement, with deficiency likely. About 60% of the K requirement is applied during the fruit-development period. Atemoyas also have a fairly high requirement for magnesium (Mg) and calcium (Ca). Heavy vegetative growth during the fruit-development period competes for nutrients such as boron (B) and Ca, resulting in boron-deficient fruit. Boron-deficient fruit develop hard, brown, lumpy tissues around the central core. Deficiency in B and, to some degree, Ca is considered a causal factor for these lumps (Cresswell and Sanewski, 1991). Applying B at a slight excess can be phytotoxic, especially in sandy soils. A desirable practice is to use organic fertilizers, with inorganic fertilizer as a supplement to maintain a balance and to control cropping (Sanewski, 1991).

For sweetsop, a periodic application of NPK is best, split into three parts applied every 4 months. The early-spring application would include all the P for the year and 20% of the N and K requirements. In summer, the other 70% of N and 40% of K are applied, and the rest of K is left for autumn application. A physiological disorder called black speck is caused by Ca deficiency, which is corrected by spraying with a foliar Ca solution. This physiological disorder causes small, dark spots in the shoulder and waist of the fruit, but it can invade the whole skin in extreme cases.

Pest management

Diseases

A number of diseases have been reported in the literature (Table 6.6). Anthracnose, caused by *Colletotrichum gloeosporioides* (*Glomerella cingulata*),

Table 6.6. Major diseases of *Annonas*.

Common name	Organism	Parts affected, symptoms	Region or country
Anthracnose	*Colletotrichum gloeosporioides* (*Glomerella*)	Flowers, fruit, leaves, dieback, seedling damping off	Universal
Armillaria root rot	*Armillaria leuteobubalina*	Roots, base of trees, decline	Australia
Bacterial wilt	*Pseudomonas solanacearum*	Tree wilt	Australia
Black canker (diplodia rot)	*Botryodiplodia theobromae*	Leaf scorch, twig dieback	Universal
Black canker	*Phomopsis*	Leaf scorch, twig dieback	Australia
Purple blotch	*Phytophthora palmivora*	Spots on immature fruit, fruit drop, twig dieback	Australia
Rust fungus	*Phakopsora cherimoliae*	Leaves	Florida
Fruit rot	*Glioclacium roseum*	Fruit	India

is the most serious in areas of high rainfall and atmospheric humidity and during the wet season in dry areas (Alvarez-Garcia, 1949; Dhingra *et al.*, 1980). This disease causes twig dieback, defoliation and dropping of flowers and fruit. On mature fruit, the infection causes black lesions.

Black canker (*Phomopsis anonacearum*) and diplodia rot (*Botryodiplodia theobromae*) occur mostly on neglected trees and cause similar symptoms of purplish to black lesions, resulting in mummified fruit. Marginal leaf scorch is also caused by these two fungi and causes twig dieback. Diplodia rot has darker internal discoloration and deeper, more extensive, corky rot in fruit. A fruit and leaf spot is caused by a soil-borne fungus, *Cylindrocladium colhounii*, which can cause almost total loss of fruit during years of persistent heavy rains. Symptoms begin with small, dark spots, primarily on the shoulders of the fruit, which spread along the sides, enlarge, become dry and crack. Infection is skin deep, but fruit becomes unmarketable. The control measures recommended are good orchard maintenance with heavy mulching and lower-branch pruning to prevent splashing of soil during heavy rainfall (Sanewski, 1991).

Bacterial wilt of atemoya is caused by *P. solanacearum* and is characterized by rapid wilting and death of young trees and slow decline of old trees. There is a general decline of vigour and defoliation on affected limbs. Vascular discoloration of woody tissues occurs in the roots and up to the trunk at ground level. It has caused up to 70% tree death in 12 years in orchards using *A. squamosa* rootstocks in Queensland.

In sweetsop, *Phytophthora* blight (purple blotch) is caused by *Phytophthora citrophthora* and *Phytophthora nicotianae*, which infest fruit and leaves, mainly during the wet season; the fruits get mummified and stay on the tree or drop, and the infected leaves show water-soaked spots that turn brown-black. Another sweetsop fruit disease is attributed to *Gliocladium roseum*, which affects 20–90% of the fruit in India. Symptoms consist of water-soaked spots, which turn soft and brown. There is also a bacterial wilt caused by *P. solanacearum* that produces a rapid wilting and death of young trees and slow decline of old trees. Vascular discoloration occurs of woody tissues of the roots up to the trunk at ground level.

INSECT PESTS

Some insect pests occur in numerous growing areas (Table 6.7). One of the most serious insects in Trinidad is the *Cerconota* moth, which lays its eggs on young fruit. The emerging larvae tunnel into the pulp, causing blackened, necrotic areas. It is common to find every fruit larger than 7.5 cm infested.

Table 6.7. Major insect pests of *Annonas*.

Common name	Organism	Parts affected	Country/region
Bephrata wasp (soursop wasp)	*Bephrata maculicollis*	Fruit	Mexico, Americas, Trinidad, Surinam
Wasp	*Bephratelloides paraguayensis*	Fruit	Americas, Barbados
Cerconota moth (soursop moth)	*Cerconota annonella*	Fruit	Americans, Trinidad, Surinam
Thecla moth	*Thecla ortygnus*	Flowers, young fruit	Americas, Caribbean
Banana spotting bug	*Amblyphelta lutescens*	Young fruit	Queensland
Mealy bug	*Dysmicoccus* spp.	Stem, leaves	Universal
Citrus mealy bug	*Planococcus citri*	Fruit	Queensland
Southern stink bug	*Nezara viridula*	Fruit	Caribbean
Caribbean fruit fly	*Anastrepha suspensa*	Fruit	Caribbean, Mexico
Mediterranean fruit fly	*Ceratitis capitata*	Fruit	Peru, Spain
Queensland fruit fly	*Bactrocera tryoni*	Fruit	Australia
Potato leaf hopper	*Empoasca fabae*	Leaves	Caribbean
Red spider mite	Several genera and species	Leaves, flowers	American tropics
Scale insects	*Saissetia coffeae*	Leaves, stem	Universal
Coconut scale insect	*Aspidiotus destructor*, other genera and species	Leaves, stem	Caribbean

Bagging the fruit is sometimes done. This moth has been reported in the American tropics as far south as Brazil and is a major limiting factor in Surinam (Paull, 2008).

The bephrata wasp (*Bephrata maculicollis*) is widely distributed throughout the Caribbean, Mexico, Central America and northern South America. This wasp is considered to be the most important pest in Florida (Campbell, 1985). The larvae infest the seeds and cause damage to the pulp, as they bore through the flesh to emerge when the fruit matures. The *Thecla* moth is widespread through parts of the Caribbean and in the American tropics, but it is not considered to be as serious as the *Cerconota* moth and *Bephrata* wasp. Primary damage is to the flowers. The larvae feed on flower parts, such as the perianth, stamens and stigmas, with the flowers failing to set fruit. Bagging the fruit can be very effective and an economic estimate has to be done.

The banana-spotting bug (*Amblyphelta lutescens*) and the fruit-spotting bug (*Amblyphelta nitida*) are considered to be serious atemoya pests. *Amblypelta nitida* is rare in northern Queensland, with both being pests in southern Queensland. The bugs cause small, black, 2–10 mm spots on the shoulders of young fruit and penetrate about 1 cm into the fruit. The damage resembles the symptoms of diplodia rot (black canker).

Mature green annonaceous fruits have been shown to be rarely infested by the Mediterranean fruit fly (*Ceratitis capitata*) and Oriental fruit fly (*Dacus dorsalis*), but they are found, on occasion, in tree-ripened fruit. In Peru *C. capitata* is one of the most important problems in cherimoya as well as some *Anastrepha* species (Franciosi, 1992). Also, in Spain 'Fino de Jete', the major cultivar grown, is very susceptible to the *C. capitata* fruit fly. In Australia, the Queensland fruit fly (*Bactrocera tryoni*) infests ripening atemoya fruit. 'African Pride' appears to be more susceptible than 'Pink's Mammoth'. Use of bait sprays and field sanitation are recommended measures to minimize fruit-fly infestation (Smith, 1991). Fruit bagging also provides protection.

Mealy bugs and various species of scale insects are found universally and usually become a serious pest on neglected trees. The former is reported to be a major pest on marketable fruit in some areas of Australia. Red spider mites can become a serious problem in dry areas or during dry seasons. Scale insects are normally a minor problem.

Nematodes can be a problem in some places like Chile, where *Helicotylenchus* and *Pratylenchus* cause significant reduction in plant growth in certain areas (Gardiazabal and Rosenberg, 1993).

Weed management

Problem weeds, especially grasses and twining weeds, should be controlled by cultivation and herbicides before planting. Young trees should be protected from weed competition by hand-weeding, mulching or contact herbicides. The shallow root systems limit the use of cultivation under the tree. A translocated herbicide may be needed for perennial weeds and is applied as a spot spray.

HARVESTING AND POSTHARVEST HANDLING

Harvesting season, yield and harvesting

The harvesting season is quite similar in most areas, differing only in range (Table 6.8). Sweetsop is usually harvested during the summer months, from July to November, and can be extended to March (Fig. 6.7). Atemoya is harvested in autumn in the southern hemisphere and winter in Australia (Fig. 6.7) and from October to January in Poona, India.

A major problem in *Annona* cultivation is obtaining commercial yields. In order to increase yield, hand-pollination (Fig. 6.4) has become an important aspect of cultivation practices in some areas, especially for atemoya. Use of pollen stored under poor conditions, naturally defective pollen and pollinating during the hottest period of the day result in very poor fruit set.

Rootstocks have been shown to greatly influence yield (Sanewski, 1991). Trees of the same age and cultivar on cherimoya rootstock yield almost double that of trees grafted on sweetsop. Cultivar differences in yield have also been noted (Fig. 6.8). Estimated yield per tree of 6-year-old 'African Pride' on cherimoya rootstock is about 90 kg, while that of 'Pink's Mammoth' of the same age and on the same rootstock is about 30 kg. In other cases yields of 80–150 kg/tree are recorded for cherimoya and sweetsop, equivalent to 15–25 t/ha.

Fruit is harvested when fully mature and firm. The skin colour changes as the fruit approaches maturity. Skin of immature cherimoya and sweetsop is greyish-green but turns to yellow-green at maturity. In the latter fruit,

Table 6.8. Peak harvesting seasons for some *Annona* species.

Countries	Cherimoya	Atemoya	Sweetsop
Australia		Mar.–Sept.	
Argentina	Feb.–July		
California	Mar.–Apr.		
Caribbean			June–Sept.
Chile	Aug.–Dec.		
Florida	July–Oct.	July–Sept.	July–Sept.
Hawaii		Aug.–Nov.	
India (Poona)	Nov.–Feb.	Oct.–Jan.	Aug.–Nov.
Portugal (Madeira)	Nov.–Feb.		

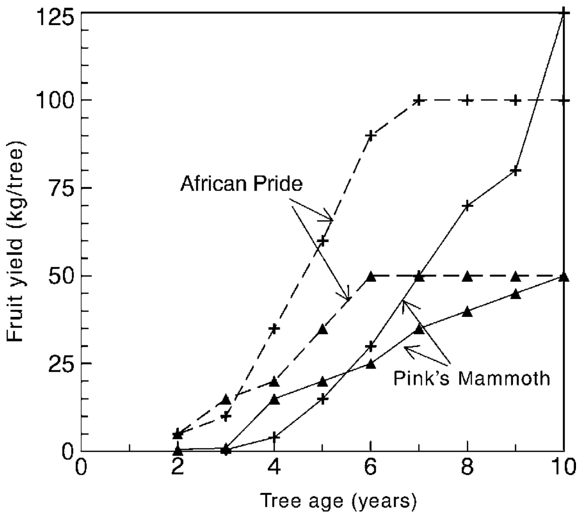

Fig. 6.8. Approximate yields of two atemoya cultivars, 'Pink's Mammoth' and 'African Pride', on cherimoya (+) and sweetsop (▲) rootstocks with tree age (after Sanewski, 1991).

adjacent carpels towards the blossom end commonly separate, exposing the white pulp ('creaming'). 'Creaming' between segments of the atemoya fruit is considered to be an indication of maturity. Fruits are harvested when 40% of the surface shows 'creaming' (Sanewski, 1991). Determining harvest time by dating floral anthesis is impractical, as flowering occurs over many months. If a rigid hand-pollination protocol is used, with removal of naturally pollinated fruit, days from anthesis can be used.

Fruit is hand-harvested and put into lug boxes or baskets. Sometimes the fruit is harvested using pruning shears, in order to leave a portion of the peduncle attached to limit stem end rots. Fruit should be harvested preferably early in the morning, when temperatures are still cool. Atemoyas are harvested every 3–7 days, with experienced pickers harvesting from 150 to 180 kg fruit/h.

Postharvest handling

Harvested fruit should be handled with care to prevent bruising of the skin. This is especially important for fruits that are marketed for fresh consumption, such as cherimoya, sweetsop and atemoya. Fruit of some cherimoya cultivars can be kept for 7–10 days at 17°C. Normal ripening occurs at temperatures between 15 and 30°C, and storage temperatures below 15°C cause chilling injuries and a failure to develop full flavour, although some Chilean varieties such as ‘Concha Lisa’ tolerate 7–8°C and ‘Bronceada’ 10–11°C. Fruit harvested early in the season will have fewer sugars but stores better than fruit harvested late in the season. Cherimoyas can be coated with different wax formulations to reduce water loss, delay firmness and enhance fruit appearance (Gardiazabal and Rosenberg, 1993).

Storage conditions recommended for sweetsop are 15°C, with an RH of 85–90%. Atemoya fruit can be stored up to 2 weeks at 15–16°C or 1 week at 10–12°C; fruits stored at 0–5°C turn black. At lower temperatures, skin discoloration occurs rapidly. Precooling of fruit is essential to help extend shelf-life. Some trials have been made to store under controlled atmosphere.

Except for the atemoya in Australia, there are no reports of established grade standards. Australian standards specify mature atemoya fruit should be 75 mm in diameter, firm, with ‘creaming’ between segments on the skin. Containers are 0.5 bushel (8–10 kg) in size, made of wood, fibreboard or polystyrene (450 mm × 215 mm × 180 mm), well ventilated and marked with ‘custard apple’ and the number of fruit. The presence of soft fruit and even one fruit-fly-damaged fruit can lead to rejection of the consignment.

Compositional changes during fruit ripening

All *Annonas* are climacteric fruit. Cherimoya has two respiration peaks during ripening instead of the single peak of other climacteric fruits. The fruits also seem to release more ethylene than most other fruit and have a higher rate of metabolism, which shortens its postharvest life. ‘African Pride’ atemoya respiration reaches a peak about 3 days after harvest, and the eating stage is reached in another 2 days. Total time from harvest to eating ripeness is about 5 days at 20°C.

UTILIZATION

Cherimoya is a fair to good source of vitamins, while sweetsop is a good source of P, thiamine and ascorbic acid (Table 6.9). Atemoya is also a good source of ascorbic acid.

These *Annonas* are usually consumed as dessert fruit. Once peeled, the pulp tends to oxidize fairly soon and acquires a brownish colour. Several pies, custards and fine desserts, which can include combinations with whipped cream and meringues, are made with cherimoya and atemoya. The peeled pulp can be eaten mixed with orange juice, as they do in Chile. A delicious ice cream can also be made with these fruits or they can be included in yogurt. The perishable nature of the fruit and often short supply limits availability to local markets or air shipment to more-distant markets.

Table 6.9. Proximate fruit composition of cherimoya, soursop and atemoya in a 100 g edible portion (after Wenkam, 1990).

Nutrients	Cherimoya	Atemoya	Sweetsop
Water (g)	68.71	78.7	75.97
Energy (kJ)	460	310	360
Protein (g)	1.54	1.4	1.89
Lipid (fat) (g)	0.13	0.6	0.57
Carbohydrate (g)	28.95	15.8	20.82
Fibre (g)	–	2.5	1.41
Ash (g)	0.67	0.4	0.75
Minerals			
Calcium (mg)	9	17	17
Iron (mg)	–	0.3	0.3
Magnesium (mg)	–	32	22
Phosphorus (mg)	24	–	54
Potassium (mg)	–	250	142
Sodium (mg)	–	4	2
Vitamins			
Ascorbic acid (mg)	12.20	43	35.9
Thiamine (mg)	0.11	0.05	0.10
Riboflavin (mg)	0.11	0.08	0.06
Niacin (mg)	1.00	0.8	0.89
Vitamin A	0	–	0
Seed/skin %	35.00	28.0	45.00

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7

Avocado

The avocado (*Persea americana*) is the most common English name but it is also known as alligator pear and butter pear. Spanish-speaking people call it aguacate, cura or cuprandra, while in Chile, Peru and Educador, it is called by its Inca name, palta. In French, it is known as avocat and avocatier. The name ‘avocado’ refers to the fruit and is derived from the Aztec Nahuatl language word, ahuacatl, meaning ‘testicle’. This name is in reference to the shape of the fruit, which was regarded by the Aztecs as the fertility fruit. The species is now cultivated worldwide in tropical and subtropical climates.

BOTANY

Family

The laurel family (*Lauraceae*) is composed of about 55 genera, with more than 2000 species. This basal family in the dicots is in the Order Laurales, which was sometimes included in the Magnoliales. They are mostly evergreen trees and shrubs, occasionally aromatic, and native mostly to tropical and subtropical regions. There are about 150 species of tropical evergreen trees, many of which are cultivated as ornamentals for their laurel-like leaves.

Important genera and species

The genus *Persea* Mill. is the best known for the fruit called avocado or aguacate, *P. americana* Mill. (*Persea gratissima* C.F. Gaertn.). The fruits of most *Persea* species are small and worthless. Only *P. americana* and *Persea schiedeana* Ness. bear large fruit, the latter species being watery and fibrous but pleasant in flavour and eaten by people in its native habitat in Mexico and Central America. Other species of commercial or ornamental value include *Cinnamomum camphora* (L.) Nees and Eberm., camphor tree; *Cinnamomum* *zeylanicum* Breyn., cinnamon tree; *Laurus nobilis* L., bay or sweet bay; and *Umbellularia californica* Nutt., California bay tree.

Origin and distribution

There is general agreement that the centre of origin of the avocado is in the eastern and central highlands of Mexico and in the adjacent highland areas of Guatemala to the Pacific coast. Early European travellers during the 16th century found avocado in cultivation and distributed throughout Central America and northern South America. This is evidenced by the native names given to avocado in many languages and by archaeological findings. Carbon dating indicates that Mexican avocados were used as food as early as 8000–7000 years ago (Williams, 1976). Separate human selection began 4000–2800 BC by MesoAmerican Indians, which led to three well-demarcated ecotypes, known as Guatemalan, Mexican and West Indian (Coastal Guatemala) (Fig 7.1). These three separate domestications are supported by ethnobotanical and genetic marker studies (Popenoe, 1920; Ashworth and Clegg, 2003). The races were separate until after European contact in the 16th century (Chen *et al.*, 2009).

Early accounts indicate that it was not cultivated in the Caribbean islands during the pre-Columbian period and was introduced to Jamaica by

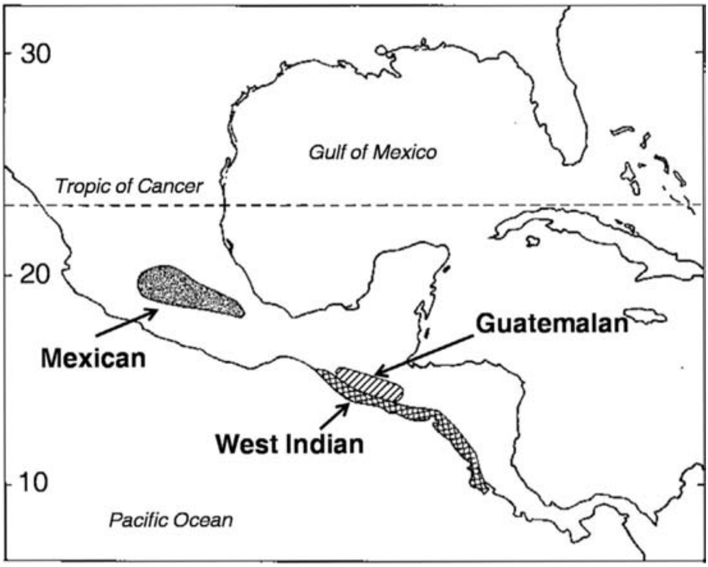

Fig. 7.1. Possible evolutionary centres of the three cultivated avocado races (redrawn from Scora and Bergh, 1992).

the Spaniards in about 1650. Distribution to the African and Asian tropics occurred during the 1700s and 1800s. The first recorded importation into Florida was in 1833, into California in 1848 and into Hawaii during the early 19th century. By 1855, avocado trees were common in gardens of Oahu and were distributed to the other islands of the Hawaiian chain (Yee, 1978). It is now widely distributed throughout the tropics and subtropics, but the use of the fruit differs in different areas. Although the avocado has been available in most South-east Asian countries, it has not been cultivated widely, due to a preference for many other fruits. The main producers are Mexico, the USA, Indonesia, Dominican Republic, Colombia, Chile, Peru and Brazil, with Mexico, Chile, Israel, Spain and South Africa being the main exporters and Peru trying to join this group.

The West Indian race is adapted to the humid tropics and is very chilling-sensitive, with some salinity tolerance. The fruits of the West Indian race are small with medium-thin, leathery skin; low oil content; loose seed and maturing 160–240 days after flowering (Table 7.1). The closely related Guatemalan race is postulated to have originated at somewhat higher elevations in Guatemala and adjacent areas, based on abundance of wild populations (Fig. 7.1). Leaves of cultivated types of this race are not anise-scented; Popenoe (1920) reported anise-scented wild forms. This race has some cold tolerance and the fruit has a thick, tough skin that remains green until maturity. The Mexican race is predominantly found in the higher

Table 7.1. Comparison of selected characteristics of three horticultural races of avocado (Bergh, 1975; Bergh and Ellstrand, 1986).

Trait	West Indian	Guatemalan	Mexican
Climate	Tropical	Subtropical	Semi-tropical
Cold tolerance	Least	Intermediate	Most
Salt tolerance	Most	Intermediate	Least
Leaf anise	Absent	Absent	Present
Young leaf colour	Pale yellow	Green with red tinge	Green
Mature leaf colour	Pale green	Dark green	Dark green
Bloom to fruit maturity	5–9 months	10–16 months	6–9 months
Size	Variable (to large)	Variable (intermediate)	Variable (to small)
Colour of fruit	Green or reddish	Green	Often dark
Skin thickness	Medium	Thick	Very thin
Skin surface	Shiny	Rough	Waxy bloom
Seed size	Variable	Small	Large
Seed cavity	Variable	Tight	Loose
Oil content	Low	High	Highest
Pulp fibre	Less common	Less common	Common
Pulp flavour	Sweeter, milder	Rich	Anise-like, rich

elevations of Mexico (Fig. 7.1). Leaves of the Mexican race are anise-scented and 60% of the essential oil is the monoterpene estragol (Scora and Bergh, 1992). These races are recognized as subspecies *P. americana* var. *americana* (West Indian), var. *drymifolia* (Mexican) and var. *guatemalenis* (Guatemalan) and are based upon taxonomic, biochemical, isozyme and molecular data (Bergh and Ellstrand, 1986; Furnier *et al.*, 1990; Ashworth and Clegg, 2003; Chen *et al.*, 2009). Ben-Ya'acov *et al.* (1995) have suggested adding a new race, which they call var. *costaricensis*. Due to the outbreeding nature of these taxa and human selection and cultivation, there are many interracial hybrids and some of the principal commercial cultivars are of hybrid origin.

ECOLOGY

Ecological requirements of avocado should be viewed in terms of the areas of geographical origin. It is generally considered to be a subtropical plant, except for the tropical West Indian race. Regardless of origin, the avocado has shown adaptability to a wide range of ecological conditions, from the tropics to approximate latitudes of 30° N and S. This wide distribution may be due to the broad genetic differences of the three horticultural races. In some high Andean regions, Mexican avocados grow well under these harsh conditions.

Soil

Avocado is grown in a wide variety of soil types. Deep soils of volcanic origin, sandy loam soils, calcareous soils and other soil types have supported good growth. Soil pH may range from 5 to around 7. Since avocado is highly susceptible to root rots, good drainage is crucial and a high water table undesirable. Trees show dieback in parts of fields when the water table is less than 1 m.

Avocado has little tolerance for saline conditions. Kadman and Ben-Ya'acov (1970a) produced various degrees of leaf burn by irrigating an avocado orchard with water containing 150–170 mg chlorine/l. It has also been shown that West Indian seedlings are more tolerant to salt than Mexican seedlings, with Guatemalan having an intermediate tolerance (Table 7.1).

Climate

Rainfall

Most cultivars are sensitive to water stress and to excess moisture caused by poor drainage. In Hawaii, avocado trees have grown well under annual rainfall of 3125 mm, largely due to the excellent drainage provided by the 'a' a' soil (crushed lava rock). Generally, a moderate rainfall range between 1250 mm and 1750 mm per annum with good distribution is desirable. Almost all avocado-growing areas have wet and dry periods, necessitating some form of supplemental irrigation.

Avocado inflorescences are not damaged by moderate amounts of rain for short periods, although relatively dry conditions are preferred during flowering. Avocado roots are shallow, and prolonged dry conditions during the critical periods of flowering and fruit set can cause flower and young-fruit drop. Among the three races, West Indian cultivars are more adapted to high-summer rains, while the Mexican races possess greater tolerance to water stress and lower humidity.

Temperature

Humans have attempted to broaden the range of the three races for economic reasons by cultivation in areas with seasonally adverse conditions. The West Indian race is best adapted to a humid, warm climate and monsoon rains, with optimum temperatures around 25–28°C (Table 7.1). Higher temperatures depress photosynthesis, thus lowering yields. This race is susceptible to frost and has a foliage tolerance to a minimum temperature of 1.5°C. Mature trees of Mexican cultivars have been observed to tolerate temperatures as low as –4 to –5°C without damage to the foliage and wood, although flowers are damaged. The Guatemalan race is adapted to a cool tropical climate but is less tolerant of low temperatures than the Mexican race (McKellar *et al.*, 1992). Cultivars have shown tolerance to light frost down to −2°C, but flowers are damaged by even light frost (Bower, 1981a).

Night temperatures of 15–20°C and day temperatures of ~20°C are the most suitable temperatures for floral development, pollen-tube growth and embryo development (Table 7.2). Generally, high humidity, exceeding 50%, is desirable, especially during flowering and early fruit set. The Mexican–Guatemalan hybrids, such as 'Fuerte', have shown wider temperature tolerance to cold than those of the Guatemalan race. Vegetatively, 'Fuerte'

Table 7.2. Effect of growing temperature (day/night) on vegetative growth and flowering of 'Hass' avocado (after Chaikiattiyos *et al.*, 1994).

Temperature (°C)	Percentage of terminal shoots		
	Panicle	Vegetative	Dormant
15/10	35	0	65
20/15	20	0	80
25/20	0	100	0
30/25	0	100	0

survives temperatures above −4°C, although the flowers are damaged and fruit set can be very poor at 17/12°C (day/night).

Solar radiation and photoperiod

Avocado is a typical C_3 plant, with maximal CO_2 exchange occurring at 20–25°C. The light saturation point for photosynthesis of mature 'Hass' avocado trees is 1110 μmol quanta/m^2/s photosynthetic photon flux, about half that at midday in the tropics. Leaves take about 40 days from bud-break to when they become net exporters of photoassimilates. During these 40 days leaves may compete with developing fruit for available photoassimilates, and this competition influences fruit retention and fruit development. Day length is apparently of little importance, as there have not been any published studies on avocado responding to photoperiod.

Wind

The avocado tree is easily damaged by winds, due to its brittle branches. Moderately high winds can cause severe damage. If orchards are not located in naturally sheltered areas, windbreaks are advised.

GENERAL CHARACTERISTICS

Tree

The avocado tree is variable in shape, from tall, upright trees to widely spreading forms with multiple branches. Trees can attain heights of 15–18 m, with manageable height being controlled by pruning. Although classified as an evergreen, some cultivars shed leaves during flowering, which are replaced rapidly from terminal shoots. Others shed their leaves gradually, so that they are never without leaves completely. The dark green leaves are spirally arranged and variable in size, from 10 to 13 cm wide and from 20 to 25 cm long, entire, elliptic or ovate to lanceolate (Fig. 7.2).

New growth occurs in flushes (Fig. 7.3). Flushes of shoot and root tend to alternate on a 30–60-day cycle (Ploetz *et al.*, 1991). Root growth continues throughout the year in subtropical areas, even at a low rate between the flushes, while shoot growth may stop. The period between flushes varies with location (Fig. 7.3) and cultivar. Growth flushes in summer tend to be asynchronous, with only a portion of a tree canopy being involved. Trunk starch concentration ranged between 4.5 and 6.3% during active tree and fruit growth. In trees where the fruits are not harvested until full maturity with 30% dry matter, a trunk starch concentration of 5.3% occurs prior to flowering, versus 7.7% in trees harvested earlier (Kaiser and Wolstenholme, 1994).

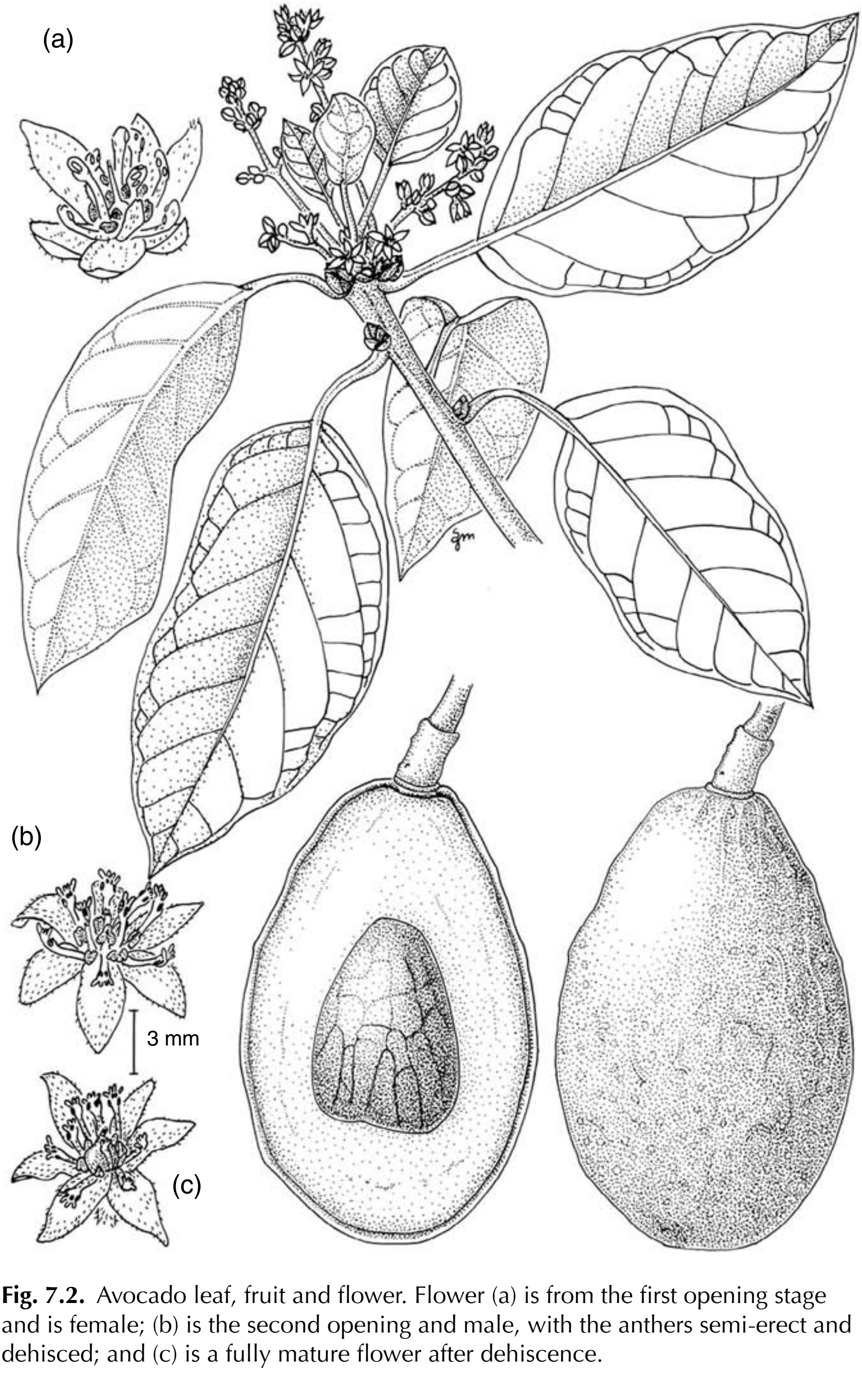

Fig. 7.2. Avocado leaf, fruit and flower. Flower (a) is from the first opening stage and is female; (b) is the second opening and male, with the anthers semi-erect and dehisced; and (c) is a fully mature flower after dehiscence.

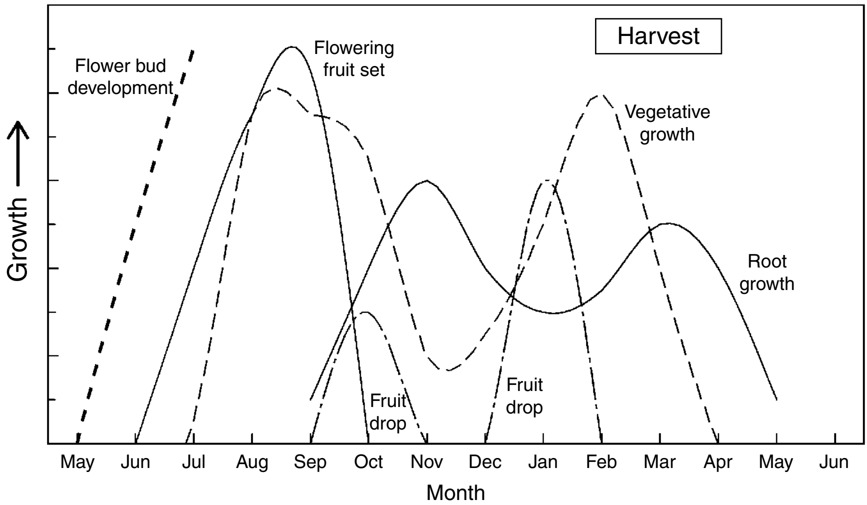

Fig. 7.3. Phenological cycle for bearing cv. 'Fuerte' in Queensland, Australia, showing the development and interaction between root, shoot, flower and fruit growth. The cycle will vary with the cultivar and needs to be determined for each location (redrawn from Whiley *et al.*, 1988a).

The juvenile period in avocado can be from 5 to 15 years. If girdled in early autumn 3 years after planting, flowering and fruit set can be increased significantly. Since the cultivars 'Pinkerton' and 'Gwen' have precocious offspring, juvenility is likely to have a genetic basis, which is modified by environment (Lavi *et al.*, 1992).

Inflorescence and flower

The small, pale green or yellowish-green flowers are borne on multi-branched axillary panicles terminating in a shoot bud (Fig. 7.2). One or two million flowers may be produced in a single flowering period, although only about 200–300 fruit mature (Whiley *et al.*, 1988b). This flowering leads to considerable water loss, and the recommendation is to irrigate during this period. The flower is bisexual with nine stamens, six of which form the outer circle and three in the inner circle. At the base of the inner circle are located a pair of nectaries, alternating with three staminodes, which also secrete nectar. Each stamen has four pollen sacs, which release cohesive pollen. The single pistil contains one carpel and one ovule (Bergh, 1976).

The avocado flower has a unique flowering behaviour (Fig. 7.4), and all avocado cultivars and seedlings, irrespective of race, fall into one of two complementary groups, designated 'A' and 'B' (Table 7.3). Flowers of the

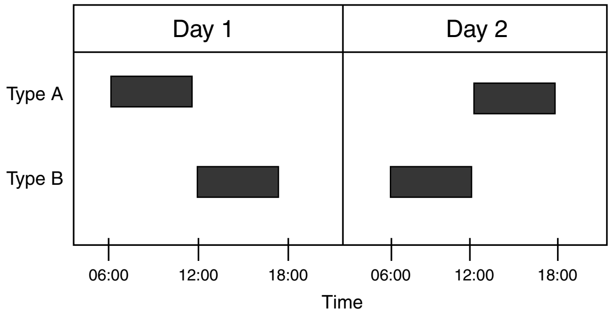

Fig. 7.4. Protogynous dichogamy pattern of flower opening involves two types, A and B, with both types found in the three ecological races. This behaviour enhances cross-pollination. These patterns may be disrupted by low temperatures and some overlap occurs.

'A' class open in the morning for 2–3 h, functioning as females with a white stigma, while the stamens remain closed and are in a horizontal position. These flowers close at approximately noon and reopen the following day during the afternoon hours for 3–4 h, functioning now as males, with stamens in a vertical position. The stigmas are no longer functional. Flowers of the 'B' class open in the afternoon as females, the stamens remaining closed. These flowers close in the evening and reopen the next morning as male flowers. This phenomenon is called protogynous, diurnally synchronous dichogamy (Bergh, 1969). The dichogamy is protogynous, as the pistil matures before the stamens in both classes and all flowers of a class are synchronized to be functionally female at one time of the day and functionally male at another time. Looking at the whole tree with numerous flowers opening any day during the flowering period, varieties of the 'A' group are in the female stage during the mornings and in the male stage during the afternoons and those of the 'B' group are in the female stage in the afternoons and in the male stage in the mornings; this way they complement each other for fertilization purposes. Temperatures of 17/12°C and 33/28°C during flowering time can prevent pollen-tube and embryo growth, resulting in the production of unfertilized, underdeveloped fruit. This disruption of fruit set, with endosperm and embryo development not being observed at low temperatures (17/12°C), is more marked in type 'B' flowers (cv. 'Fuerte'), where no female flower opening occurs (Sedgley and Grant, 1983). The flowering cycle is extended by cool temperatures from the usual 36 and 20 h for types 'A' and 'B', respectively. Growing temperatures of 25–30°C during the day and night temperatures of 15–20°C are considered optimum (Table 7.2). A much cooler temperature range during winter will stimulate flowering (Whiley, 1984). Type 'B' cultivars ('Fuerte') are generally less productive than type 'A' ('Hass') under cool flowering conditions.

Table 7.3. Classification of selected avocado cultivars according to flower types and climate adaptation.

Type A	Type B
Subtropical	
Anaheim,Wurtz	Bacon, Edranol
Hass, Lamb Hass	Fuerte, Ettinger
Gwen, Hazzard	Nabal, Millicent
Jalna, Pinkerton	Ryan, Sharwil
Reed, Rincon	Zutano,Colin V-33
Tropical	
Catalina, Collinson	Booth 7, Booth 8
Choquette, Fairchild	Gripiña No. 2, Hall
Lula, Princesa	Itzamna, Kampong
Russell, Semil 34	Linda, Monroe
Semil 42, Semil 44	Pollock, Prince
Simmonds, Waldin	Semil 43, Winslowson

Flowering occurs from late autumn to spring, depending upon the cultivar and prevailing temperatures (Fig. 7.3). West Indian and Mexican cultivars generally may start to flower early, in October or November and October–December, respectively, north of the equator. The West Indian avocado is called the summer avocado in Hawaii. Guatemalan cultivars and many Guatemalan × Mexican hybrids begin to flower around March, extending to May, and are called winter avocado in Hawaii. In the largest 'Hass'-growing area in the world, Michoacán, México, the trees can flower three or four times per year; the first, called 'crazy' flowering, occurs in August–September, the second or 'advanced' in October–November; the 'normal', which generally is the heaviest, occurs in December–January and, finally, the 'March' flowering, which takes place at the beginning of spring. These flowering events may not occur in all trees, and the intensity of flowering will vary according to the fruit set in the other flowering cycles (Salazar-García, 2000).

Pollination and fruit set

The protogynous, diurnally synchronous dichogamy in avocado flowers is the normal behaviour and occurs if warm weather prevails during flowering. Synchronous dichogamy of flowers of the same cultivar restricts self-pollination and encourages cross-pollination between those of complementary groups. Exposure to sun, wind and temperature changes can cause variability in the time of floral anthesis, prolonging the open period and time between the two open periods, and increasing the overlap of female and male opening on a single tree. However, with moderate day temperatures (25°C) and cool nights

(20°C), there is sufficient overlap of flower types to permit self-pollination of up to 93%. The possibility of self-pollination is enhanced by relatively long pollen viability. There is also evidence that the stigma remains white and is still receptive on the second day (Davenport *et al.*, 1994). The avocado can be insect-pollinated, although self- or wind pollination is possibly the norm (Davenport *et al.*, 1994). Insects, including honey bees, can carry the sticky pollen on their bodies and are capable of depositing viable pollen from one flower cycle to another within the same cultivar.

In spite of the fact that some studies have shown relatively high rates of self-pollination, most investigators have advocated interplanting of pollinator cultivars of the complementary class in orchards, in order to increase fruit set (Bower, 1981c). In the case of areas with mild climates, such as Michoacan, México, there is no need for interplanted pollinator cultivars and most orchards are made up by solid blocks of 'Hass' (Salazar-García, 2000).

Some cultivars are more effective in increasing fruit set than others. This may indicate the presence of varying degrees of incompatibility among cultivars, with some complementary cultivars superior to others. Mexican cultivars are more efficient pollen providers in California and Israel, while Guatemalan cultivars are more effective in Florida, because of greater cold tolerance of pollen improving the chances in the fertilization process (Gazit, 1976). Under warmer conditions, West Indian hybrids are good as pollen donors, probably due to their greater tolerance of higher temperatures. However, fruit set may be a poor measure of final matured fruit, as all cultivars lose flowers and developing fruitlets, regardless of pollination.

Following pollination, considerable fruit drop occurs due to poor pollination and excessive vegetative growth (Wolstenholme and Whiley, 1992). There is probably sufficient carbohydrate available from mature leaves to support the growth of both developing fruitlets and young leaves (Finazzo *et al.*, 1994). This supply during early fruit development does not limit fruitlet growth or stimulate fruitlet abscission. However, the lack of an adequate spring shoot growth, though competitive, will mean that fruit set and early fruit growth will be dependent upon older leaves and stored carbohydrate, which may be depleted by flowering. The later vegetative growth flush near harvest is crucial for final fruit growth, build-up of carbohydrates and the following period of root growth (Fig. 7.3). This is discussed further with respect to maturity of fruit at harvest and biennial bearing.

Fruit

The avocado fruit is a one-seeded berry (Fig. 7.2). The single large seed is composed of two cotyledons enclosing an embryo and is surrounded by a thick fleshy mesocarp. The skin varies in thickness up to 6 mm, depending upon the race (Table 7.1) and has 20,000–30,000 stomata per fruit, less than on a leaf.

The skin colour of the ripe fruit ranges from several shades of green to yellow-green, from reddish to maroon and from light to dark purple. The buttery flesh (mesocarp) is greenish-yellow to bright yellow to cream when ripe. Oil content ranges from 7.8 to 40.7% on a fresh-weight basis (Kawano *et al.*, 1976). Size varies from the small fruit of some Mexican types, about 225 g or less, to the large Guatemalan types, 1.4–2 kg or more (Table 7.1). In shape, the fruit is usually pyriform to oval and round.

In West Indian and Mexican cultivars, the fruit matures 150–240 days after anthesis, while Guatemalan cultivars take more than 250 days (Fig. 7.5). All show a typical sigmoid growth curve (Fig. 7.6). There is little delay before growth occurs in fruit, seed and pericarp thickness.

CULTIVAR DEVELOPMENT

Cytogenetics and genetics

Persea species generally have a diploid number of 24 chromosomes. Among *P. americana* materials examined, Garcia (1975) found one triploid (2n = 36) and

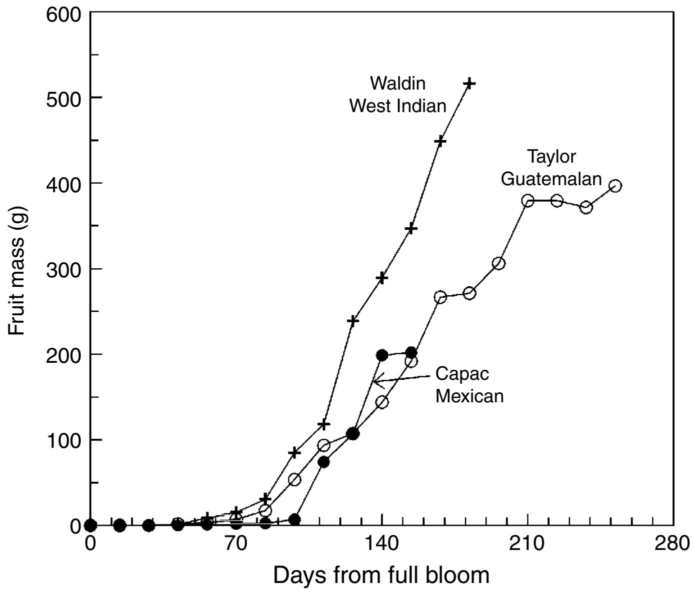

Fig. 7.5. Increase in fruit mass of three cultivars from different ecological races, showing the difference in time for fruit to reach maturity and final fruit size relative to the ecological race (redrawn from Valmayor, 1967).

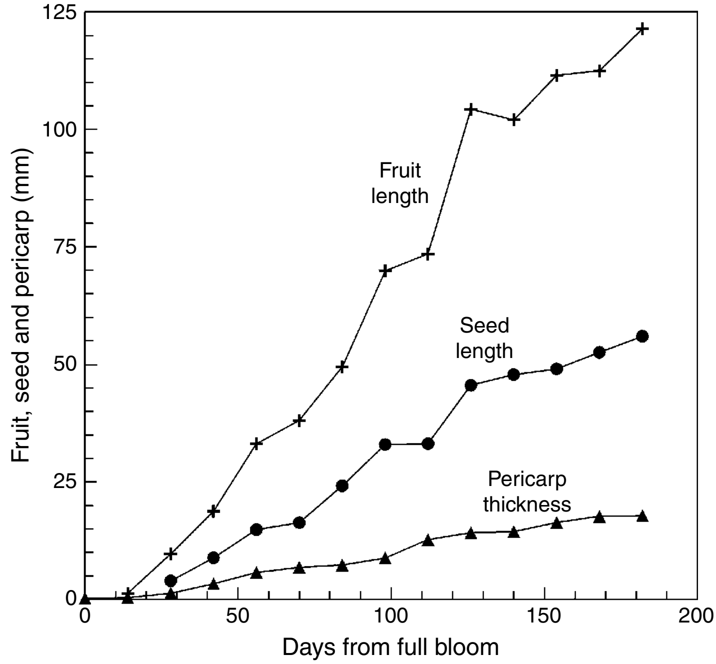

Fig. 7.6. Rate of total fruit and seed growth and the increase in pericarp thickness of the West Indian cultivar 'Waldin' (redrawn from Valmayor, 1967).

a tetraploid (2n = 48). Karyotype in *Persea* is asymmetric, with chromosomes ranging in size from 2.3 µm to 6.1 µm.

Garcia and Tsunewaki (1977), using peroxidase isozyme analysis, found significant variations between Mexican strains, within and between nine states in Mexico. The three races showed significant variation in their pattern of activities. The frequency of significant variations within strains of the three races is high in the Guatemalan (62.5%), intermediate in the West Indian (50.0%) and relatively low in the Mexican race (39.0%). Isozymes have also been used as genetic markers to detect different genotypes resulting from natural outcrossing and controlled pollinations (Bergh and Ellstrand, 1986). A number of molecular approaches have been used as genotypic markers and assignment of racial composition. Efforts to apply these techniques in avocado breeding programmes are hampered by the long generation time and the inability to perform controlled pollinations (Violi *et al.*, 2009).

Skin colour, flowering group and anise scent in the leaves are probably coded by several loci, having several alleles in each loci (Lavi *et al.*, 1993a). The juvenile period also has a major genetic component. Quantitative traits, such as tree size, flowering intensity, fruit weight, fruit density and harvest duration, show both additive and non-additive genetic variance (Lavi *et al.*, 1991).

Breeding

Intensive avocado breeding has been conducted over many years in the USA, Israel, South Africa and other countries. However, until recently, cultivars in the avocado-growing countries of the world originated as chance seedlings (Bergh, 1976).

Breeding methods may be by self-pollination or by hybridizing two selected parental cultivars, the choice depending upon objectives of the breeding programme. The avocado is highly heterozygous, because of significant cross-pollination between complementary cultivars, and significant variability can be obtained among self-pollinated progenies (Lavi *et al.*, 1993b; Violi *et al.*, 2009). Selfing can be achieved by the use of cages with pollinator bees enclosed within the tree or by using isolated trees of a desired parent cultivar (Bergh, 1976). Outcrossing is reported to be nil where trees of a cultivar are separated from other genetic lines by 100 m or more. Variations in daily weather conditions during the flowering period may disrupt the diurnal synchrony of the flowers, allowing self-pollination.

Cross-pollination is necessary when two or more desirable traits are to be combined or when traits intermediate between two cultivars are desirable, but this has proved difficult with avocado. The major cultivars in subtropical areas are hybrids of the Guatemalan and Mexican races, as the Mexican race is the source of cold-hardiness. In tropical regions, hybrids of the Guatemalan and West Indian races prevail.

Selection and evaluation

Breeding objectives may be divided into traits that are universally desired and those which are regionally specific. Tree characteristics sought after in all growing areas are ease in propagation, vigour, precocity, spreading, short fruit-maturation period, heavy and regular bearing, and wide adaptability with resistance to disease and insect pests. Traits specific to regions are cold or heat tolerance and salinity tolerance. Other qualities, such as dwarfing or semi-dwarfing, genetic uniformity, freedom from sun-blotch disease, caused by a viroid, and drought resistance, are also constantly evaluated (Bergh, 1976).

Universal fruit characteristics are resistance to diseases, pests and blemishes, long tree storage, uniform ripening, minimum fibres and long shelf-life (Currier, 1992). Traits that differ due to specific climatic conditions or market preferences are fruit size and shape, skin colour, oil content and chill tolerance. Market preference is usually based upon consumer familiarity with certain traits. Fruit size is a good example. Consumers in California generally prefer a size range of 200–300 g, while in most Latin American countries larger fruits are preferred.

Breeding for cold-hardiness is a major objective in the subtropics. 'Brooksville', a seedling of the Mexican race, has shown outstanding cold-hardiness, withstanding artificial chilling to −8.5°C. 'Gainesville', another Mexican type, withstands field temperature as low as −9.4°C. The cold-hardiness of these cultivars has to be combined with genes for dependable productivity and fruit market acceptance (Knight, 1976).

Avocado rootstock breeding is an important aspect of the total breeding programme. The avocado root rot, caused by *Phytophthora cinnamomi*, has led to testing thousands of seeds and bud-wood from avocado trees that have resisted the disease over many years and other *Persea* species collected in their native habitats. Small-fruited species, such as *Persea caerulea* (Ruiz y Pavón) Mez., *Persea donnell-smithii* Mez., *Persea pachypoda* Nan and Mart. and *Persea cinerascens* Blake, though having strong resistance, are graft-incompatible with the avocado. Hybridization between the small-fruited *Persea* species and avocado has not been successful. California and Florida have been the most active places doing hybridization, introducing species and varieties from their native sites and trying existing local or foreign materials in search of better rootstocks; Israel, South Africa, Australia and lately Chile have also been working on this important matter.

Rootstocks

In California, several rootstocks have been tried and used, especially for root rot resistance, with salinity and alkalinity resistance being less important. After many years of using Mexican seedlings like 'Topa Topa' and 'Lula', with the increase of the root rot problem in the 1970s the industry adopted the rootstock 'Duke 7', a Mexican seedling of 'Duke' with moderate resistance to root rot, which became the first commercially successful rootstock that was propagated vegetatively. Another resistant rootstock, 'Martín Grande' (G-775C), a hybrid from *P. americana* and *P. schiedeana*, did not perform well and was discarded. 'Thomas', 'D9' and 'Barr Duke' (all Mexican) have greater resistance than 'Duke 7' and are available (Ben-Ya'acov and Michelson, 1995). The latter three were all found in infected fields. In the absence of root rot, the rootstock can significantly influence canopy growth and yield. 'Duke 7' and 'Thomas' produce significantly more fruit per cubic metre of canopy than other rootstocks, with 'D9' and 'Martín Grande' being the poorest performers (Arpaia *et al.*, 1992). During the last few years 'Toro Canyon', of the Mexican race, has become important; it is more resistant to root rot than 'Duke 7' and more tolerant to salts than the Mexican seedling rootstocks; it also has resistance to *Phytophthora citricola*. Two releases from the University of California-Riverside are 'Zentmyer' and 'Uz' of the Mexican race, which look very promising. Additionally, California has introduced, and will probably be using commercially, the 'Dusa' and 'Latas' (Mexican × Guatemalan) clonal rootstocks developed in South Africa. 'Dusa' has already been released to nurseries since it is root rot and salinity tolerant. Several dozen selfing or outcrossing seedlings showing exceptional resistance to *Phytophthora* root rot are under trials.

South Africa has serious root rot problems, and they followed a path similar to California in the early years of last century and used Mexican seedling rootstocks. In the 1950s, because most of their Mexican mother plants were contaminated with sun blotch, they started using the Guatemalan 'Edranol', which had no resistance to root ríot, and later 'Duke', and then after many trials 'Duke 7', which is now the standard rootstock, providing reasonably healthy, productive and uniform trees (Kremer-Köhne and Köhne, 2007). Recent rootstock selections from South Africa, 'Latas' (Merensky I), 'Dusa' (Merensky II) and 'Evstro' (Merensky III) have great production potential with 'Hass' and tolerance to *Phytophthora* root rot and salinity. 'Dusa' is more root rot tolerant and productive than 'Duke 7' and it has been made available to growers in several countries. Australia uses plants grafted on seedling rootstocks that are very diverse; this complicates management of the orchard. They have started a programme to identify superior rootstocks and are looking for an efficient clonal propagation system. They will start selecting material from superior trees in the field and will evaluate imported rootstocks. Chilean breeders used plants grafted mainly on 'Mexicola', and other Mexican-race seedlings are going in the same direction. While in Peru 'Topa Topa' seedlings are generally used, and West Indian types imported from Israel are used in areas with salinity.

A rootstock with resistance to salinity is a focus of research in Israel, California, Chile, Australia and the north and central coasts of Peru. The three races differ in their ability to resist the uptake of salts (Table 7.1), in their ability to retain the toxic salts in the root system without translocating them to the scion and in their tolerance within their tissues. The West Indian rootstocks have the highest level of tolerance to salinity, followed by Guatemalan and Mexican races (Ben-Ya'acov and Michelson, 1995). Israel has taken two approaches: (i) selection of types that produced a resistant seedling population; and (ii) selection of individual resistant plants for vegetative propagation. Unfortunately, the true West Indian and high-salinity-resistant types are difficult to propagate by cuttings. The cold-tolerant Mexican 'Toro Canyon' and 'Duke 7' have the best salinity rating; 'Thomas' and 'Martín Grande' had intermediate ratings; and 'Barr Duke' had the lowest rating. The recent rootstock selections from South Africa, 'Latas', 'Dusa' and 'Evstro', show some salinity resistance.

The main problem with clonal rootstocks is that the plants lack a tap root, and therefore special care has to be taken that water supply is timely and adequate, especially in the most superficial portion of the soil, during the first year or so, otherwise the plants will suffer and many of them will not recover properly.

Cultivars

Cultivars from California, and some from Chile, Australia and Israel, are best suited for subtropical areas or for higher elevations above 800–1000 m in the tropics; they normally have a higher oil content, which for many consumers makes them tastier. The cultivars developed in Florida and the Caribbean Islands are most suited for the tropics and normally have a lower oil content, and most of them are green when ripe and are therefore called 'green skins' in the international trade. Some California and Florida cultivars have become international (Table 7.4), providing the basis for avocado development in many countries. 'Hass' a Guatemalan type, is the most widely distributed, grown and exported cultivar, replacing 'Fuerte', a Mexican–Guatemalan hybrid. One or both have dominated the plantings in Australia, Israel, South Africa, Mexico, Chile, Peru, the Canary Islands and other areas (Table 7.4). In California, 'Hass' has gradually become the dominant cultivar, largely due to the relatively poor yields and inconsistent bearing of the type 'B' cultivar 'Fuerte', whose flowering is disrupted by low temperatures; 'Zutano', 'Bacon', 'Gwen' and 'Pinkerton' are other commercial cultivars. In the last years 'Lamb Hass' and 'Gem' and a few others have been developed as alternatives or complements for 'Hass'. In Mexico 'Colin V-33' was selected from a population of open-pollinated 'Fuerte' seedlings; it is a type 'B' with very-good-quality pulp, green-coloured fruit, superior to 'Fuerte'; it is considered a dwarf plant and can be used as a dwarfing interstock (Barrientos-Priego *et al.*, 2000). In California, the fruit of most cultivars can be stored on the tree for months after reaching maturity, depending upon season, so not many cultivars are needed to market fruit throughout the year. However, this tree storage can lead to more pronounced biennial bearing.

Florida cultivates a larger number of mostly West Indian and West Indian–Guatemalan hybrids to extend the market season (Campbell and Malo, 1976). Cultivars are grouped into early-, mid- and late-season. 'Pollock', 'Waldin', 'Simmonds' and 'Nadir' are some early-season types. Some mid-season

Table 7.4. A list of selected cultivars grown in major avocado-growing areas.

California	Florida	Australia	Israel	South Africa	Mexico	Spain	Chile	Peru
Fuerte	Pollock	Zutano	Fuerte	Fuerte	Fuerte	Hass	Hass	Hass
Hass	Simmonds	Sharwil	Hass	Hass	Hass	Bacon	Fuerte	Fuerte
Zutano	Nadir	Bacon	Nabal	Edranol	Bacon	Fuerte	Negra	Nabal
Bacon	Booth 8	Fuerte	Ettinger	Ryan	Reed	Reed	la Cruz	
Reed	Lula	Hass	Horshim		Criollo	Zutano	Bacon	
Pinkerton	Hardee		Wurtz		(Local)	Gwen	Edranol	
Gwen	Ruehle				Zutano			
	Choquette							

cultivars are 'Booth 7', 'Booth 8', 'Collinson', 'Hall' and 'Hickson', while late-season cultivars are 'Lula', 'Monroe', 'Choquette', 'Booth 3' and a few others (Table 7.4). A similar situation occurs in Hawaii, where a large number of cultivars are grown, including introductions from California, Florida, Australia and Mexico and selections of local origin. 'Sharwil', an Australian cultivar, has become a leading cultivar, with a recent release, 'Green Gold', increasing in acreage. Puerto Rico and the Dominican Republic cultivate some of the Florida cultivars along with some locally developed cultivars, such as the West Indian-Guatemalan hybrids 'Semil' and 'Gripiña'.

Mexico grows 'Fuerte' and "Hass' as the main cultivars, along with other California and Florida ones. The 'Criollo' is mentioned as a selection of the Mexican race and is well adapted to median ecological areas of Mexico (Diaz-Avelar, 1979). Besides Mexico, Brazil has developed a substantial industry, mostly with introduced cultivars, such as 'Fuerte', 'Hass', 'Carlsbad', 'Corona', 'Edranol', 'Nabal' and 'Ryan', and cultivars of local origin, such as 'Solano', 'Ouro Verde', 'Quintal' and 'Fortuna'.

In Australia, 'Hass' and 'Fuerte' have been planted most frequently, especially along the coastal areas of northern New South Wales and southern Queensland. 'Sharwil', a local selection (Guatemalan–Mexican hybrid), has gained considerable popularity, although in some areas it had fluctuating yields. Under tropical conditions in the Northern Territory, the Mexican and Guatemalan cultivars yield poorly (Sedgley *et al.*, 1985). South African production is largely from 'Hass' and other California cultivars. Israel's production was initially based on California cultivars, until an intensive selection programme over the years produced a large number of local cultivars, such as 'Ettinger' and 'Horshim'.

In Asia, the avocado has not attained the popularity it has in other areas, although it was introduced into Malaysia over 120 years ago. In Indonesia, avocado grows well at 200–1000 m on well-drained soils, and trees are generally propagated by seeds. In the Philippines, many cultivars have been introduced from the USA since 1903, and avocado is grown in nearly all parts of the country, although it has not attained the popularity of other fruit.

CULTURAL PRACTICES

Propagation and nursery management

Avocado is primarily propagated commercially by budding or grafting upon seedling rootstocks. However, the variability of seedling populations with respect to certain desirable characteristics, such as resistance to *Phytophthora* root rot and tolerance to salinity and calcareous soils, has posed problems (Ben-Ya'acov and Michelson, 1995). Seedling production has largely changed from grafting nursery-grown trees to grafting container-grown trees. Seeds are taken from fruit picked from trees free of sun-blotch and are treated in a water bath at 49–50°C for 30 min, cooled and surface-dried in a partially shaded area. Seeds are planted (broad side down) in polyethylene bags, with a well-draining potting mix. Seeds germinate in about a month. The papery seed coats should be removed. If seeds are not very fresh, cutting off a piece of seed tip or doing some vertical cuts at the side of the seed will improve germination speed and percentage; sometimes a slice of bottom can also be cut off.

Seedlings may be cleft or side-wedge grafted 2–4 weeks after germination. Scion wood from terminal growth of sun-blotch-free cultivars should be used. Propagation is usually done in shade houses, preferably with temperature control if the environment has a wide temperature range. Grafted plants must be hardened for approximately 2 weeks under full sunlight before field transplanting. Under open-field conditions in the central coast of Peru, with 13–15°C lowest temperatures in winter, Duarte *et al.* (1975) reduced by 2 months the time to obtain a grafted plant with seeds sown at the start of autumn and by 1 month with seeds sown at the end of autumn, by spraying the seedlings three times with 250 or 500 ppm GA at 2-week intervals, starting when they had reached 15 cm.

Leafy avocado cuttings of some genotypes under mist consistently rooted nearly 100% under practically any conditions, while others did not root at all or rooted with difficulty (Kadman and Ben-Ya'acov, 1970b). Generally, West Indian cultivars with strong resistance to salinity are difficult to root. Cuttings from mature trees were difficult to root and, in those that rooted well, they took 4–10 months to root. Cuttings from 1-year-old seedlings show a higher percentage of rooting in 4–12 weeks. A 50% light intensity in the intermittent-mist system during the summer is better for rooting than full sunlight. The anatomy of the avocado stem provides a reason for the difficulty in rooting as the fibre bundles and the sclereid ring are thicker in the West Indian types, intermediate for Guatemalan and hybrid types, and least for the Mexican cultivars.

Air layers and cuttings have been successfully rooted. Variability exists in ease of rooting air layers between races and even among cultivars of a race, and the difficulty of large-scale production has discouraged commercial development. Generally, Mexican cultivars root most easily, followed by Guatemalan and West Indian, whether by air layering or by cuttings. Time required for rooting of air layers ranged from 146 to 518 days, depending upon cultivar and the time of the year. Etiolated stems show few or no sclereid connections between fibre bundles, suggesting that the sclerenchyma ring may be acting as a barrier to root emergence (Gomez *et al.*, 1973). Hence, shoots of most avocado cultivars produced in light do not root nearly as well as shoots produced in darkness.

Seedlings produced upon scions of the desirable rootstock cultivar are grafted by tip grafting as close to the base as possible. Shoots of the scion are allowed to grow and then cut back to near the base. When new buds show signs of growth, the entire plant is placed in a dark room, with the temperatures maintained at 21–23°C. When the new shoots reach about 8–10 cm in the dark, the plants are again placed in light, with a tar-paper collar placed around each etiolated stem and filled with vermiculite to continue exclusion of light from the base of the shoots. Only the tips of the shoots are exposed to light, in order to produce green leaves. This procedure is done under shade to prevent sunburn. Shoots are then allowed to grow until several leaves have matured. The collar is then removed and shoots are detached for rooting in propagation frames. Rooting hormones have shown no beneficial effects, although some reports from Australia indicate that a 360° scrape of the etiolated shoot prior to the application of the potassium salt of indole butyric acid consistently gave a crown of roots. Rooted shoots are transplanted into 10 cm peat pots and grown in an enclosed area for further root and top growth and gradually hardened. These rooted plants are then transplanted into larger polyethylene bags for more growth and hardening, then grafted when they attain appropriate size. The side-wedge technique is usually used, so some terminal foliage on the rootstock is retained until scion growth begins.

In California, South Africa and to a lesser degree in Spain and Chile, clonal rootstocks are used and propagated based on the double-grafting–etiolation method. A large avocado seed such as 'Lula' is grown in a container to serve as a nurse stock. When the nurse seedling that was sown into a planting sleeve is large enough for grafting, a splice or cleft graft with a tolerant rootstock is made. A metal girdle is loosely put above the bud or graft union so that it will eventually girdle the stem; the grafted rootstock is forced to root above the girdle (Brokaw, 1975). The nurse seed with the grafted tolerant rootstock is then grown in the dark till the graft is 20–40 cm tall. The container is then removed from the dark, and sterile rooting medium is supplied to cover the base of the bud union. Adventitious roots develop from the tolerant rootstock. Once the rootstock growth hardens off, it is grafted with the desirable scion variety and grown for 2–3 months. The double-grafted plant is then grown for several months before planting. Rooting hormone or minor cuts near the bud union between the tolerant rootstock and the nurse seed can enhance the rooting success of the rootstock. Once in the field it is assumed that the rootstock will extend its roots and the nurse seed will be excluded from the system due to the girdle. In South Africa, an improvement to this method was developed (de Villiers and Ernst, 2007). This consists of positioning a 55 ml micro-container on the etiolated shoots coming from the grafted rootstock. Roots will form in these containers, and after grafting the desired cultivar on to these shoots, they will be separated from the nurse seedling just above the nurse graft and taken to the nursery for hardening; after this they will be transplanted into nursery containers or bags. The advantages of this improvement are that more than one plant can be obtained from a nurse seed;

reduced plant cost because of the efficiency of this technique; the root system of the rootstock is separated from that of the seedling, which assures better sanitary conditions, and it can be inspected at transplant time; plants with a better root system and with a more uniform growth in the field are obtained.

Field preparation

Land preparation for avocado does not differ from that for other tree crops. Development of a drainage system is a prime consideration. Subsoiling or ripping down to at least 0.5 m or more, preferably running diagonally across the slope to allow subsurface movement of water, aids drainage. If soil pH needs adjusting, this could be done during the final stages of land preparation. Cover crops, such as legumes or grain, can be preplanted a year before orchard planting to increase organic matter and minimize erosion and root rot.

Transplanting and plant spacing

The use of grafted, container-grown trees has dramatically minimized transplanting mortality. Polyethylene bags can be removed with all the soil intact around the roots. Soil in the planting hole should be moist but not wet. In dry areas, application of water in the holes a few days before transplanting is advisable to moisten the soil. In the tropics, transplanting can be done during the dry season, if irrigation is readily available; otherwise, transplanting should be done at the beginning of the rainy season. In the cool subtropics, where low winter temperatures can be expected, young plants may need to be protected or transplanting delayed until the coldest period has passed. In Peru, some growers prefer to plant the rootstocks in the field and later graft or bud on to them; this results in a more vigorous growth of the plant during the initial years.

The cultivar's natural growth habit (spreading or erect), vigour of the rootstock, and the environment and soils are major determinants of the mature tree size, and this influences spacing and the continued productivity of the orchard. Close spacing is sometimes used, with later thinning to obtain maximum benefits per unit area. Initial close spacing can be justified only for precocious cultivars and is beneficial only if trees are judiciously thinned when this becomes necessary. For non-precocious cultivars, the yields obtained before tree thinning becomes necessary may not justify the additional cost. Traditional spacings in Florida are 7.5–10.5 m in rows and 7.5–12 m between rows, which precludes canopy overlap. Narrower spacings of 4.5–6 m in rows and 6–7.5 m between rows lead to higher yields while the trees are young. In South Africa, similar narrow spacing of 7.5 m × 7.5 m (177 trees/ha) is recommended for 'Fuerte' and 7 m × 7 m (204 trees/ha) for 'Hass', requiring later tree thinning or topping. At close spacing on the square, thinning is done by removing the trees in every second diagonal row (Bower, 1981b). In Peru, distances of 6 m × 4 m and 6 m × 3 m are being used, while in Chile 6 m × 2 m, 6 m × 3 m and even 3 m × 3 m are being tried. The narrow plant spacing needs careful formation and maintenance pruning to avoid overcrowding. Intermediate plants will have to be removed as the canopy starts to overlap. High-density schemes allow for higher initial yields, but management, especially pruning, has to be more precise.

Placement of pollinizer trees in the orchard so that an adequate ratio can be maintained after thinning may need to be considered in some spacing schemes. The old guideline was one pollinizer for every nine trees. Large blocks of a single cultivar have shown good production, presumably by self-pollination, but interplanting pollinizer cultivars undoubtedly increases fruit set for some cultivars that may not have pollen or are a poor pollen source. 'Ettinger' is an excellent pollen source for 'Hass' and there is a higher survival of fruit to maturity.

Irrigation

The avocado can tolerate neither water stress nor excess moisture, especially when drainage is inadequate. Water stress reduces yields, fruit size and tree vigour. The soil around the trees should be moist but not wet. Irrigation frequency depends upon field condition, soil drainage and tree density, as well as canopy size and prevailing weather conditions and past irrigation records. Evapotranspiration data and tensiometer readings averaged over a period of days provide a more accurate means of determining irrigation timing. The application rate is calculated, taking into account the evapotranspiration rate since the last irrigation, rainfall, percentage canopy coverage of the ground and efficiency of water use. Young, non-bearing trees require light, more frequent irrigation. Older trees can withstand longer intervals between irrigations but never to a point of water stress. Only 50% of the tree's requirements should be given in the middle of the cool season and spring, in order to favour flowering rather than vegetative growth. When fruit set is completed, irrigation reverts to normal amounts during fruit development. High irrigation rates are necessary during flowering and may be necessary as the fruits approach maturity and if the weather is hot and dry (Fig. 7.3). Care has to be taken not to let the soil dry too much at the time of flowering and fruit set, since a marked increase of water in the soil can produce a significant drop of small fruit. Irrigation is necessary down to at least 60 cm. Total water applied per year is estimated at about 35–50 ha-cm for mature trees (Gustafson, 1976).

On level land, less-efficient furrow irrigation or sprinklers can be used, with micro-irrigation systems (drip or micro-sprinklers) being more efficient in water use. Mature trees require eight or more drip emitters around the tree, providing greater control and higher efficiency of water use (up to 80%). Later plantings of avocado in California are on the sides of steep hills, which can be irrigated only by drip irrigation or mini-sprinklers, as in Chile.

Pruning

The growing tips should be pinched off young trees, allowing the development of a more compact tree. This pinching is continued until the tree is too tall. Lower limbs are removed only if they interfere with irrigation and fertilization. Management should be keyed to avoiding vegetative and reproductive growth occurring at the same time. Since avocado is polyaxial, it must continue to increase in size to remain productive. Shoot growth in the warm season occurs in spurts of up to 1 m, which is needed in order to put on leaves required for fruit growth (Fig. 7.3). Tree trimming aims at a canopy that has fruit at all heights and reduces the competition for light. Pruning at the bud ring (several closely spaced buds without subtending leaves), formed at the conclusion of a shoot growth flush, releases more buds and increases shoot complexity, and hence bearing sites. Cutting below this ring depresses tree vigour and releases only one bud (Cutting *et al.*, 1994). Bud-ring pruning can extend the period before trimming is necessary. Pruning should be timed to the end of the autumn period. Tree growth can also be reduced by spraying with paclobutrazol, an inhibitor of gibberellin synthesis, though its use is not approved in some countries. Tree thinning is recommended in South Africa when 90% of the orchard floor is shaded. Topping (stag-horning) is also practised on healthy trees to rejuvenate a crowded orchard, where the trees are cut back to 1–3 m from the ground. Tree thinning, topping or stumping is essential to avoid canopy crowding and the loss of bearing volume in the lower third or more of the tree. Severe topping to ~3 m means the loss of production for 2–3 years, while less severe topping to ~5 m can increase fruit yield and the amount of fruit set in the lower half of the tree (Crane *et al.*, 1992). Cultivars with upright vigorous growth habits may be severely affected by topping and orchards may have to be rejuvenated in sections over several years, by topping to 5 m. For very high density, the plants should be cylindrically shaped, while for not so high densities a pyramidal shape is more appropriate.

Fertilization

Fertilizer practices differ in avocado-producing areas, due to differences in climate, soil, cultivars and management practices. Numerous attempts have been made to determine critical foliar nutrient levels, in order to regulate the application of macro- and microelements. The following ranges of foliar levels for macronutrients are established: nitrogen (N) 1.6–2.0%; phosphorus (P) 0.07–0.20%; potassium (K) 0.75–2.0%; calcium (Ca) 1.0–3.0%; and magnesium (Mg) 0.25–0.50% (Malo, 1976). The ranges for micronutrients are: iron (Fe) 50–200 ppm; zinc (Zn) 50–150 ppm; and manganese (Mn) 30–70 ppm.

Critical levels have been difficult to establish, due to the highly variable yields of avocado. Nitrogen seems to be one of the controlling factors in avocado yields, as this is the only element that has shown a curvilinear relationship to yields. Maximum production of 'Fuerte' is found at a moderate level of N in the leaves, with reduced yields occurring at levels below and above the moderate level. In 'Fuerte', a range from 1.6 to 2.0% N in the leaves in late summer is a desirable level in order to maintain high production. Nitrogen fertilization is not recommended during the cool season, with application delayed to the summer leaf and root flush (Fig. 7.3). This application should include P and K. A later application of P and K should also occur near the peak of fruit set (Whiley *et al.*, 1988a).

As for many tree crops, including avocado, a soil pH of 7.0 and above creates problems with Fe and Zn deficiencies, refered to as lime-induced chlorosis. Iron chelate is used to correct Fe deficiencies. Soil application of Zn is more effective in acid soils than in alkaline soils, and foliar application has not proved successful. In Florida, where deficiencies of Fe, Zn and Mn are common, good results are obtained by combining the chelates of these elements and applying them through the drip-irrigation system. Boron (B) deficiency occurs in some soil types, and 'Sharwil' appears to be more sensitive to B deficiency.

Pest management

Diseases

A number of avocado diseases have been reported from producing areas around the world (Table 7.5), the most serious being root rot caused by *P. cinnamomi* Rands. This is suspected when trees show a gradual decline, with leaves becoming smaller, yellow-green in colour and shedding. In severe cases, twig dieback occurs. The destruction of the unsuberized feeder roots is associated with high soil moisture in poorly drained areas of the field, with *P. cinnamomi* thriving under wet soil conditions, especially when the temperature ranges from 21 to 30°C and with a soil pH of 6.5 (Zentmyer, 1976). Soil fumigants, fungicides and sanitation have been used, with a research emphasis on the development of resistant rootstocks, such as 'Martín Grande', 'Thomas', 'Barr-Duke' and 'D9' (Gabor *et al.*, 1990). The use of resistant rootstocks is integrated with hygiene, sanitation and cultural methods (Coffey, 1987). Trunk-injected phosphonate fungicide (Aliette-Fosetyl-Al) is timed to coincide with the shoot maturation (Fig. 7.3), the phosphonate being carried

Table 7.5. Some important diseases of avocado.

Common name	Organism	Parts affected, symptoms	Region or country
Root rot	*Phytophthora cinnamomi*	Feeder roots, tree decline	Worldwide
Verticillium wilt	*Verticillium dahlia* (*Verticillium albo atrum*)	Wilting of branches, death of trees	California, Australia, Florida
Armillaria root rot and crown rot	*Armillaria mellea*	Large roots, gradual death of trees	California, Mexico
Sun blotch	Sun-blotch viroid	Stunted, decumbent growth, distorted leaves, yellow or red streaks on fruit	Many areas
Anthracnose	*Colletotrichum gloeosporioides*	Leaves, most serious on fruit, especially after harvest	Worldwide
Stem-end rot	*Dothiorella aromatica* (*Dothiorella gregaria*) *Diplodia natalensis*	Purplish-brown spots on fruit surface, flesh discoloration, offensive odour	USA, South Africa, Israel, Australia, parts of South America, Caribbean
Cercospora spot	*Cercospora purpurea*	Leaves, young stems, fruit	Florida, other areas
Scab	*Sphaceloma perseae*	Foliage, fruit	Humid tropics and subtropics

to the mature shoots and then translocated to the roots, peaking in the root in about 30 days (Whiley *et al.*, 1995). In California, the root-ball of replant trees should be drenched with a solution of phosphonate at the time of planting, followed by two to three foliar sprays with the same chemical. This chemical can also be sprayed on to the foliage of diseased trees as long as functional leaves are present. If too few functional leaves remain on the tree, heavy pruning is performed to induce new shoots and leaves before spraying phosphonate. Phosphonate applications are repeated three or four times a year. However, the chemical does not eliminate the fungus from the soil and must be used with management practices.

In Mexico, *Phytophthora* root rot control is based upon integrated crop management (ICM). The ICM approach is based upon improving plant vigour, restoring the equilibrium between the root and foliar systems, increasing the soil flora beneficial to the avocado and harmful to disease organisms, improved irrigation and fertilization, reduced fungal and insect attacks and avoiding management practices that weaken the tree and favour the disease attack.

The main measures consist of: (i) periodic incorporation of cattle manure to a depth of 30 cm to keep the organic matter content of the soil around 3–3.5%, checking this periodically; (ii) chemical fertilization through soil and foliage to keep adequate foliar levels of elements; (iii) rejuvenation pruning of affected trees with more than 70% defoliation to restore root/foliage ratios; (iv) proper irrigation to avoid plant stress, by not allowing soil moisture to drop below 70% of field capacity; and (v) adequate sanitary controls to reduce damage by other enemies (Mora *et al.*, 2000). This approach has provided results comparable to or better than the use of chemicals. Chemicals are still recommended when tree decline is serious. In Australia, root rot has been minimized by building up heavy mulch with bagasse, grass or cereal straw. This reinforces the importance of using organic matter to create a better environment for plant-friendly organisms and fungus antagonists.

Many of the diseases reported are not necessarily serious, although the potential for causing heavy losses exists. Avocado scab is considered to be an important disease of avocado fruit and foliage in Florida (McMillan, 1976). Among fruit diseases, anthracnose, stem-end rot and avocado scab can cause serious problems. Anthracnose requires control practices in the field during fruit development.

Sun blotch, caused by a viroid, is of concern. Trees are stunted, with cracked bark, necrotic streaks on branches, and white or light green areas on the fruit. There are no known vectors, and what makes it a potentially serious problem is the presence of many symptomless carrier trees. The disease is transmitted by use of seedling rootstocks from such trees, as well as grafting with scion wood from infected plants. Scion wood from a healthy tree grafted upon a 'carrier' rootstock becomes infected. In the major avocado-growing countries, indexing techniques have been developed and used to identify healthy cultivars for scion wood, as well as those needed for rootstocks (Broadley, 1991).

INSECTS

There are many insect pests reported in avocado orchards, although they do not usually pose any serious problems (Table 7.6). Occasionally, a sudden increase of a specific insect can cause severe damage. This increase in an insect pest is often associated with a sudden change in weather conditions. Avocado red mite can cause significant leaf damage and a reduction in photosynthesis and transpiration (Fig. 7.7), possibly leading to a reduction in yield. Insects such as scales, aphids, mealy bugs and various mite species are also commonly found in orchards, but natural enemies have been shown to provide satisfactory control.

In some producing areas, fruit flies may require some form of disinfestation procedure for fruit to be exported to some markets. Studies in Hawaii with 'Sharwil' avocado have shown that it is not normally a host to the Mediterranean fruit fly (*C. capitata*), melon fly (*Dacus cucurbitae*) and the

Table 7.6. Some important insect pests of avocado.

Common name	Organism	Parts affected, symptoms	Region or country
Mediterranean fruit fly	*Ceratitis capitata*	Fruit	Hawaii
Oriental fruit fly	*Dacus dorsalis*	Fruit	Hawaii
Queensland fruit fly	*Bactrocera tryoni*	Fruit	Australia
Black coffee twig borer	*Xylosandrus compactus*	Branches, twigs	Hawaii
Chinese rose beetle	*Adoretus sinicus*	Leaves of young plants	Hawaii
Fuller rose beetle	*Pantomorus godmani*	Leaves of young plants	Hawaii
Spotting bug	*Amblypelta nitida*	Young fruits	Australia
Pine-tree thrips (greenhouse thrips)	*Heliothrips haemorrhoidalis*	Fruit scarring	California, Florida, South Africa, Hawaii, Canary Islands (wide distribution)
Red-banded thrips	*Selenothrips rubrocinctus*	Leaves, fruit scarring	Wide distribution
Fruit and twig borer	*Stenoma catenifer*	Perforates fruit, seed, shoot terminals	Tropics
Seed and fruit borer	*Heilipus laurii*	Seed and fruit	Tropics
Seed borer	*Conotrachelus perseae*	Seed and fruit	Mexico
Stem borer	*Xyleborus* spp.	Stems and branches	Tropics
Red spider mite	*Oligonychus yothersi*	Leaves, fruit scarring	Mainly Chile
Scales	*Oligonychus perseae*	Leaf scarring	Mexico
	Saissetia and others	Sap suckers	Wide distribution

Oriental fruit fly (*D. dorsalis*) at the mature green harvest stage. Under dry conditions, eggs are deposited between the pedicel and the fruit, making it a host.

Weed control

Young avocado trees are sensitive to herbicides, so weeding around the trees is usually done manually. Black polyethylene mulch around the plant is effective

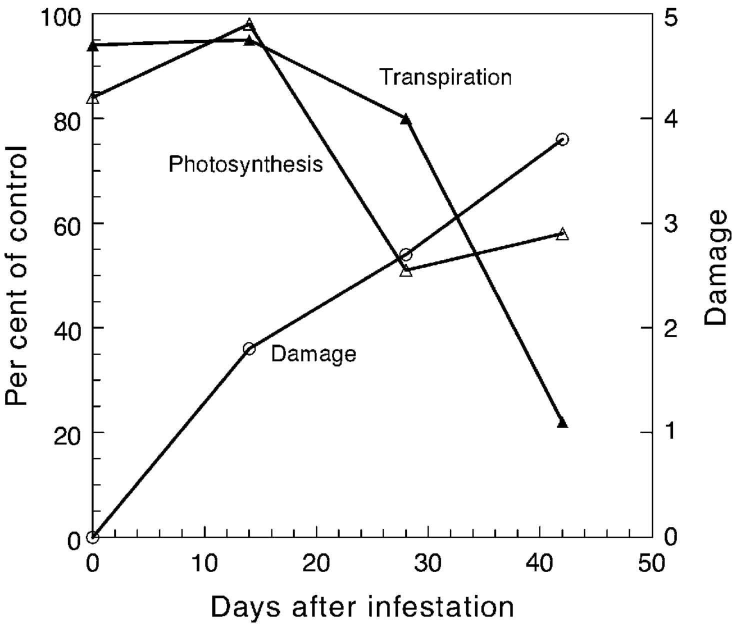

Fig. 7.7. Influence of avocado red mites (*Oligonychus yothersi* McGregor) on leaf transpiration, photosynthesis and damage (redrawn from Schaffer *et al.*, 1986).

in preventing annual broadleaved weeds but not effective against perennial grasses and nut-sedges (Nishimoto and Yee, 1980). In bearing orchards, the canopy provides enough shade to prevent weed growth. Inter-rows up to the periphery of the trees may be mowed or controlled with herbicides. Disc harrowing of avocado orchards is discouraged, as the shallow feeder roots will be damaged.

HARVESTING AND POSTHARVEST HANDLING

Harvesting and handling

The stage of fruit maturity when harvested can significantly influence the occurrence of biennial bearing in some avocado (Whiley *et al.*, 1992). In the tropics, later harvesting of 'Fuerte' fruit having 30% dry matter results in pronounced biennial cropping. Results for a cool subtropical location in South Africa suggest no effect of later harvesting on subsequent yield (Kaiser and Wolstenholme, 1994). Some cultivars can be stored on the tree and harvested according to marketing schedules. The length of time fruit can be left on the tree depends on the cultivar and season. However, this ‘on-tree storage’ can lead to biennial bearing or crop failure in the following year. Generally, cultivars of the West Indian race have little or no tree-storage time, and hybrids, particularly Guatemalan × Mexican, have a longer tree-storage life. Other tree-storage limitations are fruit drop and development of an off-flavour or rancidity with over-maturity. A higher yield can also be obtained if harvesting is staggered, with 50% of fruit harvested with 21% dry matter and the remainder at 30%.

A major problem is the stage of maturity for harvest, especially for cultivars that remain green upon ripening. Some avocados will start changing skin colour and then fall from the tree when mature, and a few lines can begin ripening on the tree. Other green-coloured avocados develop a yellowish tint on the stem near the fruit. Maturity of cultivars that normally change skin colour from green to reddish or purplish, such as ‘Hass’, is easy to ascertain. Immature fruit, if harvested, take longer to soften and they shrivel upon storage, with the flesh becoming ‘rubbery’ rather than buttery. Most countries with commercial avocado production have developed some sort of standards for determining maturity. The increase in oil content is correlated significantly with maturity. As the fruit advances towards maturity, oil content increases, the level depending upon the cultivar (Barmore, 1976). In California, oil content was used as a standard of maturity, with a minimum of 8% oil, based on fresh mass of fruit, exclusive of skin and seed. Oil content as a measure of maturity was impractical in Florida, due to wide variations in oil content among and within cultivars. Some cultivars, particularly those belonging to the West Indian race, never reach the 8% oil content, as in California. Florida uses minimum fruit weight and diameter as related to number of days from fruit set, thus establishing the earliest harvest date for each cultivar (Hatton and Campbell, 1959). Fruits originating from known bloom dates become progressively smaller in size from the earliest bloom date to the latest (Hatton and Reeder, 1972).

Moisture content is also used as a measure of maturity, as it does not involve oil determination, and there is a negative correlation between oil and moisture content. As oil content increases during maturation, there is a similar decrease in moisture content. A 10 g sample of flesh from a total of ten fruits is collectively grated and spread on an open dish and dried in a microwave oven for a few minutes. The minimum dry matter percentage for different cultivars ranges from 17 to 25%. For example, for ‘Fuerte’ the minimum dry matter percentage is 19%, ‘Hass’ 20.8%, and ‘Zutano’ 18.7%. In more mature fruit the dry matter can reach 30%. After the minimum moisture content has been met, fruit comparable to the sample fruit can be picked and ripened at room temperature. If the sample fruits ripen within 8–10 days without shrivelling, they are considered to be mature, and the grower can proceed to harvest comparable-sized fruit on the tree. Grade standards frequently set a minimum dry-matter percentage of around 20% for ‘Fuerte’, 22% for ‘Hass’, 25% for

'Gwen' and 19% for 'Zutano' (Rainey *et al.*, 1992). This method is rapid and less time-consuming and does not involve oil determination.

Fruits are harvested by cutting or snapping off the stem at the base of the fruit, with about 12 mm of the stem attached. Aluminium picking poles are usually equipped with a cutter and a bag to catch the fruit. Large trees on suitable terrain can be partially mechanized by the use of a three- or four-wheeled, self-propelled, hydraulically powered platform, from which pickers can use short poles. Pallets or bins should be placed under the shade of trees while waiting to be picked up for transport to the packing plant. This prevents overheating of fruit, as precooling is not generally practised.

Postharvest treatments

Most packing houses are automated, with all debris removed automatically and fruit cleaned with roller brushes. Cleaned fruits pass through graders, where all diseased, injured and defective fruits are removed and fruits are separated into size lots for packing. Sizing is done by use of drop-roll (diameter) sizers or by weight sizers. Each producing country has its own grading standards and size classes. The major quality criteria are size; skin colour; freedom from wounds, blemishes, insect damage and spray residues, and absence of disease, physiological disorders and bruising. Standards for Europe allow for three classes of avocado, based on appearance, defects, tolerances, uniformity, packaging and marketing. The minimum mass is 125 g and a range of size from 125 to 1220 g in 14 ranges is used in all classes (Anon., 1995). Fruits with lower quality go to processing or are used for local sales.

Sizes of packing cartons differ in various countries. They are usually corrugated paperboard cartons for single- or double-layer packing, ventilated for good air circulation. Pads or styrofoam trays with cup impressions may be used to prevent bruising. Prepacked consumer units in 'clam shells' (polyethylene containers) and mesh bags are also used. Fruit may be waxed or wrapped and packed by hand. All fruit in a specific size container must weigh between a specified minimum and maximum range. Cartons are labelled with fruit number and size range. In California, packed cartons are cooled at 5–15°C, depending on cultivar, before loading into transport vehicles. 'Hass' can be stored at 5°C for 3–4 weeks. Longer storage leads to greyish-brown internal flesh discoloration and irregular blackening of the skin.

Storage temperature for delaying ripening varies with the cultivar temperatures of 12.5, 8 and 5°C are used for West Indian, Guatemalan and Mexican cultivars, respectively. A relative humidity of 80–90% is recommended. Other storage methods, such as controlled atmosphere (CA) and hypobaric (low-pressure) storage, have been evaluated. With CA storage at 2–5% oxygen (O_2) and up to 10% carbon dioxide (CO_2) at 5°C and 98–100%

relative humidity is occasionally used to delay softening and reduce respiration and ethylene production.

Fruit can be ripened at 25°C or by exposure to 10–100 ppm ethylene at 17–20°C for 12–72 h, depending upon fruit maturity, and then transported to markets. Following ethylene treatment fruit will ripen in 3–6 days. The ethylene-treated fruits are marketed locally, as the current market strategy is to provide ripe fruit for immediate consumption.

UTILIZATION

The avocado is considered a nutrient-dense food (Rainey *et al.*, 1994). It has the highest fibre content of any fruit and is a source of food antioxidants (Bergh, 1990a). Avocado has a high oil content, although Florida cultivars are lower in oil content compared with cultivars from California. Major fatty acids are the mono-unsaturated oleic acid, followed by palmitic and linoleic acids. Palmitoleic acid is found to approximate percentages of linoleic acid, and values are slightly higher or lower depending upon the cultivar analysed. The nutrient values of the different ecological races also vary, but, in general, it is a fair to good source of P, provitamin A, riboflavin and niacin (Table 7.7). The protein content of 1–2% is considered to be greater than in any other fresh fruit (Bergh, 1990b). Avocado also increases the diet's content of antioxidants, foliates, K and fibre (Rainey *et al.*, 1994).

Avocado is mainly used fresh in salads, its high fat content combining well with acid fruit and vegetables, such as pineapple, citrus and tomatoes, or with acid dressings. A major commercial avocado product is guacamole, used as a favourite dip with potato chips, tortilla chips and similar products. Avocado may be used to supply the fat content of frozen desserts, such as ice cream and sorbets. Miller *et al.* (1965) provide numerous recipes for various types of salads, cocktails and desserts. In some places, avocado is eaten as a dessert, adding sugar to it instead of salt. Shakes and ice creams are also made of the pulp. Recently there is a growing industry of producing avocado oil, which is a very healthy product, using subtropical varieties.

Deterioration of flavour and enzymatic discoloration are serious problems in the commercial processing of avocado (Ahmed and Barmore, 1980). Avocado is not conducive to heat processing as it results in an off-flavour. High polyphenoloxidase and total phenol contents contribute to the processed product's browning potential, with differences in browning potential occurring among cultivars. Enzymatic browning of avocado products can be minimized by processing a cultivar with low polyphenolase activity into an acidified product containing an antioxidant (e.g. ascorbic acid), packing under N or a vacuum and storing at low temperatures.

Table 7.7. Proximate analysis of avocado (Wenkam, 1990).[a]

	Halumanu West Indian type	Nabal Guatemalan type
Water (g)	82.8	69.9
Energy (kJ)	431	874
Protein (g)	1.5	1.03
Lipid (g)	9.3	21.8
Carbohydrate (g)	5.7	6.3
Fibre (g)	1.6	2
Ash (g)	0.8	0.9
Minerals		
Calcium (mg)	8	77
Iron (mg)	0.5	0.4
Magnesium (mg)	–	–
Phosphorus (mg)	34	42
Potassium (mg)	–	–
Sodium (mg)	–	–
Vitamins		
Ascorbic acid (mg)	–	5.5
Thiamine (mg)	0.03	0.09
Riboflavin (mg)	0.09	0.14
Niacin (mg)	1.23	–
Vitamin A (IU)	–	802

[a] Amounts are per 100 g.

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8

Banana and Plantain

Banana is a general term that refers to all wild species, landraces and cultivars belonging to the family *Musaceae*, genus *Musa* (Ortiz, 2008). The commercial banana is a giant, perennial, herbaceous monocotyledon, propagated vegetatively; it is important in the humid tropical lowlands, with year-round fruit production, but it can also grow in certain subtropical areas. The fruit is served as a dessert (banana) or cooked and eaten as a staple (plantain). The banana (English) has various names: bananier (French), pisang (Malay, Indonesian), kluai (Thailand), chuoi (Vietnam), xiang jiao (Chinese).

The most important type of fruit commercially is the dessert banana, which is eaten fresh and makes up most of the international trade of this genus. The second most important group is the plantain, which is an important staple food in many countries in Africa, Latin America and South-east Asia, where extensive areas are grown mainly for local consumption. There are also the East African highlands and the Asian cooking bananas, and finally the East African beer bananas. In some cases, the same genomic group can include varieties used as plantains or as dessert bananas.

BOTANY

The genus *Musa* has more than 50 species, with some of these species having numerous subspecies. This diversity has lead to the genus being divided into three sections from the five traditional sections: *Musa* (2n = 22, incorporating *Rhodochlamys*), *Callimusa* (2n = 20, incorporating *Australimusa*) and single-species section *Ingentimusa* (2n = 28) (Wong *et al.*, 2002). Among these sections, there are wild, seeded plants and edible clones, with overlapping geographical distributions. *Ensete*, the other genus in the family, ranges from Asia to Africa, while *Musa* ranges from Africa through Asia to the Pacific (Reynolds, 1951).

Genus *Musa*

Edible bananas are derived from either *Musa acuminata* (A) or *Musa balbisiana* (B), or a combination of both. Cultivars are diploid or triploid, with some new tetraploids developed by breeding. Considerable somatic variation has led to a great range of cultivars. Cultivars are described by their name and genomic make-up, e.g. 'Pisang Raja' AAB, the AAB indicating that it is a hybrid with two genomes of A and one genome of B. Most dessert bananas are AA or AAA, with the triploid AAA being the most important in the trade. The different groups and subgroups have somewhat distinct fruit characteristics (Table 8.1).

M. acuminata has a number of morphological characters that separate it from *M. balbisiana*. For example, *M. acuminata* has an open petiolar canal, which in *M. balbisiana* is closed. *M. acuminata* has prominent bract scars, bracts that

Table 8.1. Fruit characteristics of some major cultivars within groups and subgroups.

Group	Subgroup	Characteristics
AA	Sucrier	Small fruit (8–12 cm long), thin golden skin, light orange firm flesh, very sweet, 5–9 hands per bunch, 12–18 fingers per hand
	Lakatan	Medium to large straight fruit (12–18 cm), golden yellow, flesh light orange, firm, dry, sweet and aromatic, 6–12 hands per bunch, 12–20 fingers per hand
AAA	Gros Michel	Medium to large fruit, thick skin, creamy white flesh, fine-textured, sweet and aromatic, 8–12 hands/bunch. Susceptible to Panama disease
	Cavendish	Medium to large fruit, yellow skin, white to creamy flesh, melting, sweet, aromatic, 14–20 hands per bunch, 16–20 fingers per hand. Susceptible to Race 4 of Panama disease
AAB	Silk	Small to medium yellow fruit (10–15 cm), thin yellow-orange skin, white flesh, soft, slightly subacid, 5–9 hands per bunch, 12–16 fingers per hand, skin frequently has blemishes
	Pisang Raja	Large fruit (14–20 cm), thick skin, cooking banana, creamy orange flesh, coarse texture, 6–9 hands per bunch, 14–16 fingers per hand
	Plantain	Yellow skin, creamy orange firm flesh, few hands per bunch
ABB	Bluggoe	Medium to large cooking banana, thick coarse skin turns brownish-red when ripe, creamy orange flesh, starchy, 7 hands per bunch
BBB	Saba	Stout, angular, medium to large cooking banana (10–15 cm), thick yellow skin, creamy white flesh, fine-textured, 8–16 hands per bunch, 12–20 fingers per hand

are lanceolate and curl, and two regular rows of ovules, compared with four irregular rows in *M. balbisiana*. Using and scoring 15 morphological characters allows the relative contribution of the two species to be determined in hybrid cultivars. Triploids and tetraploids are larger and more robust than diploids.

Origin and distribution

The primary centre of origin is thought to be Melanesia (Malaysia, Indonesia, the Philippines, Borneo and Papua New Guinea); *M. acuminata* Colla. has seeded fruit. Dessert cultivars were developed from it via parthenocarpy and sterility, aided by human selection and vegetative propagation. *M. balbisiana* Colla. also has a wild, seeded fruit, is more suited to drier areas and occurs from India to New Guinea and the Philippines, though absent from central Melanesia (Espino *et al.*, 1992). It was similarly taken into cultivation, with the selection of natural diploid, triploid and tetraploid hybrids.

ECOLOGY

Soil

Deep friable loams with natural drainage and no soil compaction are preferred. Soils with poor percolation due to excess of clay or with an excessive amount of sand should be avoided, as well as soils with high amounts of gravel. Soils having pH between 4.5 and 7.5 are used, although 5.8–6.5 is recommended. Soil textures ranging from sands to heavy clays are used. A granular soil structure is the preferred for better water movement and root growth, with high organic matter and fertility ensuring high yields. Most exported bananas are produced on highly fertile alluvial loams. Plantains also do best in this type of soils, but they will do better than the AAA dessert banana in lower-quality soils; apparently the 'B' in their genome is responsible for this adaptability.

Soil depth should be around 1.0–1.2 m, with no superficial water tables or impermeable layers. Soil drainage is essential since, although the plant prefers moist soil, it does not tolerate standing water. Flooding for a week will kill most banana plants (Duarte, 1991). Banana will tolerate some salinity: 300–350 mg/l of chlorine and up to 1500 ppm total salts.

Climate

Rainfall

Bananas require a regular water supply that matches or slightly exceeds the free-water evaporation rate. Irrigation is essential for high yields if rainfall is less than evaporation and it also provides the advantage of fertilization via the irrigation water. Areas with very high rainfall may be too overcast for optimum photosynthesis, have more disease problems and require extensive drainage. The plantain group is less susceptible to water stress than dessert bananas (Belalcazar, 1991), and this is another reason why small farmers grow them around their houses. Plantains do well with about 30 mm weekly rainfall in the coffee region of Colombia.

Temperature

A temperature range of 15–38°C occurs in most production areas, with the optimum temperature being ~27°C. The optimum for dry-matter accumulation and fruit ripening is about 20°C and for the appearance of new leaves about 30°C. Growth ceases at 10°C and can lead to 'choke-throat' disorders, where inflorescence emergence is impeded and poor fruit development occurs. Temperatures less than 15°C can be withstood for short periods, while temperatures less than 6°C cause severe damage (Turner, 1994), and temperatures below 4°C result in irreversible damage. Frost causes rapid death. At temperatures above 38°C growth stops and leaf burn occurs. Plants growing in the subtropics produce fewer leaves per year than those in the tropics and take longer to produce and develop fruit (Table 8.2). Sucker emission and development are also slower. Bananas grown at higher elevations that have lower temperatures tend to produce sweeter fruit, because of cooler nights. In certain cooler areas, such as the Canary Islands, bananas are produced in plastic greenhouses.

Plantains and cooking bananas are grown at sea level but also at higher elevations in Latin America, Asia and Africa. In many cases, they are grown as subsistence crops and are planted even at 2000 m above sea level in places where mean minimum temperatures are not below 15°C and the absolute minimum does not drop below 8°C. Clonal differences do occur in the ability to adapt to cooler temperatures. In Colombia, an important producer of plantains, commercial production occurs from sea level to 1350 m, though clones such as 'Harton' are not planted above 800 m. Lower temperatures

Table 8.2. Phenological differences between cultivars of Cavendish subgroup ratoon plantation in the humid tropics (Honduras: cv. 'Grand Nain', Stover and Simmonds, 1987) and subtropics (South Africa: cv. 'Williams', Robinson and Nel, 1985; Robinson and Human, 1988).

	Humid tropics	Subtropics
Mean number leaves per month (warm/cool season)	3.5/2.5	4/0.5
Total leaves per year	40	25
Planting to harvest (months)	9–11	15–20
Harvest to harvest (months)	6–8	11–13
Flowering to harvest (warm/cool season, days)	98–117	120–204

do reduce yields significantly, making commercial production uneconomic. It is estimated that the vegetative cycle is extended by 10 days for every 100 m increase in elevation (Belalcazar, 1991). At higher elevations, the form of the fruit bunch changes, with hands becoming more separated.

Wind

Bananas and plantains are very susceptible to wind damage. In all producing regions, moderate winds between 20 and 50 km/h cause moderate to severe tearing of the leaves. This leaf-tearing can reduce productivity, but as long as there is no significant loss of foliar surfaces, it does not normally have a major effect. This tearing does reduce plant transpiration when maximum daily water stress occurs, while net photosynthesis is little affected (Belalcazar, 1991), giving higher photosynthetate production by unit of water transpired. This beneficial effect may be important during the dry season. The problem with winds above 50 km/h is that they cause loss of leaf pieces, break the pseudostem or uproot the plants, in the latter two cases the crop is lost until the ratoon suckers complete their cycle. In certain areas of Central America, a phenomenon called 'blow down' is frequent; this is caused by gusts of high-velocity winds that unexpectedly hit certain areas and break all tall pseudostems, producing almost the same effects as a hurricane but in a limited area.

Light

For dessert bananas, as well as for plantains, solar radiation should be as high as possible for best growth and yields, although fruit sunburn can occur, especially if water supply is low; petioles can also be burnt. Shaded or overcast conditions extend the growth cycle by up to 3 months and reduce bunch size (Fig. 8.1). For plantains grown under lower radiation levels, the plants tend to be taller. Plant density plays a role in relation to light, since denser plantings intercept more light at the top but there will be less radiation at ground level, reducing sucker production.

Photoperiod

No evidence exists that photoperiod influences flowering. Increasing the photoperiod from 10 to 14 h increases the rate of new leaf appearance, probably due to more photosynthesis.

GENERAL CHARACTERISTICS

Plant

This 2–9 m perennial herb has an underground, compressed stem or corm that is the real stem. The visible part that looks like a stem (pseudostem)

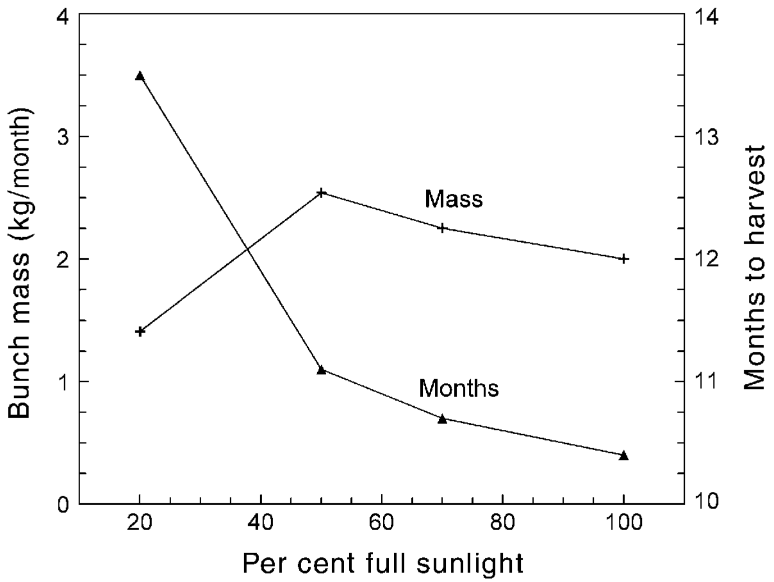

Fig. 8.1. Effect of shading on the bunch weight produced per month (kg/month and months to harvest). Low light reduces the leaf area produced, and a positive relationship exists between leaf area of the third mature leaf and final bunch weight: $y = 4.83x - 12.83$. $r^2 = 0.75$, significant at $P < 0.05$ (after Murray, 1961).

consists of overlapping leaf sheaths. The apical bud of this corm produces the leaves, and at certain stage it differentiates into the flower bud, which, in the same way as the leaves, grows up through the centre of the pseudostem until it emerges at flowering (Fig. 8.2).

The corm has lateral buds that produce shoots (suckers) near the parent (Fig. 8.2). These suckers grow and, when old enough, flower and bear fruit and are the basis for the successive ratoon crops that these plants normally produce for many years. Suckers can be of two types: the 'sword' sucker is one that has very narrow leaves when young and its pseudostem has a conic form; the other type is the 'water' sucker, which has a cylindrical pseudostem and wide, almost rounded leaves. 'Water' suckers are eliminated in the plantation and normally are not used for propagation, while 'sword' suckers are selected to become the ratoon crop and preferred as propagation material, although trials with plantain (Belalcazar, 1991) have shown that 'water' suckers can result in an equally productive crop if given proper care when young.

Adventitious roots that arise from the corm form a dense mat and spread extensively 4–5 m from the parent and down to 75 cm or more. Plantains of the AAB genome have a shallower root system than export bananas.

The large leaf lamina are 1.5–4 m long by 0.7–1 m wide, with pronounced midribs and parallel veins (Fig. 8.2). Stomata occur on both surfaces, with

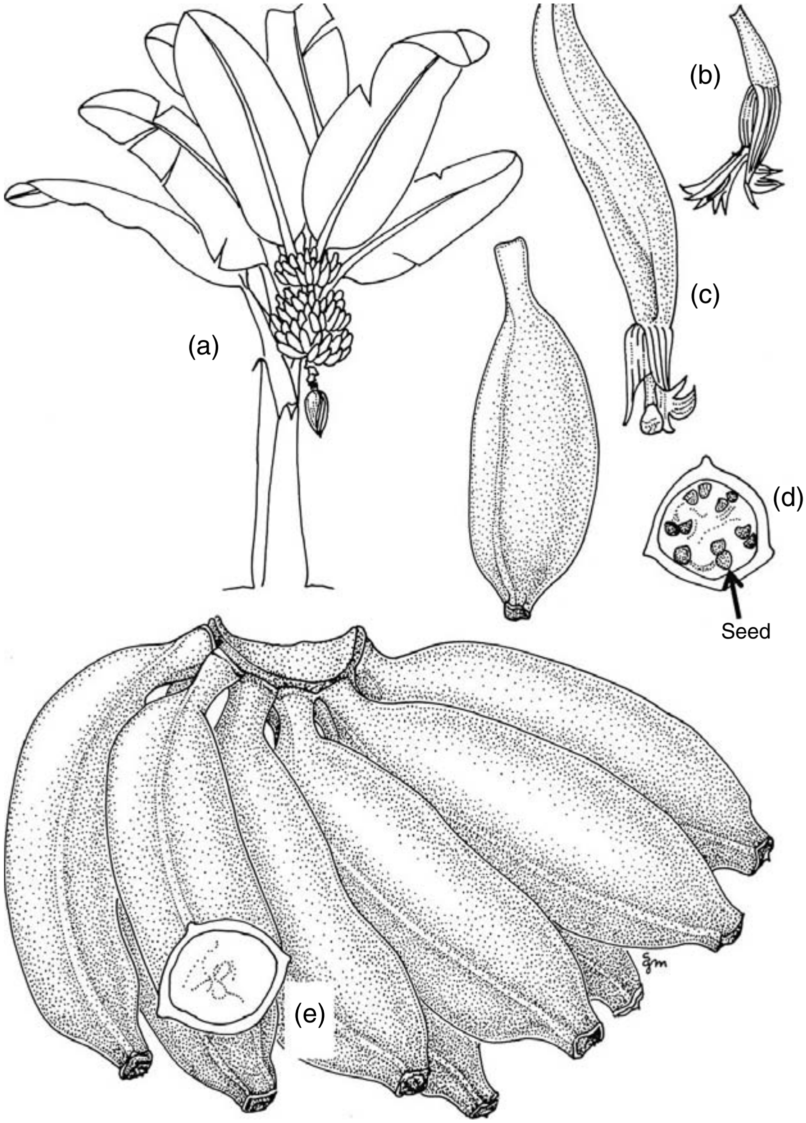

Fig. 8.2. Plant, leaves and bunch (a), floret (b), young fruit (c), and transverse section of seedy fruit (d) and the more common seedless fruit (e) of banana. The hands of seedless fruit are cut from the bunch stem, leaving a portion of the stem that is called the crown.

three times more on the adaxial surface. The leaf takes 6–8 days to fully unroll from the tip, and in the tropics the leaves last *c.* 50 days. Leaves emerging just before the inflorescence can live up to 150 days or more. Twenty-five to 50 leaves emerge, with 10–15 functional leaves present (total area 25 m^2) at inflorescence emergence. The number of leaves at flowering is positively correlated with bunch weight (Fig. 8.3); fewer than six to eight leads to significant reduction in bunch weight. After flower emergence, no more leaves are produced, so the plant should have as many as possible functional leaves at this time. The main problem with the major leaf disease Sigatoka is that it reduces the number of functional leaves and their useful area.

Flowers

One terminal inflorescence emerges through the pseudostem and bends downwards after emergence (Fig. 8.2). The flowering spike consists of groups of two rows of appressed flowers enclosed within large, ovate, reddish bracts at each node. The bracts reflex and are shed as the fruit develop. The female flowers emerge first and the males at the distal end. Sometimes hermaphrodite flowers develop in the middle of the bunch, but they generally abscise. Flowers at each node are referred to as a hand; each hand has 12–20 flowers per node and there are 5–15 hands with female flowers. The bracts open sequentially, about one per day. The peduncle continues to elongate up to 1.5 m, terminating in a male bud, which continues to produce male flowers enclosed within the bracts. The last hand (false hand) of the female flowers

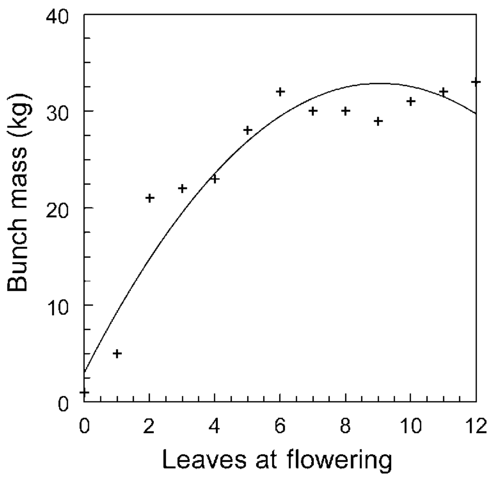

Fig. 8.3. The effect of number of functional leaves at flowering on bunch weight (redrawn from Turner, 1970).

has few fingers (fruit) and the rest of the nodes have non-functional pistils. The infloresence stem (rachis) is cut below the false hand, where a finger is left attached to maintain a connection with the plant circulatory system and avoid rachis rotting. The detached rachis removes the male flowers. In plants with no false hands at the time of fruit thinning, a finger will be left in the last hand.

The 10 cm female flowers of cv. 'Cavendish' have an inferior ovary of three united carpels with a short perianth. The perianth consists of five fused and one free segment, forming a tube around the style and sterile androecium and three-lobed stigma. Male 'Cavendish' flowers are 6 cm long with five stamens, which rarely bear fertile pollen.

Pollination and fruit set

Natural pollination

The fruit develops parthenocarpically. The ovules shrivel early and are recognized as brown specks in the mature fruit along the axial placenta (Fig. 8.2). Very infrequently, seeds are found in mature fruit of edible cultivars, especially those with a 'B' genome. The 'Cavendish' group has absolute female sterility with few viable pollen. The 'Gros Michel' (AAA) dessert banana produces seed once in a while and therefore is used as the female parent in many crosses. 'Pisang Awak' (ABB) can sometimes be very seedy if pollen-bearing diploids are growing nearby.

Floral induction and fruit set

There are no external symptoms of the start of inflorescence development. The flowering stimulus is unknown. Externally, it is not temperature or photoperiodism, and internally it is not the number of leaves developed, as the number of leaves is more or less fixed, depending on cultivars and environment.

Fruit morphology

The fruit, although it develops from an inferior ovary, is a berry. The exocarp is made up of the epidermis and the aerenchyma layer, with the flesh being the mesocarp (Fig. 8.2). The endocarp is composed of a thin lining next to the ovarian cavity. The axial placenta has numerous airspaces and ventral vascular bundles.

Each node of the rachis has a double row of flowers, forming a cluster of fruit that is commercially called a 'hand', with the individual fruit called a 'finger'. 'Cavendish' bananas can have 16 hands per bunch, with up to about 30 fingers per hand, and the bunch can weigh up to 70 kg. There are many different sizes and shapes of fruit, with plantains being usually very large compared to the dessert-type bananas or others. The same is true for external and pulp colour, which normally vary from cream to slight orange.

Growth and development

Pollen sterility is due to triploidy, while female sterility is due to at least three complementary dominant genes and modifier genes. These sterility genes are found in wild populations and have been selected for fruit edibility. Parthenocarpy is separate from sterility. For the first fortnight after anthesis the ovules increase in size (50% over initial), and later they shrivel and ovary growth slows. Parthenocarpic bananas that have seeds (‘Pisang Awak’ ABB) show a stimulation of fruit growth, due to the presence of developing seeds. Pollination can stimulate fruit growth, even without seed development (Israeli and Lahav, 1986).

There are periclinal and anticlinal divisions from 6 weeks before inflorescence emergence (anthesis) to 4 weeks after emergence. This division is followed by cell expansion for 4–12 weeks after emergence. Skin mass increases rapidly in the first 40 days after flowering, with the fruit pulp not beginning to develop until day 40 (Fig. 8.4). Starch accumulation parallels finger length and diameter increases (Lodh *et al.*, 1971). The fruit matures in the tropics 85–110 days after inflorescence emergence. Fruit development may take up to 210 days in the cooler subtropics or under overcast conditions (Table 8.2). Harvest maturity is a commercial stage (three-quarters round), with the fruit still having some angularity and being only 75% of its potential maximum size. Export bananas are harvested in the tropics at 14–15 weeks after flower emergence, while plantains are harvested after 11–12 weeks. Fruit allowed to fully develop to a round shape may show skin splitting. Depending upon the persistence and viability of the remaining leaves, fully developed fruit may also show sunburn.

Since fruit number and size decrease from the proximal to the distal (bottom) hands, fruit thinning is sometimes practised. In most cultivated types, the bunches bend because of the fruit bunch weight. As the inflorescence emerges from the pseudostem, it bends towards the sun. Fruits on the inner whorl of a hand can be 15% smaller than those on the outer whorl. Normally the last or last two hands that have smaller hands are eliminated if higher fruit calipers (diameters) are desired. The male inflorescence can be removed soon after full development of the bunch without damaging the female hands; this removal reduces the weight and can, in some instances, slightly increase the caliper of the remaining fruit.

In plantains, there are normally fewer flowers per bunch, although some of the new tetraploids have a very heavy load of fruit. Some plantain types do not have the male part of the inflorescence or it is rudimentary.

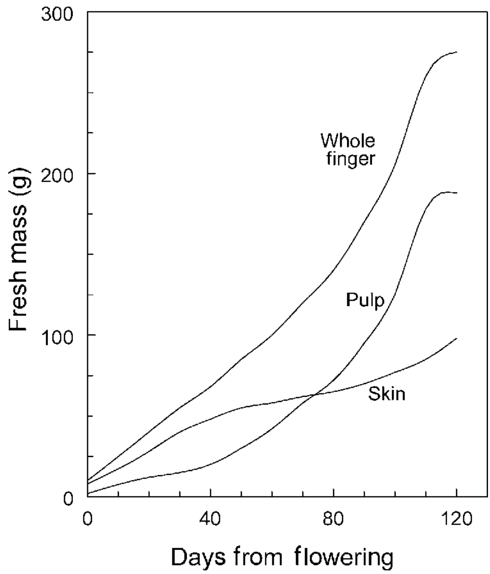

Fig. 8.4. Growth of finger, pulp and skin fresh mass of 'Gros Michel' in the Caribbean (Simmonds, 1982).

CULTIVAR DEVELOPMENT

Genetics and cytogenics

The haploid number is n = 11, with 22, 33 and 44 chromosomes being found in the diploids, triploids and tetraploids. There are 200–300 clones, of which more than half are triploids. Triploids are more vigorous, easier to grow and higher yielding than diploids (Gowen, 1995). Some tetraploids have been developed that have desirable characteristics such as Sigatoka tolerance and high yields.

Problems in breeding

The majority of breeding efforts have been directed at the AAA group, because the group has the highest export potential. However, female sterility and the low numbers of viable pollen make conventional breeding very difficult. Some inferior cultivars can, under controlled conditions, produce seeds; however, it takes 3 years from seed to seed. In the Honduran breeding programme of the Honduran Agricultural Research Foundation (Fundación Hondureña de Investigación Agricola, FHIA), the AAA 'Gros Michel' dessert banana is used in many instances as the female parent for crosses, as some fruits have seeds.

After a cross with 'Gros Michel' as female parent, the hybrid seeds are extracted by ripening large numbers of these fruits derived from the cross, peeling them and passing the pulp through a strainer that retains the few seeds present.

Considerable breeding efforts and selection of crossed material may lead to the development and release of cultivars with suitable horticultural characteristics and increased disease resistance (Gowen, 1995). Apart from the efforts supported by the International Network for the Improvement of Bananas and Plantains (INIBAP) (Vuylsteke *et al.*, 1993), there have been a few efforts to develop better varieties for small and medium-sized growers serving local markets with local varieties in Brazil, Africa and India. In Honduras, FHIA has produced a complex pedigree hybrid (FHIA 03), a 'Bluggoe' type of cooking banana, resistant to black Sigatoka, 'Moko' and Panama disease, which is planted in East and West Africa, and in Cuba by small farmers. They have also released 'FHIA-25', another AAB cooking banana, as well as 'FHIA 21', a plantain, both are resistant to black Sigatoka.

Selection and evaluation

Considerable efforts have been expended in characterizing various cultivars under comparable conditions (Rowe and Rosales, 1996). Somaclonal variation and mutation breeding is widely used. The focus of these programmes is resistance to black Sigatoka, *Fusarium* wilt (Panama disease), bunchy-top virus and nematodes. Gene transfer from unrelated species also offers considerable opportunities for improved planting materials. Besides selection for resistance to the above diseases, other priorities include resistance to the weevil that bores into the corm, dwarfism, tolerance to drought and cold, and improved bunch yield, harvest index, fruit quality (texture and flavour) and storability (Novak, 1992). Similar priorities exist for plantains, with susceptibility to black Sigatoka and low bunch yield being the major limitations, followed by some of the same priorities as for dessert bananas. New plantain types have been easier to produce than dessert bananas and some are being grown extensively in many tropical areas.

Major cultivars

There are at least 200–300 banana clones in various countries, many having different names in different localities (Table 8.3). There are numerous germplasm collections around the world, including those in Indonesia, Malaysia, Thailand, the Philippines, India, Honduras, Jamaica, Brazil, Cameroon and Nigeria. The large number of synonyms for many of the better cultivars makes for some confusion (Lebot *et al.*, 1993).

Table 8.3. Major genomic groups and some cultivars. The seedless diploid (AA) and triploid (AAA) are regarded as desserts, while the seedless diploid (BB) and triploid (BBB) are cooking bananas. These and the many hybrids are all referred to as *Musa* spp., followed by the code and subgroup (SG) name (Cavendish, Gros Michel, plantain, etc.).

AA	AAA	AAB	ABB	BBB	Other
Sucrier syn.	**Gros Michel (SG) syn.**	**Silk syn.**	**Pisang Awak (Indo, Mal), syn.**	**Saba (Phil), syn**	**Atan (AAAB), AA**
Pisang Mas (Mal, Indo)	Bluefields	Apple (Hawaii)	Ducase (Aust)	Cardaba (Phil)	**Kalamagol (AABB)**
Kluai Khai (Thai)	Pisang Ambon (Mal)	Pisang Rastali (Mal)	Katali (Phil)	Kluai Hin (Thai)	**Gold Finger (AAAB)**
Amas (Aust)	Disu	Pisang Raya Serek (Indo)	Kluai Namwa (Thai)	Pisang Nipal (Mal)	
Susyakadali (India)	Kluai Hom Thong (Thai)	Latundan (Phil)	Pisang Klotok (Indo)		
Lakatan (Phil), syn.	**Cavendish (SG)**	Woradong	Kanpuravalli (India)		
Pisang Barangan (Indo)	Dwarf Cavendish, syn.	Cantong	**Bluggoe, syn**.		
Pisang Herangan (Mal)	Chinese (Hawaii)	Tundan	Pisang Kepok (Indo)		
Senorita	Canary Banana	**Lady Finger, syn.**	Pisang Abu Keling		
	Dwarf Chinese	Pome Pacha Naadan	Kluai Hak Muk (Thai)		
	Basrai (India)	Pisang Raja (Mal, Indo)	Nalla Bontha (India)		
	Governor (West Ind) syn.	Radja (Phil)	Moko (Trinidad)		
	Enano (Latin Amer)	Larp	Da Jiao (China)		
	Giant Cavendish, syn.	Houdir	Fen Da Jiao (China)		

Continued

Table 8.3. Continued.

AA	AAA	AAB	ABB	BBB	Other
	Mons Mari (Old)	**Mysore (India), syn.**			
	Williams (NSW)	Colombo			
	Grand Nain	Poovan (India)			
	Bongali Johaji (India)	Honderawala (India)			
	Beijiaw (China)	Plantain (SG)			
	Honchuchu	**Horn, syn.**			
	Pisang Ambon Putih (Malay), syn.	Pisang Tanduk			
	Kluai Horn Dek Mai (Thai)	Tindok			
	Ambon (Phil)	**French, syn.**			
	Pisang Embun	Nendran (India)			

CULTURAL PRACTICES

Propagation and nursery management

Sexual

Seeds are only used in breeding programmes. Many of the important commercial cultivars are female-sterile.

Asexual

Suckers with their basal corm or entire corms are used as planting material. A sucker is a lateral shoot that has a basal corm and a short pseudostem that arises at the base of a plant from the mother corm. Suckers are normally used by small farmers or when few plants are needed. The difficulty with suckers is their size, which makes handling and transportation difficult. In addition, disinfection, which is essential to avoid transporting insects, disease and nematodes, is often ineffective. A young sucker just emerging from the soil or a large sucker with narrow leaves and a large corm are normally planted with the remaining roots at the same depth as they were originally, and the excess leaves will be pruned back.

The banana exporting companies normally use corms that are at the base of a plant that has not flowered and that was raised in special nursery fields; these corms will have a weight of 2.5–5 kg. In other cases, 1.6–1.8 m tall sword suckers that have a diameter of 15–20 cm at 20 cm from the soil are used. The suckers are dug out and 15–20 cm of the pseudostem retained. Sometimes large, older corms (bull heads) from plants that have flowered can be used for planting if propagation material is scarce. Smaller pieces of corms can also be used.

The ideal is to disinfect the corms. The corm is pared so no dark spots and roots are left, and the pared corm is dipped in a mix of a fungicide, nematicide and insecticide for 5–20 min. The large exporting companies use a hot water dip at 56–58°C for 15–20 min or 65°C for 12–15 min. If no pesticides are available or are not allowed, simply paring the corms is helpful to limit transfer. Corms to be used for planting should never be left overnight on the ground, they should be either covered tightly or put on a trailer or truck, to avoid reinfestation by banana weevil.

When propagating material is scarce, several techniques can be used to increase the number of suckers. A sucker is planted and, before it differentiates a flower bud, several practices can be used to prevent further growth of the apex and induce axillary bud growth. One practice is to drive a stake into the pseudostem at a 45° angle, aiming to destroy the apical meristem, or a coring tool is used to achieve the same objective. Another technique is to partially cut the pseudostem before flowering at about 1.5 m from the ground, so the top will bend and it will look like a ‘7’, or to cut it down; in other cases the outer leaf sheaths are pulled down to the bottom of the pseudostem, in order to expose the axillary buds, and then soil is mounded around the base. All these practices prevent flowering, and induce axillary bud growth that develops into numerous suckers.

For high-density plantain plantings developed in the last decade in Central America for the 'Curraré Enano' (AAB) plantain variety, the corms are graded by size into three or four grades then planted in different areas to ensure field uniformity. Larger corms, 500–2000 g, are planted directly into furrows in the field in either a horizontal or vertical orientation. Smaller corms of 200–500 g are planted into plastic bags and kept for 6–8 weeks before grading by size, with the larger corms planted into the field. The advantage of planting bagged plants is that no field irrigation and weeding are necessary before planting out and the growth in plastic bags means that a more uniform stand and no empty spaces are obtained, as only sprouted suckers from the corm are planted. The corms are pared and if possible disinfected before planting in the field or bags, as for dessert bananas.

Tissue culture (*in vitro* plantlets) allows for rapid multiplication of uniform, disease-free materials (Loyola Santos *et al.*, 1986). Other advantages of tissue culture include very high field establishment rates, uniformity of harvest timing, precocity and high production, at least in the first crop cycle. These advantages have to be balanced against higher cost, extra care at multiplication and the transmission of viruses that have not been eliminated. Somatic variation is the major problem and care in multiplication is necessary to reduce the incidence to an acceptable level (<3%) (Smith, 1988).

Field preparation

The field should be ripped, ploughed and disced before planting. This may involve cross-ripping to 1 m to break up any soil compaction. Lime, phosphorus (P) and potassium (K), as determined by soil analysis, should be added at this time. Sloping land should be prepared so as to avoid erosion. Drainage is vital to avoid waterlogging, which can reduce yields. The water table should be kept below 1.2 m in depth. Extra drainage can be installed during field preparation via trenches and drains. Drainage preparation can be a fairly expensive task in the export banana production fields, as the fields are expected to remain in production for many years. In Chapter 3, there is a brief description of these drainage systems.

Transplanting and spacing

A planting hole slightly larger than the material is dug or a furrow made. The corms are usually covered with 10–15 cm of soil. Planting is scheduled in subtropical areas to meet certain harvest periods in the first crop cycle (Galán Saúco, 1992). Also in the subtropics, the late summer through to the winter is avoided, so as not to expose young plants to low temperatures. The concern in the tropics is to avoid hot weather or a dry season; hence, the best time for planting is just before the wet season. In hurricane-prone areas, planting is done before the hurricane or typhoon season, so that the plants are still short and less prone to being blown over.

Planting densities from 1000 to 3000 plants/ha are used in triangle, rectangle, single- or double-row cropping patterns. Double rows combine higher density with a 3.5 m alley for access. The actual density depends upon cultivar and climate. Higher densities are used in hot, dry localities to generate the necessary shade and microclimate for maximum yields. The vigour of a plantation is related to the canopy characteristics, leaf area index and yield. If only one growth cycle is to be used, a higher density may be planted (3000 plants/ha), for three or more growth cycles; a lower density is recommended (2000 plants/ha) for highest gross margin.

Export bananas are usually planted in equilateral triangles or in double rows; in a few cases a square arrangement that is 2.4 m × 2.4 m is used. The equilateral triangle (hexagonal) system allows for a better use of space; normally the sides of the triangle are 2.5 or 2.7 m, resulting in 1800–2000 plants/ha. In the double-row system, two closely planted rows are separated by a wider space from the next double row. The double rows are 1 m apart; the plants are at 2.25 m in the row and 3.75 m is left between the double rows, giving a total of 1840 plants/ha. This system allows for the movement of small equipment in the field and makes harvest easier by allowing a cable system to be set up parallel to the double-planted rows, from which the bunches are hung with strings to avoid the pseudostems from falling over because of the fruit weight and damaging the bunch.

Orientation of double rows N to S or E to W does not significantly effect yield (Belalcazar, 1991). More important is to orient rows to avoid erosion in fields planted on a slope and wind damage from the prevailing winds.

High-density annual plantings

In recent years, especially with plantains, a system using high-density planting and a single harvest developed in Colombia (Belalcazar, 1991) is now being used in Central America (Lardizabal and Gutierrez, 2006). The field is prepared and planted in double or single rows in a rectangular arrangement, with 3333 to around 4000 plants/ha. To achieve 3333 plants in the double-row system, there would be 1.2 m between the twin rows and 1.5 m in rows, with 2.8 m between the double rows. In single-row arrangement, the plants are 1.50 m in row and 2.0 m between rows. For 4000 plants/ha, the distances between double rows and single rows are reduced. When 50–60% of the plants are harvested, the new planting can be started with corms or plants in bags planted into the space between the double or single rows; once harvest has finished the old plant stumps are eliminated. The big advantage of this, aside from higher yields, is that harvest time can be decided in advance, to avoid harvesting and marketing fruit when market prices are depressed because of oversupply. Additionally, since plants become more susceptible to Sigatoka after flowering, a high-density planting system limits disease incidence in the first part of the cycle and reduces the need to spray for disease control. The system is more appropriate for plantains, which normally do not last as long planted in the field as export bananas, and are normally replanted after two or three harvest cycles. If a fixed harvest season is important, the new planting can be done in a different field if the original field is not ready for replanting. The system has also been successfully implemented for dessert bananas.

Cableway

Cableways are an important innovation in banana harvesting and handling by the large banana exporters. The cableway greatly reduces mechanical injury to the fruit during transportation to the packing house. It is also used to take fertilizers and other materials to the fields. When ‘Gros Michel’, a tough-skinned variety, was replaced because of Panama disease by ‘Valery’ and later ‘Grand Nain’, as both clones have delicate skins, it gave the impetus to use cableways, as well as the use of packing boxes for export fruit.

Irrigation practices

Irrigation water can be supplied by furrow or over-canopy sprinkler, with drip irrigation and micro-sprinklers becoming more popular. Irrigation is used to supplement rainfall and its scheduling requires a calculation of amount and frequency. This schedule is based on pan evaporation, soil water-holding capacity, banana root depth, water depletion and crop water use. The important characteristics of banana are its: (i) high water-loss potential, associated with its large, broad leaves; (ii) shallow root system – *c.* 90% of roots are in the top 300 mm; (iii) poor ability to absorb water from a drying soil; and (iv) rapid physiological response to water deficit. Soil water potentials more negative than −20 to −40 kPa can adversely affect growth, with relative impact depending upon local climate – hot and dry (severe impact) to moist and humid (less impact). In the case of plantains, the same is true; however, plantains are slightly more tolerant of water scarcity than dessert bananas, but yield can be depressed by drought.

Micro-sprinkler use has become popular with banana and plantain exporters in Latin America. Sprinklers are spaced ~11 m from each other, in a square arrangement, on a riser at about 70–80 cm above the soil level. This system offers many advantages, the main being the use of less-powerful pumping equipment than required for the large cannons, which would cover about a hectare, previously used. The micro-sprinklers, being below the canopy, do not splash water from one leaf to another and thus prevent the spread of fungal diseases like Sigatoka. In recent years, drip irrigation has shown promise, though vandalism from labourers or neighbours who cut the hoses and steal them is a problem for small producers. Drip irrigation works very well in well-managed plantations with field security.

Pruning and bunch propping

Other than removal of the male inflorescence, no other vegetative pruning is normally practised. Withered styles and perianths persisting at the end of the fruit are usually removed at the packing station after harvest, but are sometimes removed by hand 8–12 days after the bunch emerges, to reduce fruit scarring and disease (cigar-end rot). Early removal of one or more hands from the distal end of the bunch is practised to increase fruit size by reducing inter-finger and hand competition. This hand removal is done by the exporting companies for dessert bananas and plantains to achieve better calipers (fruit diameter – size) in the remaining fruit.

Bunches falling from the plant or the whole plant falling over can lead to considerable bunch damage and can lead to rejection of the affected fruit for export. Lodging is due to poor corm anchorage, poor planting material or very large bunches. The problem is reduced if single or double poles are wedged against the throat of the plant under the curvature of the bunch peduncle or twine guys are extended from this same point in the opposite direction of the fruit bunch and tied to lower positions on nearby plants.

Sucker management and leaf removal

Sucker management is an essential step to remove unwanted suckers developing from the base of the parent corm and to select a suitable sucker to produce the ratoon crop. The strategy is to remove suckers that receive nutrients from the parent plant and which would extend its cycle and reduce its yield if they remained (Fig. 8.5). This operation is vital in the subtropics.

Desuckering is done by hand by cutting and gouging every 4–8 weeks, and paraffin-oil injection so that suckers do not use too many of the resources available to the parent (Fig. 8.5). Selection of ratoon suckers is critical to maintaining yield, production and appropriate plant spacing. A sucker on the most open side is usually selected as the daughter plant and left as the follower, taking into consideration field spacing. The plants ‘walk’ since the ratoon

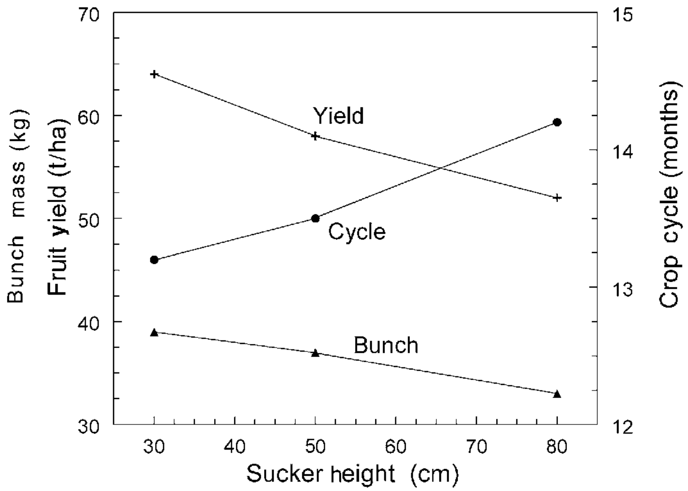

Fig. 8.5. Effect of the amount of unwanted sucker growth of 'Williams' banana before removal, on remaining sucker (follower) bunch mass, annual yield in the first ratoon crop and the crop cycle duration between the first and second ratoon. Unwanted suckers were removed when they were 30 cm, 50 cm and 80 cm high, leaving one following sucker per plant mat. The leaf area of the 80 cm sucker was 39 times greater than the 30 cm sucker (redrawn from Robinson and Nel, 1990).

comes at the side of the original plant; therefore care has to be taken that all plants 'walk' in the same direction by carefully selecting the ratoon suckers in order to keep the original distances between plants. Normally a machete is used for this operation and care should be taken to disinfect it before every new plant, to avoid transmission of bacterial diseases such as 'Moko'.

Removal of dead leaves is practised to reduce disease spread and to prevent senescent leaves from hanging over suckers and reducing light and to prevent fruit scarring. At least six to eight healthy leaves should remain on the plant at flowering to ensure maximum bunch development (Fig. 8.3). Plants with severe leaf removal or damage (e.g. as a result of insect feeding) have reduced bunch weights. The green life of the harvested banana is also reduced by leaf loss.

Fertilization

Regular fertilization practices are followed on large commercial plantations (15% of total world production) to maintain optimum productivity, while in the less-intensively cultivated plantation less supplementary fertilization occurs (Martin-Prevel, 1990). Deficiency symptoms have been described for leaf blade and petioles. Mineral analysis of banana plants has been used and ranges of deficiency and adequacy suggested. For plant growth and fruit production, large amounts of nutrients are required. These nutrients come from the soil and decaying plant material, and the remainder comes from applied organic matter and fertilizer. The amount of nutrients removed by the harvest of cv. 'Cavendish' fresh fruit with a yield of 50 t/ha/year includes 189 kg/ha nitrogen (N), 29 kg/ha P, 778 kg/ha K and 101 kg/ha calcium (Ca). As a proportion of the total nutrients taken up by the banana plant, this is equivalent to 49% of the N, 56% of the P, 54% of the K and 45% of the Ca. These total amounts and proportions are about half of those for plantain (Table 8.4). Most of the data have been derived from experimentation with bananas produced for export, especially from varieties in the 'Cavendish' subgroup. Cultivar and subgroup differences have been recorded, with the optimum nutrient supply not being the same for all cultivars. Seasonal influences on fertilization are much greater on bananas growing in the subtropics, where temperature probably has the greatest influence. Intercropping needs should also be considered.

The large N and K requirements are modified by the local soil nutrient concentrations. The rate of application depends on climate, soil type, variety, management practices and yield. Since vegetative and reproductive stages of development are found in one field at the same time, and as the initial stages of fruit inflorescence development are crucial for final yield, a constant supply of nutrients is essential for high yield. If the pseudostem is left standing after bunch harvest, up to 40% of the nutrients (especially N, P and K) can be removed by the following ratoon sucker (Fig. 8.6) and increase the bunch weight of this next generation. Delaying fertilization can have a significant impact on yield, reducing it by 40–50% or more; a 3-month delay makes it difficult for the plants to recover.

Because of the extensive root system, fertilizer should be applied away from the pseudostem, mostly on the side of the next ratoon. Solid fertilizer is applied three to four times per year, more frequently if there is high rainfall, for this a 60 cm semicircular strip of fertilizer 30 cm wide is broadcast 30–40 cm in front of the ratoon sucker. Fertilizer applied through irrigation water (fertigation) is more efficient and gives better control of application time and rate to meet demands. Frequency of fertilizer application is increased when fertigation is used monthly, weekly or continuously, especially if drip irrigation is used. Foliar application is also used.

Numerous forms of fertilizers have been tested. If the different forms meet the management strategy and crop needs and do not lead to excessive runoff or leaching, most are suitable. The most common forms of nitrogen are ammonium nitrate (NH_4NO_3), ammonium sulfate $(NH_4)_2SO_4$ and urea; it should be applied three to six times per year. For phosphorus, simple or triple superphosphate is usually applied once a year due to slow P mobility, at rates of 40–60 kg of P_2O_5/ha/year, while, for potassium, potassium chloride (KCl), potassium sulfate (K_2SO_4) and potassium nitrate (KNO_3) are used, the sulfate

Table 8.4. The quantity of nutrients in banana and plantain with yields of 50 t/ha or 30 t/ha, respectively, from 2400 plants/ha and bunch masses of 25 kg and 15 kg (Lahav and Turner, 1983), and critical nutrient concentrations in the lamina of the third-youngest leaf of the vegetative plants (Stover and Simmonds, 1987).

Nutrient	Fresh fruit (kg/ha)		Remaining in plant (kg/ha)		Proportion removed in fruit (%)		Leaf lamina critical concentration in banana
	Banana	Plantain	Banana	Plantain	Banana	Plantain	
N	189	76	199	189	49	29	2.4%
P	29	11	23	16	56	41	0.15%
K	778	243	660	945	54	20	3–3.5%
Ca	101	9	126	149	45	6	0.45%
Mg	49	11	76	53	39	17	0.2–0.22%
S	23	9	50	19	32	32	n/a
Mn	0.5	0.2	12	7	4	3	60–70 ppm
Fe	0.9	0.4	5	3	15	11	60–70 ppm

N, nitrogen; P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; S, sulfur; Mn, manganese; Fe, iron; n/a, not available.

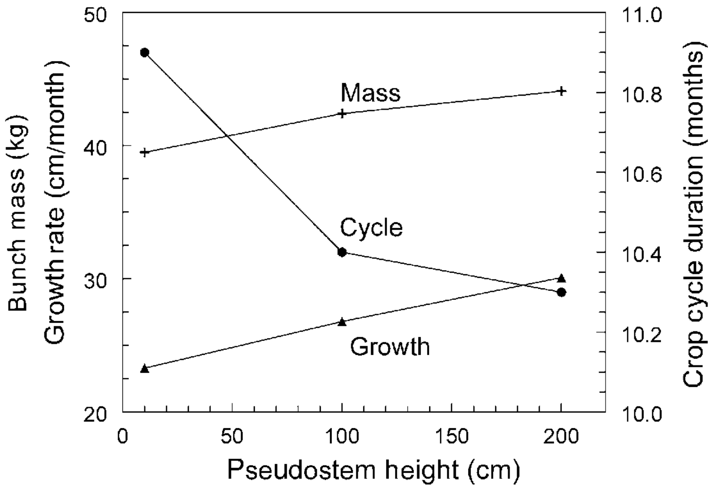

Fig. 8.6. The effect of cutting height of pseudostem at primary bunch harvest on the growth rate of the follower plant in the month after cutting, crop cycle in months to harvest of the follower, and the weight of the follower bunch (after Daniells and O'Farrell, 1987).

form adds sulfur to the soil, the rates vary widely. For example, using KNO_3 at 100 kg/ha in South Africa is suitable where minimum leaching occurs, while 250 kg/ha is needed in Israel and up to 600 kg/ha is used in other countries with high runoff, leaching and yields. Under less-intensive cultivation, organic matter plus 0.25 kg each of urea and KCl per mat (production unit) supplement is applied every 3 months. In some areas, no K is recommended, e.g. the Sula Valley of Honduras and the Jordan Valley of Israel.

If some calcium or magnesium deficiency is observed, dolomitic rock, or magnesium sulfate, calcium carbonate or magnesium oxide can be used. For sulfur deficiency normally a sulfate fertilizer will solve the problem. For minor elements foliar application is preferably to soil applications of the deficient element.

In the high-density annual planting being used in some places in Latin America for plantains, if no drip irrigation is in place, research has shown that two dry fertilizations of N and K per cycle are enough, with 30–40% of the total yearly amount applied when the plants have developed the first leaf in the field, and the other 60–70% when they have developed ten leaves; applications are applied around the single pseudostem (Belalcazar, 1991). Phosphorus is applied at planting time.

Bunch covers

Polyethylene bunch covers (30–40 μm thick) are almost universally used to improve yield and maintain fruit quality (Fig. 8.7). Some covers have a pesticide impregnated into them to reduce thrips or mite damage. The covers produce a warmer microclimate around the bunch, which can accelerate fruit development; they also prevent fingers inside the bunch covers from being chafed by leaves and covered by dust and pesticides; the cover can also discourage some insects from entering. The higher temperature and humidity generated inside the bunch cover are helpful in subtropical areas, though not required. For tropical areas, perforated covers are used for aeration and cooling. Covers are applied after the bracts have fallen and should hang 15 cm below the distal hand. Thinner covers are used in the tropics, where wind is less of a problem. The banana exporting companies are also using protective pads between developing hands, so that no bruising or chafing occurs to the fruit.

Fig. 8.7. Bunch covers provide protection of developing fruit from pathogens and insect damage. The coloured plastic hanging from the bottom of the bunch indicates date of emergence and is used to indicate harvesting (a). Cableways are used in large plantations to transport bunches of fruit to the packing sheds to minimize mechanical injury during handling (b).

Disease and pest management

Diseases

Fruit diseases can cause severe problems if not controlled (Table 8.5). The most virulent disease of banana and plantain is black Sigatoka, which is found worldwide, except for subtropical areas or tropical areas where it does not rain and in the Caribbean. Sigatoka disease has two forms: the yellow, caused by *Mycosphaerella musicola* and this form is more prevalent in cooler areas, and black Sigatoka or black leaf streak, which is a much more virulent type caused by *Mycosphaerella fijiensis*. Both alter the photosynthesizing capacity of the leaf because they produce necrosis that can extend to the whole leaf area, and at the same time there is an induction for premature ripening of the fruit because of more ethylene being released by the infected leaves, thus reducing calipers and yields. Control in intensive production systems relies on the use of fungicides, which have to be rotated and are very expensive, increasing the production costs significantly. Therefore, this approach may not provide a long-term solution for small growers and others serving local markets.

One way to reduce fungicide costs, which in intensive production systems can account for 25–30% of the production costs, is to use disease forecasting, which is based on the evaluation of climatic conditions and calculating the stage of evolution of the disease (SED). The idea is to spray as soon as it is considered necessary with a strong systemic fungicide mixed with pure mineral oil and rotate products with different modes of action to reduce fungicide resistance development. This approach has reduced the 40–60 applications per year to 12–14. Biofungicides have been tried, but in high disease pressure areas they do not work well, but they can be combined with contact fungicides, allowing reduction of the rates that are presently used. Eliminating the necrotic leaves or parts of the leaf is another practice to reduce dispersion of conidia and ascospores. Breeding for resistance is essential, using natural resistance in other banana varieties, or biotechnology to transfer resistance will probably provide a long-term solution.

Fusarium wilt (Panama disease) has caused severe disruption of banana and plantain production where susceptible cultivars, such as ‘Gros Michel’, are grown; fortunately, resistant genotypes do exist, but the fungus can also mutate and eventually affect them. The two other major diseases are the bacterial disease ‘Moko’ and the viral bunchy-top disease. For ‘Moko’ prevention is the best strategy, consisting of isolating and eradicating any infected plant and its neighbours and having tools used for cutting in the plant, especially the machetes used for desuckering, disinfected after each cut with Vanodine™ or a similar product.

Preharvest diseases, including fruit freckle (*Phyllostictina musarum*) and speckle (*Deightoniella torulosa*), can cause fruit skin spotting. ‘Cigar-end rot’ is associated with *Verticillium theobromae* and *Trachyspharea frutigena*, infecting

Table 8.5. Principal diseases of banana, causal organisms, distribution, varietal susceptibility and symptoms.

Disease	Causal organism	Distribution	Varietal susceptibility	Symptoms
Bacterial				
Moko	*Pseudomonas solanacearum*: only distinct strains of race 2 attack bananas and plantains	Central and South America, southern Caribbean, Philippines, Indonesia	Cavendish AAA susceptible, Bluggoe ABB susceptible, Horn AAB resistant, Pelipita ABB resistant	Root: progressive transient yellowing, older leaves first, necrosis and collapse of base petiole, younger leaf panels flaccid and necrotic, premature bunch development, discolored vascular bundles cream to brown or black in all parts of corm, roots, suckers. Fruit: male bud blackens and shrivels, vascular discoloration extends up fruit, bunches blacken and rot and then it progresses down pseudostem
Blood disease	Possibly related to Moko	Indonesia	Bluggoe ABB susceptible	Similar symptoms to Moko leaf yellowing but more conspicuous, reddish tinge to discolored vascular bundles, infects fruit via style
Rhizome rot	*Erwinia chrysanthemi*	Worldwide	Certain AAA and AA varieties susceptible incl. Cavendish	Rotting of corms, plant falls over. Soft, pale brown or yellow rot in outer cortical tissue. Entry through wounds, especially in wet conditions
Fungal				
Panama disease (Fusarium wilt)	*Fusarium oxysporum* fsp. *cubense*	Race :1 worldwide, Race 2: widely distributed, Race 3: Central America, Race 4: Canary Islands, Taiwan, Australia, South Africa	Gros Michel, some Cavendish varieties and some plantains	Progressive yellowing from the oldest leaves, longitudinal splitting lower portion of the outer leaf sheaths, wilting and buckling of leaves at the petiole base. Initial site of infection feeder roots. Sometimes confused with Moko disease

Disease	Causal organism	Distribution	Varietal susceptibility	Symptoms
Sigatoka leaf spots				
Black Sigatoka – Black leaf streak	*Mycosphaerella fijiensis* *Paracercospora fijiensis*	Worldwide, except some islands in the Caribbean and subtropical areas	Cavendish and most other commercial varieties are susceptible. Some resistance in *M. acuminata* and AA diploids	Dark leaf spots on lower leaf surface, which enlarge and coalesce, causes significant reduction in leaf area and yield, and premature fruit ripening
Yellow Sigatoka	*Mycosphaerella musicola*	Worldwide, more common higher elevations cooler areas	Less serious than black Sigotoka, plantains (AAB) resistant.	Starts as pale yellow streaks on the upper leaf surface, they enlarge and coalesce
Viral				
Banana bunchy-top virus (BBTV)	Vector banana aphid	South-east Asia, Australia, India, Central Africa, Pacific	Gros Michel AAA susceptible, Cavendish AAA susceptible, Saba BBB tolerant	Infected leaves become stunted and chlorotic at the margins. Bunching of leaves at the apex. No fruit production, suckers infected
Banana mosaic	Cucumber mosaic virus. Many aphids as vectors	Worldwide	Cavendish AAA susceptible, Horn AAB susceptible	Sharply defined interveinal chlorosis of leaves can lead to rotting heart leaf and cylinder. Stunted plants
Banana streak virus (BSV)	Vector mealy bugs, infected planting material	Worldwide	Cavendish AAA susceptible, Mysore AAB susceptible	Yellow streaks, continuous or broken, running across the leaf blade. More pronounced in warm weather

the flower perianth and slowly developing along with fruit growth. The end of the fruit darkens and later is covered with spores looking like a lit cigar. The disease is found in Latin America, West Africa, Egypt and Australia. The pulp develops as a dry rot. Removal of pistil and perianth 8–12 days after bunch emergence and polyethylene bunch covers help to reduce incidence.

A complex of different organisms is known to cause the most serious worldwide postharvest disease – crown rot. The wound caused when the bunch is dehanded is colonized by the organisms, the rot spreading into the pedicels during shipping and sometimes into the pulp. A number of organisms have been found, with the actual complex varying with region; most common isolates have been *Colletotrichum musae*, *Fusarium* spp., *V. theobromae*, *B. theobromae* and *Ceratocystis paradoxa*. Spores are carried by wind or rain splash; however, dehanding knives and delatexing tanks may be bigger sources. Good dehanding practices, with clean cuts using sharp knives, and sanitation of packing sheds and areas are essential. Exporters use alum and a fungicide to try to control this infection.

Anthracnose on the fruit skin and neck rot are both caused by *C. musae* and can be a serious problem when the fruit becomes overripe. Sanitation and postharvest fungicide are used for control.

Insect pests and nematodes

Insect pests are generally of minor importance (Table 8.6). Occasionally, severe fruit scarring can occur. Borers are a problem where control practices, such as planting clean material and insecticide schedules, are not followed. The continuous nature of banana production makes pests such as nematodes more important (Table 8.6).

The main insect problem in many areas of the world is the black weevil (*Cosmopolites sordidus*). The weevil lays eggs in the corm, and the larvae coming from them bore into the corm, causing extensive corm rotting because of secondary infection. The damage to the roots and the expansion of the rotting to most of the corm leads to weakening of the plant, which lowers production, and frequently toppling of the plant with total loss of the bunch. The main control measures should be paring and disinfecting the corms before planting, eliminating residues of old plants before a new planting, fallows and the use of traps with pheromone or pseudostem piece traps; both attract the adults. In the pheromone traps, the weevils are drowned and in the pseudostem piece traps they can just be hand-collected or can be poisoned if an insecticide is added to the piece.

Nematodes can severely limit production, with the extent of the problem varying with cultivar, soil conditions, type of nematode and plant vigour. Nematicides are used for fruit destined for export and are applied every 4–6 months, but they are expensive, their use has to be continued and many of them are being banned by the importing countries. More economic measures include: improved fallow to eliminate old material, done in combination with

Table 8.6. Major pests of banana.

Pest	Latin name	Spread	Susceptibility	Symptoms
Banana borer/ weevil	*Cosmopolites sordidus*	Worldwide	No clones resistant	Burrows into rhizome, network of tunnels, lays eggs at base of pseudostem, adults (12 mm long) feed on pseudostem, nocturnal
Bunch pests				
Thrips	*Chaetanaphothrips* spp. red rust thrip	Central America, South America, Asia, Australia		Rust blemish to fruit skin, especially between fingers of immature fruit
	Frankliniella spp.	South-east Asia, Australia,		Corky scab on developing fruit
	Flower thrips	Caribbean, Latin America		
Scab moth	*Nacoleia octasuma*	Australia, Pacific Islands		Brown scabs on developing fruit
Nematodes				
Burrowing nematode	*Radopholus similis*	Most areas except East Africa, Israel, Canary Islands, Egypt and Taiwan	AAA more tolerant than AAB	Elongated blade, lesions on root
Lesion nematode	*Pratylenchus goodleyi*	African highlands, Canary Islands	Cavendish susceptible	Similar to *R. similis*
	Pratylenchus coffeae	Tropics	AAB more commonly associated	
Root-knot nematodes	*Meloidogyne* spp.	Worldwide		Deformation and stunting of roots. Gall formation

an injection of herbicide into the pseudostems, resulting in the nematode population being significantly reduced; use of water isolation ditches so no nematodes enter the field through water coming from neighbouring fields; use of healthy plant material – initially it could be tissue-cultured although it is very expensive; use of tolerant or, hopefully in the near future, resistant varieties and the reintroduction of biodiversity with new and different green manure or cover crops, manure incorporation and other practices (Rísede *et al.*, 2010).

Weed management

Weeds are a major problem during stand establishment before canopy closure occurs. Cultivation needs to be carefully carried out so as not to damage the surface feeder roots, using hand-hoeing around the plants. Herbicides can be used once the banana canopy is sufficiently high to avoid contact with the leaves. Mulching and intercropping during early stand development can be used. Failure to weed can lead to severe yield decline. It is very important to keep the area around the new plants clean during the initial weeks until they develop and then continue to clean until the shade of the canopies will reduce the weed problem.

Orchard protection – windbreaks

Banana plants tolerate wind up to 30 m/s. Higher speeds lead to tearing of leaf laminas. Windbreaks may be necessary if prevailing winds tear leaves into strips less than 5 cm wide (Turner, 1994). The need for a windbreak must be balanced against the effects of shading, the area needed, competition for water and nutrients, and the limited protection on the leeward side. Plant propping is carried out to reduce the impact of winds or the excessive weight of the bunch.

HARVESTING AND POSTHARVEST HANDLING

Harvesting

Individual fingers increase in weight and begin to lose angularity in cross section during maturation. Fruits for export are harvested while still green at 75% maturity with some angularity, 10–14 weeks after flower emergence in the tropics and up to 9 months in the cool subtropical areas. The idea is to export only fruit that is not over-aged and that has a minimum caliper. The age of the fruit is established by tying a coloured ribbon to the bunch cover at the time the cover is put in place, so the different ribbon colours indicate the week the bunch emerged. The maturity is checked by determining the caliper of the middle finger of the outer whorl of the second hand. When the caliper reading is between 31 and 41 mm in diameter, the bunch is ready to harvest. If the caliper reading is less than the 31–41 mm minimum, the finger is rechecked the next week, and if after the week the caliper is still too small, the bunch will be harvested and fruit sent to the local market. In this way, over-aged fruit are not exported. If over-aged fruit are included in export fruit shipment, it is possible that they will start to ripen in transit and induce ripening of the whole shipment.

Small growers tend to harvest bunches when more than three-quarters mature with little angularity and at fully rounded stage. More mature fruit have a shorter postharvest life and are more liable to be sunburnt and split. Other criteria used to judge maturity include drying of leaves, drying of stylar ends and days from bunch emergence. The days from bunch emergence can vary from 7 to 24 weeks, depending upon cultivar, season, crop management and environment. Other measures include pulp to peel ratio and skin firmness.

The bunch is removed from the plant by cutting a notch in the pseudostem while supporting the bunch with a pole and slowly lowering it on to the shoulder pad of a harvester. The stem is then fully cut, leaving a 300 mm peduncle. The bunches are transported to the packing shed on padded trailers or on an overhead cable system. Dehanding can be performed in the field, with the hands transported to the packing shed on padded trailers. Care is essential in these steps to avoid any mechanical injury that would reduce fruit quality.

Plantains in the tropics are harvested for export about 11 weeks after flower emergence, and colour ribbons are again used as a guide to establish bunch age. Plantain maturity standards vary widely and lead to considerable variation in product quality.

Postharvest treatments

Bunch covers are removed in the field or after the bunches reach the covered packing shed. Bunches must be protected from exposure to direct sunlight to avoid sunburn injury during transportation and at the packing-shed holding area. Hands are removed with a sharp, curved knife or curved chisel, leaving part of the crown attached. The hands, irrespective of whether dehanding takes place in the field or in the packing shed, are placed in clean water to remove dirt and latex exuding from the cut crown; this should last a minimum of 20 min. Care is needed to avoid the build-up of fungal spores in the water of the wash tank, by frequent changes and the use of chlorine.

The hands are removed from the tank and sometimes cut into clusters of adjacent fingers, with defective fingers being removed. The clusters are placed in trays that pass through a fungicide-treatment spray or dip on a conveyor. The conveyor then passes the trays to a packing station, where weight adjustment occurs and the fruits are packed into cardboard cartons, with a thin plastic liner to prevent chafing injury and water loss. Hands or clusters are tightly packed to avoid movement during shipping. Carton sizes vary from 12 to 20 kg, with Central American cartons holding 18.1 kg of fruit. Cartons may then be cooled to 13°C before shipping to market. In small local operations, bunches may be sold, with dehanding taking place upon sale to the consumer. Alternatively, hands may be shipped to market in a number of different containers. Export dessert bananas, because of the regular nature of the hands and curved nature of the fingers, can be easily packed. Many other cultivars are not as easily packed, as the fingers are not arranged in a regular manner, e.g. ‘Pisang Mas’ (AA).

Green bananas are shipped at 13–14°C to delay ripening. Lower temperature can lead to chilling injury, whose symptoms include a dull, grey skin colour, poor ripening, poor conversion of starch to sugar, poor flavour development and susceptibility to decay. Symptom development is dependent upon exposure temperature and time, and susceptibility depends mostly on the cultivar. Maturity, prior growing conditions and previous temperature exposure may also be factors. ‘Dwarf Cavendish’ shows injury after 20 days at 11°C and ‘Lacatan’ after 12 days at 14°C. Plantains, such as ‘Pisang Awak’, are less susceptible to chilling injury than dessert types.

Marketing

Market quality standards vary widely, with export bananas having the most stringent standards. In large measure, this is related to consumer preferences and the condition of the bananas received at the market. In western supermarkets, unblemished fruits are preferred, even required, while in markets in tropical areas postharvest handling is very abusive and fruits with blemishes are normal, with degree of fruit ripeness being a deciding factor.

Export quality standards are applied before and after shipping and include: blemishes and fruit shape, finger length and diameter, cluster size and arrangement, and carton weight. A minimum finger length on a hand is 203 mm for export from Central to South America, with the whole hand being culled if one finger does not meet this standard. When hands are cut into clusters, the cull fingers are carefully cut out. The diameter for ‘Cavendish’ fingers ranges from 31 to 41 mm. Fingers with obvious blemishes are culled. Such standards can lead to cull rates of up to one-third, with culled fruit being sold locally, processed or dumped.

Banana fruits are very susceptible to both abrasion and impact injury. The major marketing problem of export bananas is mechanical injury, which shows itself as black sunken areas on the skin after ripening. The thin plastic liner in export cartons minimizes chafing damage to fingers that rub against the side of the carton during handling. Latex allowed to dry on the skin oxidizes as brown and black stains and can lead to downgrading of fruit. Other concerns are diseases, particularly crown rot, which may affect the whole carton and promote uneven fruit ripening. Because of weak pedicels, the fingers of some cultivars fall from the hand during ripening, exposing the pulp.

Plantains have a tougher skin than bananas and so there is less danger of causing harm to them by improper handling; in general they should be treated the same way as bananas, but in most instances they use less elaborate systems for harvest, transport to the packing house and packing than for bananas.

Plantain boxes weigh 22.6 kg. Alternatively, green plantains are partially ripened, peeled and frozen, with a heat treatment to minimize enzymatic browning reactions.

Ripening

Dessert bananas are allowed to ripen and are chiefly eaten raw when they have low starch, high sugar and developed flavour. Plantains have high starch content and are eaten when green or ripe after boiling, frying or roasting. The conversion of starch to sugar during ripening of plantain-type bananas is less complete than in dessert bananas (Fig. 8.8).

The ripening process for the export dessert-type bananas is normally carried out by specialists under controlled conditions just before distribution and marketing to consumers. When bananas are allowed to ripen naturally, it is difficult to predict when fruit will be ready to eat. Under controlled ripening conditions, ethylene is supplied from compressed gas cylinders, ethylene generators or ethylene-generating chemicals, such as ethephon. Commercially, bananas are treated with about 100 ppm ethylene for about 24 h under controlled temperature and humidity conditions and ventilation to prevent carbon dioxide (CO_2) build-up. Newer systems pressurize the room to allow uniform ethylene distribution and temperature. Temperature control allows fruit to be ripened on a specific schedule to colour stage 3 for distribution in from 4 days at 19°C to 10 days at 14.5°C. The humidity control has a significant impact on the final skin colour developed and flesh softening.

In local markets, fruits are ripened by covering with a tarpaulin or cloth after inserting a packet of calcium carbide (0.3 g/l) to generate acetylene. Acetylene is a 100 times less effective analogue of ethylene. A prolific ethylene-producing ripening fruit, such as avocado, can also be used as an ethylene source, as can burning of incense sticks or young leaves of a number of trees, such as gliricidia (*Gliricidia sepium* Stend) (Acedo and Bautista, 1991).

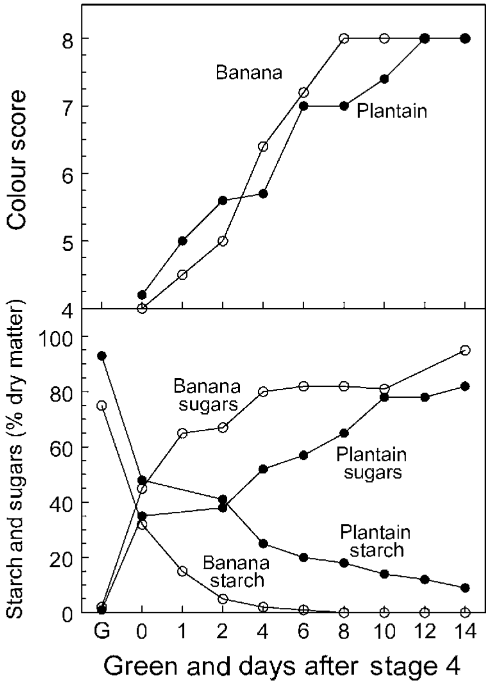

Fig. 8.8. Change in dessert bananas' and plantains' colour score (a), and starch and total sugars (b) (redrawn from Marriot *et al.*, 1981).

UTILIZATION

The main carbohydrate difference between bananas and plantains is that bananas are less starchy than plantains (Fig. 8.8). Bananas had 1% starch when fully ripe and 0% when overripe, while plantains had 9% starch when fully ripe and 3% when overripe (Marriot *el al.*, 1981). The same bananas had 23% sugar when ripe or overripe while plantains had 20% sugar when ripe and 27% when overripe. The moisture content of ripe bananas is ~80%, versus ~65% for plantains. Bananas are at their best when yellow, plantain when black.

The flavour, texture, convenience, ease of eating and nutritional values have made dessert bananas very popular (Baldry *et al.*, 1981). Banana is a useful source of vitamins A, C and B6 and has about twice the concentration of K compared with other ripe fruit (Table 8.7). Plantain as a staple provides considerable energy and protein, although the diet needs to be supplemented. In West and Central Africa, people derive about one-quarter of their energy requirements from plantains (Wainwright, 1992).

Bananas are used in special diets where ease of digestibility, low fat, no cholesterol, minerals (high K, low sodium (Na)) and vitamin contents are

Table 8.7. Proximate fruit composition of banana and plantain in 100 g edible portion (Wenkam, 1990). Differences in mineral content can be due to cultivar, fertilization, water supply and environment.

	Williams (AAA)	Brazilian (AAB)	Plantain (BB)
Water (g)	71.3	79.2	64.1
Energy (kJ)	418	301	523
Protein (g)	1.08	1.75	1.28
Lipid (g)	0.13	0.18	0.03
Carbohydrate (g)	26.56	18.03	33.39
Fibre (g)	0.11	0.25	0.43
Ash (g)	0.9	0.82	0.87
Minerals			
Calcium (mg)	5	2	4
Iron (mg)	0.49	0.35	0.54
Magnesium (mg)	40	26	35
Phosphorus (mg)	18	13	21
Potassium (mg)	494	302	393
Sodium (mg)	1	1	3
Vitamins			
Ascorbic acid (mg)	5.1	8	17.5
Thiamine (mg)	0.044	0.026	0.038
Riboflavin (mg)	0.045	0.041	0.064
Niacin (mg)	0.69	0.61	0.43
Vitamin A (IU)	88	82	31

required. The fruit does not cause digestive disturbance; it readily neutralizes free acid in the stomach and does not give rise to uric acid. These special diets are used for babies, the elderly and patients with stomach problems, gout and arthritis.

Only a very minor proportion of the total world banana production is processed. The procedures used include canning as slices, drying as slices or flakes, freezing of juice, extraction, frying and fermentation. Puree is canned or frozen and used in baby foods, baking and drinks. Banana essence is a clear colourless liquid used in desserts, juices and drinks. Dried ripe fruit can be made into flour. The lack of acidity makes processing difficult, because of the need for pasteurization. A year-round supply of fresh fruit makes preservation less economic. A beer is brewed from plantains, also called beer bananas, and consumed in Uganda and Tanzania.

Plantains can be eaten green or ripe. Green plantains can be peeled and cooked or cooked and mashed and mixed with bacon or pork meat pieces or boiled and mashed and made into balls that are eaten in soups. The green fruit can also be cut into round or long slices that are deep fried and eaten as a snack. In some cases, thick slices about 10 mm wide are cut, partially fried and then expanded by pounding them, after which the frying is completed; these slices, called 'patacones' or 'tostones', are very popular in Latin America and are eaten as a side order with meat and other food preparations. Plantains are also left to ripen completely until their peel turns black, at this point they are usually sweet (Fig. 8.8); after this they are peeled and sliced or halved and fried or baked to be eaten with the main course. Alternatively, the ripe fruits are baked as a very nice dessert with added sugar, cream or butter, and cinnamon.

Corms, shoots and male buds are also eaten as a starch source or vegetable. Immediately after harvest, the pseudostem still has considerable starch reserves. The male bud, with the outer fibrous bracts removed, is boiled in South-east Asia and eaten as a vegetable, after several changes of water to remove astringency. Banana leaves are used as food wrappers for steaming.

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9

Litchi and Longan

Litchi (*Litchi chinensis* Sonn.) and longan (*Dimocarpus longan* (Lour.) Steud) are members of the *Sapindaceae*. These sub-tropical and tropical trees, respectively, are grown widely in the tropics. The fruit is marketed fresh, dried, canned and as juice.

BOTANY

The *Sapindaceae* is composed of around 150 genera and 2000 species of trees, shrubs, and a few herbs and vines, usually monoecious, distributed widely in the warm tropics and subtropics. The common family name soapberry refers to the tree (*Sapindus saponaria* L.), a native of tropical America producing a fruit containing a soap-like substance (37% saponin). The majority of species are native to Asia, with a few species in South America, Africa and Australia. Among the numerous genera, four related genera and five species are of interest to the fruit horticulturist:

1. *Blighia sapida* Koenig, the Jamaican akee, is native to Guinea and is commonly grown in the Caribbean Islands, particularly in Jamaica. The brightly coloured yellow to red fruit has thick walls in three parts, each containing a white nut-flavoured pulp with a shiny black seed attached at the tip. Pulp from immature or overripe fruit and the pink raphe attaching the aril to the seed are poisonous. When the pods open naturally, the pulp can be fried or boiled. When fried, it resembles scrambled eggs.

2. *Dimocarpus longan* (Lour.) Steud., longan, lungan, langngan, dragon eye (English), lengkeng (Malaysia, Indonesia), longanier, oeil de dragon (French), lamyai pa (Thailand), or nhan (Vietnam) is reported to have originated in north-eastern India, Burma or southern China in the Yunan province. Commonly called dragon eye, the trees attain heights of 9–12 m under suitable environments and it is more vigorous than the litchi (Menzel *et al.*, 1988b). The longan is generally grown in similar areas to that of litchi in China and Thailand but climatic requirements are less exacting.

3. *Litchi chinensis* Sonn., ssp. *chinensis*, the litchi, is a subtropical species indigenous to south China. It is principally cultivated in Guangdong, Fujian, Guangxi and Sichuan provinces. Groff (1921) discusses in detail the origin of the names litchi and longan. The Chinese characters for litchi convey the idea that the fruit of the litchi must be removed from the tree by means of knives with the twigs attached. Many cultivar names are pronunciations of various southern Chinese dialects and spellings, which has led to some confusion. The most recent Chinese descriptions use the spelling litchi and national dialect name (Mandarin – common language). Other spellings and common names are lichee, litchee, leechee, lychee, lin-chi (Thailand), laici (Malaysia), lici, litsi (Indonesia), letsias (Philippines), li-chi or lizhi (China), vai, cayvai, or tu hu (Vietnam).

There are two subspecies; one is found in the Philippines (ssp. *philippinensis*) and the other in Indonesia (ssp. *javanensis*). The Philippine subspecies has a long, oval-shaped fruit with thorn-like protuberances that split when ripe, exposing an inedible aril, partially covering the seed. The Indonesian subspecies is similar to the Chinese species and crops more regularly in hot equatorial areas, though it has not been exploited commercially.

4. *Nephelium lappaceum* L., the rambutan (Indonesia, Malaysia, Philippines, English), litchi chevelu (French), and ngoh and phruan (Thailand), and *Nephelium ramboutan-ake* Bl., the pulasan, ngo-khonsan (Thailand) and kapalasan (Indonesia) are both native to the Malaysian peninsula and are now distributed widely in South-east Asia. This species will be covered in Volume 2.

ORIGIN AND DISTRIBUTION

The cultivation of litchi in China antedates the beginning of the Christian era according to Chinese writings going back to 1766 BC (Storey, 1973). Early distribution into other tropical and subtropical regions occurred during the 16th and 17th centuries. The litchi was introduced into India in 1798 and has developed into a significant industry. Litchi and longan reached Europe during the early part of the 19th century and are mentioned as having reached Trinidad before 1880, with a few trees being grown in Florida as early as 1883 (Groff, 1921). The first litchi tree is said to have been brought to Hawaii about the year 1873 by Mr Ching Chock, a Chinese merchant, and was planted on the property of Mr Chun Afong and became known as the 'Afong' tree, identified as Gui Wei (Kwai Mi), later re-identified as similar to 'Da Zao'. The office of Foreign Seed and Plant Introduction in the United States, Department of Agriculture began introducing litchi plants in 1907. The late Professor G.W. Groff, who resided in south China almost continuously from l907 to l94l as Dean of the College of Agriculture, Lingnan University, Guangzhou, China, was responsible for the introduction of a large number of cultivars into the

USA. His contributions number 17 out of the 25 cultivars and clones now established in Hawaii. Today, the litchi is found in most countries of Latin America, the Caribbean, India, Mauritius, Africa, Australia, Israel, the Canary Islands, Madeira Islands, and many other countries.

ECOLOGY

The litchi and longan are evergreen subtropical plants, indigenous to areas where cool, dry winters and warm, wet and humid summers prevail. Such conditions are found mostly in subtropical regions and at higher elevations in the tropics. In Guangzhou, summers are known for their rains and high humidity (>80%) during night and day. The winter is cool and dry, and frost is rare. Litchi is described as a water-loving, low-elevation plant, which is planted largely along the banks and dykes in the Pearl River delta in Guangdong. However, there are upland cultivars (mountain litchi) grown on hillsides or in orchard systems with very little tillage after the trees mature.

Soil

Observations indicate that the litchi and longan thrive on a wide variety of soil types as long as drainage is good enough to prevent waterlogging. Satisfactory litchi growth occurs in India and Florida in neutral to slightly alkaline soils, with free lime present. In south China, the litchi soils are alluvial silty loams to clays in the Pearl River delta or laterite soils on the hills. Longan thrives best on deep clay loams, and both species prefer a slightly acid (pH 5.0–6.5) soil.

Climate

Rainfall and moisture

High rainfall and humidity induce good growth in litchi and longan, with litchi being able to resist floods. Roots of litchi trees covered with water for 8 days showed no deleterious effects, even when fruiting. In China and Thailand, litchis are also grown on banks with high water tables beneath them.

Ample annual rainfall is considered to be around 1250–2000 mm for litchi and 1500–3000 mm for longan. When rainfall is lower, irrigation is essential. A dry autumn and winter is important to prevent litchi vegetative growth (Fig. 9.1), which is essential to good flowering (Nakata and Watanabe, 1966). In south China, litchi anthesis occurs during the rainy season (130–375 mm/month) and when relative humidity is higher than 80%. Too much rain during anthesis, however, can reduce flower opening and insect activities needed for pollination. A major problem of litchi culture in Hawaii, with the exception of the Kona district of Hawaii, is that rainfall comes in late autumn and winter, making it difficult to control vegetative flushing. Irrigation after a period of soil water stress is reported to aid in longan

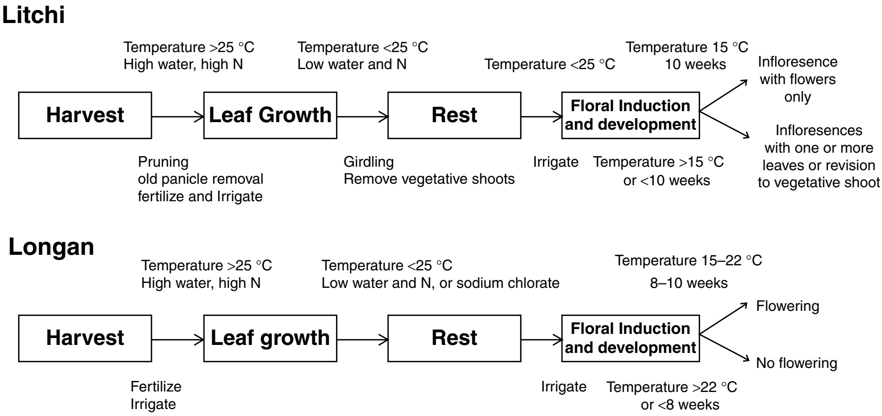

Fig. 9.1. Fruiting cycle of litchi (after Menzel and Simpson, 1994) and longan as affected by temperature, nitrogen fertilization and water availability. Litchi leaf low nitrogen levels need to be in the range of 1.75–1.8%. There can be more than one flush of leaf growth during the year. Longan can be induced to flower with a sodium chlorate treatment.

flowering (Fig. 9.1), even though the tree flowers profusely in areas with high water tables. Both crops require adequate moisture, from rainfall or irrigation, during fruit set and growth.

Temperature

Young litchi and longan trees are severely damaged or even killed at −2 to −3°C, with dormant and mature trees having more tolerance to low temperatures. Periodic cold is required for flowering, though in Guangzhou, air temperatures rarely drop below 0°C. The total duration of relatively low temperatures rather than the frequency or time of occurrence during a critical period seems to be the determining factor (Fig. 9.1). When trees are deeply rooted, low air temperature is more important than soil moisture (Menzel *et al.*, 1989). There is considerable cultivar difference in response to temperature (Menzel *et al.*, 1989). In a test involving seven cultivars, all cultivars showed panicle emergence after 6 weeks at 15/10°C or at 20/15°C; however, there are differences in the degrees of flowering between the cultivars at 20/15°C (Table 9.1). There is no flowering at 25/20°C or 30/25°C. Temperature also influences the time from emergence to anthesis: 14–16 weeks at 20/15°C, versus 6–8 weeks at 15/10°C. The greatest number of inflorescences per branch occurs if low temperatures are maintained until anthesis. If temperatures are increased from varying the period at 15/10°C to 30/25°C after emergence and before anthesis, there is a reduced number of female flowers and some floral buds revert to vegetative growth (Fig. 9.2). Pollination is optimum at about 19–22°C and occurs in 5–7 days. At lower temperatures, pollen tube growth is strongly inhibited. Hot, dry conditions may reduce

Table 9.1. Effect of temperature and cultivar on percentage of litchi terminal branches flowering. Trees at 25/20°C and 30/25°C did not flower (Menzel and Simpson, 1988). Panicles can be of two types; one has only flowers, while the other has a mixture of leaves and flowers, and is referred to as a leafy panicle.

Cultivar	Branches flowering %							
	Vegetative shoot		Leafy panicles		Leafless panicles		Flowering panicles	
	15/10°C	20/15°C	15/10°C	20/15°C	15/10°C	20/15°C	15/10°C	20/15°C
Da zao	0	50	93	50	7	0	100	50
Bengal	0	49	71	32	29	9	100	41
Shui dong	0	58	39	3	61	28	100	31
Gui wei Pink	0	20	55	69	46	8	100	77
Gui wei Red	0	80	7	3	93	5	100	8
Salathiel	0	17	0	20	100	58	100	78
Huai zhi	0	4	0	14	100	81	100	95

yields, as poor fruit set occurs at 33°C. In hot equatorial areas, litchi grows vegetatively and seldom flowers.

Longan is less demanding than litchi for flowering, requiring 15–22°C for 2–3 months for flower induction (Fig. 9.1). The exact chilling and cultivar differences in this requirement are not known. In hot equatorial areas, longan grows vegetatively and seldom flowers. Flowers can be induced by a chemical treatment discussed below.

Light intensity and photoperiod

Litchi is a day-neutral plant, and floral initiation is associated with starch content of leaves and stems. Shading, such as when litchi trees begin to crowd each other in an orchard, leads to a decline in production, due to smaller panicles and a decrease in the number of panicles on a tree (Lin *et al.*, 1991). Shading to 50% of full sunlight causes a 40% reduction in the panicles formed and a 65% reduction in panicle length. There is little information on the response of longan to varying light levels; it is thought to be day neutral.

GENERAL CHARACTERISTICS

Tree

The litchi is a spreading evergreen tree, growing to 10–12 m under favourable conditions. It is generally considered to be a slow grower with a long life. A Chinese writer, Wen Hsun Chen, said that at the time of his writing (before 1924), the cultivar ‘Chenzi’ (Chen Family Purple, ‘Brewster’) was already 300 years old and still thriving (Groff, 1921). Depending upon cultivar, trees may be broad with low-hanging branches or have upright branches and a compact, rounded head. Branches are brittle and even large limbs are easily broken by winds.

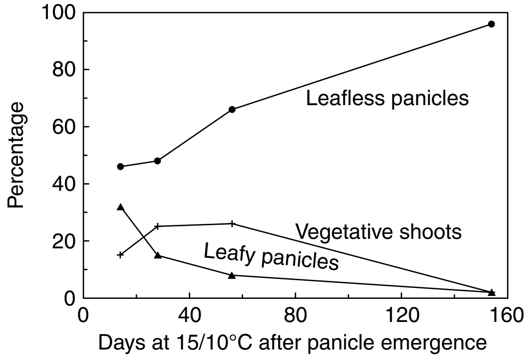

Fig. 9.2. Effect of post-panicle emergence temperature response to 15/10°C before transfer to 30/25°C on 'Gui wei' litchi panicle development (after Menzel and Simpson, 1991).

Leaves are arranged alternately, pinnately compound with two to five pairs of leaflets arranged in opposite positions or slightly obliquely along the rachis (Fig. 9.3). The leaflets are elliptical to lanceolate, 2.5–6.4 cm wide, 7.6–17 cm long, and deep green. Young, emerging flushes range from pale green to pinkish to a copperish red. Growth flushes can occur several times a year and are vegetative flushes of several leaves in summer and can be floral in winter. Vegetative flushing is encouraged immediately after harvest in summer by fertilizing and irrigating (Fig. 9.1). The floral flush is a terminal inflorescence. A close relationship exists between number of leaves associated with a flowering panicle and number of fruits on that panicle (Fig. 9.4). Hence, a minimum number of two leaves per fruit is required.

The longan tree can grow to 20 m and has either a spreading or erect habit. The compound longan leaves are around 25 cm long with 6–12 leaflets, alternate or nearly opposite, oblong, 5–15 cm long with blunt or pointed ends (Fig. 9.5). The leaves are dark glossy green on the upper side and pale green underneath.

Flowers

The small litchi flowers are 3.0–6.0 mm in length when fully expanded (Fig. 9.3), and borne in profusion on leafless or leafy, well-branched terminal panicles. In the northern hemisphere, appearance of panicles can begin as early as November to as late as April, depending upon cultivar and environmental conditions. Flowers are yellow-green or brownish-yellow, apetalous with small valvate sepals (Fig. 9.3), a fleshy disc and up to eight stamens. Among the numerous, apetalous flowers on the panicle, three sex types are described for litchi. These sex types are designated Types I, II and III,

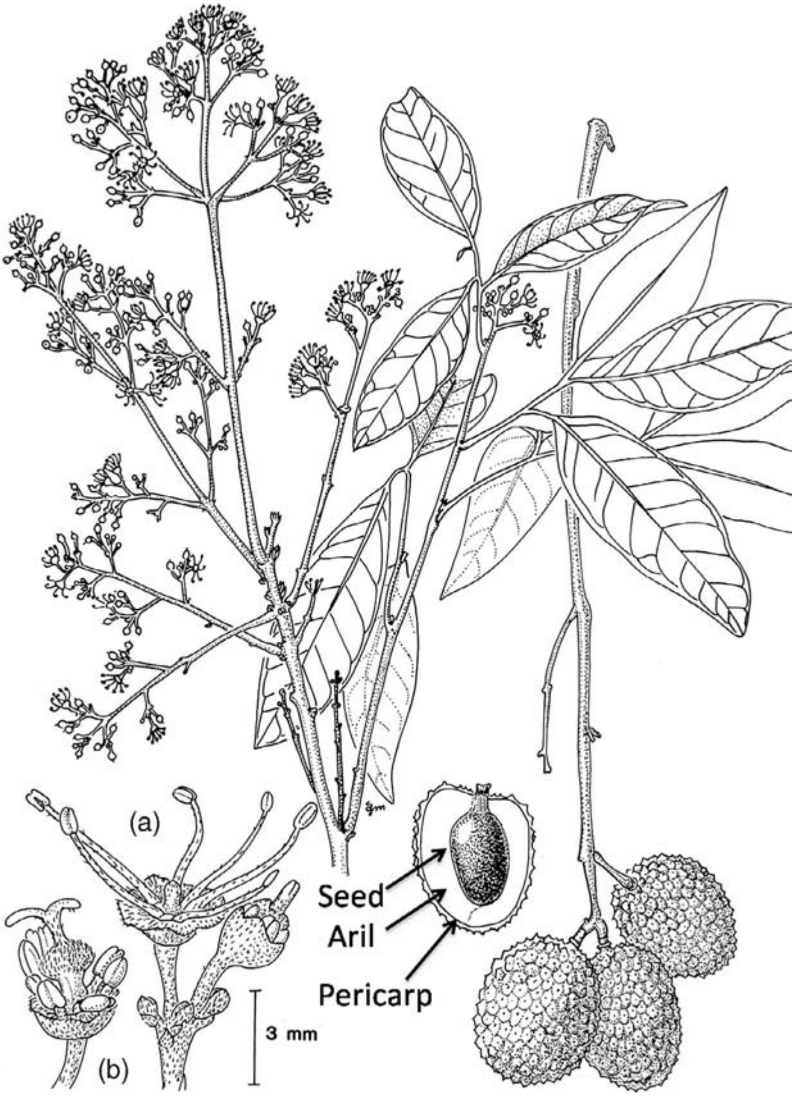

Fig. 9.3. Leaf, flower and fruit of *Litchi chinensis*. (a) male flower with reduced pistil and six stamens, and (b) 'hermaphrodite' flower, which functions as a female with a well-developed pistil (two carpels and a bilobed stigma and six to eight stamens that do not dehisce (sterile)). From Nakasone and Paull (1998).

based on the chronological order of development. Type I is morphologically and functionally a male (Fig. 9.3), possessing six to eight stamens producing an abundance of pollen and lacking ovule differentiation. Type II flower is morphologically a hermaphrodite functioning mostly as female, with a well-

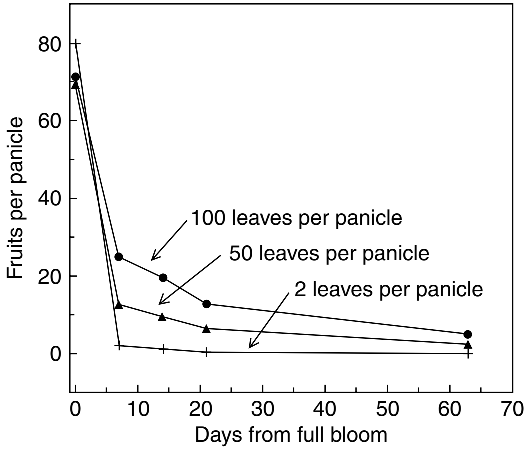

Fig. 9.4. Effect of leaf number on the litchi panicle branch to number of fruit set per panicle for cultivar 'H-1224' (after Yuan and Huang, 1988).

developed two-carpel pistil and a two-lobed stigma (Fig. 9.3). The five to eight stamens do not dehisce normally and have little viable pollen. Type III flowers function as a male, though they are morphologically a hermaphrodite with a rudimentary pistil lacking style and stigma. The six to eight stamens produce numerous viable pollen grains. Approximately two-thirds of the flowers on a panicle are composed of Type III and only about 20% of the flowers are potentially fruit-producing (Type II). Observations indicate that the ratio of functional females (Type II) to functionally staminate flowers (Types I and III) varies with cultivar (Table 9.2), with 10–30% being female (Limangkura, 1966). Similar sex types occur in longan (Lian and Chen, 1965), of small, greenish-yellow to brownish, self-incompatible flowers having five sepals and five petals (Fig. 9.5). Insects are the major pollinators (Alexander *et al.*, 1982).

Litchi floral anthesis occurs in cycles of sex types (Mustard, 1954), with a period of about 10 days during which only functional male flowers are open. This is followed by a transitional period of 2–3 days when both staminate and female (Type II) flowers open, then 2 days of only female flowers. This is followed by 2–3 days of transitional types, and finally male flowers for a period of 7–10 days. The number of days to complete each of the cycles appears to differ somewhat among inflorescences and between cultivars and with environmental conditions. Inflorescences produced around the same time generally produce the same sex types. It has been observed that the initial flowers are all functionally male in one season, and in the following season initial flowers at one site may be all functionally female and at another site all functionally male. Thus, the inflorescence may begin floral anthesis at any sexual phase of the cycle, going through the above sequence. The expression

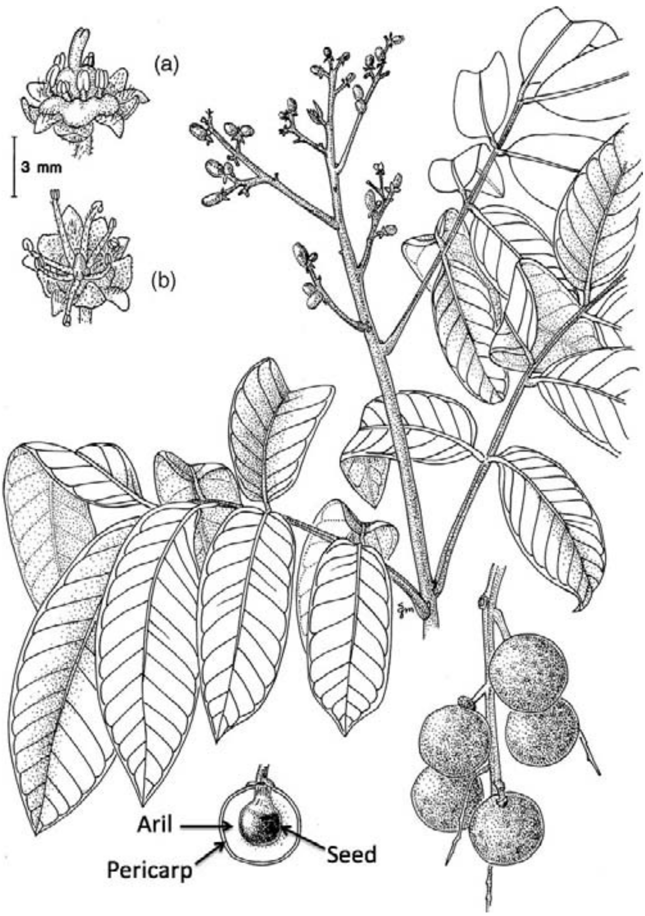

Fig. 9.5. Leaf, flower and fruit of *Dimocarpus longan*. (a) female flower with two carpels and a bilobed stigma and stamens on short filaments, which do not dehisce, and (b) male flower showing eight hairy stamens with bilobed anthers (from Nakasone and Paull 1998).

of sex type may be related to temperature, with lower temperatures leading to a higher percentage of Type II flowers.

Longan flowers are small, greenish-yellow to brownish, and self-compatible with five sepals and five petals. Longan has the same three different flower types as in litchi: staminate flower (Type I), hermaphrodite flower functionally as 'female' (Type II) and hermaphrodite flower functionally as 'male.' Longan shows a similar progression of flower types under normal conditions: first functionally male, then hermaphrodite and finally male. However, the Type II may bloom first under some cultural management

Table 9.2. Distribution of the three sex types of flowers per panicle of two litchi cultivars (Limangkura, 1966).

Cultivar	Flowers per panicle	Functional flower type (%)			Potential fruiting flowers (%)
		I	II	III	
Groff	964	14	20	66	20
Hei ye	1042	22	19	59	19

practices or different climatic conditions. An overlap of the types occurs on one tree since not all panicles open at the same time.

Pollination and fruit set

Natural pollination

Controlled pollination studies have shown the presence of a relatively high degree of self-sterility in litchi. Limangkura (1966) self-pollinated litchi flowers and produced 4.2% set, while cross-pollinated flowers yielded 6.9% set. Litchi inflorescences caged to prevent insect visitation had 0.026–0.105% fruit set as compared to 0.17–11.25% fruit set on inflorescences open to insect visitation (Pandey and Yadava, 1970). Bees (*Apis* and *Mellifera* spp.) make up 98–99% of the total insect visitors to the flowers, mostly during the morning hours, when nectar secretion occurs. The stigmas of litchi flowers are receptive to pollination for 72 h from the time it divides into the two lobes, and the anthers remain functional up to 1–3 days after anthesis.

Controlled pollination studies in longan have shown the presence of a relatively high degree of self-incompatibility. Bees (*Apis* and *Mellifera* spp.) are the major pollinators and comprised 98–99% of the total insect visitors to the flowers. The visits occur mostly during the morning hours, when nectar secretion occurs. Too much rain during anthesis can reduce flower opening and the insect activity needed for pollination. Irrigation after a period of soil water stress is reported to aid in flowering, even though the tree flowers profusely in areas with high water tables.

Floral induction, fruit set and chemicals

Growth regulators and other horticultural techniques have been tried by many researchers to overcome the problem of irregular litchi flowering, to enhance fruit set and to reduce seed size (Menzel, 1983; Joubert, 1986). Sodium naphthalene acetate (SNA) at 200 and 400 ppm promoted blossoming in 'Chenzi' only when climatic conditions favoured vegetative growth. The inhibition of vegetative growth is a requisite for floral initiation, and SNA mimics low temperatures that inhibit growth. There is no increase in floral initiation and yields by SNA treatment during years with dry autumn months and on trees that yielded heavily during the previous season.

A combination of ethephon and kinetin is more effective in reducing litchi shoot length and inducing high proportions of floral buds than either chemical alone (Chen and Ku, 1988), while unsprayed shoots remain vegetative. Killing winter flushes by the use of chemicals to promote litchi flowering is also practised. A 25% urea solution, ethephon (1500 mg/l), maleic hydrazide (0.125%) and DNOC (dinitro-orthocresol) at 0.1–0.5% forces the young winter leaf flush to abscise, with subsequent emergence of axillary flowering. A 0.5% urea spray applied to the late-summer growth flush causes the soft leaves to turn green, mature quickly and produce flowers in the spring. The higher the concentration of ethephon applied at the time when trees approached flowering, the lower the percentage of flowers produced.

Girdling (cincturing) branches or the trunk in late summer increases flowering and fruiting (40–800%) in litchi trees that would have flowered poorly in the spring. If no pronounced growth flush has occurred in the 6 months before the floral initiation period, or the trees are in poor condition or have had a late-autumn vegetative flush, they have increased flowering (Menzel and Simpson, 1987). Trees to be girdled should be fertilized immediately after harvest and irrigated to induce flushing and then girdled in late summer when the leaves have become fully matured (Fig. 9.1). Girdling of limbs and trunks of trees that start flushing in late summer has no significant effect on trees that would have flowered profusely on their own. Early recovery from girdling is associated with vegetative flushing during winter (Menzel and Paxton, 1986b).

Retention of litchi fruit after setting is a universal problem. Fruit development is punctuated by four phases of abscission (Fig. 9.6), the first occurring within 15 days of anthesis, in which more than 92% of pollinated flowers drop due to endosperm degeneration and subsequent embryo abortion. The second period of abscission is possibly due to degeneration of the embryo sacs. Phase IV does not occur in fruits that have aborted seeds. There are many causes of fruit drop, including unfavourable climatic conditions and nutrient deficiencies. Spraying newly set fruit twice at 15-day intervals with 35–100 ppm of 2,4,5-T and NAA progressively reduces fruit drop, improves fruit size and even hastens ripening (Prasad and Jauhari, 1963). Lower concentrations also reduce litchi fruit splitting, another serious problem in many areas. Growth regulators (GA 100 ppm, NAA 20 ppm, 2,4,5-T 10 ppm, chlormequate 250 ppm) sprayed on litchi cv. 'Rose Scented' at the pea stage had reduced fruit drop (Khan *et al.*, 1976). Spraying 'Early Seedless' and 'Calcuttia' with 20 ppm IAA enhances fruit set; 50 ppm GA-3 increases fruit retention and 100 ppm GA-3 improves fruit weight, with a combination of IAA and GA-3 being suggested (Singh and Lal, 1980).

Reduction of seed size or the production of seedless fruit has also been an objective in the use of growth regulators. Kadman and Gazit (1970), using

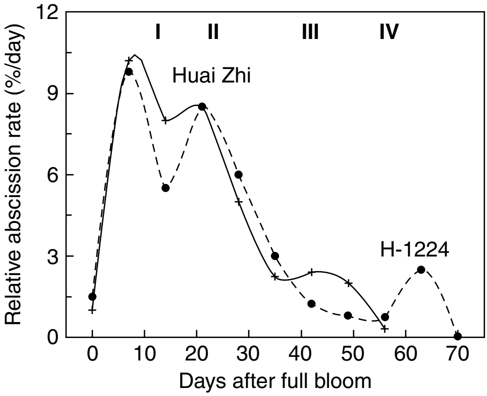

Fig. 9.6. Litchi fruit abscission rate, taken as a mean over 2 years, occurs in at least four stages (I–IV). Normal-seeded 'Huai zhi' (+) harvested 75–80 days after full bloom and aborted-seeded 'H-1224' (·) harvested at 70–75 days after full bloom (after Yuan and Huang, 1988).

2,4,5-TP (trichlorophenoxypropionic acid), prevented fruit drop to a higher degree and resulted in more than 75% of the litchi fruit having small seeds. However, if the inflorescence is first treated with 2,4,5-TP and then sprayed with a combination of 2,4,5-TP and gibberellic acid, fruits are 50–100% larger than those treated only once, and 90–100% of the fruits are seedless.

The development of forced flower initiation in longan by the use of potassium chlorate (Fig. 9.7) has extended the production area and also assured more regular yielding (Yen *et al.*, 2001). However, significant variations in flowering application methods have been reported. The variation is due to variety, developmental status of plants at forcing, soil conditions and climate (Yen *et al.*, 2005). Potassium chlorate is applied as a soil drench (200–1000g per tree), either as the salt or in solution is more effective than as a leaf spray (1–2%), injection (1–5%) or trunk girdling (300–600 g). Treatment with chlorate leads to flower induction and the appearance of flower buds in about 40 days, though it can induce leaf chlorosis and drop. Common bleach decomposes, especially at high temperatures to chlorate and a level of ~4 g/l has been detected (Matsumoto *et al.*, 2007). Trees treated with 7.6 l of household bleach (~30 g chlorate) were induced to flower (Fig. 9.7), and bleach was more effective than 250 g of chlorate. The greater effectiveness of bleach suggests potentially rapid decomposition in the soil to chlorate. The effectiveness of bleach supports an earlier observation that water released from soybean shoot factories induced longan to flower. Bleach is used to sterilize the seeds before germination and to wash down the equipment.

The rapid induction of flowers by chlorate means that a longan grower can take orders for fruit to be delivered 6 months later under good conditions.

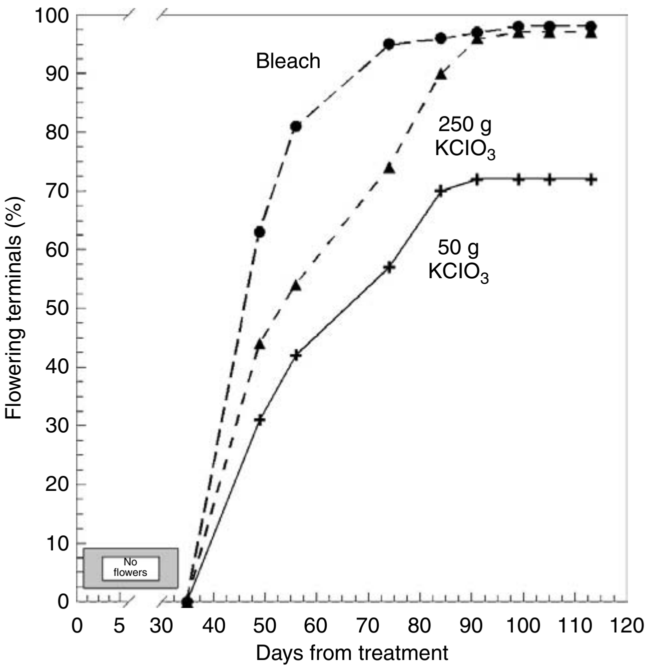

Fig. 9.7. Induction of longan flowering with potassium chlorate and bleach (redrawn from Matsumoto *et al.*, 2007). No flowers were observed for the first 35 days.

Another advantage of this treatment is that blocks of trees can be forced to flower sequentially to produce fruit almost year-round. Fruit quality is more affected by cultural management rather than potassium chlorate flower induction. The application of potassium chlorate has changed the pruning methods. Heavy pruning after harvest is now used to control tree size, followed by potassium chlorate application.

Fruit

Litchi fruit takes from 80 to 112 days to reach maturity from anthesis, depending upon the cultivar and environment (Fig. 9.8). Litchi aril growth begins about 25 days after anthesis and the aril growth then parallels total fruit growth. The fruits show a dramatic increase in total sugars from about 3 to 16–20% during the rapid growth period of the aril. Photosynthesis in the leaves behind the fruit cluster is more important than photosynthesis in older, shaded leaves or stored starch in the stem (Hieke *et al.*, 2002). The tart flavour

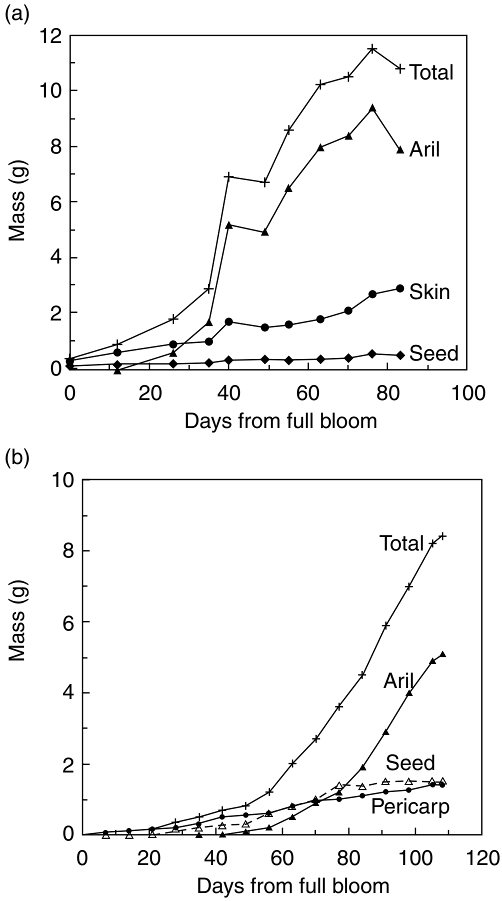

Fig. 9.8. The fruit growth pattern of (a) litchi cultivar 'Groff' fruit (after Paull *et al.*, 1984) and (b) longan cultivar 'Dong bi' fruit (after Ke, 1990).

of immature litchi fruit is due to high organic acids. The increase in Brix/acid ratio as fruits mature is due to the decrease in organic acids and increase in sugars (Paull *et al.*, 1984), contributing significantly to the litchi flavour. Peel anthocyanins increase and chlorophyll decreases during this same late growth phase. Cultivar differences do not allow peel colour to be an accurate measure of maturity. Late-season cultivars show a longer initial growth phase than the early and mid-season cultivars.

The size and shape of the litchi fruit are characteristic for different cultivars. 'Chenzi' has fruit averaging 23 g; other cultivars' fruits can weigh more than 30 g. The ratio of edible aril to seed is more important than large fruit size. Most cultivars have medium to large seeds, occasionally producing fruit with small, shrivelled seeds. The Hawaiian cultivar 'Groff' has perhaps the smallest-sized fruit (approximately 12.5 g), but produces small, shrivelled seeds, 'chicken tongue', in about 95% of the fruit, greatly increasing the edible portion to 50–70%. In cultivars with shrivelled seeds, little embryo development occurs, and the seed growth that does occur stops 30–40 days from anthesis.

Usually only one of the two locules in the litchi and longan ovary develops to form a normal fruit. The other aborts and remains at the base of the normal fruit. Occasionally, both carpels develop equally to form two normal fruit. The aril tissue in litchi and longan develops from just above the degenerating obturator and is formed by an outgrowth of the funiculus (Huang *et al.*, 1983). Aril growth parallels embryo development, though embryo development is not required for litchi aril growth. If embryo development is arrested during the liquid endosperm stage and when little embryo growth has occurred, the final fruit is filled with aril and a small aborted seed, called 'chicken tongue' (Huang and Qiu, 1987). When no endosperm development takes place, no embryo or aril development occurs and you get a 'hollow' fruit. Both of these conditions relate to fertilization disorders. Aril development is not uniform and thus overlaps at the chalazal end of the seed. The aril is therefore free from the seed in both litchi and longan.

Longan fruit are brownish, globose to ovoid, 1.5–2.0 cm in diameter; the skin is thin without protuberances and dull green when developing; the aril is white, translucent and sweet, with an aromatic spiciness. The fruits show a single sigmoid growth curve, with the major portion of seed development occurring between 50 and 70 days from anthesis, reaching maturity in 100 days. During early development the seed is the major sink in longan fruit, and aril growth occurs only after the seed has attained full size and maximum weight, about 50 days after anthesis (Fig. 9.8b). Growth of aril accounts for most of the increase of fruit weight during late development and reaches 60–70% of the fruit fresh weight. Growth periods were significantly different among longan varieties (from 140 to 200 days) and are not correlated to final fruit size.

Sugar accumulation in the longan aril begins after the main period of seed development, 70–100 days post-anthesis (Ke, 1990). The fruits can reach 25% total soluble solids and are ready for harvest when the total soluble solids reach at least 17–20% and suitable fruit size (above 8–10 g). Sugar accumulation in the aril begins after the main period of seed development, 70–100 days post-anthesis. The fruits show a dramatic increase in total sugars, from about 3 to 16–20% during the rapid growth period. The phenomenon is called 'desweeting' in China and Taiwan. The rate of desweeting varies with cultivar. Fruits of slow-desweeting types can be retained on the tree longer, and are better for adjustment of harvest time. The soluble solids of the cultivar 'October' in Taiwan can be maintained above 20% for 50 days.

CULTIVAR DEVELOPMENT

Cytogenetics and genetics

There are suggestions that the litchi may have been derived from more than one wild progenitor. Haploid chromosome numbers of 14, 15, 16 and, rarely, 17 have been reported, with diploid numbers of 28, 30 or 32. The diploid number for longan is 2n = 30. It is possible to generate intergeneric hybrids using litchi as the female parent with longan. The hybrid plants are similar to the maternal parent with smaller leaves.

Breeding and selection

Like most single-seeded fruit, the litchi and longan do not lend themselves to breeding by a controlled pollination system between two selected parents (Zee *et al.*, 1998). The highly heterozygous nature of the species means that planting open-pollinated seeds derived from within a cultivar collection is the usual procedure used in new cultivar development. For example, the Hawaii litchi cultivar 'Kaimana' is a selected seedling of open-pollinated seeds of 'Hei Ye'.

Litchi genetic diversity is indicated by the large number of cultivars in China and India, and these provide the basis for the development of new cultivars. Singh and Singh (1954) reported that the 33 or so cultivars grown in India are all selected from seedling populations derived from introduced Chinese cultivars.

It is difficult to identify longan cultivars by skin colour alone. Useful criteria for identification include the retention of total soluble solids after harvest, crispness and smoothness of the flesh, and taste (Table 9.3).

Selection and evaluation

Galán Saúco (1989) has presented a detailed list of characteristics for a litchi cultivar:

- Fruit: large, with small or shrivelled seed and a high proportion of edible aril; bright red skin colour; long shelf-life and ability to retain skin colour under storage conditions; firm flesh with acceptable sugar/acid ratio; and resistance to diseases.
- Tree: vigorous; precocious; regular and high yielding; resistant to water stress, wind, soil salinity, diseases and insects; and adapted to regular flowering under warmer temperatures in the tropics.

Table 9.3. Fruit characteristics of selected litchi and longan cultivars.

Cultivar	Synonyms	Season	Vigour	Fruit quality	Fruit wt (g)	Edible %	TSS	Flesh colour	Skin colour	Seed size	Cropping regularity	
											Tropics	Subtropics
Litchi												
Da zao	Tai So	early	vigorous	fair	24	72–77	15–18	milky white	bright red	large	regular	irregular
Hei ye	Hak Ip, Blackleaf, Groff	mid	moderate	good	19	78	16–20	milky white	dull red	large	irregular	irregular
Huai zhi	Wai chee	late	dwarf	good	21	72	15–18	milky white	dull red	large	irregular	regular
Gui wei	Kwai May (Mi), Bosworth	mid	vigorous	very good	17	70–83	18–21	white	light red	mostly small	irregular	irregular
No mi ci	No Mai Chee	mid to late	vigorous	excellent	25	82–86	18–21	milky white	bright red	small	irregular	irregular
San yue hong	Sum Yee Hong	early	medium	fair	40	62–68	15–20	milky white	bright red	large		
Chen zi	Chen Family Purple, Brewster	early	vigorous	good	20	54–58	15–18	waxy white	deep red	large medium	irregular	irregular
Longan												
Kohala		mid		spicy	15						regular	
Sao-an-liao		mid			15	62	13		dark brown	small		
Duan ru		mid			13		14					
Yang tao ye	Carambola leaf	mid			16		11					
Fen ke		mid		crispy	11	66	20	white	dark yellow	medium		

Continued

Table 9.3. Continued.

Cultivar	Synonyms	Season	Vigour	Fruit quality	Fruit wt (g)	Edible %	TSS	Flesh colour	Skin colour	Seed size	Cropping regularity: Tropics	Cropping regularity: Subtropics
Daw				good							regular	irregular
Chompoo				excellent							regular	irregular
Biew Kiew				excellent								irregular
Fuyan	Lucky eye	late	vigorous	good	12	67	15	transparent crispy	dark brown	small		regular
Wuyan	Black round	mid	vigorous	good	17	71	14	white	light brown	large		regular
Shi xia	Shek Yip, Shi Yuan	mid	vigorous	excellent	10	69	19	white crispy	dark brown	small		regular

Sometimes a selection is elevated to a cultivar status by satisfying only a few of the above characteristics (Table 9.3). Such a selection is ‘Groff’, by virtue of consistent bearing over a 7-year period, producing flowers usually several weeks later than other Chinese cultivars grown in Hawaii and producing aborted seeds in about 95% of the fruit. Average fruit size is 12.5 g, smaller than other Chinese cultivars grown in Hawaii, but there is approximately 20% more edible aril for the same weight of fruit (Storey *et al.*, 1953).

Breeding for adaptation of cultivars to the higher temperature conditions in the warm tropics is an important criterion (Menzel, 1983). Menzel and Paxton (1986a), using glasshouses at high temperatures (30°C day/25°C night) to evaluate litchi seedlings for low vigour, found this to be a useful technique for initial screening prior to field evaluation of adapted genotypes that would flower and fruit under warm conditions. The rate of flushing in the glasshouse at high temperatures agreed with the relative vigour and consistency of flowering of the parent cultivars in the field.

Similar criteria have been developed for longan (Table 9.3). Longan fruit criteria include retention of total soluble solids after harvest, crisp and smooth flesh, good taste, uniform size and high aril content.

Cultivars

According to Groff (1921), Chinese nurserymen recognized the difficulties in perpetuating the desirable characteristics of highly regarded cultivars under conditions other than those in which the fruit originated. The environment profoundly influences cultivar characteristics, and this may explain the large number of cultivars, with 74 cultivars mentioned in Wu Ying Kuei’s list of very ancient origin. Among the many known cultivars in China, the cultivars ‘San yue hong’ (‘Sum Yee Hong’), ‘Shui dong’ (‘Souey Tung’), ‘Fe zi xiao’ (‘Fay Zee Siu’), ‘Hei ye’ (‘Haak Yip’), ‘Gui wei’ (‘Kwai May’), ‘No mi ci’ (‘No Mai Chee’) and ‘Huai zhi’ (‘Wai Chee’) in Mandarin, with the Cantonese in brackets, are most widely grown (Table 9.4). Sixty-seven cultivars and selections are described for Guangdong, with 26 of these being major commercial cultivars (Anon., 1985). ‘Brewster’ (‘Chen Zi’, ‘Chen Family Purple’) trees are vigorous, large and one of the faster-growing cultivars. ‘Hei Ye’ has been observed to be a slow grower, low by comparison to cultivars such as ‘Chen Zi’ and ‘Gui Wei’ of the same age but becomes spreading.

Cultivars in Thailand are ‘Da zao’, ‘Hei ye’, ‘Huai zhi’ and ‘Hong huey’ (syn. ‘Mau mong’) (Table 9.4). Other cultivars are ‘Kim cheng’, ‘Hong thai’, ‘Ohia’ (syn. ‘Ouw’, ‘Hei ye’, ‘Baidum’), ‘Gui wei’, ‘Groff’, ‘No mi ci’, ‘Chen zi’ and ‘Mauritius’. In Australia, the cultivars most often planted are ‘Da zao’, ‘Bengal’, ‘Hei ye’, ‘Huai zhi’ and ‘No mi ci’. In the USA, Florida cultivates primarily ‘Brewster’, ‘Mauritius’ and ‘Sweet Cliff’. The ‘Mauritius’ in Hawaii is different from the Florida ‘Mauritius’. In Hawaii, most of the plantings

Table 9.4. Major litchi and longan cultivars grown in different countries (after Menzel and Simpson, 1990); name in national Chinese pronunciation unless otherwise indicated (*).

Country	Main growing area	Major litchi cultivars	Major longan cultivars
China	Guangdong	Huai zhi, Hei ye, Sun yue hong, Gui wei, No mi ci	Shixia, Chuliang
	Guangxi	Huaizhi, Heiye, Dazao, Sanyuehong, Guiwei, Nomici	
	Fujian	Shui dong, Hei ye, Da zao, Chen zi, Fu yan, Wu yuan, Shi xia	Fuyan, Wulongling, Chike
Taiwan	Taichung	Heiye, Nomici, Yuhebao, Huaizhi, Sakengzong, Sanyuehong	Chienliou*, Yangtaoye, Saoandiao, Duanru, Fenke
Thailand	Chiangmai, Lamphum, Fang	Da zao, Huai zhi, Hei ye	E-Daw*, Chompoo* (Seechompoo), Haew*, Biew kiew*, Dang*, Baidom*
India	Bihar State	Shahi*, Rose Scented*, China*	
Madagascar	Wet coastal belt	Da zao	
South Africa	Transvaal – Lowveld	Da zao	
Reunion		Da zao	
Mauritius		Da zao	
Australia	Eastern coastal strip	Da zao, Bengal*, Huaizhi, Gui wei, Salathiel*	
USA	Hawaii	Da zao, Kaimana*, Hei ye	Kohala*, Ilao*, Wai*, Sweeney*
	Florida	Brewster* (Chen zi)	Kohala*, Chompoo*, Homestead #1* & #2*

consist of ‘Da zao’, ‘Groff’, ‘Hei ye’ and ‘Brewster’. In subtropical South Africa, particularly in the Transvaal Lowveld, the Soutpansberg and Natal Coast areas, ‘Mauritius’ is the principal commercial cultivar and is a synonym of ‘Gui Wei’. The genetic diversity has led to many synonyms and confusion, along with mislabelling of different cultivars, with isozyme analysis and molecular markers now beginning to separate the different lines (Aradhya *et al.*, 1995; Viruel and Hormaza, 2004).

Although more than 400 longan cultivars have been developed in China, less than 10 are economically important (Chian *et al.*, 1996; Liu and Ma, 2001). More than 200 clonal cultivars are maintained at the National Longan Germplasm Repository at the Fruit Research Institute, Fujian. More than 50 cultivars have been identified in Taiwan, though less than 5 cultivars are widely cultivated (Yen and Chang, 1991). In Thailand, 'E-Daw' accounts for more than 90% of longan production (Subhadrabandhu and Yapwattanaphun, 2001). There are about 20 cultivars of longan in Australia, mostly introduced from China, Thailand and the USA. A longan clone 'Kohala' has been released in Hawaii and displays prolific vegetative growth and produces heavy crops in Hawaii as well at Homestead, Florida. There are numerous longans, with a wide range of characteristics (Table 9.3). Molecular markers are being developed to identify longan cultivars.

CULTURAL PRACTICES

Propagation

Sexual

Seed propagation is used to produce litchi seedlings from selected cultivars for breeding and selection studies and for production of rootstocks for grafting. Litchi seeds remain viable in the fruit for about a month after harvest with a moisture content of 45%; viability is soon lost within 4–5 days once removed from the fruit and the moisture content falls below 27%. Seeds packed in moist sphagnum moss may be shipped, though seeds frequently germinate in the packing within a week. Germination and seedling development is improved by the use of the large seeds and mycorrhizal soil for germination. Seeds germinate within 4–10 days in soil, sand, vermiculite, perlite, peat, wood shavings or mixtures of these materials, with adequate moisture and aeration. Seedlings are not used for new planting as they have a long juvenile phase of up to 10 years.

Longan seeds are also recalcitrant and quickly lose their viability after removal from the fruit. Similar to litchi, longan seedlings have a long juvenile period of greater than 8 years.

Asexual

Litchi and longan are usually propagated by air-layering, the method used by Chinese propagators for centuries. Moist peat or sphagnum moss is wrapped around the girdled area of a branch and held in place with plastic sheets cut to about 25–30 cm^2, with the ends fastened with string or some taping material, such as plastic electrician's tape. Sufficient roots are formed in 8–10 weeks, and the success rate is nearly 100%. There is no need to apply growth regulators to enhance rooting, though some recommend a lanolin paste with 250 ppm IBA, 100 ppm 2,4,5-T, and IAA or IBA at 500 ppm.

Cuttings with two to three leaves from girdled and ungirdled branches of 'Brewster', 'Gui Wei' and 'Hei Ye', treated with the sodium salt of NAA, IBA and their mixtures and misted or not in a polyethylene enclosure give poor results. Others have obtained 93% rooting and 100% survival by using green, woody cuttings dipped in 5000 ppm IBA and rooted under intermittent mist.

The variable and often low rate of success in litchi grafting is attributed to stock–scion incompatibility, poor cambial contact, grafting at the wrong physiological stage and poor management after graftage (Menzel, 1985). Graft incompatibility is suggested when only 20% of girdled 'Brewster' scion and 10% of 'Gui wei' are successful on rootstocks of the same cultivars. Histological studies of the graft unions between 'Hei ye' and the above two cultivars show a slow rate of proliferation of callus tissues. Currently, there is generally a lack of knowledge on the graft compatibility between litchi cultivars. Proper culture of rootstocks and preparation of scion-wood (girdling for starch accumulation), proper stage of maturity of scion-wood, appropriate post-graft environment, particularly high humidity, and other factors contribute to more consistent success in grafting.

Grafting is used for longan, with semi-hard terminals as scions. The scions are cleft-grafted into a node subtended by a leaf in Australia. This grafting is done on to 12–18-month-old rootstocks. In China, whip grafting, side grafting and budding are used. Top-grafting is used to top work large trees.

Field preparation

Deep ripping may be necessary if the soil is compacted. Liming to pH 5.0–5.5 should be carried out and manure incorporated before planting. Litchi trees tolerate poor drainage but do not grow well in standing water. Surface drainage should be installed if such conditions exist. If nematodes are expected to be a problem, fumigation should be carried out. Longans require well-drained alluvial soils for good development.

Transplanting and spacing

Sun-hardened trees (6–12 months old) can be planted out at any time of year if there is sufficient moisture available and there is no chance of frost. Light mulching (100 mm) after fertilization is beneficial for young litchi trees. Seedlings should start to produce fruit in 6–10 years and asexually propagated trees in 3–5 years.

Spacings of 5–12 m, depending upon cultivar size, are used. 'Gui wei' is a very vigorous tree, 'Hei ye' being moderate, while 'No mi ci' is a smaller cultivar. In Florida, litchi are planted at 7 m × 4 m, with regular mechanical pruning to avoid overcrowding (Campbell and Knight, 1987), and in subtropical areas 6 m × 6 m spacing is possible (Galán Saúco, 1990).

Windbreaks are necessary for young and mature trees for both crops. This is essential because trees propagated by air-layering do not have a tap root and are easily uprooted by winds.

Irrigation

Regular irrigation is essential during the growth of young trees. During dry periods irrigation may be needed at 2- or 3-week intervals. Moisture control is applied when the trees reach flowering age. In China, litchis are grown along canals, on dykes around paddy fields and around village ponds, and no irrigation is practised. Moisture should be withheld during autumn and winter to discourage vegetative growth and promote flowering (Fig. 9.1). High soil moisture tension for 6 months, beginning mid-summer, or even for 3 months, beginning in late summer, promotes floral initiation and fruit set by inhibiting emergence of vegetative flushes (Nakata and Suehisa, 1969). Once the inflorescence has appeared and throughout fruit development, adequate moisture is necessary. Irrigation should be terminated a few weeks before harvesting. Moisture stress under non-irrigated situations can cause developing fruit to ripen prematurely, even before the aril has fully developed. Fruit growth will resume if water is provided, leading to fruit splitting. Copious irrigation immediately after harvest is desirable to encourage new shoot growth (Fig. 9.1). In areas with dry summers, irrigation is necessary, followed by limb girdling in late summer to discourage further vegetative flushing and to accumulate carbohydrates in the trees during the autumn months (Nakata, 1953). This practice is necessary in areas where climatic conditions do not enforce a natural period of tree dormancy in the winter.

Pruning

Less research has been done on the need for and effectiveness of pruning longan trees than litchi. During the first 2–3 years, all side shoots up to 0.8–1.0m should be removed from litchi, as these will form low-hanging branches, which interfere with cultivation. In bearing litchi trees, even branches 1.5 m high will bend to the ground when laden with fruit. In Australia, the main terminals of 3–4-year-old trees are headed back in the spring (prior to flushing) in vigorous cultivars, to create a more compact tree with many terminals, thus increasing the potential bearing surface (Menzel *et al.*, 1988a). Approximately 16 cm is pruned from the tip, and from each pruned branch an average of three new terminals are produced. A pruning system is practised in Taiwan to maintain small tree size (<2 m), to obtain a wine-glass shape, to encourage regular flowering and for ease of management and harvesting (Yen, 1995). An inverted cone approach is also used: wide at the bottom and narrow at the top (3–4 m high), with mechanical trimming to maintain shape. Tree thinning is also practised after harvest, to open the canopy for light penetration, which is beneficial for inflorescence formation (Lin *et al.*, 1991). Light pruning sometimes encourages several weak flushes and results in poor flowering. Severe heading-back of a tree is harmful to future inflorescence formation. Little or no pruning is done in India and yields are said to be heavier than with the pruning practised in Taiwan. Canopy thinning after harvest is done in India. Panicle thinning or pruning is sometimes practised. Girdling is practised in October to inhibit new flushes; if too severe the next year's growth will be reduced (Yen, 1995).

Fertilization

Fertilization practices of commercial litchi (Table 9.5) and longan orchards differ due to differences in climate, soil, availability of different kinds of organic and inorganic fertilizers and other factors. The Chinese practice for litchi on alluvial or red basaltic soils provides 300–400 g of urea, 100 g superphosphate and 25–50 kg animal manure to large trees just after harvest, but not later than July. At blossoming, 100 g urea/tree or mixed NPK is applied. To prevent fruit drop, trees are sprayed with 0.1–0.2% urea; sometimes 0.2% magnesium sulfate is added.

A light fertilization application should be given with care immediately after field transplanting, due to the sensitivity of litchi roots to fertilizer burns. Heavy applications should be delayed a year or after one or two growth flushes. One-year-old trees are given ~30 g urea/plant/month. Also, 30 g of a high-analysis mixed fertilizer such as 15-4-11 is given every 3 months with

Table 9.5. General guide for litchi fertilization.

Year	Fertilizer formation	Time of application	Amount (g/tree)
First year	14-14-14	At planting time	125
	14-14-14	At 4 months	125
	14-14-14	At 8 months	125
	14-14-14	At 12 months	125
Second year	14-14-14	Once/4 months	250
Third year	14-14-14	Once/3 months	455
Fourth year	14-14-14	Once/3 months	455
Fifth year	10-20-20	Appearance of flowers (Feb, Mar)	1000–1500
	14-14-14	After harvest (May–June)	1000–1500

the urea. Fertilizer in subtropical areas is withheld during cold months to prevent flushing.

In Australia, general recommendations for 5-year-old trees are: 150 g urea, 300 g single superphosphate and 150–200 g potassium sulfate per application. These amounts are increased by 20–30% each year until year 15, when each application rate increases to 1200 g urea, 1200 g superphosphate and 600–800 g potassium sulfate. No fertilizer is applied to bearing trees in the spring, to prevent vegetative flushing in the autumn, in order to increase the prospect of good flowering. Three applications of a complete fertilizer, such as triple-14 at 114 g per tree the first year and increasing to 227 g per application in the second year, are used in Hawaii. In the third year, two or three applications at 454 g per application are applied. For bearing trees a general rule of thumb of 0.90 kg of a complete fertilizer for every 2.54 cm of trunk diameter is given upon completion of harvest to encourage summer flush. An application in late winter or early spring before floral initiation has begun can result in a vegetative flush rather than a flower flush. The main fertilization is applied immediately after harvest in the summer (Fig. 9.1), followed by irrigation and the annual limb girdling.

Critical nutrient periods are before flowering and fruit set, several weeks after fruit set and after harvest. Litchi leaf nitrogen should be *ca.* 1%. Leaf samples for analysis are taken twice a year, once at the end of harvest and the second at flowering, with only P and K applied during fruit set to avoid vegetative growth from N application. Minor elements are applied once a year at the end of the cold period.

Erratic bearing

Litchi trees 7–8 years old can produce up to 45 kg. Potential yields for 10-year-old trees are 50–70 kg, 15-year-old trees at 100 kg, and 20–24-year-old trees at 150–180 kg (Campbell and Knight, 1987). Occasionally, yields can be as high as 500 kg in very old trees. Apparently, potential yields can continue to increase with older trees, as has been demonstrated in China.

The litchi can be a heavy bearer when conditions are favourable for fruiting; however, considerable year-to-year variation in yields occurs wherever grown (Fig. 9.9). Erratic flowering can be due to unfavourable weather conditions, and even if flower production is consistent, fruit set problems contribute to variable yields (Chapman, 1984). Cultivars are very particular about their climactic requirement (Table 9.1); trees propagated from good bearing trees and planted in another location are known to have produced fruit for a few years and later ceased to produce for years.

Fruit bearing is dependent upon a number of crucial phases, which need to be optimized throughout the year (Fig. 9.1). The influence of cultivar, pruning and tree management needs to be integrated. Both species need to be

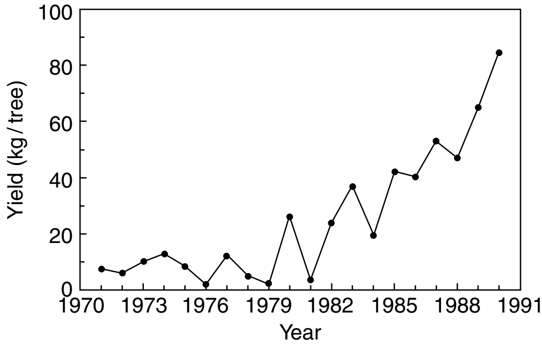

Fig. 9.9. Change in litchi production at Beilu, Guangxi from 1971. Improved management practices were used after 1981, which led to increased production and reduced, but did not eliminate, year-to-year variation in yield per tree (Mo, 1992).

stimulated to leaf growth after harvest; this is followed by a period of rest, then floral induction and development. These flushes are induced by fertilization and rainfall or irrigation (Yen, 1995). There can be more than one flush of leaves during the 5 months after litchi and longan harvest, with leaves being forced to mature and growth restricted after this phase. While mature leaves are essential for flowering, the presence of young, expanding foliage in the cool season is inhibitory to inflorescence formation; if removed, flowering capacity increases (Lin *et al.*, 1991). In autumn, young, expanding leaves can be removed mechanically or with a low rate of ethephon (1500 ppm); a higher rate will abscise more mature leaves. Tree girdling in late summer can be used to limit new shoot growth. The conditions for floral induction, besides tree condition, are temperature and water stress for litchi and temperature and possible nitrogen stress for longan. The terminal nature of the inflorescence inhibits further main axis development, with lateral shoots on branches that have fruited continuing further shoot growth, with only 22% that produce flowers in the following season.

Poor synchronization of flushing and flowering within an orchard increases management problems. Cultivars vary in their requirements for induction, leading to early- and late-season bearers.

Pest management

Diseases

A number of disease organisms infecting litchi fruit are listed in the literature, but none are considered to be serious and all are of a postharvest nature. *Aspergillus* spp., *Botryodiplodia theobromae*, *C. gloeosporioides* (anthracnose), *Cylindrocarpon tonkinense*, *Pestalotia* sp., *Penicillium* and *Alternaria* can cause some postharvest problems. Anthracnose is a problem in Florida, and the cultivar 'Mauritius' is especially susceptible, the fungus affecting young fruit and causing fruit drop. Many of these fruit fungal infections are secondary in nature, as the organisms enter the fruit only when the fruit skin is damaged. Puncture sites from fruit fly oviposition are excellent points of entry.

A serious disease of longan in China and Hong Kong is witches' broom, caused by a virus. The virus causes serious deformity of the inflorescence (Liu and Ma, 2001). It is transmitted by vegetative propagation and is seed-transmitted.

Nematodes have not been reported as a serious threat to litchi cultivation. However, tree decline in Natal and Transvaal is associated with two species of nematode. Roots become 'stubby' and brown in colour, and secondary feeder root development is inhibited.

INSECTS

Insects are of greater concern (Table 9.6) in litchi production than diseases. The erinose mite (*Aceria litchii*) is probably the most universal, having been reported from many widely scattered areas. It attacks the young leaflets, producing a thick growth of light brown to reddish-brown, felt-like hair on the undersurface. The worm-like mite is not visible to the naked eye and is very specific to litchi. Occurrence of this mite coincides with periods of new growth, regardless of season or locality, and in severe cases new shoots on the entire

Table 9.6. Insect pests of litchi.

Common name	Organism	Parts affected	Region
Erinose mite	*Aceria litchii* (*Eriophyes litchii*)	Foliage	universal
Leaf miner	*Conopomorpha sinensis*	Foliage	India and Asia
Rose beetle	*Adoratus sinicus*	Foliage of young plants	Hawaii
Trunk borer	*Anoplophora macularia*	Trunk	Taiwan
Bark borer	*Salagena* sp.	Bark/wood	South Africa
Shot hole borer	*Xyleborus fornicatus*	Branches	India
	Conopomorpha sinensis	Fruit	China
Litchi moth	*Argyroploce peltastica*	Fruit	South Africa
Macadamia nut borer	*Cryptophlebia ombrodelta*	Fruit	Australia
Litchi stink bug	*Tessartoma papillosa*	Fruit	China
Mediterranean fruit fly	*Ceratitis capitata*	Fruit	South Africa
Natal fly	*Ceratitis rosa*	Fruit	South Africa
Oriental fruit fly	*Dacus dorsalis*	Fruit	Hawaii

tree can be affected. It is effectively controlled by sprays of wettable sulfur at 2.3 kg per 378 l of water. It does not infest other relatives in *Sapindaceae*.

In Taiwan, a trunk borer (*Anoplophora macularia*) can cause death of trees within a few months by boring into the trunk and damaging the conducting tissues. The litchi stink bug can cause serious damage to fruit; the bug is effectively controlled by a parasite, *Anastatus* sp. In Australia, the macadamia nutborer (*Cryptophlebia ombrodelta*) is considered a serious fruit-damaging insect.

Mediterranean fruit fly (*C. capitata*) does not attack either species, except where the fruit skin has been broken by other means and the pulp is exposed. The Oriental fruit fly (*D. dorsalis*) does infest these fruit, causing punctures, which are often the focus of entry of fungal organisms that cause fermentation and decomposition. Other fruit flies can be serious pests in other countries.

Other pests are birds and fruit bats. In Hawaii, the White-eye (*Zosterops palpebrosus*) and the bulbul (*Pycnopus cafer)* can cause severe damage as fruits approach maturity. Fruit bats (*Pteropus* sp.) or flying foxes have caused severe losses in South Africa and Australia.

Weed control

Weed control is most important from the time of field transplanting up to 3 or 4 years old. As trees grow and expand horizontally, there is a decreasing amount of weed growth underneath the canopy, due to shading. Use of polyethylene mulch about a metre square around the plant at transplant time reduces weed growth near the plant. Litchi are reported to be adversely affected by organic mulches around the base.

HARVESTING AND POSTHARVEST HANDLING

Harvesting

Fruits are ready for harvest when they attain full red colour. Fruits harvested before full maturity are acid and do not ripen further or improve in flavour. These are non-climacteric fruit and do not respond to ethylene. Litchi and longan are harvested by cutting or breaking off the entire panicle with the cluster of fruit. The practice is to remove the panicle together with a variable portion of last year’s wood in many countries, to enhance the production of a higher number of terminals that may flower next spring (Galán Saúco, 1989). Panicles without fruit are also cut, as the presence of old panicles is reported to delay the next flush. In small orchards, bamboo or aluminum tree-pruning poles and tall ladders are used. In large orchards, mechanical ‘cherry picker’ platforms greatly facilitate harvesting. Harvesting fruit clusters on older, large trees is difficult and time-consuming. The trend of the last 20 years is to maintain tree height at less than 3 m. This height allows all management practices and harvesting to be carried out from the ground, which is faster and more efficient.

Harvesting is not done in the afternoon in China, as fruit colour is said to become dull more rapidly, or on rainy days, as wet fruit is said to break down rapidly. Panicles of fruit are packed in straw baskets or cartons containing 15–20 kg of fruit. Green leaves are also packed with the fruit, to reduce damage in transit and assist in providing moisture and preserving fruit colour. Harvested fruit are never exposed to sun, to prevent rapid drying.

Longan fruit maturity is judged by fruit shape, skin colour and the flavour of each cultivar. Most fruit can be picked from a tree with one harvest, unless multiple flowerings have occurred. No definite harvest index exists for longan, but growers usually note the changes in skin appearance: mature fruit develop a smooth and darker skin. Fruits are clipped from the stem, as hand removal often leads to some of the skin being removed. One-piece fibreboard crates, either 4.5 kg or 2.25 kg, with a plastic liner, are used, if not already packed in polystyrene punnets.

Postharvest treatments

The major problem in marketing these two fresh fruits is the rapid skin browning, which makes them unattractive, although the aril remains edible (Paull and Chen, 1987). In many Asian countries fruits are sold still attached to the panicle in bunches, while in western countries individual fruits in punnets are marketed. Much of the postharvest research has been directed towards the prevention of pericarp browning in storage and marketing of fresh fruit. The field skin colour of both litchi and longan can be retained by a sulfur dioxide acid treatment applied before insect disinfestation. All longan exported from Thailand are so treated, as are much of the litchi from some other countries. The sulfur dioxide treatment is not approved in the USA.

Retention of litchi red pericarp colour for longer periods has been demonstrated by wrapping fruit in PVC film or bagging in polyethylene bags and placing in storage temperatures of 0–10°C (Paull and Chen, 1987). Commercial quantities (5.4 kg) of litchi and longan packaged in large polyethylene bags and twisted closed, or individual fruits in punnets placed in cardboard cartons and sealed are best stored at 2°C for up to 32 days. At the retail level, all fruit not on display should be kept under refrigeration, preferably as close as possible to 0–2°C. If surface transportation is used instead of air freight, properly packaged fruit should be shipped at 0–2°C. Skin colour and flavour of fruit is retained for about a month.

Grade standards are similar for both species and are generally set between the shipper and buyer. Small, poorly coloured, immature or damaged fruit are culled. Similar mechanical injury to litchi tubercles leads to a site for skin browning. Soluble solids should be greater than 15% and acid levels low.

Longan pre-cooling is carried out by room or forced air cooling. Longan in plastic baskets can be hydrocooled, though hydrocooled longan should not be treated with sulfur dioxide. Sulfur dioxide fumigation damages hydrocooled fruit skin, producing brown spots on both the inner and outer skin surface and greater SO_2 residues remain on the fruit. Sulfur dioxide treatment of fruit to be sold as fresh is not approved in the USA and restricted in Europe.

The storage recommendation for longan is 4–7°C and 90–95% RH. Fruit can be held for 2–3 weeks, though the skin losses it yellowish coloration and becomes brown. At lower temperatures, there is a rapid loss of eating quality. At storage temperature less than 5°C, fruits develop a slight off-flavour after about 1 week. Peel colour of longan stored at 0°C turns dark brown, while SO_2-fumigated longan remain yellowish-brown. The dark brown peel of longan that develops at very low temperatures is regarded as chilling injury. When fruits are stored above 10°C, postharvest disease is of concern.

Controlled atmosphere studies have been reported, though modified atmosphere storage in 0.03 mm polyethylene bags has been tested for 7 days at room temperature, then 35 days at 4°C. A modified atmosphere of 1–3% oxygen delays browning and maintains soluble solids and vitamin C content in litchi. With 1% O_2 treatment and at carbon dioxide greater than 10–13% an off-flavour develops and a build-up of ethanol occurs.

Irradiation studies have shown that litchi and longan for export can be irradiated at 250 Grays. Hot–cold disinfestation protocols and cold treatment for fruit fly disinfestation can be used for litchi and longan (Paull *et al.*, 1995).

UTILIZATION

Important producing areas are China, India, Thailand, Taiwan, South Africa, Mauritius and Australia. Proximate composition of litchi and longan indicates they are a poor source of calcium, iron, thiamine and riboflavin and a fair source of phosphorus, and do not have provitamin A. They are a good source of niacin and ascorbic acid (Table 9.7). Both fruits are usually eaten fresh and can be preserved in a variety of ways. Dried litchi and longan, popularly known as a 'nut', and canning are the most common. Peeled litchi fruit may be canned in a 40% syrup, containing 0.2% citric acid. Hand-peeling of the skin is the usual method, though a hot-lye dip and mechanical peeling are used. The canned litchi, if fresh fruit are not available, are added to rare and dainty dishes, and restaurants serve delicious litchi dishes with meat or with syrup dressings.

Table 9.7. Proximate composition of 100 g edible portion of litchi ('Gui Wei') and longan (Wills *et al.*, 1986; Morton, 1987; Wenkam, 1990). The edible portion of litchi and longan is *ca.* 72%.

	Litchi	Longan
Water (g)	77.6	83.5
Energy (kJ)	335	–
Protein (g)	0.94	0.84
Lipid (g)	0.29	0.44
Carbohydrate (g)	20.77	14.9
Fibre (g)	0.16	0.32
Ash (g)	0.37	0.43
Minerals		
Calcium (mg)	4	9
Iron (mg)	0.37	0.4
Magnesium (mg)	16	–
Phosphorus (mg)	35	36
Potassium (mg)	255	170
Sodium (mg)	7	3
Vitamins		
Ascorbic acid (mg)	40.2	42
Thiamin (mg)	0.035	–
Riboflavin (mg)	0.084	0.05
Niacin (mg)	1.91	–
Vitamin A (IU)	0	–

Fresh litchi packed in polyethylene bags can be quick-frozen and stored for more than a year and still be edible, with the skin colour and flavour reasonably well preserved. Fruit can be sun-dried in approximately 20 days; two-thirds of the moisture is removed. Oven-drying can be used to shorten the drying time, but care must be taken to use relatively low temperatures of around 40°C, as higher temperatures tend to caramelize the sugars and produce a burnt flavour and bitterness.

FURTHER READING

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10

MANGO

Mango (*Mangifera indica* L.) is also known as manga (Tamil), mangga (the Philippines, Malaysia, Indonesia) and manguier (French). It is one of the best-known and most widely cultivated tropical fruit species, with production occurring in most countries in the tropics and subtropics. The fruit is marketed fresh, dried and as a juice, and is used as a source of flavours, fragrances and colourants.

BOTANY

Mango (*M. indica* L.) belongs to the family *Anacardiaceae*, also known as the cashew family, with about 75 genera and 700 species, mostly tropical, with some subtropical and temperate species. Common nut-bearing species include *Anacardium occidentale* L., cashew nut, and *Pistacia vera* L., pistachio nut. Other related fresh fruits are in the genus *Spondias*: the yellow mombin or hog plum (*Spondias mombin* L.), the ambarella or June plum (*Spondias cyhterea* or *Spondias dulcis* Forst.), and the purple mombin (*Spondias purpurea* L.). Another species belonging to this family is the marula (*Sclerocarya birrea* spp. *caffra* Sand) of Africa.

The genus *Mangifera* consists of 69 species but not all bear edible fruit. The mango fruit is large, fleshy and sometimes fibrous (Fig. 10.1). Other species in the genus bearing edible fruit include *Mangifera altissima* Blanco, *Mangifera caesia* Jack., *Mangifera foetida* Lour., *Mangifera lagenifera* Griff., *Mangifera odorata* Griff., *Mangifera zeylanica* (BL) Hooker and *Mangifera sylvatica* Roxb.

Origin and distribution

The mango originated in the Indo-Burma region and has been cultivated in India for more than 4000 years. This fruit is intimately associated with the Hindu religion and there are numerous ancient Sanskrit poems praising

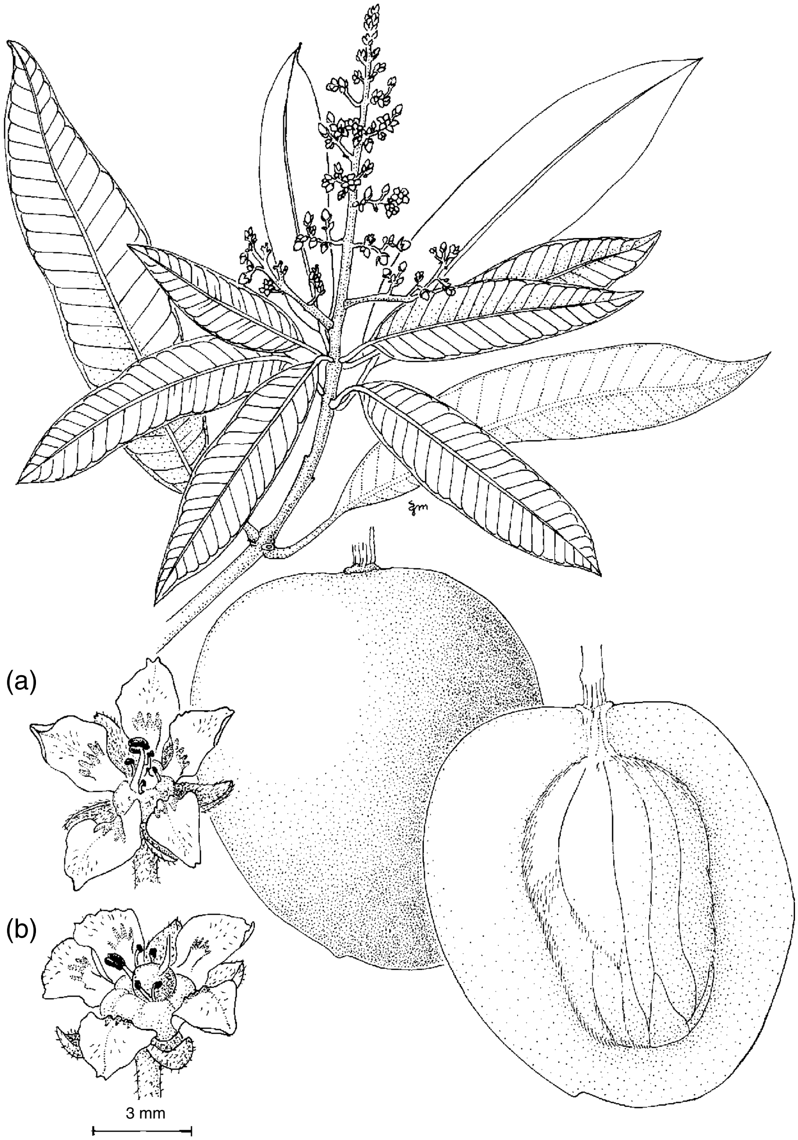

Fig. 10.1. Leaf, flowering panicle – (a) male flower with one functional stamen and four smaller, non-functional stamens with no ovary and (b) hermaphrodite flower with a large ovary with a single stigma and a single large stamen – and fruit of mango.

the blossoms and fruit (Singh, 1960). Indian traders and Buddhist priests probably introduced the mango into Malaysia and other east Asian countries during the 4th or 5th century BC and to the Philippines between AD 1400 and 1450. The Portuguese, the first Europeans to establish trade routes with India, transported the mango to East Africa and Brazil. Spanish traders took the mango from the Philippines to the west coast of Mexico before the English arrived in the Hawaiian Islands in 1778. The mango was introduced into Hawaii from the west coast of Mexico between 1800 and 1820, with credit being given to Don Francisco de Paula Marín, a Spanish horticulturist. Apparently, the Brazilian introductions were spread to Barbados and to other islands in the Caribbean area. Mango is now found in all tropical areas, as well as many subtropical regions of the world, attesting to its wide range of adaptability.

ECOLOGY

Soil

The tree is not exacting with regard to soil, although flat alluvial soils with pH 5.5–7 and a soil depth of at least 1 m are preferred. Freely drained oxisol soils, such as the deep volcanic soils in Java and the Philippines, are favoured. It can grow in 40 cm-deep soils in Florida (Malo, 1972), 75 cm in South Africa (Mostert and Abercrombie, 1998) or 80 cm in the Canary Islands (Galán Saúco, 2009). A hard layer or hardpan in the soil profile can limit root penetration and needs to be broken by subsoiling. In fertile soil, minimal nutritional problems can be expected. Exchangeable aluminium, which can be toxic, should be less than 30 ppm, and the tree is sensitive to saline conditions. Calcareous soil with a high pH and salinity problems limit mango development, although in Israel, mango is grown in very sandy soils, as well as in calcareous soils (>38% $CaCO_3$) with a pH close to 9 (Whiley and Schaffer, 1997). Suitable rootstocks have been selected and used in areas where these soil types exist, as well as in saline soils.

Climate

Rainfall

Mangoes are very drought-tolerant with a deep root system, which enables it to capture water and nutrients from deep in the soil profile. The tolerance of drought is also associated with the leaves and their latiferous cells remaining turgid through an internal osmotic adjustment (Schaffer *et al.*, 1994). The tree can withstand occasional flooding and it is seen growing and producing fruit on the banks between flooded rice paddies. Good rainfall distribution is crucial for flowering and fruit set, rather than total rainfall. A dry period is necessary for reliable mango production, as it promotes flower induction and improves flowering intensity and synchrony, especially if the dry period coincides with cool weather (Fig.10.2). In tropical high-rainfall areas, flowering is more erratic and yields are low, with excessive vegetative growth. Flowers are very susceptible to the disease anthracnose, particularly when rainfall occurs during flowering, and low rainfall is preferred at this stage. Irrigation must be applied regularly to prevent water stress during early fruit development when cell division occurs and to produce a vegetative flush after fruit harvest.

Temperature

Mango can be grown to 1200 m in the tropics, although the best production occurs at less than 800 m. A temperature around 33°C seems to be the ideal for flowering and fruit maturation and between 25 and 27° for vegetative growth (Galán Saúco, 2009). The tree can endure up to 48°C during fruit development if sufficient irrigation is available, though at 40°C some leaf damage can occur. Pollen viability declines if it develops at higher than 35°C or below 15°C (Fig. 10.3). The lower limit for vegetative growth is 15°C (Whiley *et al.*, 1988), with the damage minimum being 1–2°C, and the tree has no ability to acclimatize. Frost can severely damage or kill young trees, with older trees being able to endure −4°C for a few hours with limited damage (Crane and Campbell, 1991).

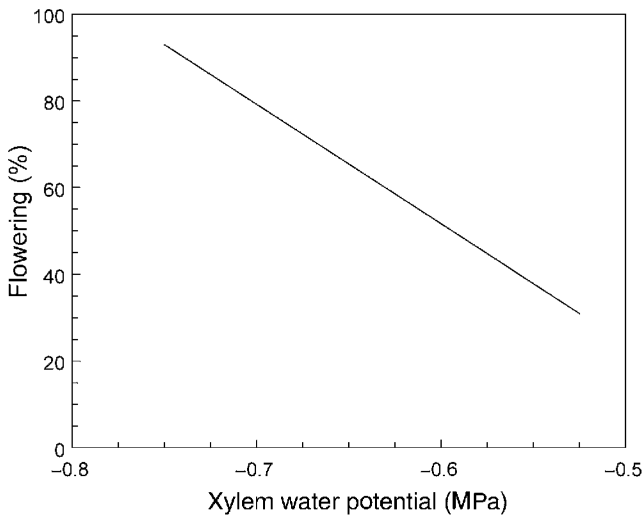

Fig. 10.2. Relationship between xylem water potential in the 6 weeks prior to 'Nam Dok Mai' panicle growth and the percentage of terminals flowering: $y = -121.83 - 286.7x$, $r^2 = 0.52$ (Pongsonboon, 1991, cited by Schaffer *et al.*, 1994).

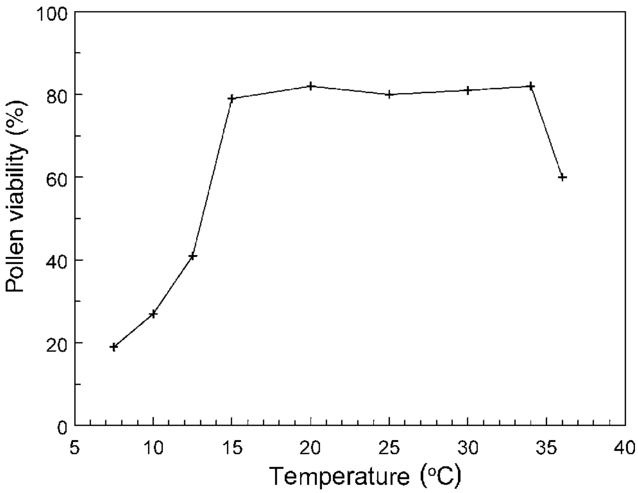

Fig. 10.3. Effect of temperature during pollen development on mature pollen viability (Issarakraisila *et al.*, 1993).

Temperature plays a key role in mango flowering, and the response varies with cultivar. For flower induction, the ideal seems to be around 10–15°C. The cooler temperatures in the subtropics are normally followed by flowering, with temperatures ~5°C inducing more male flowers on the inflorescence. Panicle growth does occur at 12.5°C, when no vegetative shoots are produced (Schaffer *et al.*, 1994). However, low temperatures (<16°C) lead to flower deformation, loss of pollen germination (Fig. 10.3) and slow pollen-tube growth and induce ovule abortion, with the production of seedless fruit (Young and Sauls, 1979). For each 125 m increase in elevation and each degree of latitude north or south of the equator, flowering is delayed by 4 days.

Light

Shading can prevent or delay flower-bud formation, and a higher percentage of perfect flowers occur on the side of the tree receiving direct sun. Mango trees have a significant number of shaded leaves and pruning can increase light penetration to these leaves, but how this influences yield is unknown; more light may result in larger fruit. Fruits also have a brighter red skin colour under higher light (Schaffer *et al.*, 1994).

Photoperiod

Photoperiod seems to play no role in flower induction (Nuñez Elisea and Davenport, 1995). Flowering occurs at all photoperiods from 10 to 14 h at an inductive temperature of 18°C day and 10°C night. The failure of biennial cultivars to flower in the 'off season' in the subtropics and flowering occurring at the equator several times a year indicate a day-neutral habit.

WIND

Yield is reduced if strong winds occur during flowering and early fruiting; however, the critical threshold for wind exposure is unknown. In windy areas, windbreaks should be installed to improve yields and reduce fruit damage. Dry winds during flowering in the subtropics can cause the loss of flowers, and sometimes a second flowering will occur with better fruit set because temperatures are more favourable (Galán Saúco, 2009)

GENERAL CHARACTERISTICS

Tree

The mango is an evergreen, symmetrical tree ranging in height from 8 to 30 m, bearing leathery, simple leaves in a compact canopy. The leaves are alternate, elliptic or spear-shaped, spirally located and fairly leathery, and 10–40 cm long (Fig. 10.1). The leaves persist on the tree for up to 4–5 years before being shed. Leaves of young flushes are usually copper-red or purplish, gradually turning to dark green.

Vegetative growth occurs in terminal flushes of the same branch (Fig. 10.4); each flush generates 10–12 new leaves with 1–3 flushes a year. The number, frequency and length of these flushes per year depend upon cultivar, temperature, tree age, current fruit load and previous cropping history. More flushes occur in the tropics than in the subtropics. The strong dominance of the terminal bud prevents lateral buds from emerging. When shoot elongation slows and stops, a state of dormancy occurs in the apex until the terminal leaves have matured, and the shoot is then ready for the next vegetative growth flush or flowering. Reproductive flushes will occur after extended periods of shoot rest in the low-latitude tropics, aided by a dry period, or during cool winter months in the higher-latitude tropics and subtropics (Fig. 10.4b) (Davenport, 2003). It is common to see different parts of a tree flushing at different times, especially in the hot tropics. Biennial or irregular flowering has been observed in several cultivars in Hawaii; vegetative flushes occurring during the June–July period are more conducive to flowering the following spring than flushes that occur earlier or later (Nakasone *et al.*, 1955).

The roots form a dense and strong system distributed in the first 2–2.5 m and having a main tap root that can penetrate 6–8 m. If the water table rises, a second root system will form above the main system.

Flowers

The induced reproductive terminal buds of the stem produce a large, branched panicle (Fig. 10.1) with 300–3000 flowers, depending upon the cultivar. The

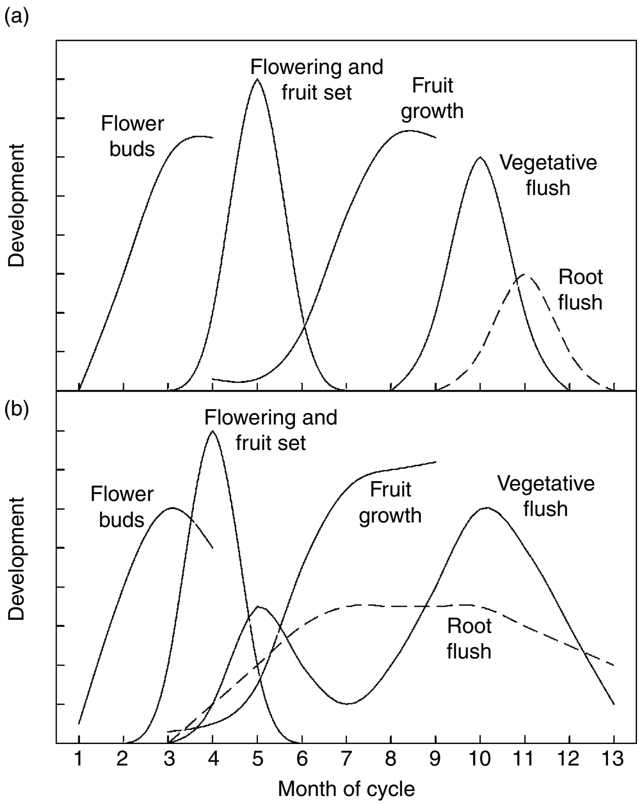

Fig. 10.4. Mango phenological cycle, having synchronous growth and flowering in (a) the subtropics (after Cull, 1991), and (b) the tropics, with asynchronous growth and flowering and a long juvenile phase (after Galán Saúco, 1996).

flowers reach full bloom in as little as 25–30 days after initiation. The panicles can be 6–40 cm long and 3–25 cm wide, with a pink or purple, sometimes greenish-yellow, rachis. Surrounding the terminal bud are smaller buds (subapical buds), which are morphologically lateral buds compressed into the apical position, subtending the terminal bud. Apical dominance disappears with the destruction of the apical inflorescence (Nakasone *et al.*, 1955).

The panicle consists of male (Fig 10.1a) and perfect hermaphrodite flowers (Fig. 10.1b). Perfect flowers consist of four or five calyx lobes and as many free petals (Fig. 10.1b). The centre of the flower is occupied by a circular disc (nectary) divided into four or five segments. The one-celled ovary with one obliquely protruding stigma is attached to this disc. There is usually only one functional stamen; the other four are reduced to abortive structures, called staminodes. The male flower (Fig 10.1a) is essentially the same, except for the absence of an ovary. Petals are pinkish-white, with several yellow ridges on the inner surface. The percentage of perfect flowers on a panicle ranges from 1.25 to 81%, with a strong varietal difference in flower-sex expression (Table 10.1). The percentage of perfect flowers is higher in the apical zone of the panicle than in the basal and central portions; climate can also affect the percentage, as can the position of the panicle in the canopy. Late-season panicles and those formed in the interior of the tree usually have a larger number of perfect flowers (Adlan, 1965). Flower and inflorescence colour and flower scent vary among cultivars.

A good crop of fruit is obtained when only a small percentage of the flowers are pollinated. Lack of fruit set is attributed to: (i) lack of fertile pollen; (ii) poor pollen-tube growth; (iii) failure of ovule fertilization; (iv) failure of pistil or ovules to develop; (v) abortions of embryo sac, embryo or endosperm; (vi) anthracnose disease of the flowers; and (vii) other physical factors (Schaffer *et al.*, 1994). Anthracnose disease is a major problem and is more prevalent if rainfall occurs during flowering. The disease will eventually affect the whole panicle, leading to flower and young fruit shed.

Pollination and fruit set

Natural pollination

About 65% of the flowers open before 6 a.m. and the rest open during the day. Anther dehiscence occurs within an hour after anthesis, with a maximum between 9 a.m. and noon. Eighty per cent of the pollen is viable (Fig. 10.3). Stigmas are receptive from 1 day before anthesis until 2 days after, with the day of anthesis being the optimum. Mango cultivars are considered to be self-fertile, but self-incompatibility has been reported. Self-pollination produces 0–1.68% set, while cross-pollination produces 6.2–23.4%, but there are clear cultivar differences. The pollen grains fall on the base of the ovary and the nectary discs rather than the stigma; hence pollination agents are required. Insects, including bees, wasps and flies, are the principal pollinating agents, as indicated by the sticky pollen, secretion of nectar, colourful corolla and flower

Table 10.1. Percentage of hermaphroditic and male flowers on three cultivars grown in Hawaii (Adlan, 1965).

Sex	Cultivar			
	Fairchild	Zill	No. 9	Total
Hermaphrodite	396	787	556	1739
Male	1660	1153	104	2917
Total	2056	1940	660	4656
% hermaphrodite	19.20	40.50	84.24	

scent. Flies seem to be the main pollination agents, with bees and other insects contributing. Wind may play a small role. Pesticide use during flowering affects insect pollination, pollen germination and ovule fertilization.

Polyembryony

Subtropical Indian cultivars and their derivatives, characterized by roundish, colourful fruit and susceptibility to anthracnose, are largely monoembryonic (Fig. 10.5a). Cultivars classified in the Indochina–Philippine group from Southeast Asia are largely polyembryonic, relatively resistant to anthracnose and often lack bright colour (Campbell, 1961). Polyembryony is the condition in which several genetically identical embryos develop from the nucellar tissue of the ovary and often suppress zygotic embryo development (Fig. 10.5b). These polyembryous fruits are typically more elongated than round (Fig. 10.6).

Fig. 10.5. Monoembryony (a) and polyembryony (b) in mango seedlings. In polyembryony, several genetically identical embryos can be formed from the nucellar tissue and often suppress the zygotic embryo.

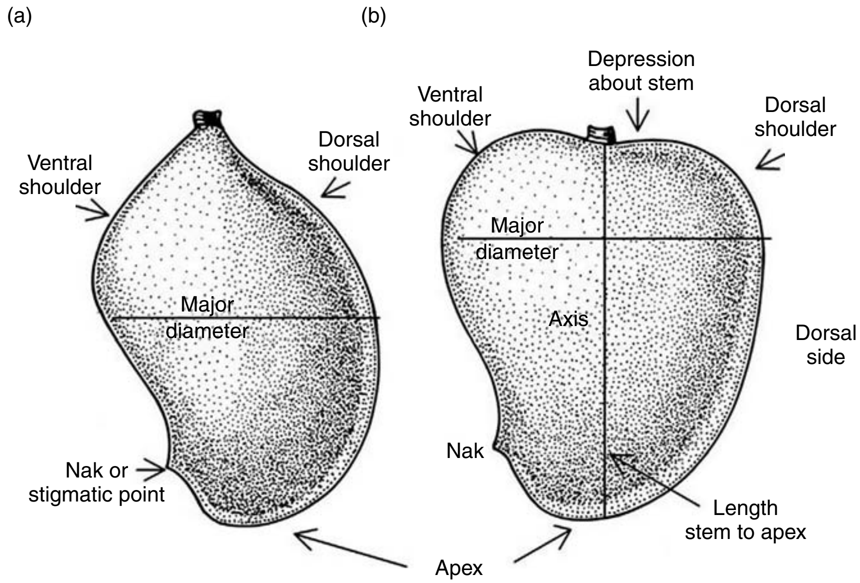

Fig. 10.6. Morphological characteristics of the mango fruit (Pope, 1929). Indochina–Philippine fruit are more elongated (a) and the Indian cultivars are more rounded (b).

Polyembryonic cultivars are generally believed to achieve higher fruit set, since apomictic embryos take over the functions of the aborted zygotic embryos and allow normal fruit development. Zygote abortion in monoembryonic cultivars stops further fruit development and usually leads to fruit drop. A small number of embryo-aborted fruit do develop into commercial-sized fruit. Seedless fruit are reported in 'Harders', 'Tommy Atkins' and 'Momi-K' (Galán Saúco, 1979), possibly due to embryo abortion taking place after growth-promoting substances required for fruit development have been produced in the endosperm.

Floral induction and fruit set

Biennial bearing and young fruit drop are major problems in commercial mango production. Shoot biochemical constituents thought to be related to flowering of regular- and irregular-bearing cultivars under different climatic conditions are not consistent. This has led to much research on overcoming the dependence upon environmental signals for flower initiation using different cultivars, using different management strategies and chemical sprays (Table 10.2). This will be discussed in more detail under cultural practices.

Both the number of hermaphroditic flowers per panicle and the fruit-bearing potential can be increased following application of 100 ppm of

Table 10.2. Chemicals for manipulating flowering or increasing fruit set and retention in mango (Galán Saúco, 1996).

Area	Chemical	Application time	Dosage (foliar sprays)	Action
Subtropics	GA_3	Prior to flower differentiation (beginning of winter)	100 mg/l	Delays flowering (repeated use during winter will eliminate flowering)
	Cyclohexamide	Flowering	0.25 g/l	Destroys apical panicles
	Dinoseb	Flowering	0.5 ml/l	Destroys apical panicles
	Pentachlorophenol	Flowering	5.0 g/l	Destroys apical panicles
	Ethephon	Full-flower stage	800 mg/l	Destroys apical panicles
	Hydrogen cyanide	Beginning of flowering season	0.4% (cv. Haden) 0.6% (cv. Keitt)	Destroys apical panicles
Tropics	NH_4NO_3	End of autumn	20 g/l	Interrupts flower dormancy
	KNO_3		40 g/l	
	Paclobutrazol	Any time during fruit bud stage or even at the end of autumn	2.5–5.0 g a.i./tree (soil drench)	Reduction of vegetative growth and flower induction; increases fruit set
General	Polyamines:	Prior to anthesis or at full bloom		Increase fruit set and fruit retention
	spermine		10^{-1} M	
	putrescine	Full bloom	10^{-4} M	
	KNO_3		2–4%	

naphthalene acetic acid (NAA) or deblossoming of terminal panicles either manually or with chemicals. Both methods delay flowering and can increase yield (Table 10.2). The stimulation of auxiliary panicles also occurs if early panicles are damaged by low temperature or winds in the subtropics. Sprays of GA can also delay flowering and fruit maturation by 2 weeks, but concentration and timing of application are critical if yield is not to be reduced (Turnball *et al.*, 1996).

Fruit

Fruit morphology

The fruit of the mango is a drupe of variable size and shape, ranging in weight from a few grams to more than 1 kg. It is fleshy, flattened, rounded or elongated in shape. A number of basic forms of the major morphological characteristics (Fig. 10.6) are used in describing the fruit (Pope, 1929).

Growth and development

Fruit growth showed a simple sigmoidal growth curve in terms of length, thickness, mass and volume against days from anthesis (Fig. 10.7). The skin

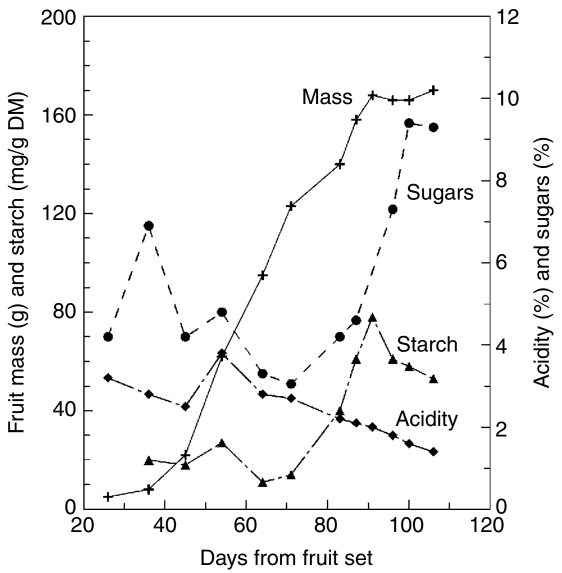

Fig. 10.7. Changes in developing 'Dashehari' fruit weight, starch and total sugars (after Tandon and Kalra, 1983) and 'Nam Dok Mai' titratable acidity (Kasantikul, 1983, cited by Mendoza and Wills, 1984).

of the young fruit is green, sometimes purplish, and, when ripe, green, yellow, orange, yellowish-red, purplish or purplish-red. The Indian group tends to mature with a yellow-and-red colour combination, while the Indochina–Philippine mangos have yellow- or orange-coloured fruit. Some fruits, such as 'Nam Dok Mai', have a slight pink hue on a yellow peel when ripe.

The peel (exocarp) is thick and the flesh (mesocarp) of ripe fruit is yellow or orange-yellow and juicy. The pericarp can be separated into exocarp, mesocarp and endocarp at about 14 days after anthesis. There is a period 9–14 weeks after fruit set when growth rate decreases, and this is associated with hardening of the endocarp and accumulation of starch and sugars (Fig. 10.7). The endocarp is hard, with fibres that may extend into the flesh. The period from fruit set to maturity depends upon cultivar and climate and can range from 10 to 28 weeks. The cv. 'Saigon' grown in a hot climate is ready for harvest in 12–13 weeks. In cool areas, where mean temperatures fall below 20°C, maturation is delayed by up to 4 weeks.

A network of latiferous canals and secretory ducts anastomoses in all directions in the exocarp and mesocarp (Joel, 1978). Cultivars with a poorly developed duct system are more susceptible to the Mediterranean fruit fly (*C. capitata* Wied.). The latiferous canals in mango begin to disintegrate during ripening and the fruit becomes susceptible to fruit flies. The sap from the skin contains urushiol, a toxin also found in other members of the *Anacardiaceae*, which causes an allergic skin rash on contact. Urushiol is catechol substituted with an alkyl chain with 15–17 carbon atoms. Some individuals are more sensitive than others.

CULTIVAR DEVELOPMENT

Genetics, cytogenetics and breeding

Cytological studies of seven species, *M. indica*, *M. sylvatica*, *Mangifera caloneura*, *M. zeylanica*, *M. caesia*, *M. foetida* and *M. odorata*, showed all to have a chromosome number of 2n = 40 (Mukherjee, 1950). *M. zeylanica* and *M. odorata* have been successfully crossed, indicating the possibility of interspecific crosses without the problem of interspecific sterility. This is supported by the uniformity of chromosome morphology. Although mango hybridization has been carried out, very few cultivars have been developed by controlled pollination. Hence, little genetic information is available.

Problems in breeding

Breeding is difficult because of the small number of seeds obtained, the complex nature of the panicle and flower (Fig. 10.1a, b), excessive fruit drop, long life cycle and heterozygosity of the crop (Knight and Schnell, 1993). The objectives of mango breeding are to develop regular-bearing dwarf trees that have an extended cropping season, good cropping in the wet tropics, attractive fruit of good size (300–500 g), free from internal breakdown and good keeping and eating quality without fibre. Active breeding programmes are carried out in many countries in the world, including India, the USA, Israel and Australia (Galán Saúco, 1996). Rating scales for important characteristics, such as size, shape, colour, firmness, fibre content, flavour, disease resistance and yield, have been developed. Characteristics are rated on 1 to 5 or 1 to 10 scales (least desirable to most desirable) in merely descriptive terms (Knight, 1985).

More recent objectives of mango improvement include resistance to diseases, such as anthracnose and powdery mildew, both devastating to fruit yields, and tolerance to environmental conditions such as soil salinity and cold temperatures. There is some variation in the degree of fruit susceptibility to anthracnose disease. Genetic transformation of mango is possible, using *Agrobacterium* as the transformant.

Cultivars

There are hundreds of named mango cultivars throughout the tropics and subtropics (Table 10.3). Each country or region also has their own selected cultivars (Table 10.4). Preferences for cultivars vary in different regions of the world. The most important commercial cultivars are derived from selections among open-pollinated seedling populations. Many excellent cultivars have been developed through introduction and selection by cooperation between researchers, growers, nurserymen and hobbyists. Seedlings can be produced by mass cross-pollination of a collection of mixed cultivars selected for known desirable characteristics among mono- and polyembryonic races (Whiley *et al.*, 1993). Only seeds from the monoembryonic cultivars are used as the female parent and planted for later evaluation. Polyembryonic lines are difficult to use as the female parent, as there is no assurance that a sexual seedling will be produced.

It is without doubt that India, with more than 1000 named cultivars and with different regions growing specific cultivars, has provided most of the germplasm for cultivar development. Florida has developed a large number of cultivars, using mainly Indian cultivars, which have shown wide geographic adaptability. 'Haden' was a major cultivar in the early mango industry in Florida. It may be a parent of other cultivars, including 'Irwin' and 'Lippens'. Other well-known Florida cultivars include 'Keitt', 'Sensation' and 'Tommy Atkins' (Campbell and Campbell, 1992). Most mango varieties planted in the Americas, the Canary Islands and many African countries were developed in Florida. The Florida varieties are also dominant in international trade and include 'Tommy Atkins', 'Haden', 'Kent', 'Keitt' and 'Van Dyke'.

Table 10.3. Some common mango cultivars grown commercially in different parts of the world.

Cultivar	Origin	Poly/ Mono	Fruit shape	Skin colour	Fruit maturation	Fibre	Eating quality	Storage	Anthracnose susceptibility
Alphonso	India	Mono	Oblique	Yellow	Mid	Low	Excellent		Low
Baptiste	Haiti	Poly	Oval	Bright yellow	Mid	None	Fair to good		
Carabao	Philippines	Poly	Long and slender	Greenish to bright yellow	Early	None	Good to excellent	Poor	Low
Haden	Mulgoba, India	Mono	Oval	Red blush or yellow	Mid	Abundant	Good to excellent		Susceptible
Irwin	Lippens, Haden	Mono	Ovate	Red	Mid	None	Good	Poor	Low
Keitt	Mulgoba	Mono	Oval	Red blush on green	Late	Little	Good to excellent	Good	Moderate
Kensington	Australia	Poly	Oblong ovate	Yellow with pink blush	Mid	Low	Excellent		Low
Langna	India	Mono	Oblong	Pink blush or greenish-yellow	Mid	Abundant	Fair to good		
Manila	Philippines	Poly	Long and slender	Bright yellow	Mid	Fibrous	Good to very good		
Mulgoba	India	Mono	Oval to ovate	Yellow with pink blush	Mid to late	Little	Good to excellent		Very susceptible
Nam Dok Mai	Thailand	Poly	Long slender	Bright yellow	Mid	None	Excellent		Susceptible
Neelum	India	Mono	Ovate	Bright yellow	Late	None	Good to excellent		

Pairi	India	Mono	Round to oblong	Orange-red	Mid	Little	Good		Moderate
Saigon	Vietnam	Poly	Oval to ovate	Yellow		None	Good to excellent		Low
Tommy Atkins	Haden	Mono	Oval to oblong	Dark red or orange-yellow	Mid	Moderate	Fair	Good	Resistant
Tong Dam	Thailand	Poly	Oblong to long	Greenish-yellow	Early	None	Good to excellent		Susceptible
Zill	Haden	Mono	Oval to ovate	Dark red to crimson or yellow	Mid	None	Good to excellent	Poor	Susceptible

Table 10.4. Producing countries, selected cultivars and main marketing season.

Country	Selected cultivar	Marketing season
Australia	Kensington Pride, Keitt, Kent, Palmer, Irwin	October to March
Brazil	Haden, Tommy Atkins, Kent, Keitt, Palmer, Bourbon, Espada, Itamarco, Maco, Rosa, Carlota	October to February
India	Alphonso, Banganpalli, Dashehari, Bangalora, Langra, Mulgoa, Neelum, Pairi	April to July
Indonesia	Arumanis, Dodol, Gedong, Golek, Cengkir	September to January
Israel	Keitt, Tommy Atkins, Kent, Maya, Haden	July to August
Malaysia	Harumanis, Golek, Maha 65, MA 200 (Malgoa)	June to August
Mexico	Haden, Manila, Esmeralda, Kent, Keitt, Tommy Atkins, Jan Dyke, Palmer	April to October
Peru	Kent, Tommy Atkins, Haden	November to February
Philippines	Carabao, Pico, Julie	June to September
South Africa	Peach, Zill, Fascell, Sensation, Tommy Atkins, Keitt	November to January
Spain	Tommy Atkins, Keitt, Lippens, Osteen	July to August
Taiwan	Irwin, Yellow #1, Haden	July to October
Thailand	Nam Dok Mai, Rad, Tongdum, Okrong	March to May
USA – Florida	Keitt, Irwin, Tommy Atkins, Kent, Van Dyke, Palmer	July to August

In Mexico, the ‘Manila’ and ‘Ataulfo’ varieties of Philippine origin are grown, while in Brazil, in addition to the main export varieties (Table 10.4), local varieties from material introduced by the Portuguese are also produced. In most of Latin America, different ‘criollo’ mango varieties are grown, which belong to the Indochina–Philippine group. These criollo types have survived as such since they are polyembryonic and almost exclusively propagated by seeds.

In the last few years some new varieties have been demanded by the US market, the largest import market, and also by the EU; these include ‘Edward’, a Florida variety, ‘Ataulfo’, a polyembryonic variety from Mexico, and others, such as ‘Madame Francis’ from Haiti and ‘Julie’ from Jamaica and the Caribbean. The EU is also starting to import other varieties such as ‘Amelie’ from Africa and ‘Nam Dok Mai’ from Thailand.

Hawaiian cultivars, such as ‘Pope’, ‘Gouveia’, ‘Momi-K’, ‘Ah Ping’, ‘Harders’ and ‘Joe Welch’, are all derived from monoembryonic parents. The recently released improved cultivars are ‘Rapoza’ and ‘Exel’, the former being a seedling of ‘Irwin’ and having large fruit with excellent eating quality;

it is a late bearer, with fruit maturing from August through October, greatly extending the season (Hamilton *et al.*, 1992). 'Exel' was also selected from a population of 'Irwin' seedlings for its high quality, attractive fruit and regular-bearing habits, with fruit weight ranging from 400 to 500 g and with 18% total soluble solids. Another desirable feature of the fruit is the thin, flat seed, which results in more than 90% edible flesh (Ito *et al.*, 1992).

Isozyme analysis has been used to verify or refute parentage of mango cultivars (Degani *et al.*, 1990). Isozymic banding has shown that 'Haden' appears to be a seedling of 'Mulgoba', and 'Zill' a seedling of 'Haden'. 'Mulgoba' has the *ab* phenotype and 'Keitt' the *cc* phenotype, while 'Haden' shows an *aa* phenotype, 'Carabao' *bb* and 'Edward' *ac*. Newer molecular-biology techniques are being used to unscramble the parentage of mangoes and to determine the extent of genetic diversity (Krishna and Singh, 2007).

Rootstocks

Most mango plants are grafted on to polyembryonic rootstocks in order to obtain plants that have a uniform root system, since they come from an asexual process and so are clones. There are several rootstocks in each country. In Latin America, some of the 'criollo' types of the Indochina–Philippine group are used; however, not all are good rootstock. In Mexico, the cultivar 'Manila' ('Carabao'), which is exported and consumed locally, is used. Israel has developed '13-1' for saline and alkaline conditions. South Africa uses 'Sabre' for sandy soils and '4/9' for heavy soils. In the Canary Islands 'Gomera-1' and in mainland Spain 'Gomera-3' are used (Galán Saúco, 2009). Australia uses the polyembryonic 'Kensington Pride', which is also a commercial fruit cultivar. Very little has been reported about the influence of rootstock on the cultivar growth.

The Indian cultivars 'Olour', 'Vellai Colamban' and 'Saber' are used as rootstocks to reduce tree vigour. Researchers have sought rootstocks with special attributes, such as dwarfing habit and tolerance to high pH and saline conditions. Two Indian hybrid cultivars, 'Mallika' ('Neelum' × 'Dashehari') and 'Amrapali' ('Dashehari' × 'Neelum'), have been reported to exhibit distinctly dwarfish characteristics in terms of trunk circumference, tree height and canopy diameter in Brazil (Pinto and Sharma, 1984). Tolerance to saline soils has been identified, and cultivar '13-1' is being used commercially as a rootstock in Israel, where calcareous soil and saline irrigation water pose serious problems (Gazit and Kadman, 1980).

CULTURAL PRACTICES

Propagation

Sexual

Mango seeds should be planted while still fresh, as they lose their viability within a few weeks. The usual procedure is to eliminate the pulp from around the seed by fermentation and washing, and superficially dry the seed in the shade for a couple of days. Uniform germination can be achieved if the kernel is removed from the hard endocarp or seed coat; this can be achieved by using pruning shears to cut the edges and remove the seed. During sowing, the concave part of the seed should face down and be buried about 4–5 cm into sand or a sandy mix. This sandy medium allows easy extraction of the seedlings with little damage to the roots when repotted. The germinated seedlings are separated and transplanted singly into polyethylene bags (18 cm (w) × 13 cm (d) × 30 cm (h)), and bags up to 45 cm in height help to avoid early root deformation. The seedlings are grown under ~30% shade. The seeds of polyembryonic cultivar produce several seedlings, some of which become twisted together and have curved stems and roots, and should be discarded and not transplanted into nursery bags. Monoembryonic seeds from breeding programmes can be planted directly into the polyethylene bags. Polyembryonic cultivars, though they can be propagated by seed as they retain the parental characteristics, are grafted to take advantage of the earlier production and shorter, stockier trees, avoiding the juvenile characteristics of seedling trees.

Asexual

Cultivars are propagated vegetatively by such methods as cuttings, grafting, budding or air-layering. Cutting propagation has been successfully achieved using hardwood or semi-hardwood cuttings, or subterminal cuttings with adult leaves being put under mist and bottom heat, and the cut surface treated with auxin (Reuveni *et al.*, 1991). This method is justified in cases of a scarcity of monoembryonic rootstock material.

Seedlings can be grafted in 6–8 months if fertilized and irrigated regularly. Grafting is usually some form of side or cleft graft, with the side-wedge method also being frequently used. Splice grafting is occasionally used. Only a well-matured terminal and the section below it should be used as scion wood, immature wood often fails to graft. Terminal scions are preferred because they will have no wound at the apex end of the scion piece. Budding methods permit the use of much younger rootstocks. Buds may be prepared in advance by removing the leaves of mature terminal wood. Removal of the leaves and the apical bud destroys apical dominance and allows axillary buds to begin to swell in 1–2 weeks. Air-layering and inarching are used in some areas to generate experimental plants rapidly. However, these time-consuming methods are appropriate when only a few plants are needed. Cultivars propagated by grafting and inarching grow faster than those propagated by stooling and air-layering. Grafting at a low height produces a spreading tree, while grafting high up on the stock produces a non-spreading type.

Field preparation

Land preparation is similar to that with other tree crops. Deep ripping may be necessary to break up any hard subsoil layer. In some cases sulfur has to be added if the soil is too alkaline. This is also the time when organic matter can be added without interference from the tree canopy.

Transplanting and spacing

Transplanting should be done just before or early in the wet season if no irrigation is available. Often, organic matter and P fertilizer are added to the planting hole (0.5 m × 0.5 m × 0.5 m) before planting. No shade is required after transplanting. Spacing is largely dependent upon environment, soil characteristics, vigour of the cultivar and the planned orchard management. Various patterns, with spacing from 6 m × 3 m to 7 m × 15 m, are recommended. High-density planting (3 m × 2.5 m) has been tested with grafted trees, and, while individual tree yields are low, total yield is higher, although extensive pruning is essential (Ram and Sirohi, 1991). In the subtropics, closer spacing (6 m × 4 m or 6 m × 3 m) is being used, with more detailed formation pruning and annual maintenance pruning to prevent the trees from becoming too large.

Irrigation

Young transplants require about 20–30 l of water every 4–5 days for about 2–3 months during establishment. For the remainder of the first year, rates may be increased to 40–50 l at 7–10-day intervals. During the second year, rates are increased to about 100–150 l per 10 days. More may be necessary during particularly dry periods. In the third year, rates of 200–300 l/tree at 15-day intervals may be adequate. Rates may be decreased or increased and the intervals shortened or lengthened, in accordance with soil type and the amounts and periods of rainfall.

Four- to 5-year-old grafted trees can begin to bear fruit, and cultural practices should be adjusted to reflect this change. For bearing trees, especially in the tropics, it is desirable to have a 3–4-month dry period prior to flowering, to reduce vegetative flush growth. This is easily accomplished in areas where this period coincides with the natural dry period. In dry areas, irrigation is desirable after the inflorescence appears and as flowers begin to set fruit. During the first 4–6 weeks of fruit development, cell division is most rapid and moisture stress should be avoided. Four-year-old trees may require around 400–500 l water/tree at 2-week intervals. Irrigation is completely cut off as the fruits approach maturity, since dry conditions favour higher sugar content. Heavy irrigation is resumed immediately after harvest to encourage new vegetative growth (Fig. 10.4). In the monsoon tropics, termination of harvest coincides with the rainy season, so irrigation is usually unnecessary. As soon as a major vegetative flush occurs, reduction in soil moisture content is desirable to mature the new flush. The choice of irrigation equipment and its management is based on capacity and efficiency of water delivery, and cost of the system plus installation. Irrigation should be programmed in accordance with the phenological growth cycle (Fig. 10.4) to achieve maximum yield.

Pruning

In most subtropical areas, the tendency is to use narrower plant spacings and keep the trees small by pruning. In the hot tropics, the trees are also kept smaller than before by pruning, but they are normally larger than in the subtropics.

Formation pruning can start in the nursery, at transplanting time or shortly after transplanting. All lateral shoots from the main stem are removed until the plants reach a height of 70–100 cm, to train the tree to a single trunk. For varieties with long hanging branches, at this height the top 10–20 cm is cut off below a node. In the subtropics this should not be done in autumn or winter, otherwise floral shoots might develop (Galán Saúco, 2009). Later lateral buds will sprout and three well-oriented and well-distanced shoots are left to become the primary tree branches. These shoots should be oriented in different directions, hopefully separated by a 120° angle; at the same time there should be a distance of 20–30 cm between them along the main stem, so that the weight of the adult tree is not concentrated at one point. For varieties that tend to produce very long shoots at a narrow angle, the selected primary branches can be forced to grow at a 45° angle. This forcing will slow their growth and induce more laterals to arise and reduce excessive tree height.

To obtain compact trees for narrow plant spacing, once the main lateral branches have stopped growing and mature, the terminal buds are pinched off, with as few leaves as possible being removed. From these pinched main lateral branches, three shoots are left to grow, and they will be pinched the same way, so that nine secondary branches are formed, and finally these can also be pinched, leaving three equally spaced new shoots on them, completing a total of 27 tertiary branches. This process is repeated during the first 2–3 years until a well-balanced plant is obtained.

When less-compact canopies are desired, pinching can be done every second or third flush, and later the canopies are opened at the centre by removing interior branches, so that the plant and fruit receive more light. In some tropical areas topping of the vegetative shoots at the second or first internode is done to obtain more-compact trees (Galán Saúco, 2009). Pruning can also be done to accommodate the trees for espaliers and trellises, where pinching is done at the height of the first wire so that two new shoots are directed along the wire and the third shoot grows up to the second wire, and repeated.

After the trees have been adequately trained, annual pruning is not usually practised. Mango trees normally make very dense growth, and occasionally light thinning of branches will become necessary to facilitate light penetration, air movement, pesticide penetration, removal of dead and diseased branches and some control over tree height. The tallest branches are cut back at the fork (point of origin) of the branch. ‘Water sprouts’ and overlapping branches may be removed annually. In Florida, pruning is done with machines called ‘ledgers’ and ‘toppers’ by cutting back the height and width of the trees to about 4 m. This is done annually immediately after harvest (Campbell, 1988). These trees have two or three vegetative flushes before becoming dormant at the onset of winter and then produce flowers in the following spring.

Pruning becomes a major endeavour when trees are allowed to outgrow the space provided. Yields are reduced and harvesting becomes difficult and uneconomical. Removal of alternate trees appears only to aggravate management problems later, as remaining trees will grow even larger. Drastic pruning of large trees to about 2 m to develop new tops on old trunks may cause approximately 3 years’ loss of income. Yearly pruning to less than ~3 m to control tree height is practised in Taiwan, without significant impact on year-to-year production. The fruits are bagged to reduce disease and insect damage, and fruits thinned to match fruit load to tree size (Fig. 10.8).

In cultivars with biennial (irregular) flowering, shoots that have flowered are removed after harvest, leaving only shoots that may flower next time. Flowering shoots that do not set fruit should also be removed soon after flowering. Removal of apical buds after each flushing cycle to increase the number of terminal shoots that could flower can lead to better fruiting and limits tree size (Oosthuyse and Jacobs, 1995). The number of terminal shoots, however, is not always related to the number of fruit set (Fig. 10.9). There is a strong correlation between number of terminal shoots and fruit number for the cv. ‘Sensation’, which retains a higher number of fruit per shoot than ‘Kent’, indicating that other factors are involved. Deblossoming of the terminal inflorescences can lead to inflorescence development from axillary buds, a 20–30-day-later harvest and higher yields (Chang and Lion, 1987).

In the lower tropics, where flowering time is modified, synchronization pruning is done every year to force the trees to produce new shoots at the

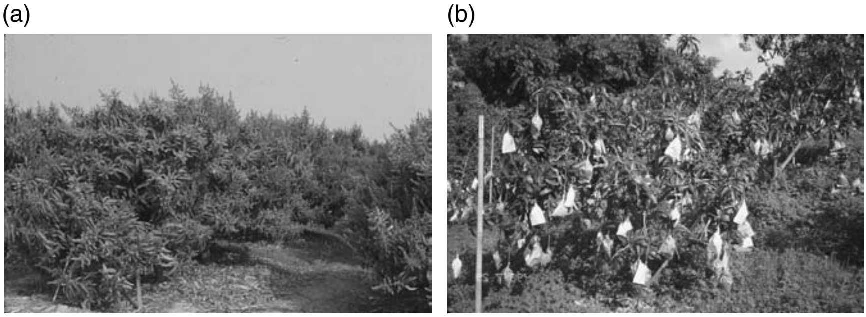

Fig. 10.8. Mango tree showing profuse and uniform flowering (a). Trees are managed to less than 2 m. When the fruits are about 7 cm across, the tree is sprayed with fungicide to control fruit diseases, the fruits are thinned and the selected fruits are bagged (b). One fruit has 6–8 leaves subtending it on the branch.

same time. For this, peripheral pruning is done all over the canopy, removing the tips of the last growth, including leftover floral peduncles, which have an inhibitory effect on future flowering. This pruning will force the tree to produce new growth, simultaneously resulting in more uniform flowering, since all new shoots are of the same age and in a similar physiological stage. This pruning should be rather light to avoid a strong tendency to get a second vegetative flush too soon, since this would not allow enough time for the shoot to rest and become reproductive. It is done soon after harvest, and it is the first step in the process of flower induction.

Fertilization

One of the basic considerations for fertilization amount and time of application is the growth and flowering cycle of the tree (Fig. 10.4). During the first 3 years, approximately 113–227 g per tree of a complete (NPK) fertilizer is applied three times a year. From the fourth year, trees are considered to be mature, as they will begin to produce commercial yields, and fertilizer is applied twice a year. One application is made when the first inflorescence begins to appear and the second immediately after harvest, to promote a new vegetative flush. Proper placement is important in ground application, as the highest feeder-root density is approximately 90–175 cm away from the trunk to a depth of 20 cm. Irrigation is necessary whenever fertilizer is applied.

The major mango-growing countries have usually developed their own fertilizer ratios and amount to be applied. Complete fertilizers, with an oxide ratio of approximately 15:15:15, are usually recommended in Hawaii (Yee, 1958). In Florida, a good crop can be obtained by providing 1.4–1.8 kg of N and K/tree/year to mature trees (Malo, 1976). Using the triple-15 fertilizer,

Fig. 10.9. Relationship between the number of terminal shoots on 2-year-old 'Sensation' and 'Kent' trees and number of fruit retained. 'Sensation' $y = 0.98x + 12.8$, $r^2 = 0.86$***, 'Kent' $y = 0.18x + 11.8$, $r^2 = 0.31$* (after Oosthuyse and Jacobs, 1995).

an application of 4 kg/tree in February–March provides 0.6 kg each of N and K. A second application immediately after harvest of 6 kg/tree provides 0.9 kg each of N and K, for a total of 1.5 kg each of N and K for the year. N and K at these levels are reported to enhance total yields, external colour and sugar content, while N in excess of 1.8 kg can produce unfavourable effects on external colour and flesh firmness (Young and Koo, 1974). When leaf N levels are greater than 1.5%, reduced fruit size is expected, with an increased incidence of 'soft nose' and soft brown rot and an increase in the number of days to ripen. Critical levels for various nutrients in mango leaves have been developed (see Table 4.3).

Flowering synchronization and induction

Ethephon, an ethylene-releasing compound, increases flowering and fruiting in 'off' years in biennial-bearing trees. In the past, to produce floral induction, Philippine farmers used smudging by burning rice straw close to the trees, with the smoke having a stimulating effect on mango flowering. This was possibly due to the ethylene gas in the smoke. In the last two decades more sophisticated approaches have been developed and are being used commercially.

In the subtropics, flowering depends on the cool winter temperatures (Fig. 10.4a) and flowering is enhanced by water stress. In cool winters, the plants will flower profusely (Fig. 10.8a). For young plants, this profuse flowering can limit plant growth and the ability to achieve the desired tree size, so the flowers and small fruit are removed during the first few years to allow the plants to become larger. In the tropics, flower induction is not dependent on a cool winter and is regulated by the time since the last flush matured after the sprouting induced by the synchronized peripheral pruning. If this shoot sprouts too soon, then the new flush will be vegetative; if the apex has rested for a longer period, a reproductive apex will form. The length of the rest period varies with variety.

The main aim of mango producers in the northern hemisphere is to harvest in March to April when prices are highest. In Central America, normal flowering occurs in January/February and the harvest then coincides with that of Mexico. Mexico, as the largest world exporter and main supplier to the USA, makes it difficult for other supplies to compete, and prices are low because of oversupply. Other northern-hemisphere suppliers use orchard management practices to induce earlier flowering and harvest 1–3 months earlier to coincide with the better market prices. This is possible as a major portion of Mexican mango production occurs under subtropical conditions in northern Mexico and they are unable to significantly modify the flowering time. Similar procedures are followed in other parts of the world in order to achieve better economic returns by harvesting before the bulk of production arrives to the market. During 'El Niño' years, when winter temperatures are higher, Peruvian and Ecuadorean mango production is affected, though little can be done to overcome the poor flower induction.

For these orchard management practices to work effectively to advance the flowering date, the following factors should be taken into account: (i) the plant leaf N concentration should be between 1.1 and 1.3% at the time of induction; higher concentrations result in vegetative shoots; (ii) the soil moisture content should not be low, in order to achieve a better reproductive response; this is difficult to control in the tropics if the induction time occurs during the rainy season; (iii) the age and maturity of shoots, with older shoots that have been inactive after vegetative growth and maturation being more likely to differentiate into a reproductive shoot. To limit vegetative growth an anti-gibberellin compound such as paclobutrazol is used. Low soil nitrogen and moisture also play a role in reducing the occurrence of early vegetative flush; and (iv) the effectiveness of the application of flowering stimulants, where the dosage, the tree coverage, age and state of the leaves and the time the product stays on the leaves influence the outcome (Huete and Arias, 2007).

Steps to induce flowering

Stimulation of new shoots

The primary goal is to stimulate abundant vegetative shoot production. This is achieved by: (i) synchronizing peripheral pruning after harvest, which will result in a uniform synchronous production of new vegetative shoots at the same physiological age. This pruning should also remove all of the last season's panicles, which inhibit future flowering. This pruning should not be extensive; (ii) a balanced fertilization programme that ensures good vegetative growth but does not provide excessive amounts of nitrogen, or lead to a deficiency; and (iii) soil moisture management that involves limiting irrigation as the leaves approach maturity to prevent the potential for premature shooting.

CHECKING VEGETATIVE GROWTH

Limiting vegetative growth can be achieved with paclobutrazol and uniconazole, the latter being ten times more potent. These products are expensive, sometimes difficult to find in most countries and if used improperly can cause permanent tree damage. These anti-gibberellin compounds inhibit sprouting and reduce the time needed between synchronization pruning and floral stimulation by about 1 month. These inhibitors are applied 1–2 months after harvest, when the shoots from the synchronization pruning have completed their growth phase. Paclobutrazol can be applied at a rate of 5–8 g/plant or 1 g/m of canopy diameter, while uniconazole is applied at a rate of 0.1 g/m^2 of the canopy shade. The application is made in 10–20 l of water put in a shallow trench at the canopy drip line; the soil should be moist before application and irrigated after, to carry the chemicals to the root zone. Another anti-gibberellin product, 'Pix' (mepiquat chloride), is sprayed at 1% active ingredient on to the canopy until run off. A 2–3 cm girdle can induce flowering but often leads to the death of ~5% of branches per year and is not recommended. Controlled scoring is now used on subterminal branches with little danger of tree damage. Controlling water stress is difficult in the tropics with frequent rain, except in tropical deserts.

Spraying flowering stimulants

Flowering can also be influenced by nitrates, such as potassium nitrate at 2–4%, calcium nitrate at 1–3% and ammonium nitrate at 1–2% sprayed on trees in the tropics, but apparently not in the subtropics. One to three additional sprays of the same chemicals can be done at weekly intervals if the effect is not satisfactory. Thiourea can be used instead of nitrates. Young shoots (1.25 months from bud emergence) of the Philippine cvs 'Carabao' and 'Pahutan' can be induced to flower uniformly by spraying 10 and 40 g/l of KNO_3, respectively. 'Carabao' flowered in 11 days, while 'Pahutan' required 20 days. Spraying older 'Carabao' shoots (8.5 months from bud emergence) with 10–160 g/l KNO_3 induced 100% flowering, with unsprayed controls remaining vegetative (Bondad and Apostol, 1979). Genetic differences among seedling trees and between cultivars means that variations in response to the chemical used occur, with the nitrate ion being the effective ion (Nagao and Nishina, 1993).

Eight factors will determine the success of these nitrate sprays: (i) the leaves have to be mature, dark green and brittle when squeezed; (ii) the nitrogen concentration of the leaves should be less than 1.3%; (iii) soil moisture should be low; (iv) application at night when cool and days are warm or after a cold front; (v) rain should not occur for at least 6 h after spraying to avoid the product being washed off; (vi) the whole tree should be sprayed to runoff; this can take 8–20 l/tree. A spreader sticker improves the effectiveness of the sprays; (vii) the best time to apply is after 4 p.m.; and (viii) the variety should be responsive. The Indochina–Philippine varieties respond readily to stimulation, while Indian variety 'Haden' responds better than 'Kent' or 'Keitt', and 'Tommy Atkins' is the least responsive. Advancing flowering date should be done in several small steps (Duarte, 2002) to avoid losing production. In the first year, flowering is brought forward 20 or 30 days, with a similar step in the following year, until the desired flowering date is achieved. Following application, flowering will occur in about 3 weeks.

Nitrates or other products do not induce or change apex differentiation: if it is a vegetative apex, a vegetative shoot will sprout; if it is a reproductive structure, a flower panicle will emerge; nitrates induce the bud to start growing. The factor that determines whether a shoot apex produces a flower panicle or a vegetative shoot is the age of the shoot from the time it started to grow after the synchronizing pruning. The older the shoot, the greater the possibility that a flower panicle will emerge. Normally 'Haden' shoots can be sprayed 4 months after synchronization pruning, while 'Tommy Atkins' needs 5 months for similar results. Davenport (1993) proposed the following model for mango flowering induction in the hot tropics:

With paclobutrazol application:

Harvest – pruning + 1 month, paclobutrazol + 3 months = 4 months to induce 'Haden'
Harvest – pruning + 2 months, paclobutrazol + 3 months = 5 months to induce 'Tommy Atkins'

Without paclobutrazol application:

Harvest – pruning + 5 months to induce 'Haden'
Harvest – pruning + 6 months to induce 'Tommy Atkins'

The paclobutrazol treatment reduces by 1 month the time that the shoot needs to be in a non-active stage to flower after nitrate application in the tropics. The result is explained by postulating that gibberellins are flower-formation inhibitors. Paclobutrazol and uniconazole have not been labelled for use on fruit crops in the USA, though they are not translocated into the fruit.

Fruit yields

Fruit yields vary with cultivar, climatic and edaphic conditions of the production site, cultural practices and other factors, such as diseases and insect pests. Yields over many years exhibit a sigmoidal curve, initially with low yields, increasing more rapidly and then dropping off as trees become crowded. The period of maximum production depends upon tree growth rate; a rapidly growing cultivar is more likely to show decreasing yields earlier, due to crowding. Mango yield studies over a sufficient number of years involving replicated plantings are relatively rare, due to time and cost.

In Puerto Rico, researchers determined yield potential, year-to-year consistency of production, estimates of incremental increase in yields over age of trees, fruit size and tree growth of 16 cultivars in their first 6 crop years. The adjusted cultivar mean yield can be separated into three yield groups, with no significant differences between cultivars within each group (Pennock *et al.*, 1972). The high-yielding group order was 'Ruby', 'Sensation', 'Eldon'. 'Lippens' and 'Irwin'; an intermediate group 'Earlygold', 'Keitt', 'Parvin', 'Zill', 'Haden' and 'Palmer'; and a low-yield group of 'Pillsbury', 'Kent', 'Edward', 'Santaella' and 'Jacquelin'. Cultivar consistency of bearing also gave three different groupings, having different cultivar make-up: 'Edward', 'Zill', 'Pillsbury', 'Ruby', 'Lippens' and 'Irwin' as regular bearers; 'Sensation', 'Santaella', 'Parvin', 'Earlygold' and 'Jacquelin' with intermediate consistency; and 'Kent', 'Eldon', 'Palmer', 'Haden' and 'Keitt' being highly inconsistent in yield (Fig. 10.10). The consistent-bearing cultivars with high yields were 'Ruby', 'Lippens' and 'Irwin'. 'Edward', 'Zill' and 'Pillsbury' show regular-bearing habit but consistently produce low yields.

A mango orchard on the south coast of Puerto Rico under similar conditions to those of the above experimental site began production about 5

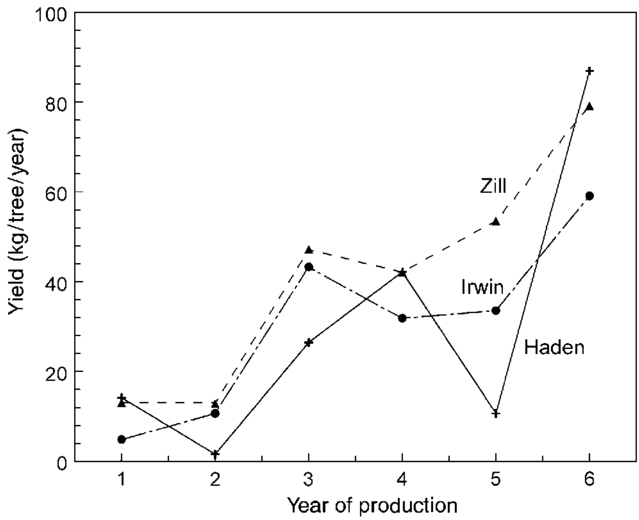

Fig. 10.10. Year-to-year variation in yield of three cultivars having different bearing habits (Pennock *et al.*, 1972).

years after field planting. The first crop had around 2.3 kg/tree, increasing to about 12.7 kg/tree/year during the next 5 years. On a per-hectare basis, with 173 trees/ha (57.8 m^2 spacing), the initial yield of 5-year-old trees would be 393 kg/ha, with a yearly increase of 2.2 t/ha (Pennock *et al.*, 1972). Yields obtained in Florida, Mexico, and Central and South America have shown that in the fifth year after planting, 0.9 t/ha can be expected, increasing to 1.7 t/ha in year 6, 3.5 t/ha in year 7, 5.2 t/ha in year 8 and 8.7 t/ha in year 9. Mature trees can yield 10–30 t/ha, with an average of 22–25 t/ha in the subtropics. In the tropics, commercial yields of 10 t/ha are expected from high-quality cultivars.

PEST MANAGEMENT

Diseases

Anthracnose (*C. gloeosporioides*) is perhaps the most important disease of the mango in almost all production areas (Table 10.5), as it attacks leaves, flowering panicles and fruit. Yields are drastically reduced when the inflorescence is attacked. This disease is especially serious in areas with high humidity and frequent light showers during the flowering period. In Hawaii, where rainfall coincides with the flowering season, almost the entire production of inflorescences can be destroyed. In the Ryukyu Islands of Japan (26°N), a crop of mango can be produced only by constructing polyethylene shelters over the trees to protect the inflorescence from the frequent light showers falling during the flowering season. For this reason, trees are kept at 1.8–2.4 m in height. In Australia, the cultivars ‘Carabao’, ‘Keitt’, ‘Tommy Atkins’ and ‘Zill’ have been identified as possessing tolerance to anthracnose (Whiley and Saranah, 1981). Control measures include weekly sprayings of the plants during flowering, alternating a systemic fungicide with a protectant; spraying during the coolest hours of the day and applying a protectant as soon as a noticeable weather change occurs are also recommended. Cleaning the orchard floor by picking old leaves and fallen fruit, as well as weed control, will also help to reduce the inoculum levels.

Powdery mildew (*Oidium mangiferae*) attacks leaves, stems and inflorescences and is a common disease of the dry subtropics, and it can also become serious, especially under drier conditions (Johnson and Coates, 1993). Normally, the treatments to control anthracnose also control both fungi, and treatment is necessary until the fruit reaches the size of a cherry.

A disease that has been reported from a number of areas and is very serious in India, Pakistan and Egypt is mango inflorescence malformation. Malformation occurs on vegetative shoots and flowering panicles. Panicles become short, branchy and compacted and produce solely male flowers (Shawky *et al.*, 1980). Lower temperatures during panicle development are

Table 10.5. Some important diseases, disorders and conditions of mango.

Common name	Organism	Parts affected, symptoms	Region or country
Anthracnose	*Colletotrichum gloeosporioides*	Inflorescence; leaf black spots, lesions on fruit	Universal
Powdery mildew	*Oidium mangiferae*	Leaves, inflorescence; whitish-grey powdery spores	Universal
Mango scab	*Elsinoe mangiferae*	Blossoms, leaves, twigs, fruit; greyish-brown spore masses, cracked tissues	Widespread
Bacterial black spot	*Xanthomonas campestris*	Leaves, stem and fruit; small watery lesions that coalesce, causing necrotic spots 2–3 mm diameter with irregular borders	Subtropical cold areas
Inflorescence malformation	*Fusarium moniliforme*	Inflorescence compact, sex shift to maleness; no fruit set; vegetative shoot compact with small leaves	Egypt, India, Pakistan, Africa, Americas
Stem-end rot[a]	*Diplodia natalensis, Fusarium, Alternaria, Cladosporium*	Fruit; blackening of stem-end of fruit, skin and pulp, over-mature fruit; rotting	Widespread
Sooty mould (not pathogenic)	*Capnodium* sp., *Meliola* sp.	Leaves, stem, fruit; sooty black appearance; symptom of scale insects, mites and mango hopper damage	Universal
Internal breakdown (jellyseed; soft-nose)	Unknown	Fruit; pulp breakdown	Florida

[a]Some similarity in symptoms; further studies required for clarification.

associated with a higher incidence. It is caused by *Fusarium moniliforme*, with mites playing a minor role. A highly significant reduction in malformation is achieved, with an increase in yield, by spraying with GA_3 and NAA, singly and in mixtures, with a second application 2 weeks later. Pruning all malformed vegetative and floral flushes, followed by spraying with copper oxychloride (4 g/l), is more effective than pruning alone to reduce the percentage of malformed panicles and increases the yield in the following season (Azzouz *et al.*, 1989).

Two other diseases with unidentified causes can sometimes cause serious loss, although little is reported in the literature. The first affects the bark at the base of the trunk, with increased gummosis on the upper trunk and large limbs. Wilting of branches occurs, followed by death, particularly to trees around 8 years old. It is especially serious in Nayarit and Sinaloa States in Mexico and has been reported from Colima State in Mexico and from Guatemala. Both *Fusarium* and *Phytophthora* are suspected but have not been confirmed. The other condition is a disease of the fruit, with no puncture wounds or insects being observed. The external symptom is a black spot 0.5–1.5 cm in diameter, usually located at the nak of the fruit. When the blackened area is cut, there is a hollow 'tunnel' leading to the seed cavity. The seed and seed cavity are blackened. When the fruit is cut open, many show the peduncular vascular system leading to the endocarp to be disintegrated (Nakasone, 1979). It was observed to be extremely serious in orchards of 'Tommy Atkins' in Nayarit and on 'Kent' in Campeche, Mexico, and subsequently reported to occur in the Canary Islands and in Guatemala, where it is called 'pepita negra'. Lakshminarayana *et al.* (1985) reported a similar preharvest stem-end disease of 'Tommy Atkins' in Mexico, except that no mention was made of the black spot on the nak of the fruit. Preliminary studies isolated a mixture of six species of *Fusarium* and produced more diseased fruit with typical symptoms than any other single isolate. Bacterial black spot (*Xanthomonas campestris*) of the mango appears to be a relatively serious disease in South Africa and Australia. It has also been seen in Hainan, China.

Insect pests

Mediterranean and Oriental fruit flies are spread widely throughout the world. Other flies are confined to specific regions, but together they constitute a major problem, particularly to the export trade (Table 10.6). Irradiation, hot water and vapour heat treatment have been developed to meet disinfestation requirements in importing countries. This is probably the most important pest of mango, since the presence of a larval form in the fruit renders it non-exportable to many countries. Exports are generally allowed to countries where the winters are very cold and the flies do not survive. The female flies lay their eggs in the developing fruit as it starts to ripen. Larvae produced by these eggs feed on the pulp and move through the fruit, causing premature ripening, rotting and fruit drop. The larvae eventually leave the fruit and bury into the ground to become pupae; this phase lasts until the adults emerge, and the cycle is repeated. Control measures include early harvest to shorten exposure time, eliminating other host plants, collecting and burying fallen fruit, and the use of traps to monitor adult populations. The release of sterile males can be very useful in isolated areas or valleys or islands where in-migration of new flies is difficult. Chemical control based on Malathion and hydrolysed protein bait is also used. Bagging is used in some countries (Fig. 10.8b); though expensive it results in fruit without fly injury, very little or no anthracnose, better colour and about 95% of the harvested fruit is saleable.

The mango seed weevil has been a major deterrent to mango export to some countries. The weevil is an Old World pest, but is found now in some parts of the New World: St Lucia, Guadeloupe and Martinique in the Caribbean region (Pollard and Alleyne, 1986). Field sanitation, chemical sprays, host-plant resistance, pest-free zones, fruit culling, using X-ray technology and irradiation are possible solutions to this problem, unless markets are found in temperate countries that do not require disinfestation. All cultivars are susceptible, with some cultivars showing lower seed infestations of 17% to a high of 86%. The weevil deposits its eggs on the surface in the sinus region of small green fruit in the lower 2 m of the tree. Upon hatching, the larva burrows through the soft pulp into the seed, goes through the pupal stages feeding on the developing seed and then finally develops into an adult weevil. When the fruit ripens and pulp decomposes, the adult beetles bore their way out of the endocarp and enter diapause in cracks and crevices on the tree until the next season. Since there is no external evidence of infestation and the fruit normally remains edible, the consumer is unaware of their presence. The weevil can affect the appearance of the flesh if the mature weevil burrows out, causing decay, which hastens ripening and may even cause premature fruit drop.

The mango hopper is a serious pest in India, the Philippines and some other areas. The hopper sucks the sap from flowering stems, causing them to wilt. In serious cases, most of the panicles are damaged. Mango flowers are destroyed by four mango blossom midge species and others attack the leaves (Table 10.6). One of these midges is a serious pest of mango flowers throughout the state of Hawaii, with several cultivars having 91% of the buds infested, leading to perfect-flower abortion. Eradication by chemical sprays is not feasible, due to the wide distribution and the large size of the trees, and biological control is not an alternative as no predators have been reported in the native habitats.

In Central America, cutting ants (*Atta*) can be a serious problem, especially for young plants because they can completely defoliate the tree. Control can include surrounding plants with an old tyre split in half and

Table 10.6. Some important insect pests of mango.

Common name	Organism	Parts affected, symptoms	Region or country
Mexican fruit fly	*Anastrepha ludens*	Larval damage to fruit	Caribbean
South American fruit fly	*Anastrepha fraterculus*	Larval damage to fruit	Americas
Caribbean fruit fly	*Anastrepha suspensa*	Larval damage to fruit	Caribbean, Florida
Queensland fruit fly	*Batrocera tryoni*	Larval damage to fruit	Australia
Mediterranean fruit fly	*Ceratitis capitata*	Larval damage to fruit	Widespread
Marula fruit fly	*Ceratitis cosyra*	Larval damage to fruit	Africa
Natal fruit fly	*Ceratitis rosa*	Larval damage to fruit	Africa
Oriental fruit fly	*Dacus dorsalis*	Larval damage to fruit	Asia, Hawaii, Philippines
Mango seed weevil	*Sternochetus mangiferae*	Seed	India, Hawaii, Philippines, S. Africa, South-east Asia, Oceania, Caribbean
Mango blossom midge	*Erosomyia indica* *Dasineura mangifera*	Sucking sap from floral parts	India, Hawaii
Mango hopper	*Idioscopus* sp.	Sucking sap from flowering shoots	Philippines, India, Africa, Oceania, Americas
Red-banded thrips	*Selenothrips rubrocinctus*	Sucking on underside of young leaves	Widespread
Coconut bug	*Pseudotheraptus wayi*	Sucking sap from young fruit, watery spot on fruit, fruit drop	Africa

half-filling this with water. Baits of chlorpyrifos insecticide used as pellets put on the ant trails or at the entrance of their nest are used. The ants take the pellets down the nest and as they come in contact with the fungus they feed on they die. Another way is to pump chlorpyrifos powder into the nest with a special blower; this will kill all ants if the product reaches all corners of the nest.

Other insect pests, such as scale insects, thrips and the red spider mites are found almost universally but they are relatively easily controlled by natural enemies and by chemical sprays and do not usually pose any problems.

Weed management

Weed control is essential during orchard establishment. Young trees can be grown under clean cultivation or sod. Frequently intercropping is practised during mango establishment with papaya, pineapple or vegetables. Canopy closure of maturing trees prevents weed growth.

HARVESTING AND POSTHARVEST HANDLING

Harvesting

Harvest maturity is determined by using criteria such as changes in colour, fullness of cheeks and hardened endocarp. The most reliable indicator of maturity is when the endocarp has hardened and there is a yellowing of the flesh near the seed; however, this is a destructive test. Immature fruit do not ripen to full flavour and should not be harvested, hence the importance of maturity determination. Fruit-set dates can be established as an index for harvesting. The fruit-set date for each tree is determined when the panicle shows a high percentage of initial fruit set. An old recommendation to judge the date of harvest was when the first fruit dropped, the fruits on the tree were ready to pick. The mango is harvested by hand from the ground, wherever reachable, or from ladders and by the use of a long pole with a metal basket or a cloth bag to hold two or three large fruit. Harvesting is also done using two people, one on a ladder to cut the fruit and let it drop into the hands of the other on the ground.

Postharvest treatments

Any form of bruising should be avoided during harvesting and transporting to the packing house. Normally the fruit will be harvested with a 3–4 cm length of peduncle; the fruit are put under the shade of the trees either on the ground in small furrows or on a layer of sawdust or in specially designed boxes with the cut part of the peduncle pointing down for about 30 min until the sap flow stops. In Australia, 'Kensington Pride' fruits are washed in the field. The use of shallow lug boxes minimizes bruising. At the packing house, fruits are usually placed in a water bath or hand-washed to remove the stem sap from the surface, and the peduncle is cut according to specifications. Sap removal is essential to prevent sap burn and should be done within 24 h (Lovey *et al.*, 1992). Fruit anthracnose can be controlled by dipping into hot water (52°C, 5 min). A combination of hot water and a fungicide or chlorine may also be used. When the fungicide is added to the hot water, the temperature can be reduced slightly (Akamine, 1976).

Grade standards are usually based upon size, colour and freedom from injury and defects. Other requirements include full development, freedom from stains and firmness. Since the fruit is easily bruised, fruits are packed in single- or double-layer cartons with adequate protective material or use of trays. The US box contains about 4.5 kg and the EU box 5 kg. In the local markets, mangoes are frequently packed in bamboo baskets or in wooden crates.

At ambient temperatures, shelf-life of this climacteric fruit is short: 7–14 days to fully ripe. Precooling to 10–13°C is beneficial during hot weather or when shipping is delayed. Fully ripe fruit can be stored at 8–10°C. The length of shelf-life varies markedly with cultivar, maturity at harvest, injury, calcium (Ca) sprays and exposure to ethylene. A dip in 4–6% calcium chloride can significantly increase shelf-life of some cultivars, with the response varying with season, field management practices and soil type. Fruit of 'Keitt', 'Tommy Atkins' and 'Muska' from successive harvests show an increasing rate of ripening changes during the 21 days' storage period at 12°C, suggesting a decrease in storage potential as the season progressed.

Mango is a climacteric fruit and ethylene can be used to reduce the time till ripening commences. A treatment of 100 ppm for 24–48 h at 25°C and 90% relative humidity (RH) is adequate. Acetylene generated from calcium carbide and ethephon can also be used. Skin colour is also enhanced by ethylene treatment by increasing degreening. The best ripening temperature range is from 21 to 24°C. At high temperatures of 32°C, ripening can be retarded.

Controlled atmospheres have been tested on mangoes and indicate some possibilities; storage in atmospheres of 5% oxygen (O_2) and 5% carbon dioxide (CO_2) is possible for 20 days, while off-flavours and skin discoloration occur at 1% O_2 or high CO_2 (15%). Cultivar differences in response have been reported and the extension in shelf-life may not be commercially viable. Controlled atmosphere for ripe fruit is ineffective. Containers with controlled atmospheres are available for transport. Modified atmosphere storage using plastic bags or wraps and waxing shows some delay in ripening. Off-flavours have been reported with some wraps and waxes that delay ripening. Waxes are widely and successfully used commercially on mango to reduce water loss.

Postharvest disorders include chilling injury, sap burn, internal breakdown and bumpy tissue (Wainwright and Burbage, 1989). Chilling injury is a storage disorder that occurs at temperatures below 12.5°C, the extent of the injury being dependent upon the storage temperature and duration: at 0°C injury occurs in 4 days, at 5°C in 8 days and at 10°C in 12 days. The symptoms include skin scald, failure to ripen and increased disease susceptibility.

Sap burn caused by fruit skin contact with sap exuded from the cut or broken pedicel reduces consumer acceptance because of the browning and blackening of the skin after lenticel penetration. The Australian cultivar 'Kensington' is very susceptible (Lovey *et al.*, 1992), while 'Irwin' is less susceptible. The sap component in 'Kensington' thought to cause the burn is the major non-aqueous terpene component, terpinolene; it can also burn 'Irwin', but in 'Irwin' the predominant terpene (6.8%) is car-3-ene. This sap is present in the latiferous ducts of the fruit and is not interconnected with the stem ducts. The latex is under some pressure and when the pedicel is broken can shoot 300 mm or more. Harvesting with the stem attached, draining with the pedicel down and washing are effective.

One fruit disorder, occurring especially in 'Alphonso' in India, is referred to as 'internal breakdown', 'spongy tissue' or 'soft tissue'. The lower half of the fruit is most affected and it may be related to preharvest heat stress. 'Soft nose' in Florida is serious, with high Ca inhibiting the disorder and high N increasing the disorder (Malo and Campbell, 1978). The 'jelly-seed' disorder is more widespread. The disease usually appears during the initial stages of maturity, with a loss of firmness of the pulp near the endocarp, which becomes jelly-like and translucent with advancing ripeness. The disorder does not develop after harvest. An open cavity may develop in the pulp at the stem end prior to pulp breakdown. 'Tommy Atkins' has been reported to be especially susceptible to this disorder, although 'Kent', 'Irwin', 'Sensation', 'Carabao', 'Alohouron' and a few other commercial cultivars of importance are also susceptible (Campbell, 1988). No pathogenic organism has been detected. The only recourse for this disorder is to harvest the fruit at the mature-green stage, before any colour break occurs on the skin.

Certain cultivars are particularly susceptible to lumpy tissue, which is not evident in green fruit but develops during ripening. The mesocarp contains white starchy lumps and the fruit surface develops indentations. Aetiology is unknown. It has been reported from Thailand and the Philippines. Internal fruit necrosis first appears as a brown area in the mesocarp and endocarp of rapidly growing fruit. This later extends to the skin and a brown-black gummy exudation occurs. These areas then collapse and are surrounded by corky tissue. This non-pathological disorder has been associated with boron deficiency.

Marketing

Consumer preferences vary, with the US market apparently preferring large-sized and highly coloured mango without the turpentine taste, colour being the more important. Mango marketing has taken on international dimensions, with major marketing centres around the world. Canada and the USA are the major markets in North America, while the major European Union (EU) markets are located in the UK, France, Germany and the Netherlands. In the Far East, Japan, Hong Kong and Singapore are lucrative markets for producing countries such as the Philippines, Malaysia, Thailand and Pakistan. The Philippine and Mexican mangoes dominate the Japanese market. The major supplier for Hong Kong is the Philippines.

Countries supplying the North American and European markets are Mexico, Ecuador, Brazil, Peru, Venezuela, Haiti, Jamaica and other Caribbean-island countries in the Americas, and Ivory Coast, South Africa and Mali in Africa. Egypt and Israel are small producers but are looking at the EU market windows. Increases in demand will largely depend upon increasing consumer familiarity with the fruit, quality and price structure. By virtue of geographical location in the southern hemisphere, South Africa, Brazil, Peru and Australia are able to supply mangoes to the North American, European and Asian markets during their winter months, thus making mango a fruit that is available year-round (Table 10.4).

UTILIZATION

The mango is rapidly becoming one of the leading trade crops in the tropics and subtropics. As postharvest handling techniques and shipping technology have improved, consumer demand has increased. The fruit is 60–75% flesh, 11–18% skin and 14–22% seed, depending upon cultivar, with the flesh being *ca.* 20% dry matter. Most of the mangoes produced are marketed in the fresh state for consumption as a dessert fruit. Fruit can be eaten green, and this practice is very popular in Thailand, the Philippines and Central America, with some starchy and crispy cultivars being preferred, such as 'Khieo Sawoey' in Thailand. Fruit may simply be peeled and sliced. Diced pieces may be added to salads and fruit cocktails. People consume mango simply because of its pleasant taste and flavour without much thought about the content of minerals, vitamins, lipids and amino acids. However, the mango is a good to excellent source of provitamin A and is considered a fair source of vitamin C (Table 10.7), although this varies greatly among cultivars, with a range between a low of 5 mg and as high as 142 mg/100 g of fresh material (Wenkam, 1990).

Table 10.7. Nutritive values of mango in a 100g edible portion (Wenkam, 1990).

Nutrient	Units	Haden	Pirie
Proximate			
Water	g	84.12	79.97
Energy	kcal	56	72
	kJ	234	301
Protein	g	0.39	0.55
Lipids (fat)	g	0.02	0.20
Carbohydrate	g	15.05	18.91
Fibre	g	0.54	0.70
Ash	g	0.42	0.37
Minerals			
Calcium	mg	8	6
Iron	mg	0.16	0.16
Magnesium	mg	12	12
Phosphorus	mg	10	15
Potassium	mg	159	126
Sodium	mg	0	3
Zinc	mg	–	–
Copper	mg	–	–
Manganese	mg	–	–
Vitamins			
Ascorbic acid	mg	15.10	15.00
Thiamin	mg	0.041	0.081
Riboflavin	mg	0.057	0.061
Niacin	mg	0.300	0.460
Pantothenic acid	mg	–	–
Vitamin A	RE	381	474
	IU	3813	4735
Vitamin B6	mg	–	–
Vitamin B12	mcg	–	–

A considerable amount of fruit is processed into various products, such as jellies, jams, marmalades, pulp, juice and canned slices, throughout the world. Green mangoes make excellent chutney and are being exported for raw consumption by Latin American and other ethnic groups in the USA and Canada. Canned mango slices have been processed in India since before 1925 (Hayes, 1966). Canned mango and dehydrated slices are important export products in the Philippines and some other countries.

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11

Papaya

Papaya (*Carica papaya* L.) is a popular fruit native to tropical America. It is usually grown for its small to large melon-like fruit. It is a herbaceous perennial, bearing fruit continuously at the leaf axils spirally arranged along the single erect trunk. The papaya is also called papaw, pawpaw, papayer (French), melonenbaum (German), lechosa (Spanish), mamao, mamoeiro (Portuguese), mugua (Chinese) and betik (Malaysian, Indonesian).

BOTANY

Taxonomy and nomenclature

The cultivated papaya belongs to the family *Caricaceae* and is the only member of the genus *Carica*. *Caricaceae* is a small family of dicotyledonous plants with six genera; four of tropical American origin (*Carica*, *Jarilla*, *Jacaratia*, *Vasconcella*) and one, *Cylicomorpha*, from equatorial Africa. *Caricaceae* species have been variously classified in families such as *Cucurbitaceae*, *Passifloraceae*, *Bixaceae* and *Papayaceae*. Approximately 71 species have been described, though Badillo (1993, 2000) reduced the number to 32 species, with the following distribution: *Carica*, 1 species, *Cylicomorpha*, 2 species, *Jacaratia*, 5 species, *Jarilla*, 3 species, *Vasconcella*, 20 species, and *Horovitzia*, 1 species.

Papaya (*C. papaya* L.) is the most important economic species in *Caricaceae*. *Carica* and *Vasconcella* species are dioecious, except for the monoecious *Vasconcella monoica* (Desf.) and some *Vasconcella pubescens* and the polygamous *C. papaya*. Most species are herbaceous, single-stemmed and erect. Other than *C. papaya* L., the other edible species are *Vasconcella candamarcensis* Hook. f., *V. monoica* Desf., *Vasconcella erythrocarpa* Heilborn, *Vasconcella goudotiana* Solms-Laubach and *Vasconcella quercifolia* Benth. and Hook (Storey, 1969). These fruit are mostly eaten cooked, being normally dry and lacking the juicy flesh of *C. papaya*. Another edible species, *Vasconcella pentagona*, is called 'babaco'.

Origin and distribution

C. papaya has not been found wild in nature and is only distantly related to the *Vasconcella* species, based upon isozyme and AFLP analysis. The greatest diversity in *C. papaya* exists in the Yucatan–San Ignacio–Peter–Rio Motagua area of Central America. The volunteer population in this area has greater diversity than domesticated populations (Morshidi, 1996; Van Droogenbroeck *et al.*, 2002). Papaya origins are rather uncertain, but there is some agreement among botanists that it originated in the lowlands of Central America, between southern Mexico and Nicaragua. Early distribution over a wide geographical region in Central and South America was aided by the abundance of seeds in the fruit and the seeds long viability. The accounts of 18th-century travellers and botanists indicated that seeds of papaya had been taken from the Caribbean to Malacca and on to India (Storey, 1941a). From Malacca or the Philippines, distribution continued throughout Asia and to the South Pacific region. Don Francisco Marín, a Spanish explorer and horticulturist, is credited with the introduction of papaya into Hawaii from the Marquesas Islands during the early 1800s. Papaya is now grown in all tropical countries and in many subtropical regions of the world (Anonymous, 2003).

ECOLOGICAL REQUIREMENTS

Major commercial production of papaya is found primarily between 23° N and S latitudes. Man has extended cultivation into regions as far as 32° N and S. At these latitudes, papayas may be best grown in well-protected areas at sea level. In Hawaii, at l9–22° N, papaya is grown at sea level and up to 300 m elevation.

Soil

Papaya can be grown on a variety of soil types, with the most essential requirement being drainage. A porous loam or sandy loam soil is preferred. In Hawaii, the crop is frequently grown on rocky, volcanic soil called a'a, composed of porous lava with some organic matter and excellent drainage; the planting holes are filled with soil prior to planting.

Soil pH should be between 5.0 and 7.0, with the range between 5.5 and 6.5 being more desirable (Awada *et al.*, 1975). At pH levels below 5.0, seedling growth is poor and mortality high. In soils with a pH range of 5.0–5.5, lime applications can increase growth and yield. Papaya can be grown successfully on problem soils. For peat soils, high rates of lime application (6–8 t/ha) are essential for cultivation. Micronutrients (boron, zinc and copper) are also applied to ensure production of high-quality fruit on these soils. Since the water table is usually high in peat soils and other alluvial soils along streams and canals, drainage is required. A major constraint is the tendency for trees to lodge in these soils, especially for heavy bearers, because of poor anchorage and limited root growth once fruiting commences. Cultivation of papaya on sandy soils requires the incorporation of large amounts of organic matter and heavy fertilization (8 kg/plant/year) coupled with irrigation. Boron deficiency and nematode infestations are two major problems encountered on sandy soils. On acid-sulfate soils, which are compact, acidic, contain toxic concentrations of certain micronutrients and prone to flooding, papayas have a relatively short economic life. This short lifespan is due to a poorly developed root system and extreme susceptibility to root and collar rot diseases under poor drainage conditions. Similarly, heavy clay soils should be avoided due to the poor drainage.

Climate

Rainfall

Papayas grow well and produce substantial yields without supplementary irrigation if there is a minimum monthly precipitation of approximately 100 mm. Since most tropical areas have monsoon-type climates with well-defined wet and dry seasons, successful production depends upon the availability of supplemental irrigation during the dry period.

A minimum relative humidity of 66% has been reported for papaya's optimum growth. Stomatal opening is controlled by humidity and, as relative leaf water content is not affected by drought stress, stomatal closure maintains leaf water status, allowing rapid return of gas exchange flux and growth upon rewatering (Marler, 1994; Clemente and Marler, 1996). Drought frequently leads to the rapid shedding of new flowers and older leaves, and poor fruit set. Five days of flooding leads to abscission of fully developed leaves which is preceded by chlorosis. Flooding frequently leads to plant death, due to root rots, while recovery from non-lethal flooding is slow, due possibly to the low root growth rate of fruiting trees.

Papaya has been ranked from extremely sensitive to moderately tolerant to salt stress. Germination and early seedling growth are the most sensitive stages to salt stress. It is probably moderately salt sensitive at other growth stages.

Temperature

Optimum temperature for growth is between 21 and 33°C; if the temperature falls below 12–14°C for several hours at night, growth and production are severely affected (Lange, 1961). Dioecious cultivars are better suited to low temperatures (<20°C), as female trees do not exhibit stamen carpellody shown by the more temperature-sensitive bisexual (hermaphroditic) cultivars (Fig. 11.1). Hermaphroditic cultivars (Solo type) grown at minimum temperature

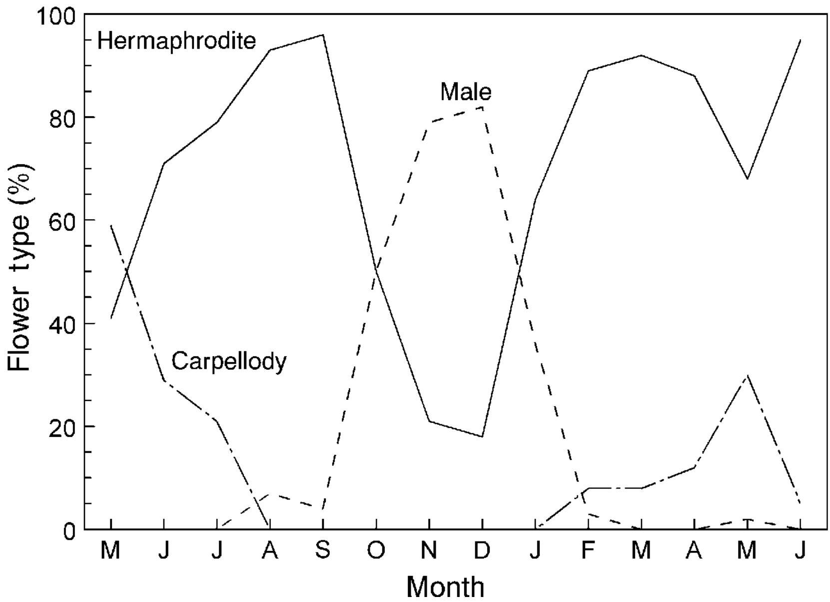

Fig. 11.1. The percentage of true hermaphrodite, hermaphrodite with functional stamens (male), and non-functional pistil and carpellodic flowers at different times of the year, on 'Solo'-type papaya tree growing in Honolulu with a mean minimum temperature of 21°C and maximum temperature of 27°C (Awada, 1958).

<17°C can have 100% carpellodic flowers. At higher temperatures (>35°C), bisexual cultivars often become functionally male, with poorly developed and non-functional female parts. This tendency varies with cultivars and within a cultivar. Net photosynthetic rate also rapidly declines above 30°C.

Temperature during the growing season significantly influences fruit growth and development from the normal 120–150 days (Fig. 11.2). The effect is most pronounced in subtropical areas. In these areas, fruit set does not normally occur in winter, and fruit set before the winter can take up to 90 days longer to reach maturity. Final fruit size is determined in the first 4–6 weeks of fruit development, and temperature plays a dominant role in the process, especially in subtropical areas. Fruits that develop in the cooler season have lower total soluble solids and final fruit size.

Radiation

Papaya in its wild state is found developing as a rapid volunteer in areas where the tree vegetation has been disturbed. The high saturation point above 1000 µmoles/m^2/s (photosynthetic photon flux) (*ca.* 800 W m^{-2}) supports its rapid development in areas having direct sunlight in newly disturbed areas. No photoperiodic effects on tree growth, production or sex expression have been reported (Lange, 1961). When exposed to shade, the plant is shorter,

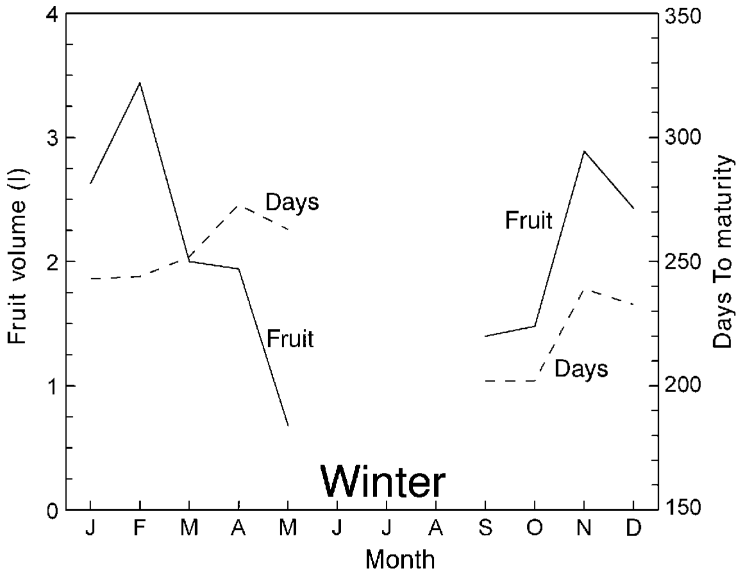

Fig. 11.2. The effect of date of fruit set on final fruit size and days from anthesis to the half-ripe stage of plants grown under subtropical conditions (Kuhne and Allan, 1970).

having smaller leaf area, lower stomatal density, increased internode and petiole length and increased chlorophyll content, and hence is regarded as a shade-avoiding species. Partial stomatal closure and opening occur rapidly with cloud-related changes in irradiance, maximizing water-use efficiency.

Windbreaks

Papaya trees are delicate and require protection from strong winds. When the root system is well developed, though relatively shallow, the tree can be uprooted by winds of 64 km/h, especially if the soil is softened by rain. Even though trees can withstand uprooting, loss of leaf area leads to flower and young fruit abscission, and low total soluble solids in the more mature fruit on the column. Full recovery from wind damage to the leaves can take from 4 to 8 weeks.

GENERAL CHARACTERISTICS

Stem

The papaya is a large, monoaxial herbaceous plant with an erect stem terminating with a crown of large leaves and can attain heights of 7–9 m

(Fig. 11.3). Although there are occasional lines or cultivars that produce an abundance of lateral branches, especially during the juvenile period, the main stem normally grows without branching, unless the growing point is injured. Natural growth of the axillary branches does occur when the trees become 3–5 years old. The stem is semi-woody and hollow and a major site of starch storage. The bark is smooth, greyish in colour, with large, prominent leaf scars. When the stem is wounded, a thin milky sap oozes from the wound.

After transplanting, shoot growth is initially slow, though considerable root growth is taking place, extending out well beyond the canopy drip line. Stem growth is then rapid up to flowering, increasing in circumference up to 2 mm per day. Growth rate peaks at flowering then declines as the tree starts bearing (Fig. 11.4). The rate of growth is influenced by nitrogen and phosphorus supply, irrigation and temperature.

Leaves

A cluster of leaves occurs at the apex of the plant and along the upper part of the stem and makes up the foliage of the tree. New leaves are constantly formed at the apex and old leaves senesce and fall. Leaves are palmately lobed with prominent veination and can measure 40–50 cm or more in diameter and have an individual leaf area of 1625 cm^2, with *ca* 15 mature leaves per plant (Fig. 11.5). In the tropics, new leaves appear at a rate of two to three a week (Chan and Toh, 1984); in Hawaii the rate is 2.4 per week during the cool season and up to 3.0 in the warm season. Petioles are cylindrical, hollow and 60–90 cm long, depending upon the cultivar. The most recently matured leaf's fresh weight (~10th leaf from 2.4 cm juvenile leaf) can vary from *ca* 50 to 170 g. The leaf petiole dry mass increases at a rapid rate until flowering then increases more slowly, peaking after fruit bearing starts (Fig. 11.5).

Inflorescence and flowers

There are three primary groups of flowers, i.e. pistillate, staminate and hermaphrodite, with many variants, especially in the hermaphrodite group (Fig. 11.3). Flowers are borne on modified cymose inflorescences that appear in the axils of the leaves. The type of inflorescence depends upon the sex of the tree. The pistillate tree produces only pistillate flowers on short, 4–6 cm peduncles, with a functional pistil devoid of stamens (Fig. 11.3a). The five petals are separate but are inconspicuously fused together at the very base of the ovary. In staminate trees, flowers are sessile and are produced in clusters on long, pendulant racemes 60–90 cm long. The individual flower is tubular with ten stamens in two series of five, attached to the throat of the corolla tube, and lacks an ovary. The hermaphroditic form (Fig. 11.3b) is between the

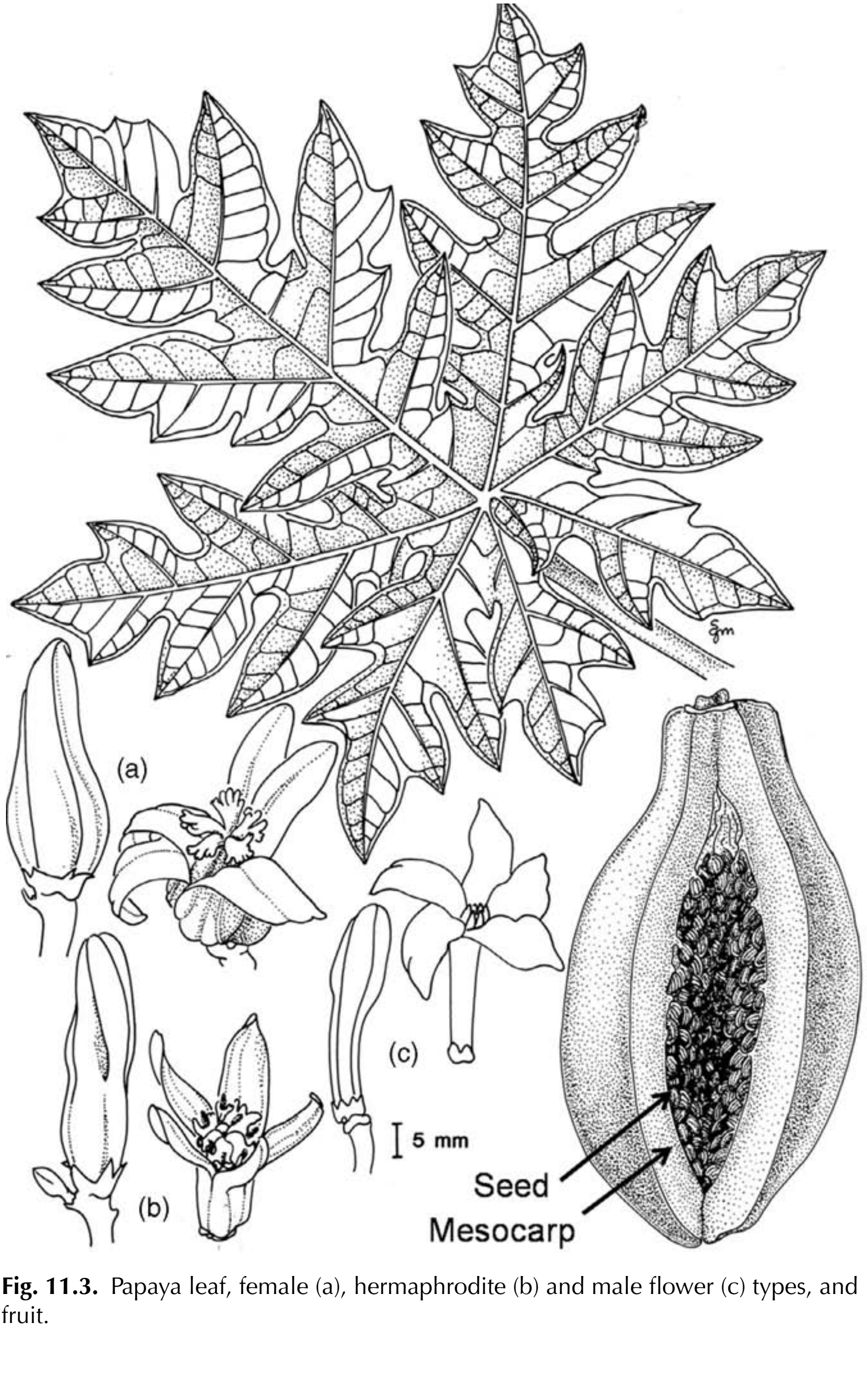

Fig. 11.3. Papaya leaf, female (a), hermaphrodite (b) and male flower (c) types, and fruit.

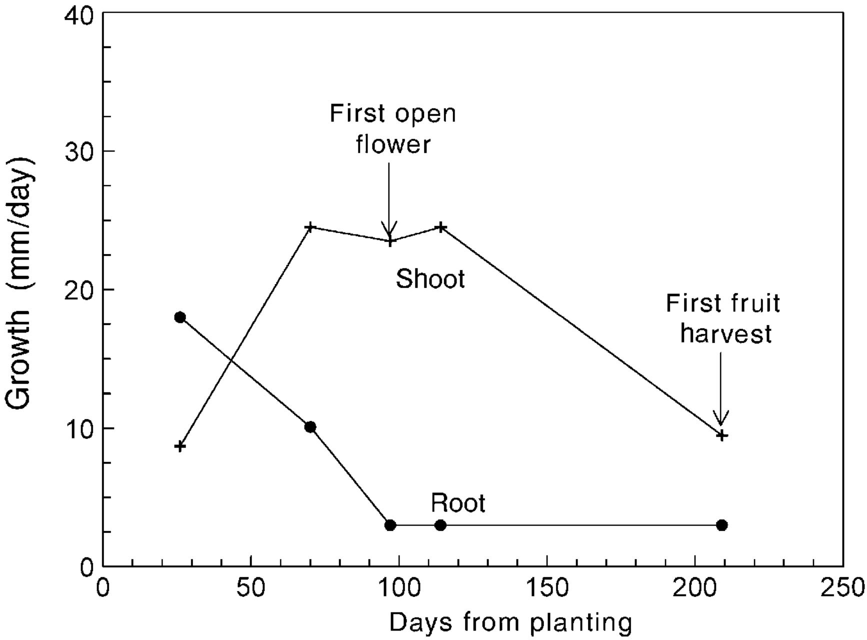

Fig. 11.4. The growth rate of papaya root and stem in the field, showing root growth rate reduction at the start of flowering and shoot growth as fruits start to develop (after Marler and Discekici, 1997).

two unisexual flower types and exhibits numerous deviations. The basic flower on a short peduncle is characterized by an elongated pistil with five stigmatic rays and five petals that are fused to about two-thirds of their length, forming a corolla tube. There are ten stamens in two series of five attached to the throat of the corolla tube. The pistil is normally five-carpellate and elongated, oval or pyriform.

Taking into account the numerous deviations, Storey (1941b) classified papaya flowers into five basic types (Table 11.1). Type I: pistillate or female flower devoid of stamens, with a distinct ovoid ovary terminating in a five-lobed stigma (Fig. 11.3a). Type II: hermaphrodite (pentandria) flower having five functional stamens and a globose five-furrowed ovary (Fig. 11.3b). Type III: hermaphrodite (carpelloid) flower having six to nine functional stamens and an irregularly ridged ovary. Type IV: hermaphrodite (elongata) flower having ten functional stamens and an elongate, smooth ovary. Type IV+: hermaphrodite (barren) flower having ten functional stamens but the pistil aborts, becomes vestigial and lacks a stigma (Fig. 11.3c). Type V: staminate flower having ten functional stamens only. The ovary is completely absent and flowers are bunched in an inflorescence. Although five basic floral types are listed, certain male and hermaphrodite trees undergo sex

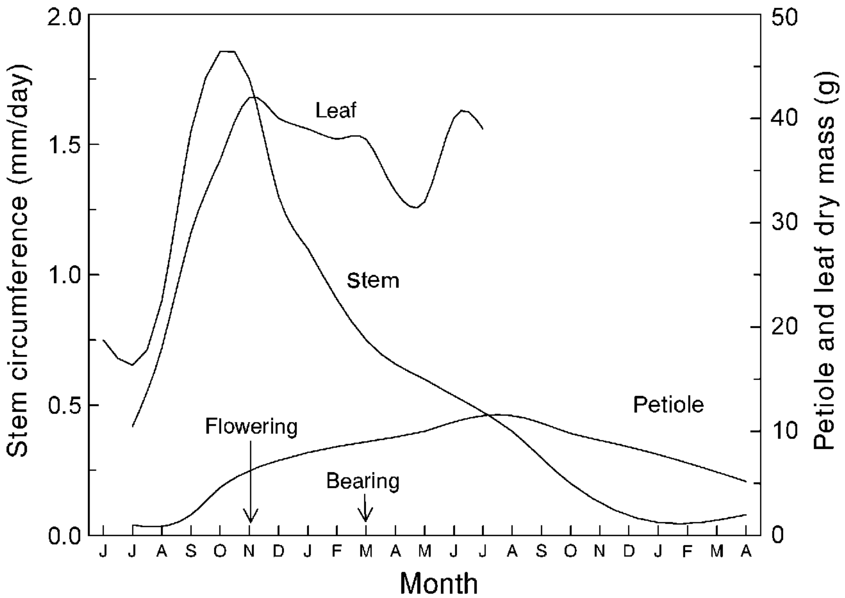

Fig. 11.5. Growth rate of papaya stem circumference, dry weight of the most recently matured leaf petiole and the 17th leaf from the 2.4 cm juvenile leaf under dry land conditions of Puna, Hawaii. The dry weight reduction in April is attributed to low rainfall in the previous 2 months (Awada, 1977).

reversal and morphological changes in various degrees under the influence of environmental changes (Storey, 1958). Type V staminate flowers may form functional ovaries and bear fruit during cool months. Type III flowers can form carpelloid fruit when exposed to low temperatures about 40 days before anthesis.

The appearance of a large number of modified flower forms occurs in progenies from appropriate hybridization when grown under a temperature regime that may range from around 13 to 32°C. Therefore, recovery of extreme sex modifications may not be seen in a breeding programme unless conducted in an area with wide fluctuations in seasonal temperatures in highly heterozygous parental types. Stamen carpellody is expressed under cool temperatures, with increasing severity as temperatures lower in the *ca* 40 days before anthesis (Fig. 11.1). Instead of ten stamens in a double whorl, there are only five stamens, with the other five fixed to the normal carpels. The fruits that develop from this carpellody are severely misshaped and unmarketable (Fig. 11.6). Female sterility occurs under warm temperatures, again with increasing severity at higher temperatures in the *ca.* 40 days before anthesis. Excessive nitrogen and moisture also favour stamen carpellody, while plant stress such as N deficiency and moisture stress influences female sterility (Awada and Ikeda, 1957).

Table 11.1. Types of papaya flowers (Storey, 1958).

Types	Tree[a]	Flower[a]	Description
Staminate	M	M	Typical unisexual flower on long peduncles.
Teratological staminate	M	M	Found in sex-reversing male tree, with some degree of carpel initiation and development. A number of hair-like processes – vestigial carpels – at base.
Reduced elongata	MF	M	Modified normal elongata flower differs from staminate flowers in having a thicker and stiffer corolla tube, abortion of pistils, and reduced ovary size and number of carpels. Frequent warm periods and late summer; last 1–2 weeks up to 6 months, depending upon cultivar and temperature.
Elongata (normal type)	MF	MF	Elongata refers to the shape of the pistil, terminating in fine stigmata; lobes develop into pyriform or cylindrical fruit, five laterally fused carpels. Petals fused two-thirds of length.
Carpelloid elongata	MF	F	Transformation of the inner series of stamens into carpel life structure. Numerous types, different number of stamens, becoming carpelloid and degree of carpellody from slight to developing locules with functional stigma. Fruit to varying degrees misshapen.
Pentandria	MF	F	Normal hermaphrodite-type, modified, unisexual, pistillate flower through stepwise stamen transformation to carpels, with loss of the original carpels. Short corolla tube, only five stamens of the outer whorl on long filaments, globose and furrowed pistil. Carpels from five to ten.
Carpelloid pentandria	MF	F	The stamens of the outer whorl become carpelloid. Carpellodic forms in carious stage, especially under cool conditions. All five stamens fully carpelloid and fuse laterally, with abortion of original carpels; flowers resemble pistillate flowers – pseudo-pistillate.
Pistillate	F	F	Unisexual flowers larger than MF flower, lack stamens. Form stable and unchanged by environment.

[a]M – male; F – female.

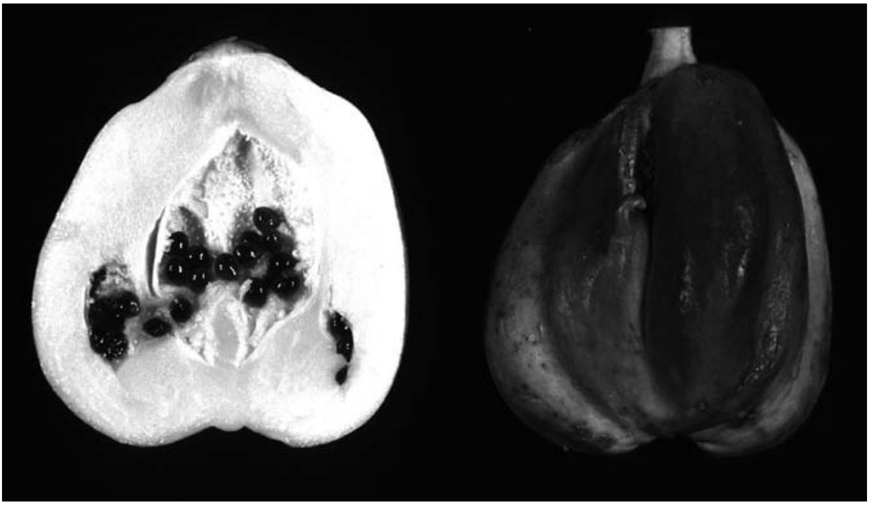

Fig. 11.6. Stamen carpellody induced by environmental conditions (temperature, water stress, fertilization) on young hermaphrodite trees significantly alters fruit shape. The mild forms are sometimes referred to as 'cat face'.

The floral primordia of 'Solo' is laid down 50–70 days prior to anthesis, at a rate of about one new flower in each leaf every 2–3 days along with new leaves. Ovaries differentiation begins 42–50 days prior to anthesis and is completed within 28 days before anthesis. Stamen differentiation begins 50–56 days before anthesis and is completed by 35 days prior to anthesis. Female flower bud emergence to anthesis ranges from ~46 days in Hawaii to 80 days in India, with the wide discrepancy being due to temperature.

Pollination and fruit set

In hermaphrodite populations, wind pollination is minimal as the stamens are packed inside the corolla tube and seldom protrude prominently out of the flower (Fig. 11.3b). The hermaphrodite flowers are cleistogamous, i.e. the anthers dehisce and release the pollen prior to anthesis of the flower, leading to self-pollination. Varieties such as 'Sunrise', 'Kapoho' and 'Eksotika' are enforced self-pollinators, and seeds gathered from hermaphrodite fruit will usually breed true to type. Self-incompatibility in cultivars is relatively rare, though there are isolated cases when controlled self-pollinations are made. Self-pollination in papaya also does not appear to result in any loss of vigour.

In mixed planting of pistillate and hermaphroditic trees or in purely hermaphroditic stands, no pollination problems are experienced. Problem occurs when dioecious cultivars are planted with an inadequate number of male trees. In Australia, the recommended ratio of female to male is

8:1. However, one male tree per 15–20 female trees provides adequate wind pollination if male trees are located with respect to prevailing winds. Parthenocarpy in papaya is rare. Seedless fruit or fruit with very low seeds can be produced on female trees. These fruits are generally smaller in size. Auxins have also been reported to induce parthenocarpic fruit.

Fruit set is no problem under open pollination in an orchard. On hermaphrodite trees, it is most common for the terminal flower to set while the laterals abscise. Under favourable conditions one or two laterals may be set and only persist for 2–3 weeks or remain to produce undersized fruit that crowd the fruit column. This crowding leads to fruit compaction and misshaped fruit. Fruit thinning may be practised. The degree of compaction is due to the peduncle length. Fruit set is variable; if lateral flowers are not desired and only one fruit per leaf axil is desired, set is usually 100%; if three flowers are formed and only one fruit is desired then the set is 33%. Annual fruit set depends upon the length of the female sterility period in hot weather, and with one fruit per peduncle the range is 85–95%.

Fruit

The papaya fruit is a fleshy berry, from 50 g to well over 10 kg, and superficially resembles a melon, being spherical, pyriform, oval or elongated in shape (Fig. 11.3). Fruit shape is a sex-linked character and ranges from spherical to ovoid in female flowers to long, cylindrical or pyriform (pear-shaped) in hermaphrodite flowers. The skin of the fruit is thin and usually green when immature, turning to yellow or orange when ripe. The fruit is normally composed of five carpels united to form a central ovarian cavity, which is lined with the placenta, carrying numerous black seeds. Placentation is parietal, with the seeds attached by 0.5–1 mm stalks. The seeds are dark grey to black when mature and enclosed in a sacrotesta. The ovarian cavity is larger in female fruit than hermaphrodite. The shape of the cavity at the transverse cut ranges from star-shape with 5–7 furrows, to smooth and circular in shape.

In fruit development, all tissues in gynecia less than 1 mm are meristematic. Later the outer layer of the epidermis increases in size while the subepidermal layer continues to divide both anticlinally and periclinally. The central parenchyma of the pericarp increases in size and divides, with the placenta forming opposite the marginal vascular bundles. This meristematic lasts 28–42 days and determines final fruit size (Fig. 11.7). Fruit growth shows two major phases. The first lasts about 80 days post-anthesis, with a large increase in dry weight occurring just before fruit maturity. Fruit development takes 150–164 days, which is extended another 14–21 days in Hawaii in the colder months. In subtropical areas, such as South Africa, development can vary from 190 to 270 days (Fig. 11.2). The growth of the fleshy mesocarp parallels seed development and total fruit growth (Fig. 11.7).

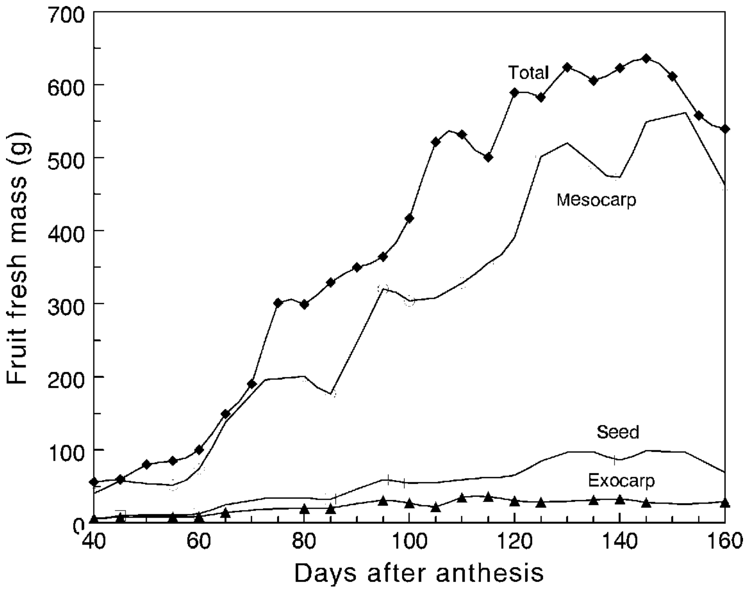

Fig. 11.7. The increase in papaya fruit total fresh weight and for skin, seeds and flesh (after Qiu *et al.*, 1995).

Flesh colour is white in immature fruit to a pale orange-yellow, salmon pink or red, depending upon cultivar, when ripe. Total fruit starch declines from 0.4% to less than 0.1% during the first 80 days of fruit development (Fig. 11.8). Sugars, however, do not begin to accumulate until 110 days from anthesis, during the last 28–42 days of fruit development. Flesh total soluble solids can be as low as 5% up to 19%.

Green fruit contains an abundance of milky latex that contains the protease papain. The pericarp consists of a network of lacticifers that develop close to the vascular bundles and anastomose profusely throughout the fruit. This latex is under pressure and spurts out when the skin is pricked. Laticifers collapse as the fruit ripens and there is little or no latex at the fully ripe stage. Commercially, the skin is scarified to induce latex flow, which is allowed to dry then collected to be later processed into papain.

CULTIVAR DEVELOPMENT

Cytogenetics and genetics

The species in the genus *Carica* possess nine pairs of chromosomes and a small genome (375 Mb). Meiosis is normal in the three sex types and there are no

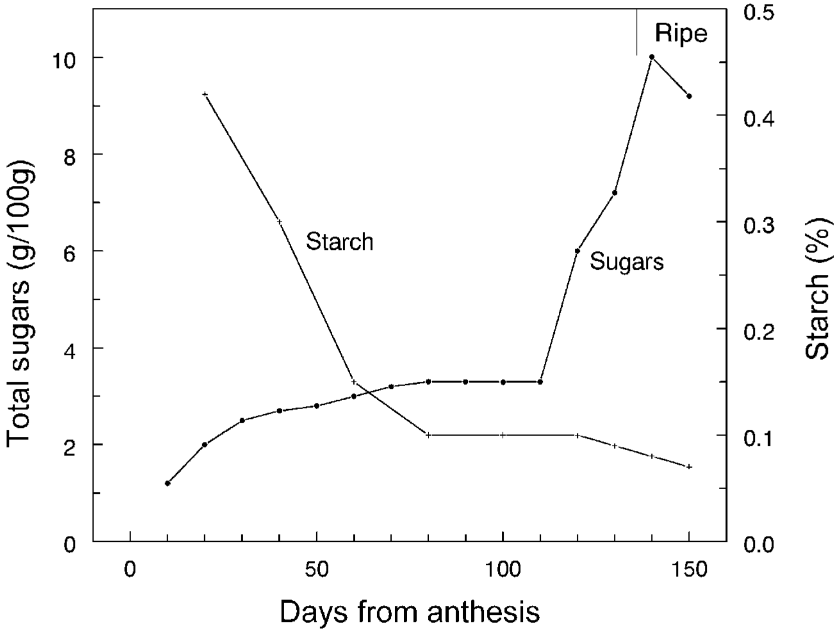

Fig. 11.8. Changes in fruit starch and total sugar of developing 'Solo' papaya fruit. Note the dramatic increase in sugars during the last phase of fruit development (Chan *et al.*, 1979; Chittiraichelvan and Shanmugavelu, 1979).

known polyploid cultivars. Seeds of self-pollinated 'Solo' and 'Eksotika' and the cross-pollinated varieties 'Sekaki' and 'Khaek Dum' can be reproduced readily with good genetic purity, if care is taken in seed production. For the F_1 hybrids, such as 'Rainbow' and 'Eksotika II', seed is difficult to produce as two inbred parents have to be crossed for production of the hybrid seeds.

Some *Vasconcella* species have resistance to diseases to which *C. papaya* L. is susceptible, e.g. *Vasconcella cauliflora*'s resistance to distortion ringspot virus. This resistance has lead to attempts to cross these species. Successful interspecific hybrids have been reported between other *Vasconcella* species but not with *C. papaya* L. However, hybrids of *C. papaya* L. with *V. cauliflora* and with *V. pubescens*, *V. quercifolia* and *Vasconcella stipulata* were obtained using embryo rescue techniques to overcome post-zygotic barriers to hybridization. *In vitro* propagation coupled to rapid disease resistance screening, anther culture to generate haploid papaya lines and *Agrobacterium*-mediated gene transfer has been used to develop disease-resistant papaya lines.

Sex of papaya is determined by monogenic inheritance involving three alleles (Hofmeyr, 1938). The alleles are M for male, M^H for hermaphrodite and m for female. All homozygous dominants, i.e. MM, MM^H and M^HM^H, are lethal to the zygotes. Therefore male genotypes (Mm) and hermaphrodite (M^Hm) are enforced heterozygotes, while the female genotype (mm) is a double recessive. Seeds derived from these cross-combinations will have twice the number of hermaphrodites compared with females (Storey, 1938, 1941a). It is possible to self and cross male trees when there is reversal of sex from a staminate flower to a form that has a functional ovary, and these are used to develop inbred lines of dioecious papayas. Sex is determined at flowering time, usually 4–6 months after planting. Molecular probes can be used to predict the sex of papaya at seedling stage.

Fruit size shows wide variation, ranging from about 5 cm in diameter and 50 g in weight to over 50 cm in length and 10 kg or more in weight. Fruit weight is a quantitative character determined by multiple alleles (Chan, 2001). Fruit shape in papaya is a sex-linked character. The female flower has a globose ovary, which develops into round or ovoid fruits. In contrast, the elongata or hermaphrodite flower has a slender, tapering ovary and this subsequently develops into a fruit that is elongated and cylindrical or pyriform in shape, depending on the variety of papaya.

Precocity or earliness to fruiting is a factor of the number of nodes produced to first flowering node, while the number of nodes to flowering and the internode length determine height to first fruit. These characters are governed by additive gene effects, with the hybrid having the arithmetic mean between the two parents (Nakasone and Storey, 1955). Subhadrabandhu and Nontaswatsri (1997) reported that height of first flower and number of nodes to fruiting were controlled by both additive and non-additive genes.

Carpellody of the stamen is the development of misshapen or 'cat-faced' fruits due to fusion of the stamens to the ovary tissues in hermaphrodite flowers (Fig. 11.6). Carpellody and female sterility may involve a number of gene pairs involving three loci, two for carpellody (c/c, c/c) and one for sterility (s/s). Their normal alleles (+) are partially or completely dominant. The s/+ combination is normal. In c/+, the + is partially dominant over 'c', so there will be some carpellody. The 's' factor, whether homozygous or not (s/-), is epistatic over the 'c' allele when the carpellody factors are heterozygous. The phenotype would be normal but unstable, depending upon environmental conditions. If either of the 'c' factors is homozygous (c/c), the combined strength of the two alleles at one locus can overcome epistasis, thus exhibiting carpellody. High heritability ($h^2 = 82\%$) is obtained for carpellody, but effective phenotypic selection may be interfered with by the 'change-in-rate' type of interaction between genotype and plant age (Chan, 1984). Increased expression of carpellody may also be brought about by cool temperature, high soil moisture and high nitrogen (Awada, 1961).

Flavour and odour can range from pleasantly aromatic, as in the 'Solo' and 'Eksotika' varieties, to musky, as in the 'Maradol' variety. Muskiness is due to the homozygous recessive allele of a single gene (Storey, 1969). Total soluble solids content is usually associated with sweetness and may range from 5% to about 19% total soluble solids (^{0}Brix) in the 'Solo' varieties. This trait is governed by quantitative genes with additive effects, and hybrids are expected to have intermediate values between the parents.

Papaya flesh colour ranges from intense gold to deep red, with varying intermediate shades (Table 11.2). In Malaysia and many South-east Asian countries, the preference is the red-fleshed varieties, while Hawaii and Australia prefer the yellow-fleshed types. Flesh colour is governed by a single gene, with yellow (R) being dominant over red (r). Varying intermediate shades of pink may be attributed to modifier gene effects. All red-fleshed (rr) varieties, such as ‘Sunrise Solo’ and ‘Eksotika’, will breed true for flesh colour, but progenies of heterozygous (Rr) yellow F_1 hybrids, such as ‘Rainbow’, will segregate in this trait.

The skin colour of papaya fruit is usually green when immature, changing to yellow or reddish-orange when fully ripe. The ‘Morib’ is an interesting local selection that has attractive yellow fruit skin even at an immature stage. The tree is dwarfed and has yellowish-green foliage. Fruit skin colour is governed by a single gene, with green (G) being dominant and yellow is expressed in a double recessive (gg). It is difficult to identify the appropriate harvest index of this fruit.

The old dioecious cultivars, such as ‘Hortus Gold’ (South Africa), ‘Sunnybank’ (Australia), ‘Betty’ and ‘Cariflora’ (Florida) are cross-pollinated, yellow-fleshed and typically round fruit. ‘Cariflora’ fruits are smaller and tolerant to the ringspot virus disease. There are also gynodioecious varieties that are cross-pollinated, such as ‘Sekaki’, ‘Khaek Dum’, ‘Maradol’ and ‘Cibinong’. ‘Sekaki’, also known as ‘Hong Kong’, is the second most popularly cultivated cultivar in Malaysia after ‘Eksotika’. ‘Khaek Dum’ is Thailand’s best-known variety and is a vigorous plant that bears red-fleshed fruit weighing about 1.2 kg with 10.6% total soluble solids content. ‘Maradol’ originates from Cuba, is a short-stature variety that bears fruit very close to the ground. The fruit weighs from 1 to 2 kg, attractive with firm red flesh and 10–11%

Table 11.2. Preference of fruit characteristics in some countries.

Country	Fruit size (g)	Shape	Flesh colour	Race
Australia	800–1000	Cylindrical, spherical	Yellow	Dioecious
Cook Islands	500–1134	Pyriform	Yellow	Hermaphrodite
Fiji	397–510	Pyriform	Red, yellow	Hermaphrodite
Hawaii	397–510	Pyriform, oval	Yellow, red	Hermaphrodite
Mexico	1360–5443	Spherical, elongate	Yellow, red	Dioecious, hermaphrodite
South Africa	1000–1500	Oval	Yellow	Dioecious
Caribbean Islands	500–4000	Round, oval, pyriform, elongate	Red, yellow	Dioecious, hermaphrodite

total soluble solids content. It has a characteristic musky flavour and the fruit is quite susceptible to anthracnose. 'Cibinong' is an Indonesian variety with large red-fleshed fruit (2–3 kg) and grown mainly for its high papain yield.

Commercial F_1 hybrids of papaya are rare, although there have been reports of heterosis and improved yields in cross-combinations between different cultivars of papaya. Agnew (1968) described a vigorous F_1 hybrid derived from 'Bettina 100A' and 'Petersen 170' that was, at one time, important in Queensland. An important hybrid developed in Taiwan that has resistance to papaya ringspot virus disease is 'Tainung No. 5'. This was derived from a cross between 'Florida' (FL-77-5) and the 'Costa Rica Red'. In Malaysia, an F_1 hybrid called 'Eksotika II' was developed from the hybridization of 'Line 19' with its sib, 'Eksotika' (formerly 'Line 20') (Chan, 1993). The new hybrid has similar features to 'Eksotika', but the yield is 14–33% higher due to the larger fruit, weighing between 600 and 800 g. The appearance of the fruit is more attractive, with smooth skin and high tolerance to freckles. The flesh is firmer and the fruit stores longer, making 'Eksotika II' more preferred than its predecessor for export.

The world's first transgenic papaya was 'SunUp', which was transformed with coat-protein-mediated resistance to papaya ringspot virus disease. 'Rainbow' is the first transgenic commercial variety, developed from a cross between 'SunUp' and the conventional cultivar 'Kapoho'. Transgenic varieties of 'Kapoho' and 'Kamiya' have also been developed by introduction of the coat-protein transgene from 'Rainbow' through conventional hybridization and backcrossing.

Breeding

Some papaya breeding objectives are common to all regions, with objectives specific to different localities due to climatic differences, consumer preferences, desired sex types and export markets (Table 11.3). These objectives have changed little in the last 100 years. Desirable tree characteristics are tree vigour, low and precocious fruiting, minimum expression of stamen carpellody and female sterility if hermaphrodites are preferred, resistance to diseases and insect pests, and yielding ability. Universally desired fruit characteristics are smooth skin, free from blemishes, firm fruit with thick flesh, round seed cavity, absence of internal lumps and long shelf-life. The desired fruit size, shape and flesh colour may differ in different regions (Table 11.2). An extreme example would be a preference for papaya with the heavy musky aroma in South-east Asia, which would not be suitable in western markets. Preference for the small (450–650 g) 'Solo' fruit is increasing in tropical countries, where export is considered. Requirements for processing cultivars are the same, though larger fruit may be more desirable, with size and shape being uniform if mechanization is to be considered. Flesh colour preference is usually based

Table 11.3. Ideals in papaya breeding have not changed much since the following were proposed. Additional factors have related to disease resistance (Higgins and Holt, 1914).

	Character
Tree	Vigour
	Early and low fruiting – wide variation exists
	Freedom from branching habits
Fruit	Productive but not compact fruiting
	Small size for table use
	Large size for animal feed and papain production
	Uniformity in shape, symmetry and smoothness
	Uniformity in ripening
	Colouring before softening
	Colour of flesh – yellow, pink or red
	Easily separable without scraping flesh
	Flavour – not easily described but easily recognizable
	Keeping quality
Other	Papain yield

upon traditional experience and familiarity with cultivars. Total tree height is not a good criterion to assess tree vigour, while stem diameter or girth is a more reliable measure (Fig. 11.5). Stamen carpellody and female sterility do not occur in dioecious cultivars.

In breeding for hermaphrodite types, selections should be evaluated during the cool period for occurrence of stamen carpellody and again during the warm period for female sterility. Trees that show no carpellody in winter may show a high degree of female sterility in summer, or the opposite. Within a specific locality, if temperature fluctuations are not too wide, continual selection and inbreeding can produce lines with minimum carpellody and female sterility (Chan, 1984). In subtropical climates, where the range of temperatures between summer and winter is large, dioecious cultivars are more suitable.

Increased yields may be accomplished by increasing yields per tree, by increasing density per unit area, or both (Hamilton, 1954). Usually only the terminal flower sets fruit and others abscise or produce small, unmarketable fruit when they set. However, lines have been observed to produce two, three or even four normal-sized fruit on each peduncle. Multiple fruiting is strongly influenced by soil fertility. Peduncles must be long enough to prevent overcrowding, which can produce misshapen, ‘pancake-like’, flat fruit. Another method to increase production is by increasing trees per unit area. Petioles of papaya trees are approximately 75–100 cm, or even longer, and are more or less horizontal. This requires at least 2 m between plants in a row. A mutant ‘Solo’ line with very poor yields and short petioles (45–60 cm) that are positioned obliquely upright is available, and trees can be planted at 0.9–1.2 m apart in the row. Short, upright petiole hybrids have been produced but the yield of the commercial cultivars has not been achieved.

A common papaya disease is the root, stem and fruit rot caused by *Phytophthora palmivora* Butl., which is especially severe during wet seasons. Early studies in Hawaii involved repeated selection for seedling mortality and vigour, and replanting each advance generation in the same field resulted in a few highly tolerant lines (Mosqueda-Vazquez *et al.*, 1981). Cultivars showing high tolerance to the *Phytophthora* root rot have also exhibited tolerance to stem canker and fruit rot caused by the same organism. Other fruit diseases that appear to be important enough to warrant breeding efforts are anthracnose and chocolate spot, both caused by strains of *C. gloeosporioides*, and stem-end rot caused by *Phoma caricae-papayae*.

The aphid-transmitted papaya ringspot virus (PRV) (papaya mosaic virus or distortion ringspot virus) of different strains often limits commercial production in most papaya-growing areas. Tolerant lines have been created, and a dioecious cultivar named ‘Cariflora’ with strong tolerance to PRV has been released (Conover *et al.*, 1986). Using this material, several highly tolerant hermaphroditic ‘Solo’ selections have been made in Hawaii. More rapid tolerance is achieved using molecular biology and the transformation of papaya with the virus coat protein that confers resistance (Fitch *et al.*, 1992). Two resistant ‘Solo’ lines, one with yellow flesh (‘Rainbow’) and the other with red flesh (‘SunUp’), have been released in Hawaii.

The hermaphroditic papaya is naturally self-pollinating, and continuous inbreeding has not shown inbreeding depression. Also, F_1 hybrids between ‘Solo’ lines have not shown hybrid vigour, probably due to a close genetic relationship, with many genes in common, or to the fact that the vigour is only expressed under poor growing conditions. This narrowness in germplasm has been confirmed for ten Hawaii cultivars and three non-Hawaii cultivars by DNA analysis at 80% similarity. Heterosis has been observed in F_1s of crosses between ‘Solo’ and widely different papaya accessions and between interspecific crosses involving *V. cauliflora* × *V. monoica* and *V. goudotiana* × *V. monoica* (Mekako and Nakasone, 1975; Manshardt and Wenslaff, 1989a,b).

Cultivars

Wide variability is shown by the papayas grown in various countries; with few exceptions, most cannot be classified as horticultural ‘cultivars’ (Table 11.4). Plantings are usually heterogeneous and seeds are obtained from open-pollinated fruit. A number of horticultural cultivars have been reported to produce relatively uniform progenies (Table 11.5). Stabilizing characteristics in dioecious cultivars is more difficult than in hermaphroditic ones, as the genotype of the male with respect to the fruit characteristics is unknown. In hermaphroditic cultivars, proper selection and self-pollination can stabilize

Table 11.4. Papaya 'cultivars' reported in the literature; many are variable and not true cultivars.

Country	Cultivar	Sex type	Flesh colour
Australia	Improved Petersen	Dioecious	Yellow
	Guinea Gold	Hermaphrodite	Yellow
	Sunnybank/S7	Dioecious	Yellow
	Richter/Arline	Dioecious	Yellow
Americas			
Mexico	Verde		
	Gialla		
	Cera		
	Chincona		
USA – Florida	Cariflora	Dioecious	Yellow
	Betty	Dioecious	Yellow
	Homestead	Dioecious	Yellow
USA – Hawaii	Kapoho Solo	Hermaphrodite	Yellow
	Sunrise	Hermaphrodite	Red
	Waimanalo	Hermaphrodite	Yellow
	Rainbow	Hermaphrodite	Yellow
Venezuela	Paraguanera		
	Roja		Red
Caribbean			
Barbados	Wakefield		
	Graeme 5, and 7		
Cuba	Maradol	Hermaphrodite	Red
Trinidad	Santa Cruz Giant		
	Cedro		
Dominican Republic	Cartagena	Hermaphrodite	Yellow
Asia			Yellow
India	Coorg Honey Dew	Hermaphrodite	
	Coimbitor 2	Dioecious	Yellow
Indonesia	Semangka	Hermaphrodite	Red
	Dampit	Hermaphrodite	Red
Malaysia	Eksotika	Hermaphrodite	Red
	Sekaki	Hermaphrodite	Red
Philippines	Sinta	Hermaphrodite	Red
Taiwan	Tainung No. 5	Hermaphrodite	Red
Thailand	Sai-nampueng	Hermaphrodite	Red
	Khaek Dam	Hermaphrodite	Red
South Africa	Hortus Gold	Dioecious	Yellow
	Kaapmuiden	–	Yellow
	Honey Gold	Dioecious	Yellow

characteristics at a more rapid rate. The Hawaiian 'Solo' type is perhaps one of the few cultivars that has been continuously inbred since its introduction to Hawaii in 1911 from Barbados (Yee, 1970). Solo cultivars such as 'Kapoho', 'Sunrise', 'Sunset' and 'Waimanalo' have been inbred for many generations.

Table 11.5. Fruit and tree characteristics of five Hawaiian cultivars. Data are averages from tests conducted at three locations (winter harvest only).

Characteristics	Cultivar				
	Kapoho	Higgins	Line 8	Waimanalo	Sunrise
Height to first flower (cm)	147	97	169	76	91
Fruit weight (g)	343	367	516	695	425
Soluble solids (%)	15.7	15.9	15.0	15.2	14.5
Flesh colour	Yellow	Yellow	Yellow	Yellow	Red
Carpellodic fruit (%)	0	1.0	1.0	0.8	–
Other culls (%)	16	12	5	10	–
Marketable (kg/tree)	17	31	26	39	–
Phytophthora resistance[a]	I	S	R	R	I
Virus resistance[b]	IT	HT	S	S	S

[a]R = resistant; I = intermediate; S = susceptible.
[b]HT = high tolerance; IT = intermediate tolerance; S = susceptible.

CULTURAL PRACTICES

Propagation

Papaya is almost entirely propagated from seeds in commercial cultivation. Sound seeds usually germinate after 2 weeks in the polybags and are ready to transplant at the 8–12-leaf stage, after about 6 weeks. The seeding rate for papaya is very low as dry papaya seeds are light, weighing about 14.5 g per 1000 seeds. To establish a hectare of papaya, about 100 g of seed is required. Approximately 100–150 g of seeds with 80% germination are needed to produce the 2000 plants needed for one hectare.

Papaya seed can be harvested when the fruits reach 'colour break' stage. Growers select trees with desirable characteristics, from which seeds, generally from open-pollinated fruit, are saved. This seed produces uniform progenies if from a single cultivar. The seeds are non-recalcitrant and can be dried to moisture levels of 9–12% for long-term storage. Seeds harvested fresh from fruit have very low and variable germination. Removal of the sarcotesta and soaking in gibberellic acid promotes germination; uniformity of germination is further enhanced by seed drying and cool-temperature storage at 15°C for 30–50 days. Papaya seeds without the sarcotesta that are well-dried and stored at 5°C retain 60–70% germination for 5 years (Chan and Tan, 1990).

Seeds may be sown in trays filled with a suitable medium, peat pots, polyethylene bags or directly in the field. Germination occurs in 12–20 days. Seedlings are transplanted into 7.6 cm peat pots or into 10 cm plastic bags at the two-leaf (cotyledonary leaves) stage. Seedlings grown in containers should be hardened gradually in sunlight and field-transplanted around 1.5–2 months after germination, at about 20 cm high. In field planting up to 15–20 seeds are sown in each hole. Upon germination seedlings are thinned out to leave five or six seedlings to grow to flowering. So many seeds are planted in each hole to allow for birds and field mice loss. At first flowering, a vigorous plant of the desired sex is kept and the others removed.

Allan (1964) was the first to report the success of propagating papaya by cuttings. Large, leafy, lateral shoots that developed after winter were initially used as cuttings for rooting under intermittent mist. In subtropical countries, the cool winter checks growth and temporarily overcomes apical dominance, resulting in the proliferation of lateral shoots. Availability of cuttings became less season-dependent when they were induced from vigorous 1–2-year-old trees by topping off the shoot terminus to remove the apical dominance. The methods for induction and proliferation of suitable-sized lateral shoots for cuttings were improved further with the application of cytokinin and gibberellic acid mixtures. Vegetatively propagated papaya flower 1–3 months earlier and are 30 cm lower bearing.

Scion shoots from cultivars ‘Co-1’ and ‘Honey Dew’ can be successfully cleft-grafted on to uniformly established seedlings (Airi *et al.*, 1986). Patch and T-budding can also be used, but the success rate is poorer than cleft grafting. Field grafting can be used to replace female trees. The union is established in about 2–3 weeks and the female tree is cut back to about 60 cm from the ground.

The early success of *in vitro* propagation of papaya was limited because the sex of the seedling plants used could not be ascertained. Later, Litz and Conover (1978) reported successful regeneration of papaya plantlets by culturing apices of mature, field-grown papaya plants in modified Murashige and Skoog media. A field trial of *in vitro* plantlets indicated that they propagated true to sex without somaclonal reversion (Drew, 1988). Besides greater uniformity, the other benefits were earlier bearing, lower bearing height and improved yield.

Field preparation

Field preparation in many areas is poorly done due to lack of appropriate equipment or rough terrain. Subsoiling or ripping down to 50 cm or more is desirable on heavy or compacted soils so roots can penetrate deeply (see Fig. 3.2). Subsoiling provides better drainage if done parallel to the contour lines. Discing, levelling and furrowing follow standard practice. Planting holes 30–45 cm in diameter are best dug with a soil auger attached to tractors. Raised beds are used if there is a chance of flooding (see Fig. 3.3).

Transplanting and plant spacing

After about 6–8 weeks in the nursery, the seedlings should reach the eighth to twelfth-leaf stage and are most suitable for field planting. In rainfed areas, field planting is done at the beginning of the rainy season. Seedlings grown in pots and bags are planted directly, with the removal of the pot or bags. Transplanted plants must be watered soon after planting to settle the soil around the root system.

Spacing between plants and between rows varies widely. Universally practised is the single-row system, with between plant spacing ranging from 1.8 to 3 m and between row spacing varying from 1.8 m to as much as 3.6 m (see Fig. 3.7b). The between-row spacing largely depends upon degree of mechanization; a standard tractor requires *ca* 3 m. The most frequently used spacing is 2.0–2.5 m within row × 2.5 m, giving a density of 1600–2000 plants/ha. The double-row system, with 2 m between a set of rows and 3.5 m between double rows, is used. Normally, two or three seedlings are planted in each hole, spaced about 30 cm apart. When the plants start flowering, the female plants are removed, leaving only one hermaphrodite plant per point. Polyethylene mulch over the beds prevents moisture losses and greatly minimizes weed growth within the beds (Fig. 3.7b). Organic mulches of grasses, wood shavings, rice hulls or other kinds of material are also beneficial.

Irrigation

Non-irrigated fields in Hawaii are located in a region with 2500–3125 mm of rain, fairly well-distributed throughout the year. However, occasional droughts of 2 or 3 months occur. Low soil moisture tends to shift the sex type to male and results in lower fruit yields, while high moisture levels can lead to excessive production of misshaped carpellodic fruit, with rapid tree growth. Dioecious cultivars fare better unless moisture stress is severe. A monthly minimum rainfall of 100 mm is needed without supplementary irrigation for some production. Irrigation should replace at least the moisture lost by pan evaporation, and 1.25 pan evaporation is required for maximum yield of mature trees (Fig. 11.9). Young trees only need about 0.3–0.5 pan evaporation. Good production occurs with 60–90 l/tree/week immediately after planting or during the wet season and 120–240 l/tree/week during the dry period.

Irrigation may be by flooding between the row space by furrows running along both sides of the rows of trees or via microsprinklers or jets or drip. Irrigation intervals of around 10–15 days may be necessary to sustain production, unless this interval is broken by rainfall. Papayas are wind-pollinated, and overhead sprinkling reduces pollen dissemination and therefore is not recommended. A drip system must be capable of providing the maximum amount rather than average demand. If a tree requires

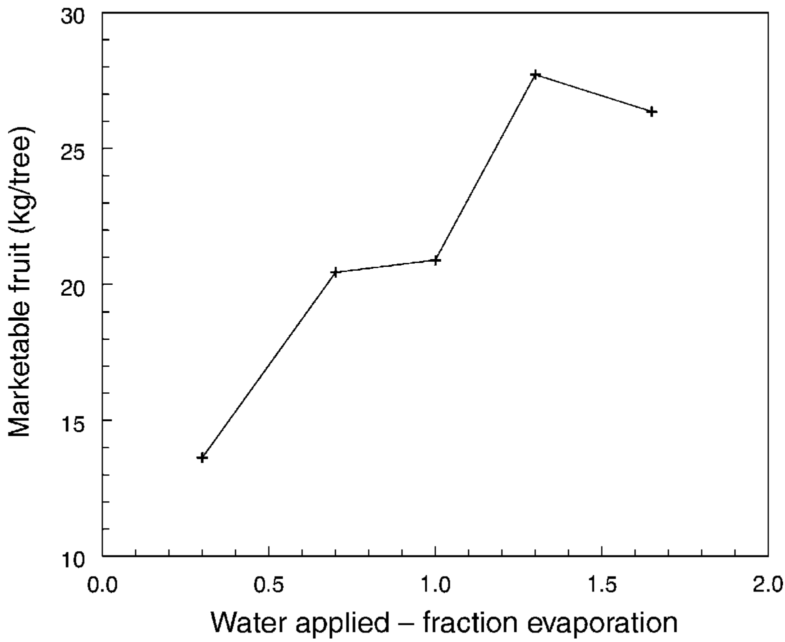

Fig. 11.9. Relation between yield of marketable fruit and the water application as a fraction of pan evaporation (Awada *et al.,* 1979).

56 l water/day but 114 l maximum during the dry season, the delivery system must have the capacity to deliver the maximum requirement. One emitter per tree has been sufficient for the first 3–4 months, but thereafter two emitters, one on each side of the tree, have been found necessary. A single micro-sprinkler (30 l/h) can also meet requirements.

Pruning

Normal tree pruning is not practised. Side shoots produced by some cultivars during the juvenile stages or enforced when the plant apex is damaged are removed as early as possible to maintain a single-stemmed tree. If the apex is damaged or destroyed, one shoot nearest the terminal is maintained to re-establish the tree. Some lower leaves are removed to facilitate harvesting, improve penetration of spray materials and generally to increase marketable yields (Ito, 1976). No statistical differences are found in total soluble solids, fruit size, number of fruits and marketable yield after a year of leaf pruning when only 15 fully expanded leaves are retained. One fully expanded mature leaf can provide photosynthetates for about 1500 g of fruit on the column on 'Solo' varieties. Trees that have very large fruits (4–5 kg each) may have fewer than ten fruits developing at a time on the fruit column, with new flowers abscising.

Fertilization

Papaya is a fast and continuously growing tree that provides fruits all the year round. An abundant supply of nutrients at regular intervals is needed to sustain good growth and production. In general, an adequate supply of nitrogen and phosphorus should be provided during the early stages to ensure optimum foliage, trunk and root development. However, at the fruiting stage, the level of potassium should be raised, while the level of phosphorus should be reduced, as high levels reduce fruit size. The level of nitrogen remains somewhat unchanged through the juvenile and fruiting stages because foliage is continuously produced. Tentative ranges of critical levels for bearing plants of 'Kapoho' Solo are: N = 1.10–1.40%, P = 0.15–0.18% and K = 2.5–3.5% (Awada and Long, 1980).

Papaya is sensitive to boron deficiency, especially when cultivated on sandy soil. Plants suffering from this deficiency exhibit characteristic symptoms: slight yellowing and downward curling of the leaf tips, with very slight necrosis of the leaf tips and margins. The leaves are brittle in texture and claw-like. During fruiting, secretion of milky latex often occurs on the fruit surface, which subsequently turns brown in colour. At the later stage, the fruit surface becomes rough or 'bumpy', giving the fruit an overall distorted or malformed appearance. Treatment of boron deficiency is by soil or foliar application of borate.

Diversity of soil types, climatic conditions and practices make it necessary to develop recommendations for specific areas based upon soil analysis and preferably foliar analysis. In the sandy loam soils of North Moreton, Australia, a pre-plant application of 0.5 kg of 5:7:4 complete fertilizer, 0.25 kg of single superphosphate and 1.0 kg of lime per individual plant (over 1 m^2 area) is recommended. For post-plant application, 100 g/plant of 10:2:16 complete fertilizer is given at about 2-month intervals, with monthly application of 150–200 g per plant site during summer and autumn. In the second year, 250 g per plant is given at 2–3-month intervals. Because of boron deficiency problems in this area, 20 g of borax is applied at 3–4-month intervals and 30g/plant is given the second year at about 7–8-month intervals.

Pest management

Diseases

The importance of frequently reported papaya diseases (Table 11.6) varies, and they may be widespread or localized. *Phytophthora* commonly causes collar and root-rot and sometimes stem canker and fruit rot in papaya. Papaya is predisposed to the disease in areas with a high water table, poor aeration and persistent high rainfall. *Phytophthora* with *Pythium* also cause seedling 'damping-off', a serious disease during the nursery stage. *Phytophthora* root rot is a major concern in all areas where the same land is used repeatedly for production. Depending upon soil type and rainfall, the replant problem may become very serious within two or three successive plantings, with seedling mortality up to 45% (Nakasone and Aragaki, 1973). Alternatively, virgin soil (soil never planted to papaya) is placed into each planting hole in a replant field; this allows the seedling to become established before the roots penetrate beyond the virgin soil and they are then less affected by root rot fungus. Development of cultivars with strong tolerance through breeding is slow, with the cv. 'Waimanalo' being such a product. Seedling damping off immediately after germination is caused by a complex of organisms. The use of sterilized germination medium with good aeration and control of moisture are preventative measures.

Fruit diseases generally occur postharvest. Incidence of some fruit diseases can be minimized by field sanitation and field application of appropriate fungicides, while others can be reduced by careful handling of fruit, as these organisms infect through wounds. Anthracnose, a preharvest infection fruit surface rot, and stem-end rot, a harvest wound rot, are the two most common postharvest rots of papaya. At the early stage of the infection, anthracnose, *C. gloeosporioides*, is manifested as tiny dark spots on the skin of fruit, and if left untreated, they form larger, depressed lesions when the fruits start to ripen. In more severe cases, especially when the fruits turn full colour, the lesions may coalesce with each other and the pinkish spores of the fungi are evident in the depressed lesions. The infected fruit becomes soft, dark coloured and unattractive.

Bunchy or malformed top is a relatively new disease of papaya. The disease is a complex involving both thrips and a normally saprophytic fungus *Cladosporium oxysporum*. Severely infected plants remain stunted and are slow to recover. Symptoms are typified by the appearance of new flushes of leaves that are malformed, with leaf spots and 'shot-holes' (ranging from 1 to 3 mm wide). Short, light-yellow streaks (due to feeding by thrips) are usually interspersed with the spots. The 'Eksotika' and 'Solo' varieties are very susceptible at the juvenile stage.

The papaya virus disease, papaya ringspot virus (PRSV) has become the limiting factor for commercial production in many areas. This disease has been referred to as papaya mosaic virus (PMV) and distortion ringspot virus (DRV). The fact that PRSV is suspected to be a number of a different viruses is due to the variations in the expressed symptoms associated with different races. Papaya ringspot virus (PRSV) has severely restricted papaya production in Thailand, the Philippines and Taiwan and has also been recorded as the major papaya disease in India, Hawaii, the Caribbean, Malaysia and Vietnam

Table 11.6. Some important diseases and disorders of papaya.

Common name	Organism	Parts affected	Distribution
Phytophthora blight	*Phytophthora palmivora*	Root, stem, fruit	Widespread
Pythium root rot	*Pythium aphnidermatum*	Root	Widespread
Damping off	*Pythium aphanidermatum, P. ultimum, Phytophthora palmivora, Rhizoctonia* sp.	Seedling stem at soil line	Widespread
Collar rot	*Calonectria crotalariae*	Base of trunk, crown roots	Hawaii, Thailand
Powdery mildew	*Oidium caricae*	Underside of leaves, petioles	Widespread
Alternaria fruit rot	*Alternaria alternata*	Fruit body	Widespread
Blackspot	*Cercospora papayae*	Fruit body	Widespread
Anthracnose, chocolate spot	*Colletotrichum gloeosporioides*	Ripe fruit body	Widespread
Soft rot	*Rhizopus stoloifer*	Injured mature fruit at stem end	Widespread
Stem-end rot	*Fusarium solani*	Wounded mature fruit at stem end	Widespread
Phoma rot	*Phoma caricae-papayae*	Stem end, wounded area	Widespread
Phomopsis rot	*Phomopsis* sp.	Stem end, wounded area	Widespread
Stemphylium rot	*Stephylium lycopersici*	Stem end, wounded area	Widespread
Fruit rots	*Botryodiplodia* sp.	Stem end, wounded area	Widespread
	Cladosporum sp.	Fruit body	
Stem-end rot	*Mycosphaerella* sp.	Stem end	

Continued

Table 11.6. Continued.

Common name	Organism	Parts affected	Distribution
Yellow crinkle	Tomato big bud organism	Leaves, flowers	Australia
Papaya ringspot virus	Aphids: *Myzus persicae, Aphis gossypii*	Leaves, stems and petioles, fruit ring-spots or distorted	Widespread
Bunchy top (mycoplasma-like bodies)	*Empoasca papayae* (leafhopper)	Death of growing point	Caribbean, tropical America
Die back	Unknown	Yellowing and death of crown leaves	Australia, Israel
Yellow crinkle	Leaf hopper	Yellowing of old leaves; crown leaves show translucent areas	Australia

(Table 11.6). In Taiwan, papaya is restricted to annual rather than perennial production and cultivation and is often carried out in large net-houses to keep out the disease-carrying, non-persistent aphid vectors.

The symptom on the fruit is dark green, concentric rings, hence the name for the disease. On the younger stem and on the petioles, elongated, green, water-soaked streaks appear. Infected plants also show chlorosis in the young leaves, and the upper portion of the crown appears prominently yellowed. Fruits are also low in sugar content with poor flavour.

There are no control methods once the plant is infected. Eradication, sanitation methods and isolating the papaya-growing area by a papaya-free buffer zone allow papaya to continue to be grown. An orchard or growing area isolated far enough from disease sources remains uninfected because by the time aphids can move from the virus source to the healthy orchard, they are non-infective due to the non-persistent characteristic of the virus in the aphid. Also, curcurbit plants should not be interplanted in papaya orchards as they are alternate hosts to the virus. A cross-protection method using a mild strain confers some immunization, enabling plants to be 82% more productive than unprotected trees in field trials. Breeding and selection has resulted in development of tolerant varieties such as 'Cariflora', 'Tainung No. 5', 'Sinta' and 'Eksotika'-derived breeding lines. The genetically modified variety 'Rainbow' transformed with the virus coat protein gene has shown excellent resistance to the disease in Hawaii. Transforming of papaya with the viral coat protein has been successful; however, each virus race has a specific coat protein, so different coat protein genes are needed in different areas.

INSECTS AND MITES

Many insects have been reported on papaya, but most are unimportant and the damage is negligible or easily controlled. A few may cause severe problems in localized areas (Table 11.7). Aphids, such as *Aphis gossypii* and *Myzus persicae*, are important only as vectors of PRSV. Fruit flies are troublesome in the export trade as papayas may need to receive a disinfestation treatment for fruit fly eggs and larvae before export. Rarely are fruit at the mature-green to colour-turning stage infected; egg lay becomes a problem when fruits have 25% or more skin colour (Seo *et al.*, 1982).

Several species of mites are known to infest papaya (Table 11.7), the commonest being the red spider mite (*Tetranychus cinnabarinus*) and the broad mite (*Hemitarsonemus latus*). The mite population increases dramatically during the dry and cool spells, and they can be located on the undersurface of emerging leaves and petioles. In severe infestations, the leaves are shed prematurely and the shoot terminals suffer die back. They also cause extensive scarring (netted corky appearance) on the surface of the fruits when they feed on the epidermal tissues.

Thrips (*Thrips parvispinus)* are common on papaya flowers during the blooming season. However, during the early stages of plant growth, they feed

Table 11.7. Some important insects and pests of papaya.

Common name	Scientific name	Parts affected	Distribution
Melon fly	*Dacus cucurbitae*	Fruit	Widespread
Oriental fruit fly	*Dacus dorsalis*	Fruit	South-east Asia, Philippines, Western Pacific, Hawaii
	Dacus melanotus	Fruit	Cook Islands, South Pacific
Mediterranean fruit fly	*Ceratitis capitata*	Fruit	Hawaii, Mexico, Central, South America, Middle East, Africa
Fruit fly	*Toxotrypana curvicauda*	Fruit	American tropics, Florida
American fruit fly	*Anastrepha fraterculus*	Fruit	Subtropical, tropical America
Caribbean fruit fly	*Anastrepha suspensa*	Fruit	Florida, Caribbean
Green peach aphid	*Myzus persicae*	Virus vector	Widespread
Red and black flat mite	*Brevipalus phoenicis*	Fruit	Widespread
Broad mite	*Hemitarsonemus latus*	Emerging leaves, leaves of young seedlings	Widespread
Carmine mite	*Tetranychus cinnabarinus*	Lower surface of mature leaves	Widespread
Texas citrus mite	*Eutetranychus banksi*	Mature leaves	Widespread
	Eutetranychus orientalis	Mature leaves	Thailand
Citrus red mite	*Panonychus citri*	Mature leaves	Widespread
Monkeys			Kenya, Barbados
Birds	Four species		Caribbean, Hawaii
Bats			Vanuatu, South Pacific

on the supple young leaves and shoot and provide the infection site for the invasion by the saprophytic fungus *C. oxysporum*.

There are three species of scale insects known to infest papaya in Malaysia but only two, i.e. the palm scale, *Aspidiotus orientalis*, and the oriental scale, *Aonidiella orientalis*, are economically important. *A. orientalis* is considered the most destructive. Both the nymph and adult feed on the leaf, stem and fruit. *A. orientalis* is only found on the fruit and seldom on other parts of the plant.

Nematodes

This pest, common only on sandy soils, damages the root systems and causes stunting of the plants. Two nematodes, the root-knot nematode (*Meloidogyne incognita*) and reniform nematode (*Rotylenchulus reniformis*), are the major problems.

Weed management

Hand weeding, especially around young seedlings, mowing and mulching are often used for weed control. Plastic mulch is very effective against annual broadleaved weeds but ineffective against perennial grasses or sedges. Post-emergence herbicides such as glyphosate are currently widely used. Glyphosate is effective for a wide spectrum of weed species, and as a systemic herbicide its effects are not visible for a number of days. A common practice in some areas is to interplant papaya orchards with tree crops that later become the principal crop. Herbicides selected for the principal crop must also be compatible with papaya and registered for use for both crops.

Orchard protection

Papayas develop extensive root systems but are vulnerable to strong winds, especially when accompanied by rain. Windbreaks of appropriate shrubs or small trees planted close together across prevailing wind directions can protect the trees from severe damage. Selection of windbreak plants is best left to those with local experience of the region.

HARVESTING AND POSTHARVEST HANDLING

Harvesting

Harvesting is easy when fruits can be reached by hand; as trees become taller some form of harvesting aid, such as poles and ladders, must be used. In Hawaii, most growers use a rubber cup or chisel-shaped metal tool with a ‘V’ attached to a long pole, which is placed against the bottom of the fruit or against the peduncle and pushed upwards, snapping the fruit at the peduncle. The falling fruit is caught by the picker with the other hand or removed from the cup. The harvested fruits are accumulated in a bucket, tray or cloth picking bag. These methods are possible only with the small ‘Solo’ fruit. When the container is full, it is emptied into padded or lined bins left on field roads. An experienced harvester can harvest from 360 to 450 kg per 8-h day. Various hydraulically operated mechanical harvesting aids, such as mobile platforms, are sometimes used. The harvesters stand on the platform, which is adjusted to be at fruit height, as an operator slowly drives it down the rows.

The degree of ripeness for harvesting depends upon distance to markets. Fruits may be one-quarter to one-half ripe for local markets. Fruits to be transported long distances or exported are harvested at colour break to one-quarter ripe, depending upon the cultivar's ripening characteristics and season. Colour assessment is based upon the judgement of pickers. The Hawaii grade standard requires fruits to have 11.5% total soluble solids with the colour-break stage normally meeting this standard. Green immature fruit do not ripen well and have a total soluble solids value that is frequently less than 10%, giving a bland taste.

Postharvest treatment

The need for postharvest treatments depends upon the importing countries. Overseas markets require disinfestation treatments to eradicate fruit fly larvae and eggs from the fruit before shipment. The vapour heat method was the first disinfestation treatment used in the 1950s, and after the banning of the fumigant ethylene dibromide in 1984, vapour heat and forced heat treatment again became the industry standard. The fruit core temperature in these heat treatments reaches at least 47.2°C and the total treatment time is about 7 h (Paull and Chen, 1990). The alternative method is irradiation at a dose of about 250 Gy. This low irradiation dose sterilized the fruit fly larvae and eggs, preventing them from completing their life cycle. Irradiation at 250 Gy does not provide postharvest disease control and needs to be coupled with a postharvest disease control programme.

A fungicide–wax combination is recommended prior to packing (Paull and Chen, 1990). Incidence of storage diseases can be reduced by field spraying and proper care in harvesting and handling to avoid wounding and bruising. Skin injury is a major problem and is caused mostly by impact and abrasion during harvesting (Quintana and Paull, 1993). The latter is mainly caused when harvested fruits are being dropped into field bins with rough side walls and bottom. Careful handling is essential to avoid these unsightly blemishes, which provide an invasion site for postharvest rots.

Following the disinfestation treatment, papayas are packed into cartons in a screened area to prevent re-infestation by fruit flies. Defective fruits are culled before and/or after disinfestation and fruits are graded for size and colour and hand-packed into cardboard cartons with a capacity of about 4.5–10 kg. Cartons from areas requiring insect disinfestation are fully sealed to meet regulatory requirements, while fruits from other areas can be in open-topped cartons. Count size ranges from 6 to 18, depending upon fruit and carton size. Fruits are marketed as colour break, one-quarter ripe, half-ripe and three-quarter ripe and are normally ready to eat when there is three-quarters or more colour on the skin. Foam mesh sleeves, foam padding on the bottom of the carton or paper wrapping prevent abrasion injury, which is a major problem in fruits still having green areas of skin.

Room cooling and forced air cooling are most commonly used to pre-cool. Hydro-cooling is possible; however, rapid cooling after insect disinfestation treatments can lead to skin scalding. Storage recommendations are in the range of from 7 to 13°C and from 90 to 95% RH. At 7–10°C, storage life is limited by chilling injury, while at 10–13°C ripening slowly occurs (Chen and Paull, 1986). Papaya fruit at colour-turning (break) stage can be stored at 7°C for 14 days and will ripen normally when transferred to room temperature (Fig. 5.3). Chilling injury symptoms include skin scald, hard lumps in the pulp around the vascular bundles and water-soaking of flesh. Fruits become progressively less susceptible to chilling stress as they ripen, and the symptoms occur after 14 days at 5°C for mature green fruit and 21 days for 60% yellow fruit. Skin scald can be induced in colour-break fruit after chilling at 1°C for 24 h.

Shelf-life extension of 1–1.5 days was obtained when papaya were stored at 12°C in 1–1.5% oxygen for 6 days. Low oxygen (1.0–5%), with or without high CO_2 (2–10%), reduces decay and delays ripening. High CO_2 (30%) adversely affected internal colour, aroma and flavour, while there is no residual effect of 10% CO_2 on decay control, though skin degreening is delayed. At 10°C, fruit could be stored for 36 days in 8% CO_2, 3% O_2 and still have 5 days at 25°C for retail. Ethylene removal prior to storage has shown variable results. Controlled atmosphere has not shown dramatic improvement in storage life and the economic cost of the treatment needs to be balanced against the improvement in fruit storage life and quality.

The optimum temperature for fruit ripening is between 22.5 and 27.5°C, with fruit taking 10–16 days to reach full skin yellowing from the colour-break stage (An and Paull, 1990). Severe weight loss and external abnormalities become significant at temperatures higher than 27.5°C. Fully ripe fruit at the edible stage can be held at 1–3°C. Loss of *ca.* 8% of initial weight from colour-break papaya produces 'rubbery', low-gloss, unsaleable fruit.

Marketing

Most papayas produced in the tropics are consumed locally, due to long distances to markets and the difficulty in handling the large fruit size. Marketing standards for trade are normally set by agreement between the shipper and the wholesale or retail buyer. In Hawaii, standards for Hawaiian-grown papaya have been developed. Fruit must conform to the 'Solo' type, with similar cultivar characteristics as to size and shape, must be mature with a definite tinge of yellow at the blossom end, must be clean, well-formed and meet the total soluble solids standards, averaging not less than 11.5%

for any lot of papayas, provided not more than 5% by count of fruit in the lot have soluble solids less than 10.5%. Fruit is sized into the following size classifications: small 284–369 g; medium 369–454 g; large 454–907 g; and extra large over 907 g. A major problem with the standard is the difficulty in achieving same size and skin colour that will ripen together in the carton. Other typical requirements include that the fruit must be free from decay, breakdown, internal lumps and other undesirable characteristics and free from various categories of injury, including insect and mechanical injury.

WORLD PRODUCTION AND UTILIZATION

Production

Thirty-eight countries are reported to produce papaya. Six countries produce a minimum of 100,000 MT/year. Brazil is the largest producer, followed by Mexico, Indonesia, India, Zaire, Taiwan and the Philippines (Anonymous, 2003). World production is in excess of reported figures, as considerable production occurs in small island countries in the tropics; backyard and subsistence-farm production and that consumed locally may not enter into the world production statistics.

Utilization

The fruit is the major product from this species, though young leaves and male flowers are used as vegetables and in soap. Nutritionally, the papaya is a good source (Table 11.8) of calcium (30 mg/100 g), and an excellent source of provitamin A and ascorbic acid (Wenkam, 1990). Papayas are consumed fresh as breakfast fruit, dessert or in salads. In Asia, green fruits are cooked as a vegetable or made into preserves. Papayas are also processed into various forms, such as dehydrated slices, chunks and slices for tropical fruit salads and cocktails, or processed into puree for juices and nectar base, usually frozen, and as canned nectar, mixed drinks and jams. Papaya puree is the basis for remanufacturing of many products. Papaya puree is processed aseptically or frozen, with yield of *ca.* 50%. The flavour of aseptically processed puree is stable during processing and after 6 months in ambient storage, with some colour changes noted.

Papain is a proteolytic enzyme that digests proteins and is used as a meat tenderizer, as a digestive medicine in the pharmaceutical industry, in beer brewing, tanning industries and in the manufacture of chewing gum. Papain production is primarily centred in Tanzania and India, where labour is abundant and inexpensive. The latex is obtained from green papaya by making about four surface lancings on the fruit and catching the drippings in cups,

Table 11.8. Nutritive value of hermaphrodite 'Solo'-type papaya (Wenkam, 1990).

	Amount per 100 g edible portion
Proximate	
Water (g)	87
Energy (kJ)	192
Protein (g)	0.39
Lipid (g)	0.06
Carbohydrate (g)	12.2
Fibre (g)	0.58
Ash (g)	0.57
Minerals	
Calcium (mg)	30
Iron (mg)	0.2
Magnesium (mg)	21
Phosphorus (mg)	12
Potassium (mg)	183
Sodium (mg)	4
Vitamins	
Ascorbic acid (mg)	84
Thiamine (mg)	0.03
Riboflavin (mg)	0.04
Niacin (mg)	0.33
Vitamin A (IU)	1093

with yields of 88.5–227 g/tree of dried latex per year. Approximately 2.27 kg of fresh latex will produce 0.45 kg of dried latex.

In processing papayas 22% of the waste is seed. The seed oil content of 33% on a dry weight basis is considered high when compared to seeds of other fruit. Protein content of 29% on a dry weight basis is comparable to that of soybean, with 35%. Papaya seed meal, with 40% crude protein and 50% crude fibre, appears to be a potentially rich animal feed. A salad dressing is also made from ground papaya seeds.

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12

Pineapple

Pineapple (*Ananas comosus* (L) Merr.) is also called piña (Spanish), abacaxi (Portuguese), annachi pazham (Tamil) or nanas (Malaysian), with many languages using the South American Tupian language name ananas. This is the only species in the bromeliad family grown commercially for its fruit. The fruit was called 'piña' by 15th-century Spanish explorers because of its resemblance to a pine cone. The fruit develops by fusion of floral parts (Fig. 12.1). Pineapple is eaten fresh and canned, and the juice is sold singly and in combination with other fruit juices. Cut pieces are used as a dessert, in salads and cooked meat dishes, and in fruit cocktail mixes. Today, the pineapple is found in almost all the tropical and subtropical areas of the world, and it ranks third in production of tropical fruits, behind bananas and citrus.

BOTANY

Introduction

Pineapple is in the bromeliad family, which has about 45 genera and 2000 species. The *Bromeliaceae* originated in tropical America except for one species, *Pitcairnia felicana* (Aug. Chev.) Harms & Mildbr., a native of tropical West Africa (Collins, 1960). Plants are herbaceous or shrubby and classified as epiphytic or terrestrial. Pineapple (*A. comosus* (L.) Merr.) is by far the most economically important bromeliad. Other species of *Ananas* and *Bromelia* yield edible fruits: *Ananas bracteata* (Swartz) Grisebach, *Ananas kuntzeana* Mez., *Ananas longifolia* (Rudge) L.B. Smith & M.A. Spencer, *Ananas nudicaulis* (L.) Grisebach, *Bromelia antiacantha* Bertoloni, *Bromelia balansae* Mel., *Bromelia chrysantha* Jacquin, *Bromelia karatas* L., *Bromelia hemisphaerica* Lamarck, *Bromelia nidus-puellae* (André) André ex Mez., *Bromelia pinguin* L., *Bromelia plumieri* (E. Morren) L.B. Smith, and *Bromelia trianae* Mez. The more common are consumed locally, under names such as cardo or banana-do-mato (bush banana), piñuelas (small pineapple), or *karatas*, *gravatá* and *caroata* (derived from Amerindian

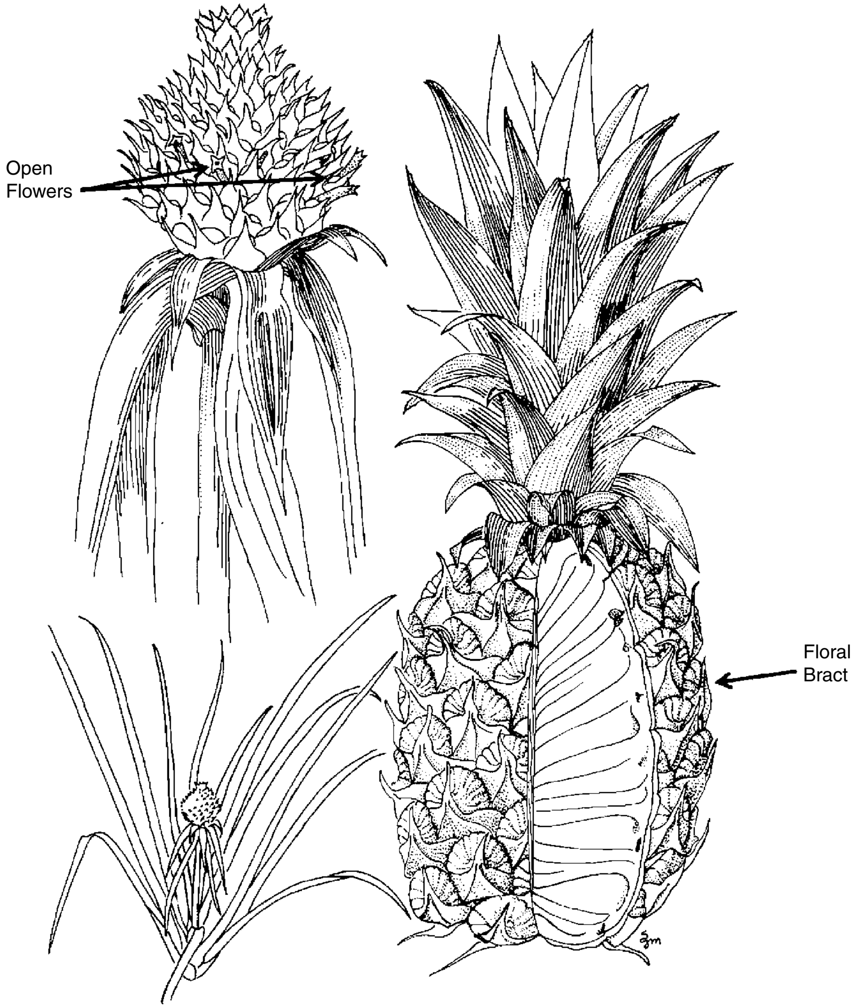

Fig. 12.1. Pineapple inflorescence and flower, and fruit. The small purplish flowers open from the base of the inflorescence. The fruit is composed of fused fruitlets and the skin of sepals partially covered by a bract.

names given to terrestrial bromeliads). For example, *B. balansae* Mel. is called gravata in Brazil and it has 80–120 fruit per plant, each weighing 6–14 g; the skin is brown and the flesh is white when ripe. Many other bromeliads are cultivated as ornamentals, gathered for fibre extraction or used in traditional medicine.

Origin and distribution

The pineapple was first seen by Europeans when Columbus and his men landed on the island of Guadaloupe during the second voyage in 1493. Early exploration by botanists in South America indicated the area of origin to be south-eastern Brazil, Paraguay and northern Argentina, because of the abundance of wild species. Based on materials collected in South America, Leal and Antoni (1980) proposed an area further north, between 10° N and S latitudes and 55–75° W longitude. This general area includes north-western and eastern Brazil, all of Colombia and Guyana, and most of Venezuela.

At the time of Columbus's arrival, the pineapple was already widely distributed throughout most of tropical America. The antiquity of this fruit even at that time is evidenced by the presence of distinct types, all of which were nearly or completely seedless. Its wide uses as food, wine and medicine at the time of Columbus's arrival in the Americas and the absence of recognizable wild progenitors of the cultivated pineapple are further evidence of pineapple's antiquity (Collins, 1948). Distribution of pineapple from the Americas is attributed to Spanish and Portuguese explorers and was aided by the resistance of crowns and slips to dessication. Pineapple was introduced into Africa at an early date and reached southern India by l550. Before the end of the l6th century, it had become established in China, Java and the Philippines (Collins, 1949).

At least 79 countries in the tropics and subtropics produce measurable quantities of pineapple (http://www.fao.org, 2008). Yields (kg/ha) are highly variable and, for those countries producing more than 5000 MT, range from 8 t/ha in Nigeria to 47 t/ha in Australia. This great variation in yields results from a number of factors. Small farms in countries that use the best technology tend to have higher yields than do large plantations utilizing the same technology, because in-field losses are easier to control on the small farm. Yields, on average, are much lower in developing countries, where access to inputs is limited by lack of capital. The exception occurs when a multinational corporation establishes a plantation in a developing country where labour costs are low. Cultivar differences also contribute to variations in yields. Where the predominant cultivars are 'Smooth Cayenne' and the Pineapple Research Institute of Hawaii hybrid clones 73-50 and 73-114 (also known as MD-2, 'Gold Extra Sweet', MG-3 and 'Mayan Gold'), yields are higher, probably more than twice as high even with the best technology, than are the spiny-leaved 'Queen' and 'Spanish' cultivars (Table 12.1). Prevailing climate also has a moderating effect on yields, with yields at the same level of technology being, on average, lower in the warm tropics than at higher latitudes.

Table 12.1. Characteristics of pineapple groups and clones (after Leal and Soule, 1977).

	Group				
Characteristic	Spanish	Queen	Abacaxi	Cayenne	Maipure
Leaves	Spiny	Spiny	Spiny	Smooth	Smooth
Fruit					
Weight (kg)	0.9–1.8	0.5–1.1	1.4	2.3	0.8–2.5
Shape	Globose	Conical	Conical	Cylindrical	Cylindrical
Colour skin	Large, deep eyes O, R	Deep eyes Y	Y	Flat eyes O	Y to OR
Colour flesh	Pale Y to W	Deep Y	Pale Y to W	Pale Y to Y	W to deep Y
Core	Large	Small	Small	Medium	Small–medium
Taste	Spicy acid, fibrous	Sweeter, less acid, low fibre	Sweet, tender, juicy	Sweet, mildly acid, low fibre, juicy	Sweeter than 'C', fibrous, tender, very juicy
Market					
Canning	F	F	F	VG	F
Fresh					
Local	G	G	G	G	G
Export	VG	G	F to P	F	F to P
Disease problems	Gummosis, wilt resistance	More resistant than 'Cayenne'	Resistant	Mealy bug wilt	Unknown
Clones	Red Spanish	Queen	Abacaxi	Smooth Cayenne	Maipure
	Singapore Spanish	MacGregor	Abakka	Cayenne Lisse	Perolera
	Green Selangor	Natal	Sugar loaf	Smooth Guatemalan	Lebrija
	Castilla	Ripley	Papelon	Typhone	Monte Lirio
	PRI-67	Alexandria	Venezolana	St. Michael	Abacaxi
	Cabezona		Amarella	Esmeralda	Rondon

Abbreviations: C, cayenne; F, fair; G, good; O, orange; OR, orange-red; P, poor; R, red; VG, very good; W, white; Y, yellow.

ECOLOGY

Major areas of commercial cultivation are found between 30° N and S latitudes, with some areas considered marginal for various reasons (Bartholomew and Malézieux, 1994). Minor plantings extend pineapple production to subtropical areas with mild climates beyond 30° N and S latitudes and even under protective shelters. Pineapple cultivars show considerable variation in their plant growth and fruit size when grown in different environments (Chan and Lee, 1985). Greater variation in cultivar yield response occurs in less favourable environment.

Soil

Pineapple can be grown in a wide variety of soil types, with good drainage and aeration being crucial. It is grown in the peat soils of Malaysia, sandy and sandy-loam soils of Ivory Coast, Queensland, Australia and Oaxaca, Mexico, and in the highly weathered red volcanic soils of Hawaii. The ideal soil type for pineapple is a sandy or well-aggregated clay soil with good drainage to prevent waterlogging and root diseases (Hepton, 2003).

In Hawaii, pineapple is grown primarily on silt loams, silty clay loams and silty clays, primarily oxisols and ultisols. These soils are well suited to pineapple because they occur in areas having high insolation, have good water-holding capacity but are well aggregated, so drainage is adequate to very good. Most of these soils are red in colour, are derived from basaltic rocks and volcanic ash alluvium, and are high in oxides of iron, aluminium and, in some cases, manganese. Soils with high levels of manganese can result in manganese-induced iron chlorosis because soil pH is maintained around 4.5, which results in high levels of soluble manganese in the soil solution. Generally, a pH range of 4.5–5 is considered best for pineapple (Hepton, 2003), primarily to reduce the incidence of heart and root rot caused by *Phytophthora* spp.

Climate

Rainfall

The pineapple is an obligate Crassulacean acid metabolism (CAM) plant with a xerophytic characteristic that enables it to withstand long periods of drought. The leaves have a water-storage parenchyma that serves as a reservoir of moisture during drought. The leaves are covered with trichomes and a highly cutinized upper epidermis. The stomata are small and are located in furrows on the underside of the leaf. At the early inflorescence development stage, 38% of water use occurs at night when the stomata are open. At midday, no water loss is detected. Water-use efficiency is 3.3 times greater for pineapple than for wheat (Bartholomew and Malézieux, 1994). Pineapples are produced under a wide range of rainfall, from 600 mm to more than 3500 mm annually, with the optimum for good commercial cultivation being from 1000 to 1500 mm. In Hawaii, pineapple is grown in areas where the rainfall ranges from 510 to 2540 mm, with an average of 1190 mm annually. Pan evaporation in the major growing area of Wahiawa, Hawaii is 1850 mm per year (5 mm per day). Even if annual rainfall closely approximates the optimal range, poor distribution can result in periods of serious drought. In Loma Bonita and Acayucan (Mexico) 89% and 82% of the rainfall, respectively, occurs between June and November.

Despite the xerophytic characteristics of pineapple, growth is adversely affected by prolonged dry periods. Plants may not attain the desirable size by the scheduled time for chemical flower induction. However, most areas of the world where pineapple is cultivated have fairly high humidity, which can reduce the impact of drought. At higher elevations, night air is cooled enough to produce heavy dew, which condenses on the leaves and drains into the heart of the plant and into the soil, providing supplemental moisture that can be absorbed by roots in the leaf axils.

Temperature

In the absence of drought, temperature is the most important factor in pineapple cultivation. The prevailing temperature determines the rate of plant and fruit growth and, in conjunction with solar radiation, has a dramatic influence on fruit total soluble solids and acidity, which are the primary determinants of fruit quality. Under controlled conditions, the rate of root growth at 18°C was less than 15% of the maximum, while the optimum temperature was 29°C (Fig. 12.2). Leaf growth responds to temperature in a manner similar to that of the roots, but growth is closer to 20% of the maximum at 18°C and the optimum temperature is 32°C (Sanford, 1962). Photosynthesis and plant growth approach a maximum when the day temperature is near 30°C and there is about a 10°C diurnal range between day and night temperatures (Malézieux *et al.*, 2003).

Warm days and cool nights provide the optimum environment for net assimilation and growth. Growth is slow at an average temperature of 20°C and at night temperatures below 15°C. In the cool season or in the cooler, higher elevations, growth is delayed; leaves are upright, rigid and shorter; the number of slips is higher; fruit may be smaller with prominent eyes; the flesh is opaque, higher in acidity and sugars are lower (Bartholomew *et al.*, 2003). However, the effects of seasonally cool temperature are confounded with insolation, because irradiance decreases with the temperature during the winter months.

Pineapple does not tolerate frost, and even night temperatures of 7–l0°C for a few h for several weeks during winter can result in leaf-tip necrosis. Such low temperatures can also cause fruit injury. A range of desirable minimum night temperatures would be 15–20°C, while a comparable day temperature range would be 25–32°C. The interaction of solar radiation and temperature significantly affects the days from forcing to harvest. Further away from the equator the amplitude of the temperature difference between seasons increases and number of days from planting to harvest also increases.

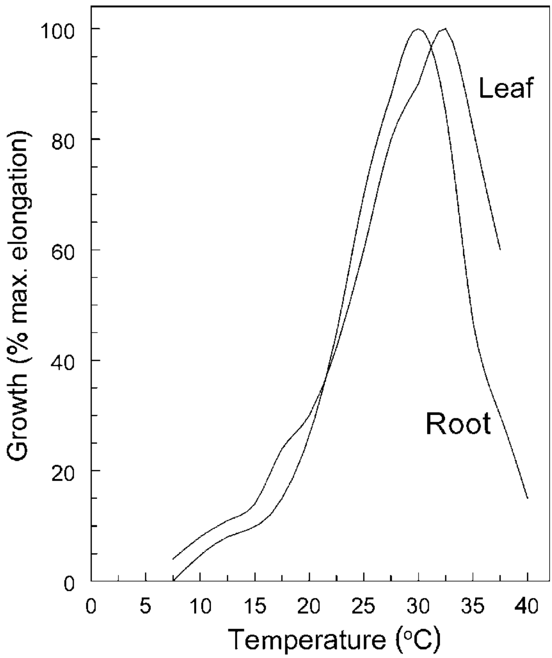

Fig. 12.2. Effect of temperature on leaf and root growth (redrawn from Sanford, 1962).

Where topographic variation exists, changes in elevation provide a means of achieving a desirable range of temperature conditions (Fig. 12.3). Near the equator, the highest yields and fruit of the best quality are generally obtained at higher elevations. In Kenya, an equatorial country, pineapple is grown at more than 1400 m, while on Mindinao, the Philippines (8° N), most pineapple is grown at an elevation of 250 m or higher. While elevation provides an opportunity to provide an ideal environment for pineapple in the tropics, economics, particularly labour costs, often determines where the crop is grown. Thailand (~15° N) is the world's largest producer of pineapple, yet most of the crop is grown near sea level in this warm tropical country. South Africa and southern Queensland, Australia represent the extremes of the climatic range over which pineapple is grown, and winter temperatures severely restrict growth rates. In southern Queensland, fruit initiated by forced flowering during the 3 coldest months all mature within about 1 month, as growth resumes as spring temperatures increase (Fig. 12.3). In South Africa and southern Queensland, minimum temperatures occasionally approach or reach freezing point for short durations, while in most other areas where pineapple is grown winter temperatures rarely fall below 10°C.

Cool night temperatures coincident with shortened day length stimulate floral induction if the plant is of sufficient size. Cool temperatures also increase

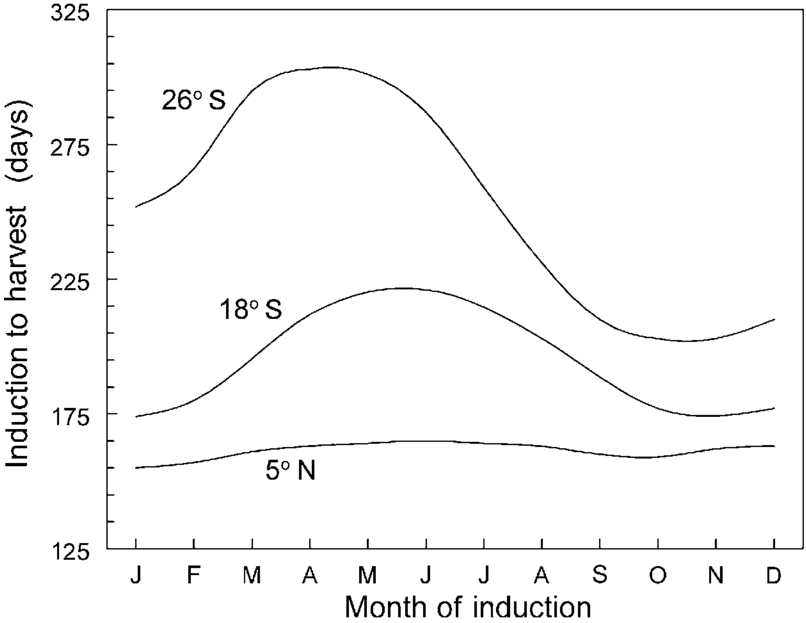

Fig. 12.3. Effect of latitude as an indicator of solar radiation and temperature on the time from forcing to harvest, 26° S is for Nambour, Australia, 18° S is Madagascar and 5° N is Ivory Coast.

the responsiveness to flower-inducing compounds (Bartholomew *et al.*, 2003) and shorten the time to floral induction under a short-day regime. High temperatures (>28°C) make chemical flower induction more difficult, with the percentage of plants forced decreasing linearly with increasing temperature. In Mexico between June and August, and in Thailand in most months of the year, fruit produced for processing generally have low acidity and total soluble solids (TSS). In Mexico, this lower quality is due to the combined effect of high temperature, excessive rain and an increased number of cloudy days, while in Thailand the response is due primarily to overly warm temperatures.

The 'Smooth Cayenne' group is the more productive in tropical conditions, while the 'Queen' group is grown mainly in subtropical areas. 'Smooth Cayenne' is most sensitive to low-temperature-induced internal browning (chilling injury, blackheart), while 'Red Spanish' is less sensitive.

Sunlight

Most pineapple is grown in regions with high insolation, at least in part because the crop is well adapted to areas with low rainfall. While the light level required to saturate photosynthesis of a pineapple leaf is believed to be less than 25% of full sunlight, high irradiance is required to sustain the high levels of productivity found in commercial plantations, where plant population densities can reach or exceed 75,000 plants/ha. In Hawaii, the maximum day-length range between the shortest and longest days is about 2.5 h, but solar irradiance in December is about 50% of that occurring during midsummer. Sun injury of leaves is relatively uncommon in most regions where pineapple is grown, as air temperatures do not exceed about 35°C. When greater than 35°C, the leaf's surface temperature on a horizontally displayed leaf is likely to exceed 50°C. Because of close plant spacing on commercial plantations, pineapple leaves are erect, as they are supported in an upright position by the leaves of closely spaced adjacent plants. Erect leaves help to distribute high midday irradiance uniformly over the leaf surface and help to reduce the heat load borne by the leaf. Due to relatively erect leaf orientation, about 95% of light interception occurs in a pineapple canopy at a leaf area index (LAI) of about 5.0.

Fruit weight is significantly correlated with mean irradiance from planting to harvest (Fig. 12.4). The lower fruit weight associated with lower irradiance is due to a lower plant weight at forcing. Fruit acidity in the month before harvest declines with solar radiation levels and there is no significant effect on total soluble solids. Cloudy days reduce pineapple growth and result in smaller plants and smaller fruit, with higher acid and lower sugar contents. A rule of thumb is that for each 20% decrease in solar radiation, the yield decreases ~10%. Mutual shading at higher planting densities leads to a linear decrease in individual fruit weight and a curvilinear increase in total yields as density increases.

Intense sunlight, particularly during fruit maturation, can cause sun-scalding of fruit, with the 'Queen' group being more susceptible than 'Smooth Cayenne'. The damaging effect can be prevented by shading the fruit or spraying a reflective coating, for example lime and a spreader-sticker, as is done in Queensland, Australia. Fruit covered with newspapers or grass, or the gathering and tying of the longest leaves over the fruit is observed in Okinawa and Taiwan and is also a common practice in Mexico and Brazil.

Photoperiod

The normal season for flowering of 'Smooth Cayenne' is during the winter, in response to cool temperatures and shortened photoperiod. However, the plant will flower naturally at any time of the year, depending upon the planting material and time of planting (Bartholomew *et al.*, 2003). Because of this response, Gowing (1961) classified 'Smooth Cayenne' as a quantitative but not an obligate short-day plant. Under controlled conditions, 'Smooth Cayenne' plants grown under 8-h days all flowered; 69% flowered under 10-h days, 53% under 12-h and 30% under 16-h days (Friend and Lydon, 1979). Interruption of the dark period by illumination suppresses flowering. Before the advent of artificial floral initiation, plants that were not induced to flower during the winter months generally flowered in the late summer and early autumn, producing winter and spring fruit. Some minimum

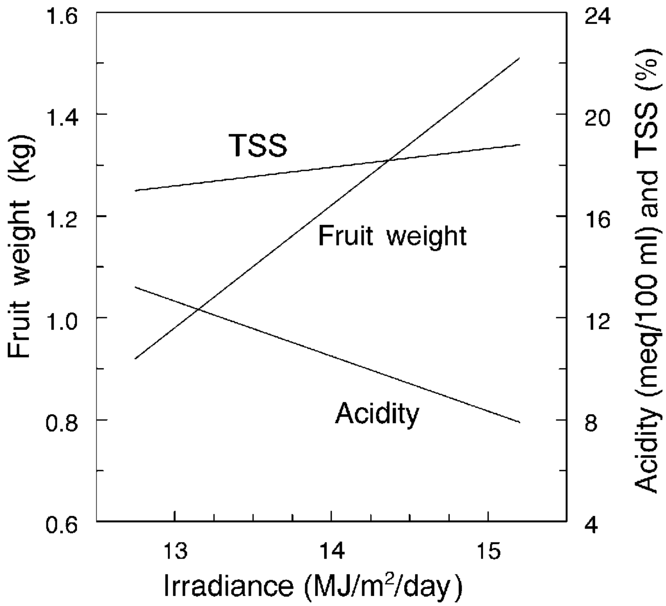

Fig. 12.4. Effect of mean irradiance from planting to harvest on average fruit weight, and mean irradiation 2 weeks prior to harvest on fruit juice titratable acidity and total soluble solids (TSS) of 'Smooth Cayenne' pineapple fruit grown in the Ivory Coast.

plant size is necessary before natural flowering will occur, and cool night temperatures apparently enhance the effects of short days (Bartholomew *et al.*, 2003).

GENERAL CHARACTERISTICS

Stem

The stem of a mature 'Smooth Cayenne' plant is 30–35 cm long and club-shaped, with the thickest diameter being 5–8 cm just below the apex. Internodes are short, ranging from 1 to 10 mm, with the middle region of the stem having the longer internodes. There is an axillary bud at each node (Krauss, 1949). Adventitious roots grow through the epidermis and vary in length from a few millimetres near the top of the stem to several centimetres at its base. Axillary buds can produce shoots, typically called suckers in the industry, which are the source of a second or ratoon crop. Suckers may be retained on the mother plant or they may be harvested for use as planting material. Such harvesting is a relatively costly operation because the shoots must be cut from the mother-plant stem. Suckers harvested for use as planting material can range in weight from a few hundred grams to more than a kilogram fresh weight (Fig. 12.5). Large suckers are unsuited for use as planting material because the shock of removal tends to induce precocious inflorescence development. Shoots, commonly called slips, also are produced from buds in the axils of the floral bracts on the peduncle. The stem of slips is comma-shaped, in contrast with the straight stem of suckers and crowns. If slips are allowed to remain on the plant for a few months after fruit harvest, they can grow to 250–450 g.

Roots

Adventitious roots are produced from preformed root primordia in the stem. Krauss (1948) separated the roots into 'soil' roots, which develop at the base of the stem and form the underground root system, and 'axillary' roots, which form above the soil surface in the leaf axils. The underground root system is relatively dense and typically extends to a depth of 15–30 cm. The roots of pineapple plants grown in deep, loose, fertile soil free from parasitic organisms and can grow downward more than 50 cm and extend 1.83 m beyond the plant within a year's time.

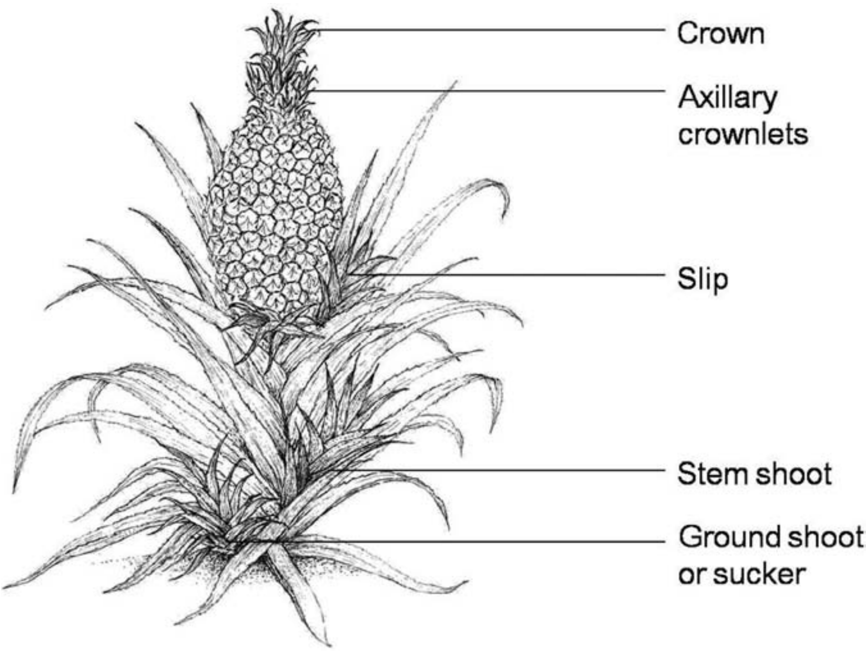

Fig. 12.5. Pineapple fruit showing multiple crowns, slips at the base of the fruit and suckers at the base of the plants (from Coppens d'Eeckenbrugge and Leal, 2003).

The axillary roots will absorb both water and nutrients, facilitating the utilization of foliarly applied nutrients. The main absorptive area of the root is in the unlignified white tissue of the root tip. Roots without white tissues at the root tips are not actively growing, are inefficient in absorbing water and may have been lost because of root rot and nematode feeding.

Leaves

Leaves are produced in a spiral around the stem in a tight rosette (Fig. 12.1). A dormant axillary bud is found at the midpoint of each leaf on the main stem. By counting from a leaf or bud at a selected node on the stem upwards in a spiral, the 13th leaf or bud will be directly above the initial leaf or bud and five turns around the stem will have been made, resulting in a 5/13 phyllotaxy (Bartholomew and Kadzimin, 1977).

The number of leaves increases regularly, with an average of five or six leaves per month. Old leaves do not abscise, and a mature plant may have 70–80 active leaves. The most frequently mentioned developmental index for carbohydrate and nutrient status is the whorl of leaves designated and described as the D-leaves by Sideris and Krauss (1936) and first used by Nightingale (1942). Usually, the D-leaves are in the fourth whorl from the base of the plant, and not more than three leaves would qualify as D-leaves at any one time. These are the longest (80–100cm) and the youngest nearly physiologically mature set of leaves. In non-fruiting plants, the leaf base of these leaves is only slightly broader than the green blade. In 'Smooth Cayenne' a small group of marginal spines is found near the leaf base and near the tip. Also, a short area of spines is formed on new growth of the leaves after temporary cessation of leaf growth due to adverse conditions. There is always a slight constriction at the point where leaf expansion was interrupted.

There are a number of structures in pineapple plants and other bromeliads that contribute to their strong resistance to moisture stress. The position and trough shape of the leaves, the presence of trichomes, and stomata located in furrows beneath trichomes on the underside of the leaf are features that enhance drought resistance. Long, multicellular trichomes are found in abundance on the lower side (abaxial) of the leaf and less on the upper (adaxial) side. It is generally believed that the trichomes absorb moisture and nutrient solution and reduce water loss through the stomata by forming a dense covering over the stomata.

A unique internal feature of bromeliads, including the pineapple leaf, is a water-storage tissue that is colourless and translucent. This tissue can be identified with the naked eye in the adaxial part of transverse sections of the leaf and contrasts with the chlorophyllous mesophyll tissue beneath. The width of both tissues in leaf cross section varies with age and environmental factors. In the pineapple-growing district of Wahiawa, Hawaii, the water-storage tissue of a turgid, fully developed leaf from a field-grown plant occupies about half the leaf cross section at the middle of the blade. This tissue becomes narrower as moisture stress increases. This tissue is absent towards the tip and margins.

Carbon is assimilated in pineapple leaves by the Crassulacean acid metabolism (CAM) pathway. The principal features of this pathway are large diurnal fluctuations in organic acids, mainly malic, and an inverted pattern of gas exchange due to the fixation of CO_2 into malate at night and its release and reduction to carbohydrate during the day (Malezieux *et al.*, 2003). The inverted pattern of gas exchange is the result of changes in the intercellular CO_2 concentration. At night the CO_2 acceptor molecule phosphoenolpyruvic acid (PEP) is produced using stored carbohydrate. The PEP is carboxylated to form oxaloacetic acid, which is then reduced to form malate. The malate is transported to the cell vacuole, where it is stored until the following day. Shortly after sunrise, malic acid moves from the vacuole to the cytoplasm, is decarboxylated to produce a molecule of CO_2 and a molecule of pyruvic acid; the low intercellular CO_2 level begins to increase and the stomata soon close. In the morning to early afternoon hours, the released CO_2 is fixed and reduced to carbohydrate by normal Calvin cycle or C-3 photosynthesis. As the malic acid level declines, the intercellular CO_2 level also decreases and the stomata open. During the remainder of the afternoon hours, CO_2 is assimilated from the atmosphere by conventional C-3 photosynthesis. Normal night opening of pineapple stomata requires sunlight on the previous day.

Inflorescence and flower

The inflorescence is terminal (Fig.12.1), developing from the apical meristem of the plant. Peduncle elongation begins at the time reproductive development is initiated and continues after flower formation. The first sign of floral initiation, whether natural or induced, is a rapid increase in diameter of the apical meristem, and 5–6 days after this change takes place, the peduncle begins to elongate. It continues to elongate as the inflorescence develops. The inflorescence can consist of up to 200 individual trimerous flowers with a phyllotaxy of 21/55 for large fruits of 'Smooth Cayenne' and 13/34 for smaller ratoon crop fruit (Ekern, 1968). Individual flowers are composed of three sepals, three petals, six stamens and a tricarpellate ovary. One to several flowers open each day over a period of 3–4 weeks, starting from the base of the inflorescence (Okimoto, 1948). The fruitlets develop from flowers that do not abscise and each flower is subtended by a fleshy bract (Fig. 12.1). The style, stamens and petals wither and the remaining floral parts develop into the fruitlet (Okimoto, 1948). The ovules and pollen grains are functional but seeds are not normally formed as 'Smooth Cayenne' is strongly self-incompatible.

When flower production ceases, the apical meristem again reverts to the 5/13 phyllotaxy, with a transition area of short leafy bracts, followed by the growth and development of the crown (Fig. 12.1).

Fruit

The fruit, more precisely defined as a coenocarpium (a multiple fruit derived from ovaries, floral parts and receptacles of many coalesced flowers), also commonly referred to as a sorosis (a syncarp of fused fruitlets from inferior ovaries), is topped by a leafy stem referred to as the crown (Fig. 12.5). The fruit 'shell' is composed mainly of sepal and bract tissues and the apices of the ovaries, while the edible flesh is primarily composed of ovaries, the bases of sepals and bracts, and the cortex of the axis, which is an extension of the peduncle.

Fruitlets develop from flowers that do not abscise (Fig. 12.1). The style, stamens and petals wither, with remaining floral parts developing into the fruitlet (Okimoto, 1948). Yeast and bacteria can enter through the nectary gland, and mature fruit is not sterile (Rohrbach and Apt, 1986). In the normal fruit there are 8 gently sloping rows and 13 shorter, steeper rows of flowers. The number of fruitlets can be estimated by counting the fruitlets on the long, gently sloping spiral and multiplying by eight, the number of spirals (Bartholomew and Paull, 1986). It takes approximately 4 months from the end of the last open flower to fruit maturity, and the total time from floral initiation to harvest takes between 6 and 7 months (Figs 12.6 and 12.7). Temperature significantly accelerates or delays development.

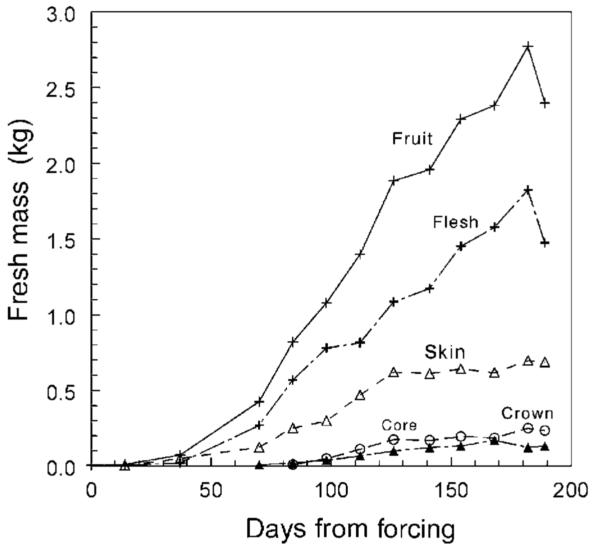

Fig. 12.6. Pineapple fruit growth and development in Hawaii.

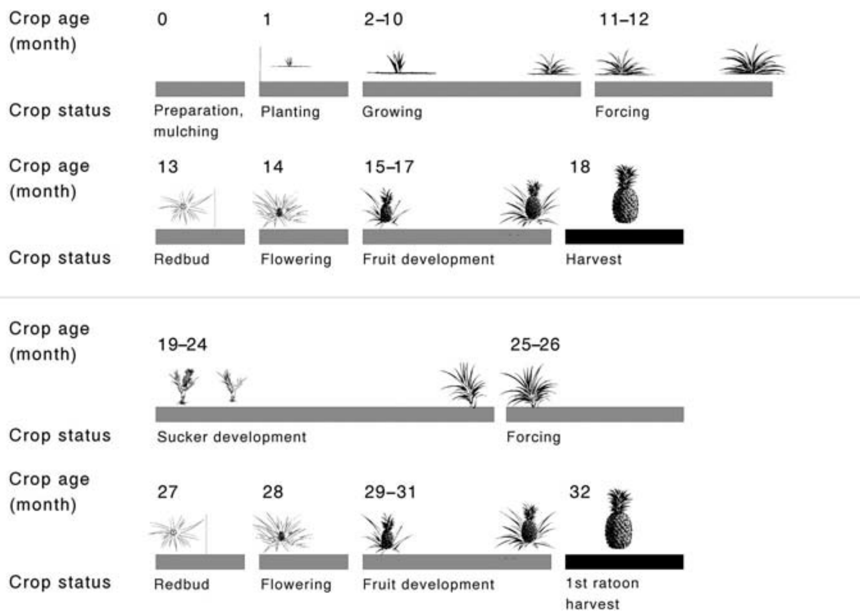

Fig. 12.7. The growth cycle of a pineapple crop to harvesting the first ratoon crop in relation to the various stages of development and crop age (Rohrbach, no date).

Cell division is completed prior to anthesis, with all further development being the result of cell enlargement (Okimoto, 1948). Fruit weight increases about 20-fold from the time of flowering until maturation (Fig. 12.6). Fruit development studies have shown that fruit weight and its components (core, fruitlets, the collective flesh, fruit shell) increase in a sigmoid fashion after the inflorescence is initiated (Fig. 12.6). Crown growth increases about 30–45 days after fruit growth has commenced. The crown has been reported to have no direct effect on the development of the fruit, though crown removal early in fruiting leads to greater fruit weight. The most marked changes in flesh composition occur in the 3–7 weeks prior to, and at, the half-yellow-shell colour stage. Just prior to this stage, fruit translucence can start to develop, and translucent development continues after harvest. Titratable acidity declines and the total soluble solids gradually increases, being more rapid in the last 6 weeks, as the fruit approaches the fully ripe stage. Fruit sugars continue to increase through to senescence, unless the fruit is harvested.

CULTIVAR DEVELOPMENT

Cytogenetics and genetics

Information on cytogenetics and genetics comes from early studies conducted at the former Pineapple Research Institute of Hawaii. Chromosome counts of 'Cayenne', 'Queen', 'Spiny Samoa', 'Ruby', 'Pernambuco', 'Spiny Guatemala', an F_1 hybrid between 'Cayenne' and an unknown wild-type from Brazil and *B. pinquin* L. showed the pineapple cultivars to possess n = 25 chromosomes and *B. pinquin* has n = 48, with no irregularities in meiosis (Collins, 1960). Several triploid plants with 75 chromosomes are found among the F_1 hybrids. The triploids appear to be products of the conjugation between an unreduced 'Cayenne' egg cell with 50 chromosomes and normal haploid pollen of a Brazilian wild type. The commercial cultivar 'Cabezona' is a natural triploid with 75 chromosomes (Collins, 1933).

Collins and Kerns (1938) described about 30 heritable mutant forms in 'Smooth Cayenne' fields, most being undesirable. One desirable processing mutant form is for elongated fruit. Collar-of-slips, a condition in which excessive numbers of slips are either attached directly to fruitlets at the base of the fruit or massed around its base, occurs in successive vegetative generations (Fig. 12.5). These plants are continuously rogued out. This character is dominant and occurs in a heterozygous state in 'Smooth Cayenne'. Spiny leaf is due to a homozygous recessive gene, and the smooth leaf condition of 'Smooth Cayenne' is carried as a heterozygous dominant. However, it is unstable and mutates frequently to the spiny leaf type; other spiny conditions also occur. Self-incompatibility in pineapple is an advantage in commercial production of seedless fruit and in cross-pollination. Pollen shows good viability for several cultivars, except that of the triploid 'Cabezona'. A single *S* locus with multiple alleles and gametophytic control of pollen phenotype are involved in self-incompatibility (Brewbaker and Gorrez, 1967), in which the pollen tube growth beyond the upper third of the stylar canal is inhibited.

Breeding and cultivars

Breeding

Pineapple breeding and selection objectives vary with the locality, but almost always emphasize disease and insect resistance (Coppens d'Eechkenbrugge *et al.*, 1997; Chan *et al.*, 2003). More recently, development of cultivars for fresh fruit consumption has been a major focus. Populations have been produced from crosses to allow selection of improved types. This selection involves constant roguing of undesirable mutations and selection of superior types. Mutation continues to occur within selected clones, so the effects of selection are not permanent, and without continued rouging and selection, commercial fields can revert to conditions of an unselected field population. In Hawaii, advanced hybrid clones were derived from many years of breeding (Chan *et al.*, 2003). In Australia, sources of germplasm consist of selections from Queensland 'Cayenne' clones, hybrid populations, meristem-cultured plants from known clones and introductions from other countries. Hybrid selections were derived from 'Cayenne' crosses with rough leaf types such as 'Queen', 'Ripley Queen', 'MacGregor', 'Alexandra' and 'Collard'. 'Singapore Spanish', a spineless plant with good fruit quality, has been widely used in their breeding programme. Malaysia has similarly used 'Smooth Cayenne' and 'Singapore Spanish' in their hybrid breeding programme. Breeding programmes in Puerto Rico, Brazil, Taiwan, the Philippines and South Africa maintain the major cultivars in their germplasm collections.

'Smooth Cayenne' is highly susceptible to mealy bug wilt (Table 12.1), though a few clones have shown variable resistance, which is transmitted to seedling progenies. Other cultivars and species have shown some resistance: 'Red Spanish', 'Pernambuco', 'Queen', *Ananas ananasoides*, *Ananas bracteatus*, *Pseudananas sagenarius* and some hybrids involving 'Cayenne' and resistant cultivars (Collins, 1960). In Hawaii, hybrid No. 59-656 is resistant to *P. cinnamoni* and *Phytophthora parastica* root and heartrot diseases.

Concomitant with breeding for disease and insect resistance has been the attempt to develop cultivars suitable for fresh fruit export. A suitable clone should have high yield, high sugar, a good balance of sugars to acids, high ascorbic acid and appealing flavour. These must be incorporated in a clone having the desired disease resistance, fruit shape and weight.

Cultivars

Collins (1960) developed a botanical key to the genera and species and the major characteristics of five 'Cayenne' clones for selection of appropriate parents. A later taxonomic key identified 18 commercial clones with vernacular names and descriptions (Antoni and Leal, 1980); this included a new group, 'Maipure', composed of smooth-leaved clones (Table 12.1). Clones in this group are primarily grown in South America. The major fruit and leaf characteristics of the principal clones can be placed in five phenotypic groups (Table 12.1). 'Monte Lirio' and 'Perolera', formerly unclassified, are placed in the 'Maipure' group. 'Cayenne' and 'Maipure' smooth-leaved groups differ in that leaves of the former group exhibit a few spines near the leaf tip, while the latter group shows leaf piping (leaf margins) with a greyish streak, due to folding over of the lower epidermis on to the upper leaf surface (Collins, 1960). Pineapple isozyme variation indicates five genetically diverse groups that do not perfectly match these phenotypic groupings (Loison-Cabot, 1992; Aradhya *et al.*, 1994). A brief discussion of the five horticultural groups follows.

Cayenne group: 'Smooth Cayenne' is the standard for processing and for the fresh fruit trade because of its cylindrical shape, shallow eyes, yellow flesh colour, mild acid taste and high yields. In most areas, 'Smooth Cayenne' constitutes a mixture of clones due to new introductions from mutations, lack of roguing and other various sources. Local selections are mostly known by their areas of origin, such as 'Sarawak' in Malaysia. 'Champaka' is a selection of 'Smooth Cayenne' originating in India and widely grown in Hawaii. The group is susceptible to mealy bug wilt and nematodes.

Queen group: This group generally produces smaller plants and fruit with spiny, shorter leaves than the 'Cayenne' group. 'Queen' is grown in South Africa, Australia and India for the fresh fruit market. 'Z-Queen' or 'James Queen' is reported to be a mutant of 'Natal Queen' and is a natural tetraploid.

Spanish group: The plants are generally small to medium, spiny-leaved, vigorous and resistant to mealy bug wilt, but susceptible to gummosis caused by the larvae of the *Batrachedra* moth. It is acceptable for the fresh fruit market but not favoured for canning, due to deep eyes and poor flesh colour. 'Red Spanish' or 'Espanola roja' is the major cultivar in the Caribbean region. 'Singapore Spanish', or 'Singapore Canning' and 'Nanas Merah', are the principal canning pineapple in West Malaysia because of their adaptability to peat soil. The flesh has a bright yellow colour. Other Malaysian cultivars are 'Masmerah', a spineless type with large fruit, and 'Nanas Jabor', a Cayenne–Spanish hybrid that is susceptible to fruit marbling and cork spot. 'Cabezona', a natural triploid, is an exception, having large plants and fruit weighing 4.5–6.5 kg. It is grown primarily in the Tabasco State of Mexico and a small area of Puerto Rico where local consumers prefer the larger fruit. The Puerto Rico clone PR 1-67 is suspected to be a hybrid between 'Red Spanish' and 'Smooth Cayenne', as these were the only clones grown in adjacent fields. The fruit has light yellow flesh with adequate sugar and resistance to gummosis, is fairly tolerant to mealy bug wilt, and has good slip production and good shipping qualities.

Abacaxi group: This group is grown mostly in Latin America and in the Caribbean region. Py *et al.* (1987) called this the Pernambuco group. The fruit is not considered suitable for canning or for fresh fruit export, but the juicy, sweet flavour of the fruit is favoured in the local markets. 'Perola', 'Pernambuco', 'Eleuthera' and 'Abacaxi' are the principal clones in Brazil, along the eastern Espirito Santo in the south through Bahia and Pernambuco to Paraibo.

Maipure group: This group is cultivated in Central and South America as fresh fruit for the local markets. These clones may be of interest to breeders in the western hemisphere as they constitute a gene pool of adapted forms almost unused in breeding programmes.

The 'Smooth Cayenne' cultivar dominates commercial production for canning and is also one of the major fresh fruit varieties. However, 'Smooth Cayenne' has objectionably high acidity during the winter months, so newer hybrids such as 73-114 (MD-2, MG-3), which have comparable yield and a better sugar to acid balance during the winter months, have rapidly expanded in importance as fresh fruit varieties and now dominate international trade. Other varieties of some importance commercially include 'Queen' and 'Spanish', both of which are primarily consumed fresh.

CULTURAL PRACTICES

Planting material and propagation

Propagules used in commercial pineapple production include fruit tops (crowns), shoots borne on vestigial fruits at the base of the fruit (slips) and shoots borne at any position on the stem (suckers) (Fig. 12.5). Genetic variation in numbers of slips produced per plant exists between clones and cultivars. Two or three crowns can be produced as a result of high-temperature injury during early inflorescence development, but large numbers of crowns (multiple) or fasciation of crowns is considered a genetic defect and such plants typically are rogued. Types and sources of vegetative propagules are kept separate, because weight, nutritional history and development environment are believed to affect time to establishment and optimum plant size for fruiting, as well as having the potential to introduce variability into the field (Hepton, 2003). Time from planting to harvest is dependent primarily on the weight of the propagule, and crowns produce fruit in 18–24 months, slips in 15–20 months and suckers in 12–17 months. Planting materials are treated with a fungicide or are 'air-cured' by drying the butt end, or both, before planting to prevent rots.

A shortage of planting material can occur when fruits are sold fresh, because the fruit is usually marketed with the crown. Most commercial clones of 'Smooth Cayenne' produce only one to two suckers per plant and seldom more than three slips. Several techniques are available to speed up propagule production required for variety and clone development or to replace planting material sold with the fruit. Cost of labour often determines which techniques are used.

Stem sectioning utilizes the axillary buds, usually on stems of mature plants. Leaves are stripped off the stem; the stem is quartered longitudinally and each quarter is divided into sections approximately 5 cm in length. The sections are immersed in a fungicide solution or air-cured for several days, or both, before planting in well-prepared nursery beds with good drainage and aeration. Shoots that grow from axillary buds can usually be transplanted in 4–6 months. A normal-sized 'Smooth Cayenne' plant stem can produce an average of 25 sectioned plants (Collins, 1960). Established crowns and shoots with adequate root systems can be split longitudinally into quarters, which forces one to several axillary buds to develop. These small plants (plantlets) can be transplanted when large enough and the process repeated. A similar technique is to gouge out the plant's apical meristem, thereby breaking apical dominance over axillary buds. One to a few suckers are produced, which, when harvested, result in the production of additional suckers. Once plant reserves are exhausted, a sucker can be allowed to grow and gouged when of reasonable size, resulting in the production of additional suckers. In Okinawa, crown leaves planted in sand produce plantlets at the leaf base. Only one plantlet is produced per leaf at a low rate. As no axillary buds are present on the leaf, shoots must be generated from meristematic callus formed at the leaf base tissue or from stem tissues adhering to the leaf base. From 40 to 70 leaf-bud cuttings can be produced from a single crown.

Plantlet production is induced by treating plants with the morphactin chloroflurenol (Maintain CF-125®; Multiprop R®) after reproductive development has been forced with ethephon. Chloroflurenol is applied 1 or 2 days after forcing and before significant flower differentiation has occurred. If timing and concentration of chloroflurenol are appropriate, up to ten good-sized plantlets are produced (Hepton, 2003). Plantlets have also been produced by meristem culture, but care must be taken to prevent excessive somaclonal variation. It is reported that up to one million plants can be produced from a single bud in 2 years through tissue culture, but this technique is generally more expensive than other propagation techniques.

Field preparation and layout

The first step in field preparation on an established pineapple farm is the destruction of existing plants, since pineapple can be a serious weed if live plants are plowed under. The fresh plant mass in a ratooned pineapple field is huge, and residue incorporation or disposal is a costly step in field preparation. Plants usually are disced multiple times or chopped to hasten desiccation, and when thoroughly dried are plowed under or burned. The decision as to whether to plow or burn is often determined by how soon the field is scheduled for replanting. Conventional tillage implements are used for primary land preparation on most pineapple farms and plantations, though in Hawaii, a teflon-coated moldboard plow was developed that would scour in clay soils and that permitted fields to be plowed to a depth of more than 80 cm. Deep plowing aids in the incorporation of the large amounts of plant residues produced by a pineapple crop. Except where deep plowing is done, the size of equipment used is determined mostly by farm size. Where the soil is compacted, subsoiling is desirable to break the hard pan to improve drainage and soil aeration. Discing to break up soil clumps and improve soil texture is important to improve dispersion of fumigants and to provide good plant-to-soil contact.

Black polyethylene mulch (~50 microns thick and 81 cm wide) helps to prevent rapid escape of fumigants, maintains warmer soil temperatures during the cool season, retains moisture at the soil surface, reduces fertilizer leaching during rainy periods, controls weed growth in the beds and increases yield. In many pineapple-growing areas where plastic mulching is too costly, mulching with straw, grass, sugar cane baggasse or other available materials is done. Crop rotation for nematode control is a possible practice when economical.

Fumigation

'Smooth Cayenne' is susceptible to several plant parasitic nematodes, which if left unchecked can devastate the plant. Pre-plant fumigation of the soil with a volatile nematicide to control root-knot and reniform nematodes is an established practice in Hawaii. In recent years, loss of some fumigants has occurred due to health and environmental concerns. Non-volatile nematicides are applied post-planting through drip irrigation systems, to provide nematode control later in the plant crop and during ratoon crop development. Even with significant nematode feeding pressure, it is often possible to produce an acceptable mother-plant crop. However, under such pressure ratoon crop growth and yield will probably be severely reduced, possibly to the point of complete ratoon crop failure, because ratoon yields are highly dependent upon the health of the plant crop root system. In South Africa, where *Meloidogyne* and *Helicotylenchus* nematodes are serious problems in pineapples, pre-plant dipping in a systemic nematicide followed by post-plant spraying at monthly intervals for 12 months increases a plant crop yield by 11 t/ha. In the absence of any history of nematode problems, soils should be assayed for nematodes before embarking on costly nematode control programmes.

Planting

Planting is commonly done manually with a 25 cm-long, trowel-shaped planting tool. Good soil preparation makes it easy to place the propagule deep enough into the soil to assure good plant-to-soil contact. Marked cords may be stretched from one end of the field to the other to keep rows aligned and to indicate plant spacing. In Hawaii, spacing is established by factory marking on polyethylene mulch. In Queensland, Australia, South Africa and Mexico, some growers use a planting machine similar to a vegetable transplanter.

Crowns, slips and suckers are planted separately in different fields. Crowns are smaller than and somewhat more uniform in size than slips and suckers. Slips and suckers can be large, with size mostly determined by the length of time they remain on the plant. Sizing prior to planting is crucial in order to obtain uniform-sized plants at the time of floral forcing, to assure a uniform-ripening fruit crop (Py *et al.*, 1987). Large suckers have a high tendency for precocious fruiting, being physiologically mature, especially when sucker weight exceeds 600 g. The following weight classes are suggested (Py *et al.*, 1987): small crowns 100–200 g and medium crowns 200–300 g, and slips or suckers small 200–300 g, medium 300–400 g and large 400–600 g.

Spacing

Plant spacing or density affects pineapple average fruit weight and yield per unit area (Fig. 12.8). Plant density and other cultural practices for 'Smooth Cayenne' are directed towards the production of a fruit size appropriate to the principal use: the fresh fruit markets or processing. Spacing is also dependent upon cultivar. Cultivars of the Spanish group produce smaller plants but have spiny leaves, so wider spacing is used than for smooth-leaved cultivars (Fig. 12.8). On small farms, growers may use a single-row system with relatively wide spacing between plants and between rows, giving plant densities of 15,000–25,000 plants/ha. In commercial plantings, a double-row system has been widely adopted, although three- and four-row systems also are fairly common. Multiple-row systems allow for increased planting density but may make harvesting operations more difficult and require good management to assure plant requirements are met. In the conventional two-row bed system, various spacing regimes are employed to achieve desired plant densities. In areas where plastic mulch is used, changes in bed width are limited by the width of mulch used. The spacing between plants in a row should not be less than ~20 cm, and spacing between rows in a two-row system would be about 35 cm, with between 90 and 120 cm from bed centre to bed centre. Planting densities typically range from 60,000 to 80,000 for 'Smooth Cayenne' and hybrids with similar growth habit (Fig. 12.8). When plants of the same size are forced, average fruit size decreases linearly as planting density increases, with the extent of the decrease being determined by cultivar and environment (Hepton, 2003). Planting densities as high as 75,000 plants/ha are used where smaller fruits are desired. There is a fruit size decrease of about 45 g for each population increase of about 2500 plants/ha.

Irrigation

The pineapple has a low water requirement and can survive long periods of water stress under natural conditions. However, under non-irrigated conditions yields are low, with poor-quality fruit of unacceptable size. Irrigation of pineapple in the Ivory Coast increased yields by 14–22 t/ha, with a cost equivalent to a yield of 5 t/h. The potential evapotranspiration of pineapple can reach 4.5 mm per day and a soil's water-holding capacity rarely exceeds 100 mm, so without rains, the water supply will be exhausted within 3 or 4 weeks. Water deficits can be indexed by the relative thickness

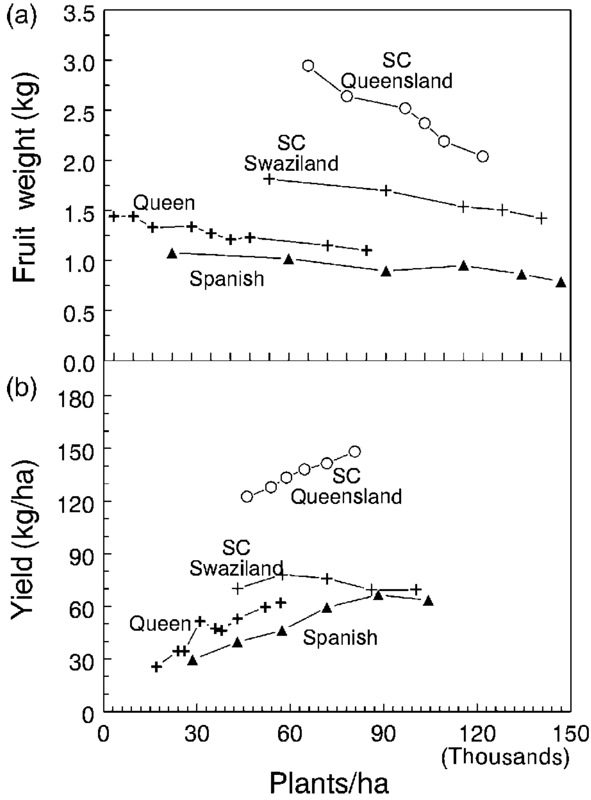

Fig. 12.8. Effect of planting density on fruit weight (a) and fruit yield (b); data are for 'Queen' grown in Ghana, 'Singapore Spanish' grown in Malaysia and 'Smooth Cayenne' grown in Queensland and Swaziland (from Hepton, 2003).

of the water-storage tissue of the youngest, physiologically mature leaf (D-leaf) and by the percentage of white root tips visible on the roots in the soil (Sanford, 1962).

Irrigation allows year-round planting, allows plants to attain a desirable plant size for forced flower initiation at scheduled times of the year and for harvesting on a firm schedule, allows the use of soils with poor water retention and allows fertilizing even during the dry season (Fig. 12.7). Weed problems are, however, increased by overhead irrigation. Sprinkler delivery systems, including a self-propelled boom sprayer, have been used. Drip irrigation has replaced other methods of irrigation in most fields in Hawaii, with one tubing orifice for every two plants. The quantity of water applied is low compared with most other crops, typically being in the range of 1.5 cm/ha/week. Drip irrigation allows fertilizers and nematicides to be applied at the root system after planting with increased efficiency and safety, and yields are increased.

Yield increases have been especially evident in ratoon crops, due to a decrease in plant mortality and the healthier condition of the plants at plant crop harvest. The healthy condition of the ratoon plants is due primarily to frequent delivery of nematicides.

Fertilization

Various published reports on pineapple nutrition indicate that the quantity of N required ranges from 225 to 350 kg/ha. The requirements for the other major fertilizer elements are best determined by soil analysis (Malezieux and Bartholomew, 2003). If K is required, the amount applied usually ranges from 225 to 450 kg/ha. The crop has a low requirement for P, and 20 ppm of P in soil is considered adequate. The P requirement can be met by pre-plant application of this element, and usually from 20 to 80 kg/ha is applied, as P, P_2O_5 or, in acid soils, rock phosphate. Some idea of pineapple fertilizer requirements may be obtained by analyses of elements immobilized in the various plant parts (Table 12.2). Large amounts of N and K are found in the plant, fruit and slips. In ratoon fields, which develop on suckers on the mother plant, nutrients removed by the first fruit crop must be replenished. This amounts to approximately 175 kg N, 27 kg P, 336 kg K, 47 kg Ca and 27 kg Mg per hectare.

Pineapple responds well to foliar fertilization, and nitrogen, boron, iron, zinc and sometimes potassium are applied this way (Malezieux and Bartholomew, 2003). While almost any inexpensive fertilizer can be used, urea and UAN32 are commonly applied as foliar sprays on a weekly or biweekly basis, from about 3 months after planting. Urea can be applied as a foliar spray at up to 20% concentration without damage, if the biuret is less than 1%. Iron nutrition is a problem in the Hawaiian pineapple soils due to the high manganese content. The Fe/Mn ratio is more critical than the level of either nutrient alone (Py *et al.*, 1987). Ferrous sulfate at up to 17 kg/ha per application is given, as needed, as a foliar spray. Plants with Fe deficiency show yellowing of inter-veinal areas. However, Fe deficiency also affects absorption

Table 12.2. Minerals immobilized or removed by pineapple plants at a density of 54,340 plants/ha.

	Amount immobilized or removed from plant (kg/ha)				
	N	P	K	Ca	Mg
Plant	437	47	538	134	134
Fruit	135	20	269	33.6	20.2
Slip	40	6.7	67	13.4	6.7
Total	612	73.7	874	181	160.9

of N, via its effects on the root system, leading to a general yellowing of the entire plant. Zinc deficiency is usually found in eroded areas, in soils with high amounts of coral sand and in soils with high pH. Deficiency causes the younger leaves to curve and twist; the symptom is unique and diagnostic. When Zn deficiency is severe, apical dominance is lost and plants sucker profusely. Zinc sulfate 0.5% (w/v), applied at 935 l/ha, is sprayed as needed. Boron deficiency is characterized by chlorosis of young leaves, development of red margins and even death of the apical region, resulting in profuse suckering. Boron deficiency is a common problem in Australia and 1–4 ppm boron is applied with ethephon at the time of forcing.

The nutrient requirements of pineapple in Hawaii are based on the concept of the crop log, which involves the development of laboratory soil and foliar indices, visual deficiency symptoms for N, Fe and Zn, and others that measure growth rate, pathogens, root parasites, moisture stress and weather conditions (Sanford, 1964; Malezieux and Bartholomew, 2003). A crop log not only indicates deficiency symptoms but also attempts to determine causes of deficiencies. Soil and foliar analyses are both important, as the former shows reserve amounts of soil nutrients and the latter indicates efficiency in absorption. An element may be sufficient in the soil but deficient in the plant, due to causes such as moisture stress, root disease or loss of the root system to pests, or an elemental imbalance causing unfavourable interactions affecting absorption (Sanford, 1962). Fertilizer is applied on a schedule to meet different requirements at different stages of growth (Table 12.3). Foliar applications should cease after forcing to prevent injury to the inflorescence and reduced fruit yields.

Chemical flower induction

The accidental discovery in the Azores that smoke from burning organic materials induces premature flowering in greenhouse-cultured pineapples led to the wide practice of burning rubbish around the periphery of the fields in Puerto Rico (Rodriguez, 1932). The active ingredient in the smoke is ethylene gas, with acetylene and calcium carbide also inducing flowering in pineapple (Aldrich and Nakasone, 1975). Forcing plants into flowering allows synchronization of harvest and makes it possible to control harvest dates to meet anticipated fresh market and cannery needs (Fig. 12.7). Fruit harvest date can be predicted with good accuracy with only daily maximum and minimum air temperature to calculate fruit heat units (Malezieux *et al.*, 1994). This model can be adjusted using historical data.

The relatively soluble sodium salt of alpha-naphthaleneacetic acid (SNA) was the first plant growth regulator used commercially to force flowering in Hawaii (Bartholomew and Criley, 1983). Ethylene and acetylene gases dissolved in water have been used in many pineapple-growing regions. The

Table 12.3. Fertilizer protocol for pineapple planted at 58,710 plants/ha, applied using a spray valve of 2500 l/ha for different stages of plant development (after Evans *et al.*, 1988).

	Stage of development (month)				
	0	0–3	4–8	9–10	11–12
Stage	Prior to planting	Growing	Growing	Growing	Forcing
Method	Into soil	Foliar	Foliar	Foliar	Foliar
Number of applications	1	3	5	2	2
Desired crop colour		Pale yellow green	Darker yellow green	Dark green	All green

Fertilizer	Rate (kg/ha/application)					Total (kg/ha/year)
Urea	22	22	33	45	55	450
Potassium nitrate	22	22	33	45	55	450
Iron sulfate	1.5	1.5	2.25	3.0	3.70	30
Zinc sulfate	0.5	0.5	0.75	1.0	1.25	10
Magnesium sulfate	2.75	2.75	3.75	5.5	6.75	55

gases require specialized equipment for effective application and safe use. In the warm tropics, SNA has not been effective, while a water solution of acetylene produced from calcium carbide or calcium carbide as granules has been successful.

Ethephon (2-chloroethylphosphonic acid) is probably the most widely used chemical in commercial pineapple production because of its effectiveness and ease of application. This chemical breaks down to produce ethylene at neutral pHs (Bartholomew and Criley, 1983). The effective ethephon concentration ranges from 500 to 1500 μg/l, with greater amounts required to force flowering in warm than in cool months. At least 90% flowering is obvious 40–60 days after applying about 1000 μg/l solutions (Fig. 12.7) with 50 kg/ha urea (Bartholomew, 1977). In some regions, adjusting the solution pH above 7 with sodium borate improves forcing success.

Acetylene and ethylene are less effective when applied during the day but highly effective when applied at night or during the early morning hours, when the stomates are open (Bartholomew and Kadzimin, 1977). In warm seasons, forcing success may be greater on days when temperatures are less than 30°C. High N level in the plant at the time of forcing may further reduce forcing success in warm weather, while withholding nitrogen fertilizer for 4–6 weeks before forcing can improve induction. Plants approaching the natural period of flowering show greater susceptibility to induction (Fig. 12.9a), as smaller plants are not as susceptible to natural flowering and are not as easily forced to flower. The minimum size for forcing is much larger under optimum growing conditions than when growth is restricted by nutrient, water or low-temperature stress. Plant weights are used to estimate suitability for forcing, as the larger the plant weights at forcing the bigger the fruit harvested (Fig. 12.9b). For 'Smooth Cayenne', when the plant fresh weight is between 2 and 4 kg the field will be forced to flower, depending on plant growth status and weather. Ratoon suckers are more easily induced to flower than the plant crop. The Spanish group is also easier to force in conditions impossible for Cayenne.

Pest management

Except for small plantings in subsistence-farming systems, pineapple is largely a monocultured crop, involving relatively large fields under more or less standardized cultural practices. Monoculture, as well as the perennial nature of the crop, is conducive to accumulation of diseases and pests, some confined to certain regions, while most have become established worldwide (Lim, 1985; Rohrbach and Schmitt, 1994) as vegetative germplasm has been transported around the world since the 1600s. The 'Smooth Cayenne' cultivar is relatively resistant to most pineapple diseases (Rohrbach and Johnson, 2003). Occasionally, damage associated with specific pests or diseases can cause serious economic losses.

Diseases and nematodes

One of the most important diseases worldwide is mealybug wilt (Table 12.4). This wilt is caused by a closterovirus and associated feeding by the mealybugs *Dysmicoccus brevipes* and *Dysmicoccus neobrevipes* (Sether and Hu, 2002), both of which are able to transmit the virus; the disease does not occur if only the closterovirus or the mealybugs are present. Ants, which protect the mealy bug colonies and transport individuals from plant to plant, also are essential to disease development. The dominant species of ant on pineapple in Hawaii and in South Africa is the big-headed ant (*Pheidole megacephala*). Ant control is essential to the control of mealybugs and the wilt; in the absence of ants, parasitoids and predators keep mealybugs under control. Mealybugs feed on the roots, on the stem above the roots, on leaf sheaths or leaves and in fruitlet floral cavities. Wilt-affected plants are stunted, becoming yellowish first and reddish later. These symptoms resemble the effects of severe drought.

Some pineapple cultivars possess partial resistance to the mealybug wilt. However, the only practical control of mealybugs and the associated ants is by use of insecticide baits to control the ants. Cultivation eliminates mealybugs, and in a newly planted field they gradually move into the field from uncultivated grassy or weedy borders, where mealybugs survive on

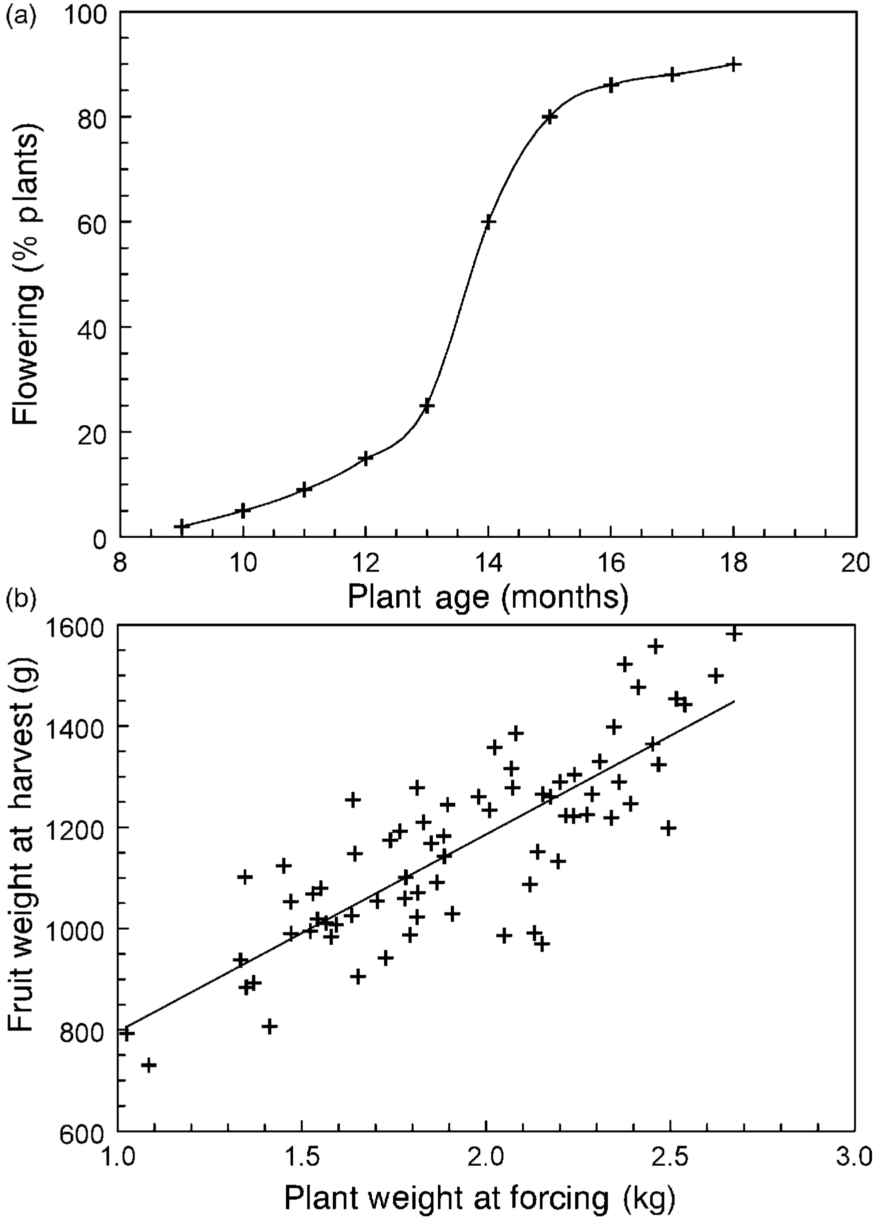

Fig. 12.9. Effect of plant age (a) on susceptibility to natural flowering (redrawn from Lacoeuilhe, 1975), and plant weight (b) at forcing and fruit weight at harvest for 'Smooth Cayenne' (from Bartholomew *et al.*, 2003).

Table 12.4. Some important diseases and nematodes of pineapple.

Common name	Organism(s)	Parts affected and symptoms	Region or country of importance
Mealy bug wilt	Viral	Plant	Universal
Pink disease	*Gluconobacter oxydens* *Acetobacter aceti* *Erwinia herbicola*	Dark brown discoloration of infected fruit flesh upon heating	Hawaii, Australia, Philippines
Interfruitlet corking	*Penicillium funculosum*	Fruitlets	Hawaii
Leathery pocket	*Penicillium funculosum*	Fruitlets	Hawaii, South Africa
Fruitlet core rot	*Penicillium funculosum* *Fusarium moniliforme*	Fruitlets	
Pineapple butt rot	*Chalara paradoxa*	Stems of planting material, and fresh fruit rot	Universal
Root/heart rot	*Phytophthora cinnamomi* *Phytophthora nicotianae*	Root, plant, fruit	Universal
Root knot nematode	*Meloidogyne javanica*	Galls, root destruction, stunts plant	Universal
Reniform	*Rotylenchulus reniformis*	No galls; destroys lateral root system, retards growth	Universal
Root lesion	*Pratylenchus brachyurus*	Lesion on root and destruction	Universal
Root lesion	*Rotylenchulus unisexus*	Root destruction	South Africa
Spiral	*Helicotylenchus dihystera*	Root destruction	Ivory Coast, South Africa, Puerto Rico, Hawaii

alternate hosts. Movement from field edges led to a practice of planting several beds of pineapple in a strip parallel to the edge of the field and separated from the main field by a road as a buffer. These buffers were sprayed regularly. Ant control using baits is more common in Hawaii.

Heart and root rot caused by *P. cinammomi* Rands and *P. nicotianae* B. de Haan var. *parasitica* Dast, Waterh. and *P. palmivora* (Butler) Butler does not occur uniformly and levels of infection can vary from year to year. *P. cinammomi* is virulent in cooler conditions while *P. nicotianae* and *P. palmivora* are associated with warmer and more tropical environments. Conditions conducive to *Phytophthora* rots include poorly drained soils, high rainfall and a soil pH above about 5.5. Crown plantings, especially during the wet season, are highly susceptible to *Phytophthora* rots, with the loss of 30–100% not being uncommon. The disease is controlled by pre-plant dips of planting materials and by foliar post-plant spray using fungicides.

Butt or black rot is a universal problem of stored planting material and of fresh fruit. The disease, caused by *Chalara paradoxa* (De Seynes) Sacc, is characterized by a soft rot and blackening of the basal portion of the stem of vegetative propagules, and similar symptoms are seen on infected fruit. Infected propagules can completely decay if kept moist, and an infection can quickly spread through an entire pile. In the absence of fungicide treatment, planting material can be protected by air-curing for several days. Fruit rot is managed by careful handling of the fruit to avoid bruising, by refrigeration and with a fungicide dip. Infection occurs within 8–12 h following wounding. Susceptibility varies with the cultivar, 'Red Spanish' types being more resistant than 'Smooth Cayenne'.

Other fruit diseases – fruitlet core rot, interfruitlet corking, pink disease and marbling disease – are universally distributed and occasionally can be important. Brown rot or fruitlet core rot occurred in only 7% of inspected fruit. Other postharvest pineapple diseases that begin prior to harvest may cause sporadic economic problems.

Nematodes are a serious problem wherever pineapple is grown on the same land over many years. Yield losses of one-third are common in the plant crop, with total failure in the first ratoon crop without nematode control. Injury caused by nematodes feeding on the roots is compounded by the roots non-regenerative nature. Fumigants do not completely eradicate nematodes. Eggs and dormant larvae are harder to kill, repopulating the soil with time and necessitating periodic post-plant application of nematicides. For maximum efficiency of fumigants, soil must be well prepared, with deep ploughing and the breaking of all clods. Too much soil moisture inhibits good dispersion of the fumigant in the soil, while fumigant escape is rapid when the soil is too dry. Polyethylene mulch over beds helps to retain volatile fumigants in the soil. Application of nematicides by drip irrigation is effective in controlling nematodes, particularly in the ratoon crop.

Pests

Insects can cause direct damage to various plant parts or vector diseases (Table 12.5). Prior to 1953, pineapple fruit were fumigated with methyl bromide before importation into continental USA. Pineapple fruits that are more than 50% ‘Smooth Cayenne’ are not now regarded as a host for tephritid flies: Mediterranean fruit fly, *C. capitata* (Wiedermann); the Melon fly, *D. cucurbitae* (Coquillet); and the Oriental fruit fly, *D. dorsalis* Hendel; hence, insect disinfestation is no longer required (Armstrong and Vargas, 1982).

The pineapple scale, *Diaspis bromeliae* (Kerner), occurs wherever pineapple is grown. In Hawaii, pineapple scale is not normally a major problem in fields, probably because of scale parasites and predators. However, because of the US quarantine requirement, fruit have to be insect-free, and even low levels of pineapple scale at harvest present quarantine problems. Scale can be controlled relatively easily by preharvest insecticide applications, taking into consideration label requirements relating to last application prior to harvest time.

The pineapple fruit mite, *Steneotarsonemus ananas* Tryon, occurs universally on the growing plant, developing inflorescence, fruit and crown. The fruit mites feed on developing trichomes on the white basal leaf tissue and flower bracts and sepals, causing light brown necrotic areas. The pineapple red mite, *Dolichotetranychus floridanus* Banks, feeds on the white basal leaf tissue, particularly of the crown. Severe damage occurs when the fruits mature under drought conditions, and it may cause death of the basal crown leaves, thereby affecting fruit quality (Rohrbach and Schmitt, 1994).

Other insects are mentioned frequently in the literature. In Latin America and in some Caribbean islands the larvae of the Thecla butterfly (*Thecla brasiliodes*) cause fruit damage, occasionally in serious proportions. Dusting or spraying the fruit at flowering stage with appropriate insecticides has given satisfactory control. In the Caribbean region, the larvae of the Batrachedra butterfly (*Batrachedra* sp.) damage fruit at the flowering stage, causing gummosis. Field observations in Jamaica during 1972 showed high incidence of damage in ‘Red Spanish’ but not in ‘Smooth Cayenne’.

Weed control

Weeds can cause serious crop losses, and on small farms, neglect of weeding at monthly intervals can result in 20–40% declines in yields. Average fruit weight in Guinea can be 0.60 kg from an unweeded field, as compared to 1.55 kg with good weed control. Weed control is a major cost item in pineapple production and is essential to assure high yields as well as removal of plants that host or harbour nematodes and insects such as mealy bugs. The weed problem can be lessened by complete mulching of the beds and interbeds, hence delaying or

Table 12.5. Some important insect pests of pineapple.

Common name	Organism	Parts affects and symptoms	Region or country
Bigheaded ant	*Pheidole megacephala*	Associated with mealybugs and wilts	Hawaii
Ants	*Solenopsis* sp. *Anaucomyrmex* sp.	Associated with mealybugs and wilts	Guyana
Pineapple scale	*Diaspis bromeliae*	Leaves, fruit	Universal
Souring beetle (pineapple beetle)	*Carpophilus humeralis*	Plant, ripe fruit	Universal
Mealybug	*Dysmicoccus brevipes*	Roots, stems, leaves	Universal
Pineapple fruit mite	*Steneotarsonemus ananas* Tryon	Developing inflorescence, fruit and crown	Universal
Pineapple red mite	*Dolichotetranychus floridanus* Banks	Feeds on the white basal leaf tissue, especially crown	Universal
Black maize beetle	*Heteronychus arator*	Lower stems and roots	South Africa
White grub	Several beetle species	Root system	South Africa
Thrips	*Thrips tabaci*	Yellow spot disease (virus transmitted by thrips from *Emilia sonchifolia*)	Hawaii, other areas
Batrachedra butterfly	*Batrachedra methesoni*	Fruit at flowering stage causes gummosis, larvae causes damage	Caribbean
Thecla butterfly	*Thecla brasiliodes*	Fruit at flowering stage causes gummosis, larvae causes damage	Mexico Central America South America Caribbean
Symphylids	*Hanseniella unguiculata*	Root tips, severe stunting	Universal

minimizing weed growth. Polyethylene sheet mulching of beds substantially alleviates weeding within beds.

Weed control in commercial plantations is achieved by chemical means, unless labour is abundant and inexpensive. Chemical weed control is efficient and rapid if done correctly at appropriate times, using mechanical applicators. Pre-emergence application, either before or immediately after planting, is low in cost and effective. For herbicides, as with other agricultural biocides, there usually are restrictions on timing of applications and limits to the quantity that can be used per hectare, per crop cycle or per year.

HARVESTING AND POSTHARVEST HANDLING

Harvesting

Prior to the use of chemicals to induce flowering, many passes were required to complete harvesting of a large field, due to the wide variation in time of flowering during the winter season, when most flower induction occurred. Chemical induction concentrated the period of flowering, therefore condensing harvesting to two to three passes (Paull and Chen, 2003). Natural or precocious flowering during cool weather with short days can significantly disrupt harvesting and marketing schedules. In Hawaii, fruit developing from precocious flowering in some years leads to a second peak, followed by a mid-year dip in production (Fig. 12.10).

Controlled ripening of fruit with ethephon prior to harvest can further reduce the number of harvesting passes. Ethephon is applied 48 h or more before harvest to accelerate shell degreening (Soler, 1992). This accelerated shell degreening is due to destruction of chlorophyll, giving the shell a more uniform colour. The application should occur when natural colouring has started, to assure good fruit quality, and is sometimes less effective in hot weather.

Fruits destined for the cannery are usually harvested at the half- to three-quarter-yellow stage. Fruit to be transported to distant fresh fruit markets is picked anywhere from mature green (no yellow colour) to quarter-coloured stage. Fruit maturity is evaluated on the extent of fruit ‘eye’ flatness, skin yellowing and acidity to total soluble solids (TSS) measurements. Consumers similarly judge fruit quality by skin colour and aroma. A minimum reading of 12% total soluble solids (°Brix) is required for fresh fruit in Hawaii, while others have suggested 14%. A sugar to acid ratio of 0.9–1.3 is recommended (Soler, 1992).

Pineapple for the fresh market is hand harvested, with pickers being directed as to stage or stages (shell colour) of ripeness required. Fruit is packed either in the field or at a central packing shed. In Hawaii, pickers walk

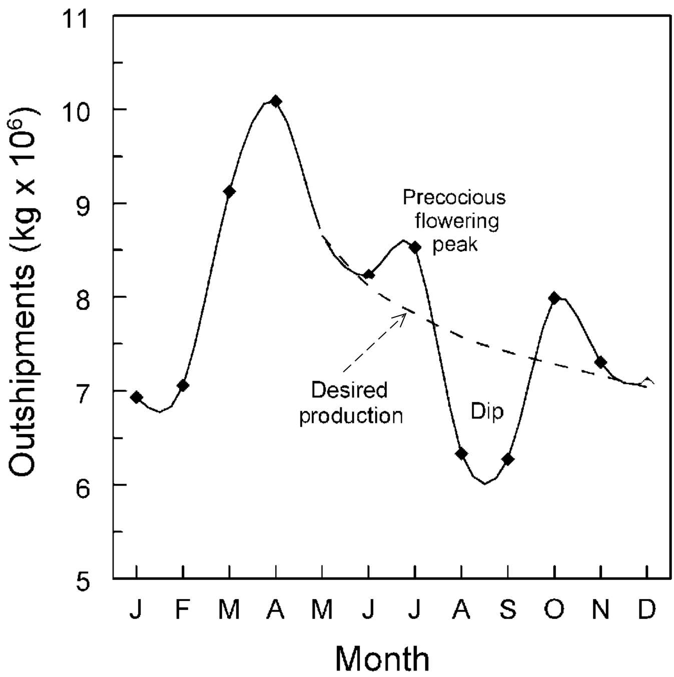

Fig. 12.10. The effect of precocious flowering in the January to February period on outshipment of pineapples from Hawaii contrasted with desired production.

in the inter-rows and place the fruit on a conveyor belt running on a boom, which transfers the fruit to a truck field bin. Fruit is placed in the bin by hand, upside-down on the crown to avoid injury. Fruits are also harvested by pickers carrying large baskets on their backs. When the baskets are full, the fruits are dumped at the ends of the rows or at the side of field roads, to be later loaded into trucks or trailers. When the fruit arrives at the packing shed, it is unloaded by hand, by submerging the field bin in water or by sliding the fruit out of the field bin into water. Fruit with high translucency ('sinkers') are separated at this step. Fully ripe, translucent fruit are unsuitable for transporting to distant markets and less-mature fruit are selected. Immature fruits are not shipped, since they do not develop good flavour, have low sugars, and are more prone to chilling injury. Care is taken to avoid mechanical damage to the crown leaves and mechanical injury to the fruit shell.

Postharvest handling

Fruits are waxed after washing, frequently with polyethylene and paraffin or carnauba and paraffin waxes. The selected wax reduces internal browning symptoms of chilling injury, reduces water loss, improves fruit appearance and assures a more even application of fungicide used to control rots (Paull and Rohrbach, 1985; Paull and Chen, 2003). There is no worldwide uniformity in acceptance of wax components, so importing-country restrictions need to be considered. If the wax injures the crown leaves, only the fruit body is waxed. Postharvest fungicide is normally included in the wax.

Fresh fruit quality standards are based upon recognized appearance characteristics (Table 12.6). The fruit needs to be mature, firm, well formed, free of defects, have flat eyes and a minimum soluble solids of 12% in Hawaii. Crown size is a crucial grade component, with a minimum size and a set ratio of crown to fruit length (0.33–1.5) for the higher grades. Crowns that develop during the summer in Hawaii tend to be larger and may require 'gouging' at harvest to meet the standard. This 'gouging' leaves a wound for possible disease entry and detracts from overall appearance. 'Gouging' 2 months before harvest to limit crown growth avoids visible scarring. Fruits are graded by degree of skin coloration, size (weight), absence of defects and disease, and other market needs before packing (Soler, 1992).

Temperatures in the range 7.5–12°C are recommended for storage, with relative humidity of 70–95%; the higher humidity significantly reduces water loss. At a temperature of 0–4°C, the fruit may be stored for weeks, but upon removal, the fruit fails to continue ripening and shows severe chilling injury (Paull, 1993). Half-ripe 'Smooth Cayenne' fruit can be held for about 10 days at 7.5–12.5°C and still have about a week of shelf-life, with no chilling-induced internal browning.

Table 12.6. USA fresh pineapple fruit standards. All grades have 10% limits on defects, 5% on serious damage and 1% on decay.

Standards	Varietal characteristics	Maturity	Free from	Slips knobs	Crown to fruit length ratio
US Fancy	Similar	Mature, firm, dry, well formed, well-developed eyes	Decay, sunburn, injury, bruising, well-cured butt	Single crown, no slips	Ratio less than 1.5, not less than 12 cm in size
US #1	Similar	Mature, firm, dry, well formed, well-developed eyes	Decay, sunburn, injury, bruising, fairly well-cured butt	<5 Slips	Ratio less than 2.0 and greater than 10 cm in size
US #2	Similar	Mature, firm, dry, fairly well formed eyes	Serious decay, sunburn, injury, bruising	Slips	Any ratio, double crown

Physiological disorders

Chilling injury

The maximum storage life of pineapple at 7°C is about 4 weeks; however, when removed, chilling injury develops within 2–3 days. The symptoms of chilling injury (CI) include: (i) wilting, drying and discoloration of crown leaves; (ii) failure of green-shelled fruit to yellow; (iii) browning and dulling of yellow fruit; and (iv) internal flesh browning (Paull and Rohrbach, 1985). Preharvest shading and pre- and postharvest low temperatures are the major factors increasing CI symptom intensity. CI symptoms have been called endogenous brown spot, physiological breakdown, blackheart and internal browning. Postharvest CI symptoms develop after fruits are returned to physiological temperatures (15–30°C). Susceptible fruits are generally lower in ascorbic acid and sugars and are opaque (Teisson, 1979a,b). Partial to complete control of CI symptom development has been achieved by waxing, polyethylene bagging, heat treatments, controlled atmospheres and ascorbic acid application.

Flesh translucency

Flesh translucency increases fruit sensitivity to mechanical injury. This condition begins before harvest and continues after harvest. TSS, flesh pigments and palatability increase to a maximum at about 60% translucency, then decrease in fruit with greater translucency. Translucency is more severe and has a higher incidence when maximum and minimum temperatures 3 months before harvest are both low, less than 23 and 15°C or, to a lesser extent high, greater than 29 and 20°C, respectively. Fruit with a larger crown has a lower incidence and severity of translucency (Paull and Reyes, 1996).

Bruising

Fruit bruising is a major problem during harvesting and packing. Bruising can be caused by impact damage, a 30 cm drop causing significant damage. This injury is normally confined to the impact side of the fruit. The damaged flesh appears slightly straw-coloured. Mechanical injury of translucent fruit can lead to leakage of fruit cell contents and loss of marketable fruit.

Sunburn

Sunburn is common during hotter periods (>35°C) of the year, when the fruit is not shaded by leaves and especially in ratoon crops. The condition is more prevalent in the outer rows and when fruit is lodged. Sun-scorched fruit first show a bleached yellow-white skin, which turns pale grey and brown, with damage to the flesh underneath. These damaged areas are more susceptible to disease organisms, particularly yeasts and bacteria.

Malformations

Knobs on the base of fruit occur in off-types. Culling of the crowns of these fruits as planting material reduces the subsequent field incidence. These fruits are not marketed, since trimming generally breaks the fruit skin and allows rots to develop. The other genetic off-type is multiple crowns (fasciation), two or more on each fruit, with the fruit taking on a flattened appearance. This condition is often related to high-temperature injury after forcing. These fruits should not be marketed and crowns should not be used for planting. Fruits with pronounced 'eyes' or fruitlets normally do not meet most grade standards, and the thicker skin means lower flesh recovery. This condition is common in fruits that flower during cool weather. Some 'Spanish' varieties are susceptible to broken core, in which the central fruit core has a transverse break, leading to the upper part of the fruit ripening ahead of the bottom.

UTILIZATION

Pineapple does not sweeten after harvest, though the acid level may decline. Canning is more successful with an acid fruit, as a lower processing temperature can be used (Hepton and Hodgson, 2003). Because canned product can be stored for long periods without deterioration, fruits destined for canning tend to be harvested during the summer months, when fruit quality is highest. The sugar to acid ratio varies widely with cultivar, growing condition and stage of harvest from 80 to 200. Ascorbic acid also varies widely with cultivar from 2.5 to 180 g/kg FM of flesh. Pineapple is a good source of ascorbic acid (vitamin C), some vitamin A, calcium, phosphorus, iron, potassium and thiamine. It is low in sodium (Table 12.7).

Most fruit produced goes into the fresh fruit market (Fig. 12.11), mostly to markets within a country. Much of this fruit is not recorded in world production figures. There is an increasing interest in minimally processed pineapples, with the shell and core removed just before purchase. The major processed products are canned slices or solid pack, with a recovery percentage varying from 20% in 'Singapore Spanish' to *ca.* 60% for 'Smooth Cayenne'. Cans of several sizes are filled with the best slices. Uncanned and broken slices are packed as chunks, tidbits or crush (Fig. 12.11). Flesh remaining on the shell, cut ends, core and trimmings are processed into juice. Much of the juice is now concentrated, with the volatile flavour components being recovered and added back to the concentrate, and frozen to maintain a higher flavour quality than the single strength. Shipping costs for the concentrate also are greatly reduced relative to those for single-strength juice. The residue of the juice recovery stream is processed into animal feed or other by-products. This residue from pressed fruit shells and pulp has been sold to dairy farms either wet or dried (Fig. 12.11).

Table 12.7. Proximate analysis of 'Smooth Cayenne' fruit (Wenkam, 1990).

	Amount per 100 g edible portion
Water (g)	86
Energy (kJ)	218
Protein (g)	0.5
Lipid (g)	0.2
Carbohydrate (g)	13.5
Fibre (g)	0.5
Ash (g)	0.3
Minerals	
Calcium (mg)	18
Iron (mg)	0.3
Magnesium (mg)	12
Phosphorus (mg)	12
Potassium (mg)	98
Sodium (mg)	1
Vitamins	
Ascorbic acid (mg)	10
Thiamin (mg)	0.09
Riboflavin (mg)	0.04
Niacin (mg)	0.24
Vitamin A (IU)	53

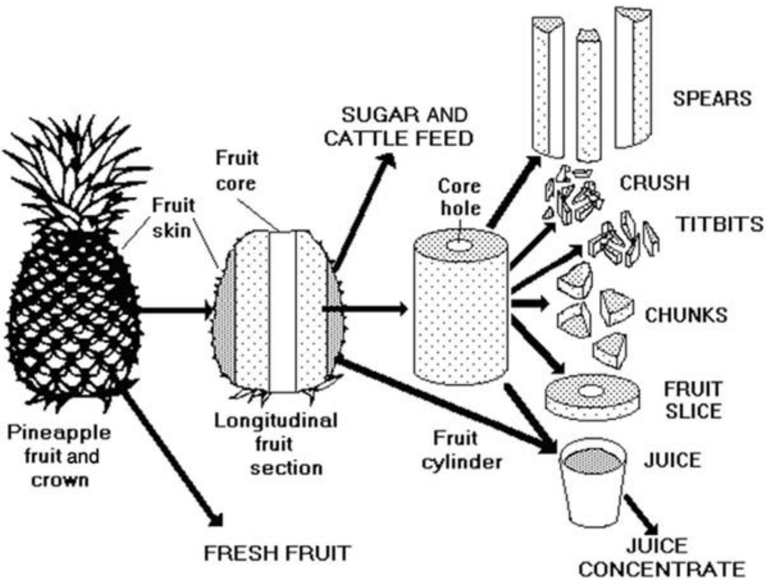

Fig. 12.11. All parts of the pineapple fruit are used in different products (Rohrbach, 2003).

Bromelain, the proteolytic enzyme found in pineapple plants, particularly in the stem, has a number of industrial and medicinal applications. Some bromeliads, including pineapple, are grown for their leaf fibres, and many more are grown as ornamentals.

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CHAPTER 8. BANANA AND PLANTAIN

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CHAPTER 9. LITCHI AND LONGAN

Litchi

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