BANANAS AND PLANTAINS

2nd Edition

John C. Robinson
and Víctor Galán Saúco

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Bananas and Plantains, 2nd Edition

John C. Robinson

Technical Consultant – Banana Tissue Culture
Du Roi Laboratory
South Africa

and

Víctor Galán Saúco

Research Professor
Department of Tropical Fruits
Instituto Canario de Investigaciones Agrarias
La Laguna, Tenerife, Spain

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DISTRIBUTION AND IMPORTANCE

ORIGINS AND EARLY DISTRIBUTION

Modern bananas and plantains originated in South-east Asian and western Pacific regions where their inedible, seed-bearing, diploid ancestors can still be found in the natural forest vegetation. Over many years, various inedible diploid subspecies of *Musa acuminata* Colla crossed naturally resulting in the production of numerous intraspecific hybrids. Some of these hybrids were parthenocarpic, female sterile and triploid in genomic structure, and local inhabitants discovered that such plants had edible fruits and could be propagated vegetatively by suckers. In this manner, superior edible crosses of *M. acuminata* would have been selected, cultivated, propagated and distributed locally as a food crop. Edible triploid bananas in South-east Asia were further selected according to vigour, fruit size and adaptability, and were developed at the expense of the original diploid types which were inferior. However, in certain areas (e.g. New Guinea) various edible diploids of *M. acuminata* were also preserved over the years.

Diploid and triploid selections of *M. acuminata* were taken by man to drier monsoon areas (India, the Philippines) where another wild and seeded diploid, *Musa balbisiana*, was growing naturally. In these areas, interspecific hybridization occurred to produce diploid and triploid crosses of *M. acuminata* × *M. balbisiana*. The early history of banana cultivation away from its centre of origin remains uncertain. The establishment of these hybrid clones on the periphery of the centres of origin would have occurred in prehistoric times, and the earliest records of cultivation are from India about 2500 years ago.

The introduction of *M. balbisiana* genes from the drier monsoon regions into *M. acuminata* clones from the humid tropics of South-east Asia conferred a measure of hardiness and drought tolerance into the hybrids. In addition, the *M. balbisiana* genes induced greater disease resistance, improved nutritional value, increased starchiness and provided hybrids suitable for cooking, as opposed to the pure *M. acuminata* cultivars which are sweeter and more suited to dessert use.

The distribution of edible bananas and plantains outside Asia is thought to have been via vegetative planting material transported by man. Any further diversification would then have occurred by natural somatic mutations.

The possible dates and routes for distributing *Musa* outside Asia are discussed in detail by Simmonds (1962) and Purseglove (1972). Bananas may have been taken from Indonesia across the Indian Ocean to Madagascar about AD 500 and thereafter into East Africa, Zaire and West Africa. Plantains arrived much later. Both bananas and plantains were known on the west coast of Africa in the 14–15th century when the Portuguese arrived. Somatic mutations obviously occurred, resulting in a large number of clones and a secondary centre of diversity in Africa. The Portuguese took bananas from West Africa to the Canary Islands, then in the 16th century bananas were taken from the Canary Islands to Santo Domingo (Dominican Republic) in 1516. This was the forerunner of further introductions into the Caribbean and Central America, where currently most dessert bananas for export are produced (Box 1.1).

Bananas and plantains have achieved greater importance as cash or subsistence crops in regions away from their primary centres of origin. The larger export trade in dessert bananas from Central America and the Caribbean began in the late 19th century and developed rapidly with the introduction of refrigerated shipment. This trade is based almost entirely on a small number of triploid cultivars of *M. acuminata*, of which around 95% are

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Box 1.1. Main milestones of banana distribution and trade.

- *c.*AD 500 – Introduction to Africa from Indonesia (via Madagascar).
- *c.*AD 1000 – Distribution throughout Polynesia and introduction to Mediterranean areas during Muslim expansion.
- 1300s–1400s – Introduction to the Canary Islands from West Africa.
- 1516 – First recorded introduction to the New World (Santo Domingo) from the Canary Islands.
- 1500s–1800s – Distribution of bananas and plantains throughout tropical America.
- Early 1800s – Introduction to the New World of cultivars 'Dwarf Cavendish' and 'Gros Michel' from South-east Asia.
- Late 1800s– Beginning of international trade.
- 1900s – Banana becomes a major food item in the temperate-zone markets of the Western world as well as the Far East.
- 1993 – Establishment of the Common Market Organization (CMO) for banana in the European Union (EU), based on a quota system and other compensatory aids for European producers and African, Caribbean and Pacific (ACP) countries.
- 21st century – Continuous complaints from dollar banana countries towards the tariff-only system in EU markets. Lower tariff fees for banana from the dollar area accentuate the trend towards a more free banana market. Final agreement has been reached in 2010.

Cavendish types. Other speciality or exotic bananas, particularly red-coloured types, but also 'Apple' ('Manzano'), baby banana ('Bocadillo' or 'Pisang Mas') and ice cream ('Lady Finger') types are also exported on a small scale to fulfil niche markets. In the case of plantains, 73% of the world crop is grown and consumed in West and Central Africa and the cultivars are mostly triploid crosses between *M. acuminata* and *M. balbisiana*.

PRESENT DISTRIBUTION OF BANANA AND PLANTAIN

Tropical banana countries which produced dessert fruit for export in 2006 were, in order of importance, Ecuador, the Philippines, Costa Rica, Brazil, Colombia and Guatemala (Table 1.1).

Table 1.1. World trade statistics – major importers and exporters of dessert bananas in 2006 (from FAOSTAT, 2010).

Major importing countries	Volume (× 1000 t)	Major exporting countries[a]	Volume (× 1000 t)
USA	3,839	Ecuador	4,908
Germany	1,292	The Philippines	2,312
Belgium	1,180	Costa Rica	2,183
Japan	1,044	Brazil	1,943
UK	925	Colombia	1,568
Russian Federation	894	Guatemala	1,055
Italy	646	Honduras	515
China/Hong Kong	459	Panama	431
Canada	458	Ivory Coast	286
France	408	Cameroon	256
Argentina	295	Dominican Republic	187
Iran	294	Bolivia	81
South Korea	280	Belize	73
The Netherlands	279	Mexico	67
Ukraine	272	Yemen	60
Saudi Arabia	235	Surinam	45
Sweden	188	Nicaragua	38
Chile	166	Saint Lucia	35
Algeria	147	Sri Lanka	35
Portugal	142	Lebanon	34
Spain	133	Jamaica	32
Austria	130	Malaysia	24
Czechoslovakia	122	St Vincent and the Grenadines	24
Others	2,023	Others	597
World imports (total)	15,851	World exports (total)	16,789

[a] Excluding re-exporting, non-producing countries and ultraperipheric regions of the European Union (RUPS).

Export-producing countries do not differ much from those referred to for the year 1992 in the first edition of this book. The important exception is Brazil which ranked 15th in 1992 and now occupies 4th position. Global export volumes have increased by around 56% (from $10,765 \times 10^3$ t in 1992 to $16,789 \times 10^3$ t in 2006). Cultivars are usually triploids of the *M. acuminata* (AAA) genome, which form the basis of world export trade in bananas. However, similar to 1992, this amounts to only 14.75% of all *Musa* production worldwide (Tables 1.1, 1.2 and 1.3).

Export operations in Latin America are usually controlled by multinational companies, but these companies, in contrast with last century, when they started operations in Third World countries, have mostly left plantation management in the hands of individuals or local company producers. Cultivation systems are generally orientated towards very large plantations, flat topography, extended plantation life, extensive technical

Table 1.2. World production statistics for bananas in 2006 (from FAOSTAT, 2010).

Country	Production (× 1000 t)	Country	Production (× 1000 t)
Asia		Central America and	
India	20,858	Caribbean	
China	7,115	Costa Rica	2,220
The Philippines	6,795	Mexico	2,196
Indonesia	5,037	Guatemala	1,001
Thailand	2,000	Honduras	890
Vietnam	1,350	Dominican Republic	548
Bangladesh	909	Panama	440
Malaysia	530	Others	1,464
Others	1,051	Total	8,759
Total	45,645		
		Africa	
South America		Burundi	1,600
Brazil	6,956	Egypt	885
Ecuador	6,127	Cameroon	860
Colombia	1,750	Uganda	615
Venezuela	509	Kenya	600
Others	481	South Africa	344
Total	15,823	Others	3,235
		Total	8,139
Oceania			
Papua New Guinea	870	Europe	
Australia	181	Spain	362
Others	163	Others	38
Total	1,214	Total	400
		Total (world)	79,980

Table 1.3. World production statistics for plantains in 2006 (from FAOSTAT, 2010).

Country	Production (× 1000 t)	Country	Production (× 1000 t)
Africa		Central America and	
Uganda	9,054	Caribbean	
Ghana	2,900	Guatemala	1,049
Nigeria	2,785	Cuba	532
Rwanda	2,653	Dominican Republic	413
Ivory Coast	1,500	Honduras	287
Cameroon	1,400	Haiti	280
Democratic Republic of	1,203	Others	470
Congo		Total	3,031
Tanzania	600		
Others	1,794	Asia	
Total	23,889	Myanmar	625
		Sri Lanka	504
South America		Others	0
Colombia	3,400	Total	1,129
Peru	1,772		
Ecuador	581	Oceania	4
Bolivia	450		
Venezuela	335	Total (world)	34,623
Others	32		
Total	6,570		

infrastructure and high quality fruit. The main importers of this fresh fruit are USA, EU countries, Russia, Japan, China/Hong Kong and Canada (Table 1.1).

Other tropical production areas, besides those in Latin America and the Philippines, grow dessert bananas for export. They are in the Caribbean (Windward Islands, Martinique, Guadeloupe) and West Africa (Ivory Coast, Cameroon). Their export volumes are considerably smaller than those from Latin America (Table 1.1). In these Caribbean/African countries, cultivation systems are orientated to smaller farm units, regular replanting, topographical variations and less permanent infrastructures, but still emphasizing fruit quality for export. A trend towards organic cultivation is being strongly developed in some countries, particularly in the Dominican Republic, which is the leading organic banana export country (Arias *et al.*, 2004; CIRAD, 2007b).

Musa (AAA) dessert bananas are also produced commercially in subtropical and Mediterranean climates, far away from their centres of origin. These areas include New South Wales, Western Australia, South Queensland, South Africa, Israel, Taiwan, the Canary Islands, Morocco, Egypt and parts of Brazil. Such localities are situated at latitudes above 20°N and S, and are

characterized by wide seasonal variations in rainfall and temperature. The industries are intensive but small, being limited by the size of local markets. Export is usually not possible due to either quality, economic or logistical constraints. However, some short-distance regional export does take place to traditional markets, for example, from Taiwan to Japan and from the Canary Islands to mainland Spain. Cultivation systems are orientated towards coping with extremes of heat or cold, competitive influences on the plant and providing efficient supplementary irrigation. In some cases, particularly in Morocco, the Canary Islands, Turkey and Israel, very successful greenhouse cultivation is practised (Galán Saúco *et al.*, 2004). A major advantage of subtropical/Mediterranean areas is that they are usually free of the crippling leaf diseases which plague bananas in the humid tropics.

Subtropical and Mediterranean countries which grow commercial dessert bananas produce very small volumes in comparison with tropical and monsoonal localities. Only Egypt with 885×10^3 t and Spain with 362×10^3 t appear individually on the list in Table 1.2. However, other countries like Australia and South Africa, with 275×10^3 t and 344×10^3 t, respectively, in 2006, have, as with Egypt, significantly increased their levels of production compared with those given for 1992 in the first edition of this book. Israel, with 122×10^3 t has maintained stable production, like the Canary Islands. Compared with this, India, the Philippines, Indonesia, China, Thailand, Brazil, Burundi, Costa Rica, Ecuador or Colombia produce massive volumes of dessert bananas. Colombia, Costa Rica and to a lesser extent Ecuador, the Philippines and Brazil, export most of their production, while the other countries market almost all their bananas internally. It is interesting that a large proportion of the published international research into banana production originates from the marginal subtropical and Mediterranean countries and this research concentrates on AAA (Cavendish subgroup) cultivars. Results have demonstrated that appropriate management can produce very high yields over a wide range of climate in these areas.

Plantains and other cooking bananas are only produced in tropical countries and are mostly consumed locally. Only 1.62% of the world plantain production is exported (Tables 1.3 and 1.4). Imports are concentrated in the USA (48% of total imports in 2006). In the humid tropics, a wide range of plantains and cooking bananas are grown for local cash cropping and for subsistence. Cultivars grown are mostly triploids and hybrids of *M. acuminata* and *M. balbisiana*, such as AAB plantains and ABB cooking bananas. About one-third of all these cultivars belong to the Horn-type plantain (AAB). Most plantains and cooking bananas are produced in Central and West Africa, although Colombia and Peru are also major producers (Table 1.3). Four African countries together (Uganda, Ghana, Nigeria and Rwanda) accounted for 51% of all plantain production worldwide in 2006. Cultivation systems in these countries are based on low-input sustainable farming methods involving organic fertilization, regular replanting, rotation cropping, hand weed control,

Table 1.4. World trade statistics – major importers and exporters of plantains in 2006 (from FAOSTAT, 2010).

Major importing countries	Volume (× 1000 t)	Major exporting countries[a]	Volume (× 1000 t)
USA	246	Ecuador	167
El Salvador	55	Colombia	130
Colombia	28	Guatemala	75
Belgium	25	Peru	57
Spain	22	Costa Rica	36
UK	21	Nicaragua	26
The Netherlands	16	Belgium	26
France	12	Venezuela	12
Others	69	Others	20
World imports (total)	494	World exports (total)	549

[a] Excluding re-exporting, non-producing countries and RUPS.

mulching, and intercropping combinations to increase cash flow. There is a general absence of chemical farming or other inputs of capital and technology (Ddungu, 1987; Jaramillo, 1987; Wilson, 1987). The recent interventions of multinationals (see below) in some African countries can drastically improve this situation.

MAIN BANANA-PRODUCING COUNTRIES

Banana-producing countries, according to world production and trade, are usually classified into four large groups, namely the dollar area, ACP countries, EU producers and other producing countries. They will be treated separately in this chapter.

The dollar area

In 2006, Ecuador was the largest exporter of bananas, doubling the exports it made in 1992 (4908 × 10³ t and 2557 × 10³ t, respectively) and more than doubling the quantities exported by the Philippines and Costa Rica, which rank second and third, respectively, as banana exporters (Table 1.1). This growth is mainly based on increased plantings and to a lesser degree by increased yields. In contrast with other dollar countries, the trend in Ecuador is small-scale production on farms of 10–50 ha and with local producers. There is only a token presence of multinationals (around 1%). Regarding marketing, local farmers are not well organized and production is bought by intermediaries, either multinationals or other big producers who establish contracts with

the farmers and export to the USA and Europe. There are good prospects for increasing banana exports from Ecuador by upgrading charge terminals and increasing yields. Also, efforts to improve social conditions of banana workers must be prioritized, since Ecuador had the lowest salaries of all Latin American banana export countries in 2000 (Arias *et al.*, 2004).

In 2006, Costa Rica was the second most important export country in the dollar area. Bananas are cultivated in relatively large plantations, controlled by private producers and multinationals. Cobal (Chiquita), Bandeco (Del Monte) and Standard Fruit Co. (Dole) controlled about 80% of banana exports in 2000 (Arias *et al.*, 2004), a figure which has not changed much in recent years. Despite the growing incidence of black Sigatoka during the 1990s, Costa Rica still has the highest productivity in Latin America. It also has the most strict environmental regulations and social standards, and also pays the highest salaries to banana workers. While this enhances increased exports to selected high price markets, it becomes difficult to compete on the normally priced banana market. Reduced production costs are difficult to achieve as a result of: (i) high salaries; and (ii) growing resistance of black Sigatoka to systemic fungicides. Unlike Ecuador, banana exports from Costa Rica have grown only moderately from 1992 to 2006 (1769×10^3 t to 2183×10^3 t, respectively) and future prospects are uncertain. However, in the UK market, three out of every ten bananas consumed are from Costa Rica and supermarkets have recently increased the consumer price (Banana Link, 2008).

Colombia, until recently number three as a dollar banana exporter, and now surpassed by Brazil, has not increased its exports by much (1500×10^3 t in 1992 to 1568×10^3 t in 2006). Despite concerted efforts to improve productivity, develop export infrastructures and reduce pesticide use, Colombia is in a conflict zone, which reduces banana development potential.

Brazil has significantly increased its position in the export market (92×10^3 t in 1992 up to 1943×10^3 t in 2006). Despite this growth, Brazil exported less than 30% of its total production in 2006 and productivity (14.1 t/ha) is low compared with either Costa Rica (55.1 t/ha) or even Ecuador (27.7 t/ha). This is due to an increased internal demand and the wide diversity of banana varieties unsuited to export (Rodrigues and Leite, 2008). Banana is produced in all Brazilian states and is an important source of income for families and private enterprises. Multinationals have only a minor influence, but the recent significant increase in exports is linked to new projects of multinationals (Anon., 2010).

Despite Mexico being an important banana-producing country, ranking fourth in Latin America, exports are low and diminished from 180×10^3 t in 1992 to 67×10^3 t in 2006. This is despite its proximity to the USA export market. As with Brazil, local consumption of banana is high due to: (i) all-year-round production; (ii) low production cost; and (iii) high nutritional value. The presence of multinationals is also minimal. Mexico produces organic bananas and has a high potential for future exports to this high-priced trade.

Guatemala had an unchanged banana surface area of around 20,000 ha during the last 50 years. Exports increased consistently, reaching 1055×10^3 t in 2006, more than doubling that of 1992. Due to poor internal transport and export facilities, its potential for increased exports seems low. Despite this, Guatemala was the largest banana exporter to USA in 2008 (Anon., 2009a).

The main producers in Honduras are multinationals (Chiquita and Dole), and the remainder are independent producers and peasant cooperatives that also market their production through multinationals. Climatic disasters, the most important in recent years being the 'Mitch' hurricane, have reduced both production and export (the latter decreasing from 800×10^3 t in 1992 to 515 $\times 10^3$ t in 2006).

Panama, once one of the most important banana export countries, has seen a significant reduction in both production and exports since Chiquita sold its largest plantation to a group of workers at the turn of the century (Arias *et al.*, 2004). Nicaragua, also once an important banana export country, continues to lose relevancy in both production and export. Other minor countries in the dollar area are Venezuela, with reduced shipments to Europe, and Peru which has increased its investments in the organic and fairtrade segments (CIRAD, 2007a), thus increasing the value of its banana exports since 2004 (Anon., 2009a).

ACP countries

The term 'ACP' refers to the 48 African, Caribbean and Pacific countries, which are ex-colonies of the EU, or signatories of the 1975 Lomé Convention and later treaties with the EU. Treaties were designed to protect their economies, largely based on agricultural production. Originally 12 banana countries were considered traditional ACP, namely: Saint Lucia, St Vincent and the Grenadines, Jamaica, Belize, Surinam, Dominica, Grenada, Ivory Coast, Cameroon, Somalia, Cape Verde and Madagascar. The three last named ceased banana exports to the EU during the 1990s, while Dominican Republic obtained ACP status in 1990 and Ghana recently began to export bananas to Europe.

Within the Caribbean zone, Dominican Republic has increased its exports (187×10^3 t in 2006) consolidating its position as world leader in organic and fairtrade exports. This is due to: (i) planting in relatively dry areas; (ii) sound cultural practices with reduced pesticide use; and (iii) certified production (about 50% of their production is certified organic; Anon., 2009a). However, their recent outbreak of black Sigatoka is affecting organic exports which decreased by 50% in 2008 compared with 2007 (Reefer Trends, 2008). Banana production is also important in Jamaica and the Windward Islands, which have small plantings of around 1 ha and with lower yields of about 10 t/ha, but this contributes much to their social and economic development. Despite a significant reduction in banana area, production is stabilized with

a core of active, modern growers who obtain good yields and adhere to the market demands for certification (CIRAD, 2007a).

Based until recently on a tariff-free quota for entrance into the EU (see below), ACP countries do not usually exceed this quota after establishment of the 1993 CMO of the EU. However, all ACP countries, including Jamaica, St Lucia and Surinam, recently increased their exports to EU which, if continued, can stabilize production in these countries. Unfortunately, 2007 was characterized by climatic disasters, such as hurricane 'Dean', which seriously reduced Caribbean production. It is difficult to predict the future for these countries although various international organizations and non-governmental organizations (NGOs) continuously emphasize the need to maintain banana production in this region. Recent agreements between Windward Islands producers of 'fairtrade' banana, and the export company WIBDECO (Rose, 2008), and also the unprecedented cooperation between Windward Islands and French West Indies (FWI) producers (Reefer Trends, 2009b), will boost Caribbean banana production.

Within African ACP countries, the situation has not changed much recently, with Cameroon and Ivory Coast (both around 250–300 × 10³ t) leading the exports to the EU. Most bananas in Ivory Coast are produced on 65 farms with a total surface area of 5500 ha, while in Cameroon, multinationals are established as important producers. Multinationals control the export trade in both countries (Arias *et al.*, 2004). Recently, Ghana entered the export trade and Mozambique and Angola have initiated planting projects with the support of multinationals, to export bananas to Europe from 2010 (Bright, 2008).

Important changes occurred in January 2008 in the EU with the liberalization of the market for ACP countries that signed a European Partnership Agreement (EPA), giving them similar advantages to European banana producers. This gives additional benefits to ACP countries for as long as the customs tariff for other countries remains high enough. However, the expected severe reduction of this tariff (see 'Political issues' in this chapter) in the near future could make this advantage tenuous (Loeillet, 2007a, 2008b).

EU producers

All European banana producers benefited until recently (see 'Political issues' in this chapter) from the CMO, established on 1 July 1993, set up to maintain production of bananas in the outer (ultraperipheric) regions of the EU, also called RUPS (see 'Factors Influencing World Trade' in this chapter).

The Canary Islands (Spain), the main producer of the EU, maintained a steady production area of around 9000 ha, with 400 × 10³ t produced annually, and exporting around 90% to mainland Spain with the rest sold locally (Galán Saúco and Cabrera Cabrera, 2006). Banana cultivation in

the Canary Islands is highly intensive, with imported soil and terraces, and small farms, averaging around 1 ha. Producers are grouped in OPPs, the Organisations of Banana Producers, which are further integrated in a regional structure called ASPROCAN, the Association of Canary Islands Producers, created to support banana production in the islands. In turn this is integrated in a supra regional body called APEB, the Association of European Banana Producers, in conjunction with Madeira, Martinique and Guadaloupe. The main advantage of the Canary Islands compared with most other banana-growing regions of the world, is the absence of Sigatoka and *Radopholus similis*, and the relative freedom from other serious banana pests. Another advantage is that they are close to the Spanish market (less than 3 days to any Spanish port).

Cultivation of banana in the Canary Islands is a clear example of how the horticultural sector and research have combined for sustainable and successful production. Research has led to the highest yields in the world, reaching up to 100 t/ha/year on the best farms. This is based on a combination of selected local varieties and improved cultural techniques, including greenhouse cultivation (see Chapter 8) which now occupies one-third of the total banana area. Publicity campaigns have highlighted the excellent taste of speciality bananas, (mostly Dwarf Cavendish cultivars), produced in the Canary Islands. Special efforts were made to change the perception of 'defects' in the external appearance of Canary Islands bananas (small size, irregular yellowing and presence of small black spots) into one of improved internal quality, in contrast to the extremely neat appearance and bright uniform yellow colour of the tropical bananas commercialized by multinationals. In this way, a clear segmentation of the Spanish market has been obtained between 'plátanos' (from the Canary Islands), more-preferred and paid for by the consumer, and 'bananas' (from other regions).

The FWI (Martinique and Guadeloupe) are also important EU producers, but seldom achieve more than 300×10^3 t of production, annually. Although most farms are small, the average size is larger than in the Canary Islands, and some farms exceed 50 ha. Average yields are 35 t/ha, much lower than in the Canary Islands and frequent hurricanes cause serious damage, as in other Caribbean countries. Similar to the other RUPS, banana growing is the main agricultural occupation. Bananas are exported only to the EU and mainly to the French market. The union of banana-producing groups of Guadaloupe and Martinique, UGPBAN, handles the promotion of bananas from FWI and works in close cooperation with ASPROCAN (Canary Islands) and also with producers in Madeira, on technical and policy issues. As in all the other RUPS, agriculture is subjected to strict regulations to protect the environment and especially to reduce pesticide use. Unlike in the Canary Islands, Sigatoka is present in FWI (only yellow Sigatoka until 2009). Nevertheless, combined efforts of growers and research centres, with support from government, have led to an integrated system of banana cultivation, combining: (i) weather forecasting; (ii) pathogen monitoring; (iii) use of vitroplants; and (iv) crop

rotation with sugar cane (Loeillet, 2008a). Through this programme, the FWI sector has reduced pesticide application by 50% in 10 years and in the next 5–10 years a further 50% reduction is projected (Lescott and Loeillet, 2008).

The island of Madeira is the other important EU producer. Average farm size is even smaller than in the Canary Islands and climatic conditions slightly cooler, which reduce banana yields. The industry is based on 'Dwarf Cavendish' but since greenhouses are forbidden due to the undesirable visual impact, the importance of banana production in Madeira has diminished since the 1993 CMO, from around $50 × 10^3$ t to $30–35 × 10^3$ t in recent years. Strong competition from Canary Islands bananas in the Portuguese market is another reason for banana decline in Madeira.

Finally in the EU, very minor production of bananas (less than 100 ha) is found in mainland Portugal (El Algarve) and also in Cyprus, Greece and Malta, but they are insignificant and locally consumed.

Other producing countries

Production from Asia and Pacific countries (area of origin of the *Musaceae* family) is mostly directed to local consumption or for regional trade. In the Philippines, bananas constitute the main fruit crop in terms of area, production and exports ($428 × 10^3$ ha, $6795 × 10^3$ t and $2312 × 10^3$ t in 2006, respectively, accordingly to Food and Agriculture Organization (FAO) statistics). Small-scale, family-based production with low yields around 10 t/ha predominates in the Philippines and only a small percentage of total production is exported, this from large plantations with high technology and yields around 40t/ha. Exports are in the hands of multinationals who market the bananas in Japan, China, Korea, Taiwan and in the Arabic countries of the Middle East (Arias *et al.*, 2004).

India, the largest producer of bananas in the world (Table 1.2), but also a country with low productivity, has only recently initiated exports to the Middle East. Australia, with production in both the semi-tropical and the subtropical areas of the country, possesses excellent research and technical services which facilitates very high banana productivity. They were able to eradicate a localized outbreak of black Sigatoka disease in 10 years and are busy eradicating bunchy top virus (Lescott, 2008). Besides local consumption, some exports are directed to Asian countries, including Japan. China has increased its production strongly in recent years and despite the importance of their internal market, will probably become an important export country in the near future. Small-scale regional exports are also undertaken by countries like Vietnam, Indonesia, Malaysia and Thailand. Egypt and South Africa are also important subtropical producers of bananas, the latter with a very efficient, high-yielding industry of about 12,000 ha, supported by good research, but with no export outlets.

Morocco and Turkey, both with around 4000 ha and Israel with around 1500 ha, are high-latitude banana producers although practically all their production is supplied to the local market. These three Mediterranean countries have most of their production under protected cultivation (see Chapter 8).

MAIN BANANA MARKETS

Markets for tropical export bananas

At the outset it is important to emphasize that more than 95% of dessert bananas exported are from the AAA Cavendish subgroup. Most bananas produced in tropical countries are exported to the two most important world markets, namely the EU and North America (USA and Canada). Other important markets are Japan, and recently Russia. A minor portion of exports go either to regional markets which include Argentina, Uruguay or Chile (non-producers of banana), or to China and other Asian countries, or to Middle Eastern Arabic countries.

Due to the protected market for bananas created by the European CMO in 1993 (see 'Factors Influencing World Trade' in this chapter), EU banana prices became the highest of all banana markets. Despite this high price, the EU market has shown a consistent increase reaching 5231×10^3 t in 2007, which is a gain of 8% over 2006 and 27% over 2003 (Table 1.5). This marked increase in EU consumption (10.6 kg/capita in 2007) is a positive effect of liberalizing the EU market. The banana market was not negatively affected by the world financial crisis of 2008/09 but the sustainability of these high prices in the short term is still uncertain (Loeillet, 2009). The EU banana market, except for the 800×10^3 t exported from the RUPS to France, Spain and

Table 1.5. Banana supplies in the EU (× 1000 t) (from Loeillet, 2008a).

Year	RUPS (%)	ACP (%)	Dollar (%)	Total	Exports	Supplies (import – export)
1993	646 (22.3)	748 (20.9)	2220 (62.0)	3614	36	3578
1997	811 (20.1)	693 (17.5)	2464 (62.4)	3968	17	3951
2000	782 (19.4)	757 (18.8)	2528 (62.7)	4067	35	4032
2003	754 (18.3)	787 (19.1)	2579 (62.7)	4120	6	4114
2004	751 (16.3)	783 (17.0)	3074 (66.8)	4608	11	4597
2005	648 (14.8)	764 (17.5)	2959 (67.8)	4372	5	4367
2006	642 (13.3)	906 (18.8)	3290 (68.1)	4837	8	4829
2007	552 (10.6)	837 (16.0)	3841 (73.6)	5231	9	5222

Portugal, is fully supplied by tropical export countries, both ACP and dollar countries. The dollar countries comprise around 70% of total EU imports (Table 1.5) with Ecuador and Colombia, followed closely by Costa Rica, being the main suppliers.

The USA is the main banana import country with around 4000×10^3 t in each of the years 2007 and 2008. Their imports have grown consistently from the early 1960s when imports were around 1500×10^3 t (Arias *et al.*, 2004). Unlike the EU market, the absence of import tariffs, and the strong dominance of multinationals have reduced banana prices to the level of the cheapest fruit in the USA (Loeillet, 2007b). However, even when record retail prices reached 1.35 US$/kg this did not reduce consumer demand for bananas in the USA (Loeillet, 2009). The US market is supplied exclusively by dollar banana countries like Ecuador (the main supplier until 2007), Guatemala and Costa Rica, the last two now with higher exports to the USA than Ecuador, Honduras or Colombia (Loeillet, 2008a).

Japan has until recently been the third largest importer of banana, closely followed in recent years by Russia (see below). Although no quantitative import restrictions are applied to bananas in Japan, high seasonal tariff duties are applied (Arias *et al.*, 2004) with imports stabilized at around 1000×10^3 t since the turn of the century. Due to its locality, Japan has been traditionally supplied by the Philippines which supplies more than 90% of their total market. Ecuador reached around 20% of this market by 2000, but has lost influence to about 5% in 2007.

Russia or, more exactly, the Russian Federation, has significantly increased its imports, becoming the fourth, if not the third most important world market for tropical bananas. From around $400–600 \times 10^3$ t between 1995 and 2002, Russian imports increased to 1000×10^3 t in 2007. Although the Russian market can still be affected by many fluctuations in prices (Reefer Trends, 2009c) bananas have surpassed apples and citrus in their fruit import market. Unlike the EU or the USA, the Russian market is not dominated by multinationals. Local stakeholders control the trade and are investing to ensure regular supplies from Ecuador. The latter is by far the main supplier of the Russian market (around 90% since 2001), with Costa Rica, Colombia and the Philippines being only complementary suppliers (CIRAD, 2007a; Loeillet, 2008a).

The import trend is very positive for tropical bananas in Asia and Middle Eastern Arab countries, and also in most other minor importing countries. A few exceptions to this trend are China, an unknown for the future due to its limitations in transport infrastructure, storage and ripening facilities, and also Australia where strict phytopathological restrictions strongly influence trade. Some Mediterranean Arab countries like Tunisia or Morocco, with heavy import duties and other restrictions, are also in this category.

Argentina and Uruguay receive important but extremely variable quantities of bananas from Ecuador (145 and 3756×10^3 t, respectively,

in 2007 compared with 0 and 264 × 10³ t in 2004). Although Ecuadorian bananas are considered an excellent quality product in MercoSur, the high costs of shipping by boat antagonize the regularity of trade (González, 2008).

A few other dessert bananas like red bananas (AAA), 'Sucrier' or baby bananas (AA), and 'Apple' or 'Manzana' (AAB) are sold for high prices in Europe and the USA but demand is very small and concentrated in gourmet or luxury fruit shops. They originate mainly from Latin America, but small quantities come from Asian countries.

Markets for subtropical local production

With the exception of the Canary Islands and the small production of Madeira island, most other subtropical banana-producing countries (Israel, Australia, South Africa, Morocco, Egypt) sell their dessert bananas in the local markets. Although these countries are obliged to open their markets to foreign imports, certain phytosanitary issues may still preclude this. For example, Australia is concerned about importing serious pathogens on fruit from the Philippines. Also, South Africa recently imposed quarantine measures on banana fruit imported from Mozambique, as a precaution against importing a dangerous fruit fly species, *Bactrocera invadens*. Areas under production closely track internal demand and prices, sheltered from foreign competition. Growers adjust fairly well to maintain reasonably profitable industries. Despite liberalization of the EU market, the Spanish market relies heavily on bananas coming from the Canary Islands. When large quantities of Canary Island bananas, called 'plátanos' arrive, prices are at their lowest and vice versa for foreign bananas (Loeillet, 2008c).

Markets for local trade and staple diets

Practically all tropical countries allocate part of their production (mostly plantains) to their local trade, with minimum competition from other countries. In many cases, non-Cavendish dessert bananas, such as 'Gros Michel', 'Apple', 'Sucrier' or 'Pisang Mas', trade well in countries like India, Brazil or the Philippines and are preferred to Cavendish on local markets. Only 1.62% of world plantain production is exported, which emphasizes their role as a staple food. The USA is the main market for plantains with imports of 263 × 10³ t in 2005 (Table 1.4; 246 × 10³ t in 2006) and small quantities (9 × 10³ t) of other cooking bananas. A total of 126 × 10³ t of plantains were marketed in the EU in 2007 (Loeillet, 2008a) with Ecuador and Colombia being the main suppliers to both the USA and EU. Major possibilities for plantains and other cooking bananas in the EU market rely on dietary habits of immigrants.

A good example is the increase in plantain consumption in Spain where the Latin American population grew considerably. Spain expanded its imports from 4.68×10^3 t in 2000 to 17.47×10^3 t in 2005 (FAOSTAT, 2010).

Markets for processing

Bananas and plantains do not lend themselves readily to processing because the lack of acidity makes preservation difficult and the year-round availability of fresh fruit also makes preservation unnecessary (Gowen, 1988). However, many processed products can be produced from banana and plantains, including purées, flour, jam, jelly, dried banana, chips and drinks (Galán Saúco, 2003; see Chapter 15). Banana chips are the only product with an important international trade.

The Philippines is, by far, the main exporter of banana chips, selling them in around 30 countries, with the USA and EU being the principal markets (Arias *et al.*, 2004). Japan, Australia and South Korea have expanded their imports in recent years. China has become the fastest-growing buyer of Philippine banana chips with imports rising from about US$120,000 in 2002 to US$5.2 million in 2006. Russia, as with dessert banana, is also becoming a popular destination for banana chips, with exponential growth between 2002 and 2006. Total annual value of banana chip exports from the Philippines is approximately US$35 million (Anon., 2009b).

Banana flour, both from green and ripe fruit, has an industrial potential and is used widely in baby foods when enriched with sugar, powdered milk, minerals and vitamins, and artificial flavouring. In several areas of South-east Asia, young fruits are pickled. Purée is used in the manufacture of dairy products such as yoghurt and ice cream, and also in breads and cakes, banana-flavoured drinks, baby food and diverse sauces, but statistics on market importance are not currently available.

In African countries like Uganda, an important part of the diet comes from unripe plantains or cooking bananas, which are first peeled, then steamed while wrapped in their own leaves, and finally pounded to a starchy paste called *matoke* which constitutes the main staple food. Both Uganda and Tanzania produce and consume locally large quantities of beer brewed from local Highland bananas (AAA). Plantains and cooking bananas are also part of the daily diet of people in the Caribbean and Latin America. 'Tostones', which are slices of double-fried green plantain, produce a tasty side dish used in lieu of the ubiquitous French-fried potato, and are very popular in the Caribbean (see Chapter 15 for more detailed information on processing of banana and plantain).

FACTORS INFLUENCING WORLD TRADE

International banana trade differs from other fruit trades by its dependence on multinational companies which have ruled it for more than 100 years, and also by its strong political implications. Despite many uncertainties and problems, the world banana market has increased consistently from 3.9×10^6 t in 1960 to 16×10^6 t in 2007 (Lescott and Loeillet, 2008). Even in times of world economic disturbance, future prospects are bright since the banana may be considered a perfect 'anticrisis' item (Loeillet, 2009) with advantages such as: (i) competitive price; (ii) high energy ratio; (iii) high nutritional and digestive values; (iv) easy to peel; and (v) excellent taste appeal for most consumers. However, there was a recent reduction in banana imports in 2009, both in the EU (6% decrease) and also in the USA (Reefer Trends, 2010).

Political issues

International banana trade has been confronted with many political events in its history. The most conspicuous of these was the so-called **'banana war'**, the longest ever commercial dispute in the history of world trade. This was between the EU, defending the interests of their own and the ACP producers, and the dollar countries grouped under the leadership of the USA and their multinationals. This 'war' was initiated in 1993 with the establishment of the European CMO for bananas but seems to have ended by 15 December 2009 with the signing of the Geneva Agreement on Trade in Banana between the EU and the Latin American-producing countries. This agreement approved progressive reductions in the tariff system until it reaches 114 €/t by 1 January 2017. The impact of this reduction may, however, exert a negative impact on EU producers, who may still claim for special measures, contemplated in the agreement, to compensate them for loss of competitiveness.

Since the establishment of the CMO for bananas (EEC Directive 404/93; EUR.lex, 2010a) the EU market has maintained a strong regulation of imports through a system of contingencies, import licences, compensatory aids to EU producers and tariff regulations which, collectively, have caused banana prices in the EU to be the highest of all banana markets. This is in clear contrast with the USA market where the banana has always been the cheapest fruit available.

Besides quality and marketing regulations, the initial policy of the CMO consisted of establishing for EU producers a tariff-free quota to export bananas to any EU member country. EU producers also benefited by compensatory assistance. Another tariff-free quota was established for ACP countries to export bananas to any EU member country. A system of import licences given through a *partenaire* system (import quotas from non-EU producers linked to imports from EU producers) also allowed EU producers to compete for specific

volumes with dollar bananas. Finally, all other imports from dollar countries, not linked to EU producers through the *partenaire* system, were penalized with very high tariffs.

Due to continuous complaints by dollar countries to General Agreement on Tariffs and Trade (GATT) and by virtue of policies of the World Trade Organization (WTO), a progressive softening of these regulations has been implemented, until the recently approved Geneva Agreement. Conversely, a regime of compensatory assistance (€278.8 × 10^6 since 2006) was given to EU producers through the POSEI programmes (specific programmes of the EU to help agricultural development of the outer islands of the EU, to compensate for problems of distance from continental EU). This was established to ensure development and sustainability of local agricultural production. A subsidy of €100 × 10^6 for ACP countries has also been promised by the EU, but was still not disbursed by 2009. ACP exports to Europe now share the same status as EU banana producers, being exempt from tariff fees in the EU market.

Environmental and social issues

The expansion and intensification of large banana plantations in the 1980s and beginning of the1990s, caused many environmental problems, the most important being: (i) destruction of wide areas of forest; (ii) excessive and uncontrolled use of pesticides with serious consequences for health and the upsurge of resistant pests; and (iii) excessive use of chemical fertilizers which polluted soils, rivers and water sources.

The sensitization of world public opinion about these environmental problems gave rise to the Rio de Janeiro Convention, organized by the United Nations in 1992 to address the conflict of 'development' versus 'environment'. World governments recognized the need to carefully manage natural resources and thereby achieve sustainable development in the world. Strong pressure by many NGOs and the preference of consumers for environmentally-friendly products, promoted important changes in policy by multinationals and other producers, to reduce the environmental impact of banana farming. Practices like waste management, water residue treatments, removal of used polyethylene bunch covers, and organic composting, have now become standard operations on many banana farms.

Many environmental problems still require a solution, primarily the widespread use of pesticides to control diseases like black Sigatoka. Strategies used are: (i) **integrated management systems**; (ii) controlled application of chemicals based on weather forecasting; and (iii) resistant varieties for banana production. Stricter regulations concerning environmental protection are incorporated in the system of **organic cultivation**, also called biological or ecological culture (see Chapter 8).

During the 1980s and early 1990s, the health or economic welfare of banana labourers had received little attention. In the second half of the 1990s, growing concern about workers' rights gave rise to what is now known as **fairtrade**. Different certification systems have been implemented by different NGOs, the most important being the label given by the Fairtrade Labelling Organization International (FLO) founded in 1997. This is a legally independent body which makes specific regulations relating to benefits/rights of farmers' associations and cooperatives, freedom of association for farm and packshed workers, prohibition of child labour and many other rights. They also included the setting of minimum prices and environmental regulations such as the prohibition of herbicides (Arias *et al.*, 2004). Recent revisions of FLO standards include the setting of a fairtrade price premium, and criteria like waste water and organic waste management (CIRAD, 2007b).

Many other certifications (see Chapter 8) exist in the banana world which combine both standards and environmental and social concerns. The main ones are ISO 9000, ISO 14000 and ISO 22000, SA 8000, Rainforest Alliance (Sustainable Agriculture Network) and GLOBALGAP. All Chiquita plantings since 2004 have the Rainforest Alliance Label to demonstrate its support for environmental preservation. With this policy, Chiquita created an image of responsibility and avoided many criticisms from ecological movements. GLOBALGAP (initially EUREPGAP) is a private certification system motivated by 22 retail chains in Europe, and created with the aim of increasing consumer confidence in traceability regulations as well as environmental and social concerns.

Despite its initial promise, the production of organically-certified bananas is currently in excess of demand, which is often forcing growers to sell the product at prices similar to conventional bananas. By 2003, imports of organic bananas only represented about 2.5% of the EU market and slightly more than 1% of the USA market, since around 35% of fairtrade bananas are currently also organic bananas. Switzerland and the UK are the main importers of fairtrade bananas (Arias e*t al.*, 2004; Lassoudiere, 2007).

Quarantine issues

Phytosanitary measures have been regularly used as non-tariff trade barriers. In the past, exporting countries had no legal basis to fight against this situation, but this has changed drastically. The WTO Agreement on the Application of Sanitary and Phytosanitary Measures (SPS), which came into force on 1 January 1995, recognizes that SPS cannot be used as unjustified barriers to trade and are valid only when based on rigorous scientific investigation and risk analysis, as well as conforming to international standards. The International Plant Protection Convention (IPPC) is the relevant body to set these standards which should be kept to the minimum

necessary to protect plant, animal and human health. Furthermore, the WTO-SPS Agreement, through the Dispute Settlement Body (DSB) regulates trade disputes among member countries. DSB may even recommend an independent scientific panel to examine the validity of the restriction. For both exporting and importing countries, evidence of plant risk status must be demonstrated, to show scientific evidence of biosecurity risks involved in the potential import (Burgess, 2003).

Phytosanitary barriers have virtually disappeared from banana trade, and this century only Australia permanently applies quarantine measures (FAO, 2001a) to fresh banana imports. This is despite consumer pressures to lift this ban in periods of shortage caused by cyclones, and also despite claims from Philippine banana growers who see excellent export potential (Colqhoun, 2007), but find Australian quarantine barriers too severe for them to export (Reefer Trends, 2009a).

Climatic disasters

Climatic disasters occur frequently in the tropical banana world. This is demonstrated by many such disasters occurring in 2007. The worst event was hurricane 'Dean' which seriously affected Caribbean production. Flooding and cold spells seriously affected vast areas of Colombia, Costa Rica and Brazil. Several gales occurred in many African countries, particularly Cameroon. Cyclones and typhoons also badly affected Asian banana-producing countries.

Climatic disasters have a strong, sometimes dramatic, impact on production with its consequent effect on trade. However, the following are making it easier and quicker to recover from such natural disasters: (i) technological advances in banana production; (ii) availability of tissue-culture planting material; and (iii)the short cycle of the crop. Also, due to good market prices following a disaster, other suppliers will quickly mobilize their bananas to fill these market gaps.

2

TAXONOMIC CLASSIFICATION, CULTIVARS AND BREEDING

The generic name *Musa* is derived from the Arabic word *mouz*. Bananas were known to the early Arabs and appear in the Koran as the 'tree of paradise'. The earliest 'scientific' classification of bananas was made by Linnaeus in 1783. He gave the name *Musa sapientium* to all dessert bananas which are sweet when ripe and which are eaten fresh. The name *Musa paradisiaca* was given to the plantain group which are cooked and consumed while still starchy. However, it is now known that these two apparent species are not species at all but both refer to closely related interspecific triploid hybrids of the AAB group. They are general names and cannot be used to differentiate between bananas and plantains.

Subsequently, several taxonomists gave species names to the many diverse forms of edible bananas that were found. For example *Musa nana* and *Musa cavendishii* were proposed for the 'Dwarf Cavendish' cultivar, *Musa rubra* for the 'Red' cultivar and *Musa corniculata* for the Horn plantain. All these names are misleading and are not now used. Many of them were applied to banana types which were in fact simple somatic mutants of older, more stable cultivars.
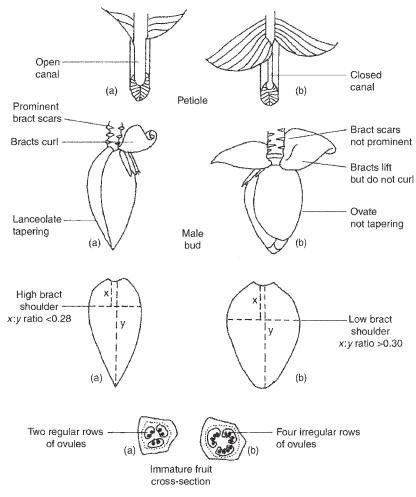
BASIS OF MODERN CLASSIFICATION

The modern method of classifying edible bananas was devised by Simmonds and Shepherd (1955). As described in Chapter 1, most modern edible bananas originally came from two wild, seeded species, *M. acuminata* Colla (A genome) and *M. balbisiana* Colla (B genome), which are native to South-east Asia. However, a few cultivars may have originated from hybridization with *Musa schizocarpa* (S genome) and at least one Philippine clone may have come from ancient hybridization between *M. balbisiana* and *Musa textilis* (T genome). Clones containing A and T genomes or even A, B and T genomes have been identified in Papua New Guinea. There is also a completely different group of cultivars common in the Pacific known as the Fe'I bananas characterized by red sap of the plant and by erect bunches. Although most authors indicate

that *Musa maclayi* is the most likely ancestor, other species like *Musa peekeli* and *Musa lolodensis* may also have been involved in their origin (Daniells *et al.*, 2001; Galán Saúco, 2003). Nevertheless, the classification proposed by Simmonds and Shepherd, based, first, on the relative contribution of *M. acuminata* and *M. balbisiana* to the constitution of the cultivar, and second, to the ploidy or chromosome number of the cultivar, is valid for most practical purposes. The original characters used by Simmonds and Shepherd (1955) to classify bananas, are shown in Table 2.1. These were subsequently refined and updated by Purseglove (1972), Stover and Simmonds (1987) and Valmayor *et al.* (1991).

Table 2.1. Characters used in the taxonomic scoring of banana cultivars (from Simmonds and Shepherd, 1955).

Character	M. acuminata	M. balbisiana
Pseudostem colour	More or less heavily marked with brown or black blotches	Blotches slight or absent
Petiolar canal	Margin erect or spreading with scarious wings below, not clasping pseudostem (Fig. 2.1)	Margin enclosed, not winged below, clasping pseudostem (Fig. 2.1)
Peduncle	Usually downy or hairy	Glabrous
Pedicels	Short	Long
Ovules	Two regular rows in each loculus (Fig. 2.1)	Four irregular rows in each loculus (Fig. 2.1)
Bract shoulder	Usually high $x{:}y$ ratio <0.28 (Fig. 2.1)	Usually low $x{:}y$ ratio >0.30 (Fig. 2.1)
Bract curling	Bracts reflex and roll back after opening (Fig. 2.1)	Bracts lift but do not roll (Fig. 2.1)
Bract shape	Lanceolate or narrowly ovate, tapering sharply from the shoulder (Fig. 2.1)	Broadly ovate, not tapering sharply (Fig. 2.1)
Bract apex	Acute (Fig. 2.1)	Obtuse (Fig. 2.1)
Bract colour	Red, dull purple or yellow outside; pink, dull purple or yellow inside	Distinctive brownish-purple outside; bright crimson inside
Colour fading	Inside bract colour fades to yellow towards the base	Inside bract colour continuous to base
Bract scars	Prominent (Fig. 2.1)	Scarcely prominent (Fig. 2.1)
Free tepal of male flower	Variably corrugated below tip	Rarely corrugated
Male flower colour	Creamy white	Variably flushed with pink
Stigma colour	Orange or rich yellow	Cream, pale yellow or pale pink

By using 15 separate characters, each of which is diagnostic of differences between *M. acuminata* and *M. balbisiana*, Simmonds and Shepherd (1955) showed that the contributions of the two species could be clearly distinguished (Table 2.1). For each character in which a cultivar agreed completely with wild *acuminata*, a score of 1 was given, and for each character in which the cultivar agreed with *balbisiana*, a score of 5 was given. Intermediate expressions of the character were assigned a score of 2, 3 or 4, according to its intensity. A diagrammatic comparison of the main morphological differences between *M. acuminata* and *M. balbisiana* can be seen in Fig. 2.1.

Fig. 2.1. The major morphological characteristics used to distinguish between *M. acuminata* (a) and *M. balbisiana* (b) clones. Redrawn from Simmonds and Shepherd (1955) and Stover and Simmonds (1987).

Concerning ploidy, edible bananas belonging to the section *Eumusa* have 22, 33 or 44 chromosomes. The basic haploid number is 11, thus cultivars can only be diploid, triploid or tetraploid. Of the 200–300 clones which are thought to exist, more than half are triploids, with the remainder being mostly diploids. Tetraploid clones are very rare. The planted area of triploid bananas is more than 100 times greater than that of diploids, and triploids are hardier, more vigorous and easier to grow. It is necessary to know the ploidy of a clone before it can be correctly classified. This can only be done cytologically with a quantitative chromosome count. Morphologically, triploids and tetraploids are larger and more robust than diploids. Also leaf thickness and cell size both increase with increasing ploidy.

The scoring technique according to the 15 plant characters, allows for a range of total score from 15 (pure *M. acuminata)* to 75 (pure *M. balbisiana).* Scores in between would be based on the relative contribution of the two species plus the level of ploidy in the interspecific hybrid. Simmonds and Shepherd (1955) and Stover and Simmonds (1987) used the groups and scores shown in Table 2.2 to classify a range of edible bananas. Silayoi and Chomchalow (1987) classified 137 accessions in the Thai banana genebank on the same basis. They recognized some deficiencies in the original classification and modified it (Table 2.2).

The main difference between these two classifications is the introduction of almost pure *balbisiana* clones in the Thai grouping, which did not appear in the list of the original classification. Espino and Pimental (1990) used isozyme technology to segregate clones of pure *acuminata*, pure *balbisiana* and their hybrids, from one another. They found broad bands of malate dehydrogenase activity which were unique to pure *balbisiana*, and other bands which indicated an *acuminata* genome. They concluded that BB and BBB cultivars were unique and distinct from hybrid ABB clones. The cooking plantain 'Saba' (BBB) is very close to pure *balbisiana* (i.e. 73 to 75 points).

Table 2.2. Classifications of edible bananas.

Genomic group	Score	References
AA diploid	15–23	Simmonds and Shepherd (1955); Stover and
AAA triploid	15–23	Simmonds (1987)
AAB triploid	24–46	
AB diploid	49	
ABB triploid	59–63	
ABBB tetraploid	67	
AA/AAA	15–25	Silayoi and Chomchalow (1987)
AAB	26–46	
ABB	59–63	
ABBB	67–69	
BB/BBB	70–75	

Valmayor *et al.* (1991) endorsed the continued adoption of Simmonds and Shepherd's classification scheme, but recommended that it be expanded and fine-tuned to accommodate the great diversity of banana cultivars in the centre of origin, namely South-east Asia. They were referring specifically to the earlier emphasis on *acuminata* cultivars and the preoccupation with breeding programmes to improve the pure *acuminata* cultivars used in the world export trade. Recent interest in breeding plantains and cooking bananas necessitates a thorough assessment of *balbisiana* germplasm in South-east Asia.

All banana taxonomists agree that no single scientific name can be given to all the edible bananas. *M. acuminata* could be applied to the pure, seedless diploid (AA) and triploid (AAA) forms of dessert bananas such as 'Pisang Mas' and 'Grand Nain', respectively. Similarly, *M. balbisiana* could be applied to the pure seedless diploid (BB) and triploid (BBB) forms of cooking bananas such as 'Abuhon' and 'Saba', respectively. However, the many hybrids cannot carry a specific name due to their mixed composition and differences in ploidy. To avoid confusion, therefore, it is internationally accepted that all banana cultivars should be referred to by the genus *Musa* followed by a code denoting the genome group and ploidy level, followed by the subgroup name (if any) followed by the popular name of the cultivar.

Some examples are:

- *Musa* AAA (Cavendish subgroup) 'Grand Nain';
- *Musa* AAB (plantain subgroup) 'Horn';
- *Musa* BBB 'Saba';
- *Musa* AB 'Ney Poovan'.

The significance of somatic mutations in bananas is very great because the number of clones has gradually increased in this way. In fact, since the advent of parthenocarpy and female sterility, the occurrence of somatic mutations has been virtually the only way that commercially usable new clones have been produced (more recently some progress has been made in the fields of conventional breeding and somaclonal variation using *in vitro* plantlets – see 'Breeding and Selection' section in this chapter). It is very likely that many somatic mutations have remained unrecognized, especially when the morphological change has been small. Only obvious mutations have been recognized, and the parental/mutant relationship established. Still other mutations may have been identified but discarded before testing and selection could take place. Some better known somatic mutants that have been selected, utilized and named are 'Extra Dwarf Cavendish' from 'Giant Cavendish'; 'Williams' from 'Giant Cavendish'; 'Highgate' from 'Gros Michel'; 'Cocos' from 'Gros Michel'; 'Dwarf French Plantain' from 'French Plantain'; 'Silver Bluggoe' from 'Bluggoe' and 'Green Red' from 'Red', and more recently inside the Cavendish subgroup 'Chinese Cavendish' from Australia, 'Lancefield' from South Africa, 'Zelig' from Israel and 'Gruesa' from the Canary Islands. The natural rate of somatic mutations is very low with bananas

propagated conventionally. However, it is increased to relatively high levels during propagation by *in vitro* techniques. Thus, it was shown by Stover (1988) that from *in vitro* multiplication of one clone of AAA 'Grand Nain', six height classes were identified among the progeny due to somaclonal variation.

MAJOR GENOMIC GROUPS AND CULTIVARS IN WORLD USE

AA group

'Sucrier' – Synonym is 'Pisang Mas' in Malaysia and Indonesia and 'Bocadillo' in South America. This is the most important edible diploid *acuminata* cultivar, having small, sweet, thin-skinned, golden yellow fruits. The plant is resistant to Panama disease and can withstand wind, although bunches are smaller and the yield poorer than with triploids. 'Pisang Mas' is the most important banana cultivar in Malaysia.

    'Pisang Ambon Putih' – This is the most important banana cultivar in Indonesia and it also ranks highly in Malaysia. It has good flavour, excellent keeping quality and high yields, but it could not be commercialized in Central America due to its susceptibility to Fusarium wilt disease.

AAA group

Gros Michel subgroup
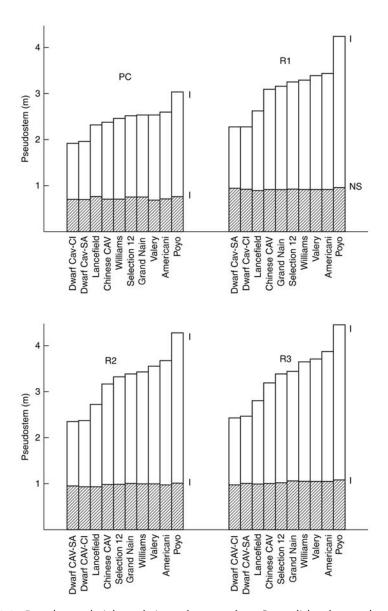
The main cultivar is 'Gros Michel'. A synonym is 'Pisang Ambon' in Malaysia, and two named mutants of 'Gros Michel' are 'Highgate' and 'Cocos'. The cultivar 'Gros Michel' produces tall, vigorous plants bearing heavy, symmetrical bunches with attractive colour and long, slender fruit. This used to be the leading cultivar in world trade until the late 1950s when plantations in Central America were decimated by race 1 of Fusarium wilt disease (*Fusarium oxysporum* cubense – FOC). In the early 1960s these plantations were replanted with the race 1-resistant AAA cultivars 'Valery' and 'Grand Nain' from the Cavendish subgroup. 'Gros Michel' now survives only in northern Ecuador.

Cavendish subgroup

This is an extremely important subgroup in world banana trade both for export in the tropics and for local trade in the subtropics. There is a large variation in pseudostem height between cultivars in this subgroup, ranging from about 1.8 to 2.0 m for 'Dwarf Cavendish' to 4–5 m for 'Lacatan', with many cultivars at intermediate height levels. Four height divisions are described below.

DWARF CAVENDISH TYPE   The main cultivar is 'Dwarf Cavendish' and synonyms of this are 'Canary Banana', 'Dwarf Chinese', 'Basrai' in India, 'Governor' in the West Indies, and 'Enano' in Latin America. It is very abundant and widespread, and is the shortest banana grown commercially. It used to dominate the banana industries in subtropical countries like Australia, the Canary Islands, South Africa and Israel where it was considered climatically adapted, stable against subtropical winds, and high yielding. However, it is susceptible to the physiological disorder 'choke throat' (see Chapter 4) thus it has slowly been phased out of these countries and replaced by taller Cavendish cultivars ('Williams', 'Grand Nain') which are not so susceptible to choke throat and in addition have higher yields and better quality fruit. However, recent selection work within Dwarf Cavendish, particularly in the Canary Islands (Cabrera Cabrera and Galán Saúco, 2005, 2006) has produced interesting, high yielding dwarf cultivars, of which 'Gruesa' has become the most commonly planted commercial cultivar in the islands. All subtropical countries, except Israel, have race 4 of Fusarium wilt disease which attacks Cavendish subgroup cultivars. For this reason, 'Williams', 'Grand Nain' and other Giant Cavendish types need to be replaced in heavily infected areas, with tolerant mutant AAA selections (e.g. 'Tai Chiao no. 1' in Taiwan).

GIANT CAVENDISH TYPE   The main clones of Giant Cavendish are 'Mons Mari' in Queensland, 'Williams' in New South Wales and South Africa (and now becoming popular in the tropics), 'Grand Nain' in Central America and also popular in Israel, Canary Islands and South Africa, and 'Giant Governor' in the West Indies. Cultivars of this type are not excessively tall but are called Giant Cavendish to distinguish them from the Dwarf Cavendish type. Within this type there is also variation in plant height of different cultivars/selections but this is less pronounced than between the four main height divisions. The morphological variations in pseudostem height and circumference, according to cultivar range in the Cavendish subgroup and to crop cycle, are illustrated in Fig. 2.2. The central positioning of 'Grand Nain' and 'Williams' in this height range can be clearly seen. 'Grand Nain' is a major export cultivar in world trade but it can be grown only in areas which are free of Fusarium wilt disease race 4. Since 2005, 'Williams' has started to replace 'Grand Nain' in many tropical export plantations in Central America and West Africa. This is due to the more hardy nature of Williams and its more 'pack-friendly' bunch.

ROBUSTA TYPE   The main clones of 'Robusta' are 'Tall Mons Mari' in Australia, 'Poyo' in West Indies and West Africa, 'Valery' in Latin America, and 'Americani' in Reunion. These cultivars are generally taller than the Giant Cavendish cultivars as shown in Fig. 2.2. 'Valery' used to be a major export cultivar in world trade but is too tall and also susceptible to race 4 of Fusarium wilt disease. It has been replaced by 'Grand Nain' and 'Williams' in many exporting areas of Central America because the latter cultivars have the advantages of shorter plants, larger bunches and a shorter cycle time.

Fig. 2.2. Pseudostem height and circumference of ten Cavendish subgroup banana cultivars and selections over four crop cycles. Cultivars are ranked in ascending order of height in each crop cycle. The lower value is pseudostem circumference. Vertical bars represent least significant difference at $P = 0.05$ and NS indicates non-significance. PC = plant crop; R1, R2 and R3 = successive ratoons. Note that circumference does not increase in proportion to height, thus taller cultivars are less stable. CI, Canary Islands; SA, South Africa. Redrawn from Robinson *et al.* (1993b).

LACATAN TYPE The main synonyms are 'Pisang Masak Hijau' in Malaysia, 'Monte Cristo' in Puerto Rico, and 'Giant Fig' in the West Indies. This very tall cultivar has limited commercial importance and only in Jamaica and the West Indies.

Cultivars, synonyms and mutants in the Cavendish subgroup are actually rather confusing. Between Dwarf Cavendish and Lacatan there is a continuous transition of Cavendish types based mainly on morphological differences (pseudostem height and circumference, leaf ratio, leaf area index, fruit length). Some of the types are recognized as distinct cultivars (e.g. 'Dwarf Cavendish' and 'Williams') whereas others are recognized as somatic mutations (e.g. from 'Grand Nain' to 'Israeli Grand Nain'). Still others are considered as synonyms of the same thing. In reality all the Cavendish clones or 'cultivars' originated by mutation from an original Cavendish clone, and over the years distinct morphological differences and groupings were produced. According to recorded off-types, the mutation rate was probably in the order of two in one million when using conventional planting material (Stover and Simmonds, 1987). The actual mutation rate could have been much higher since many off-types would have remained undetected or unrecorded. It is thus likely that some, if not most, of the 'synonyms' have in fact become different from each other due to further mutation and selection in the countries where they have been grown for many years.

'Red' and 'Green Red' subgroup

Neither of these two clones is important commercially, but they are well known due to their wide distribution. They are only backyard clones grown for home consumption and have a low harvest index. 'Red' has a red skin from which a mutation for green skin produced the clone 'Green Red'.

Other AAA cultivars

A distinct group of AAA bananas are found in the East African Highlands, from the 'Lujugira' subgroup, and are used for the production of beer or for cooking purposes. They are commonly called 'East African Highland Cooking bananas'. The cultivar 'Ibota', also called 'Yangambi Km 5' and 'Caipira' in Brazil, a dessert cultivar with acid flavour, tolerant to black and yellow Sigatoka and nematodes, also belongs to the AAA group (Lassoudiere, 2007).

AAAA group

Tetraploid *M. acuminata* bananas have been produced by breeding AA diploid pollen parents with AAA triploid female parents which are not totally parthenocarpic and sterile, but in which one or two seeds may be produced in a bunch. The traditional female parent used for this breeding process (see 'Breeding and Selection' section in this chapter) was the mutant of

'Gros Michel' called 'Highgate'. The progeny of a diploid × triploid cross are tetraploids. Some AAAA cultivars are IC.2, 'Bodies Altafort' and FHIA SH 3436.

IC.2 – This was the first banana to be released from breeding (Trinidad in 1928). It was widely distributed but bunches were small and it became susceptible to Panama disease in Central America. It has not been grown commercially since 1954.

'Bodies Altafort' – This was released from Jamaica in 1962 and is a cross between 'Gros Michel' and 'Pisang Lilin'. It is tall, prone to lodging in wind and is not grown commercially.

FHIA SH 3436 – This was released from Honduras in 1982 and is a cross between the burrowing-nematode-resistant diploid SH 3142 and 'Highgate'. It has good resistance to black Sigatoka but was found susceptible to race 4 of Fusarium wilt disease in Australia and South Africa. (See 'FHIA hybrids' at the end of this section.)

AB group

This group comprises a small number of diploid hybrids of south Indian origin. The main cultivar is 'Ney Poovan' (India) which is widely distributed but unimportant commercially. Being a diploid the plants are slender and lacking in vigour although fruits are white-fleshed with a pleasant, sweet-acid flavour. It is highly resistant to Fusarium wilt disease and leaf spot. An interesting cultivar with similar characteristics cultivated in East Africa is called 'Safet Velchi'.

AAB group

This group of triploid hybrids originated in India, therefore a wide range of clones and somatic mutations occurs there. The AAB plantains generally have starchy flesh and at maturity they are usually unpalatable unless boiled. Other AAB cultivars have sweet fruit and are used as dessert cultivars.

Plantain subgroup

There are two main types: French plantain type and Horn plantain type.

French plantain type – There are nine known forms of French plantain which are grown in different parts of India, Africa and Central America. As a group they are characterized by the persistence of the male axis and male flowers and bracts.

Horn plantain type – These are characterized by the early degeneration of the male axis and flower parts. There is a wide range of local names given to

Horn plantains and they are produced in India, Africa, Central America, the Philippines and the Pacific.

In general, plantains are tolerant to Fusarium wilt disease, but are susceptible to black Sigatoka and banana weevil. They are very important sources of staple food for indigenous populations of south India, East, West and Central Africa, and Central America. In Africa, plantains have become widely diversified due to somatic mutations over the years, and these diversified forms can be seen in clones with different pseudostem and bunch characteristics. In East, West and Central Africa, where most of the world's plantains are grown, very little attention has been given to them in terms of research. This was evidently because there were no major production problems in the context of limited input and small-scale subsistence farming systems, thus research was not considered a high priority. However, research is now critically important due to the serious threat of black Sigatoka, Xanthomonas wilt and banana bunchy top virus (BBTV), as well as rapid yield decline due to banana weevil, poor weed control, poor soil fertility and nematodes. Furthermore, there is an increasing transition to larger scale, intensive plantain production for commercial purposes, and for this a higher level of production technology is required (Ddungu, 1987; Wilson, 1987). Yield decline is also related to cultivar in that 'Giant French' plantains are declining faster than 'False Horn' plantains. Local governments and NGOs are now giving serious attention to improving plantain productivity in Africa, and throughout the world. However, this is not an easy task since molecular analysis revealed that genetic diversity among plantains is scarce and, as indicated above, most diversified forms among West African plantains have come from somatic mutations (Daniells *et al.*, 2001).

AAB dessert bananas

Besides plantains, there is a range of important AAB dessert bananas in the tropics described as follows.

'Mysore' – The most important banana clone in India representing some 70% of all bananas produced there. It is a large and very vigorous plant and has some important advantages such as resistance to Fusarium wilt disease and leaf diseases, and tolerance to banana weevil, poor soils and drought. However, it is very susceptible to banana streak virus (BSV). The fruit has an attractive flavour and yellow colour when ripe and it stores well. Its distribution outside India is limited.

'Prata Anã' – Widely planted in Brazil and currently used in both the Honduras Foundation for Agricultural Research (FHIA) and Empresa Brasileira de Pesquisa Agropecuaria (EMBRAPA) breeding programmes. It is a relatively short plant with a sweet fruit and a touch of acidity. The taste is very popular in Brazil where it is sold at much higher prices than Cavendish

bananas. It has good resistance to wind and cool conditions, but is sensitive to Panama disease which limits its expansion.

'**Thap Maeo**' – A cultivar recommended by EMBRAPA in Brazil and originating from Thailand. It is very similar to 'Mysore' but less sensitive to BSV, is resistant to black and yellow Sigatoka and Fusarium wilt disease, and with higher tolerance to nematodes (Silva *et al.*, 2008).

'**Silk**' – Some synonyms of this are 'Apple' in Hawaii, 'Silk Fig' in the West Indies, 'Latundan' in The Philippines, 'Pisang Rastali' in Malaysia and 'Manzano' in Spanish-speaking countries. 'Silk' is distributed almost as widely in the world as 'Dwarf Cavendish'. Plants are moderately vigorous but do not bear heavily compared with 'Mysore'. It is a popular dessert cultivar in the tropics, especially The Philippines, and has a white, apple-flavoured fruit flesh that must only be eaten fully ripe.

'**Pome**' – A synonym of this clone is 'Lady Finger' in Australia and 'Prata' in Brazil. It is a common dessert cultivar in southern India but only of minor importance in Hawaii and Australia. Plants are vigorous and hardy but not very prolific bearers.

'**Pisang Raja**' – A well-known dessert clone in Malaysia and Indonesia but unknown in Africa and India. In Malaysia it is often cooked first. Plants are vigorous and resistant to Fusarium wilt disease and leaf spot. Bunches have only six to nine hands, therefore yields tend to be low.

'**Maia Maoli**' – An important clone in Hawaii and the Pacific. In Hawaii, 11 subclones are recognized. It has a compact bunch containing large, compact fruits.

ABB group

Due to the predominance of *M. balbisiana* genes, cultivars in this group are very vigorous and drought resistant. The fruits are green and waxy silver, the pulp is starchy and the plants are resistant to leaf spot. The main centres of origin for this group are southern India and the Philippines.

'**Bluggoe**' – This is a starchy cooking banana with large fruits. It has at least 27 synonyms and several named mutants, including dwarf types, and is an important source of food in Samoa, the Philippines, southern India, the West Indies, Tanzania and in some Latin American countries, particularly in Venezuela, where is known as 'Topocho'. It is immune to common leaf spot but is susceptible to black Sigatoka, race 2 of Fusarium wilt disease and particularly to 'Moko' disease. In Grenada (West Indies) 'Bluggoe' was widely interplanted with cocoa and nutmeg, but since 1983 the Moko-resistant ABB cultivar 'Pelipeta' has been replacing 'Bluggoe' in the Central American region.

'**Pisang Awak**' – Synonyms of this cultivar include 'Pisang Klotok' in Indonesia, 'Ducasse' in Queensland and 'Kluai Namwa' in Thailand. This is by

far the most common banana cultivar in Thailand where it is either eaten fresh or cooked first. It is also common in north-east India and Malaysia but not in south India. 'Pisang Awak' is very vigorous and hardy but it tends to be partially fertile and may produce seedy, inedible fruits if pollinated by wild diploids.

BB group

Although it was thought until recently that pure seedless diploid clones of *M. balbisiana* did not exist in nature, morphological and cytogenetic studies carried out in the Philippines clearly indicates the existence of BB cultivars. The most important of them is the early-maturing cultivar 'Abuhon' (Valmayor *et al.*, 2002).

BBB group

There is a wide range of pure *balbisiana* clones which have been identified in South-east Asia.

'Saba' – Synonyms are 'Pisang Kepok' in Indonesia, 'Pisang Nipah' in Malaysia and 'Kluai Hin' in Thailand. 'Saba' is the most important banana cultivar in the Philippines, but of lesser importance in other countries of South-east Asia. It is a cooking banana with medium to large fruits. The pulp is creamy white, and although the flesh becomes sweet on ripening, fruits are always cooked before consumption. The male bud of 'Saba' is usually removed and eaten as a vegetable.

ABBB, AAAB and AABB groups

These three groups are the only natural tetraploids to be found. Pure *acuminata* or *balbisiana* tetraploids in nature have not been described, and hybrid tetraploids are certainly not common. Bred tetraploids are now being produced in increasing numbers.

'Klue Teparod' (ABBB) – This is a robust plant, immune to Fusarium wilt disease and leaf spot. The fruit flesh has an unpleasant spongy texture when raw but, in Thailand and Burma, the fruits are cooked to make popular sweetmeats. It probably originated in Indo-China.

'Atan' (AAAB) – This cultivar resembles AAB triploids in some respects. Leaves are horizontal to drooping which is a typical weak petiole character of tetraploids. Fruits are short, plump and tart, and the plant is resistant to Fusarium wilt disease.

'Kalamagol' (AABB) – This may be the result of a natural cross between 'Latundan' and *M. balbisiana*, and was found in the Solomon Islands. It has

very droopy leaves. Fruits are small and sweet and the plant is resistant to Fusarium wilt disease and leaf spot.

'Goldfinger' or FHIA 01 (AAAB) – This cultivar is a product of the conventional breeding programme of the FHIA. It is a cross between 'Prata Aná' (AAB) from Brazil and the diploid breeding line SH 3142 (AA) from FHIA. The cultivar was released from the breeding programme in 1989 and has undergone field evaluation in Honduras, Costa Rica, West Africa, Australia and South Africa. It is reputed to be tolerant to race 4 of Fusarium wilt disease, black Sigatoka and burrowing nematode. It is also more tolerant to cold temperatures than Cavendish subgroup cultivars. The plant carries large bunches and the fruit has a pleasant, slightly tart flesh which does not oxidize on exposure. This cultivar initially appeared very promising and was a candidate to become the first conventionally-bred dessert hybrid to be grown commercially, but this promise has not been realized except in Samoa (Daniells, 2006).

'Tropical *Musa* plantain hybrid 548-9' or 'TMP×548-9' (AAAB) – This is a product of the conventional breeding programme of the International Institute of Tropical Agriculture (IITA) in Nigeria. It is a cross between the black Sigatoka-susceptible 'Dwarf French' plantain female parent 'Obino 1'Ewai' (AAB) and the wild diploid banana pollen parent 'Calcutta 4' (AA). This tetraploid hybrid plantain is resistant to black Sigatoka and higher yielding than the female parent.

'Pacovan Ken' (PV4268), 'Vitoria' (PV4281), 'Japira' (PV42-142), and PA42-44 – These are **AAAB** hybrids developed and recommended by EMBRAPA, Brazil, with good yields and resistance to black and yellow Sigatoka and also to Fusarium wilt (Silva *et al.*, 2008).

FHIA hybrids

During approximately 50 years of conventional breeding, FHIA has developed an interesting group of cultivars which are resistant or at least tolerant to Fusarium wilt disease and black Sigatoka, and with good adaptability to different soil and climatic conditions. The most important of these are as follows:

- **Dessert types similar to 'Gros Michel' (AAAA) –** FHIA 17, FHIA 23 and SH 3436.
- **Dessert types similar to 'Pome' (AAAB) –** FHIA 01 or 'Goldfinger' (see above), FHIA 18 and SH 3640 ('Prata Graúda' in Brazil) or AABB types like FHIA 26.
- **Cooking banana types similar to 'Bluggoe' (AAAB) –** FHIA 03 (also good as a dessert type) and FHIA 25.
- **Plantains types (AAAB) –** FHIA 20 and FHIA 21.

- **Speciality bananas –** These include bananas such as SH 4001, a plantain type with a high content of β-carotene.

Despite their undoubted interest, and besides the above-mentioned case of 'Goldfinger' in Samoa, only Cuba (more than 11,000 ha of different FHIA hybrids, including FHIA 03, FHIA 18 and FHIA 23) and more recently Brazil (1134 ha in 2006), cultivate FHIA hybrids commercially (Aguilar Morán, 2006; Daniells, 2006).
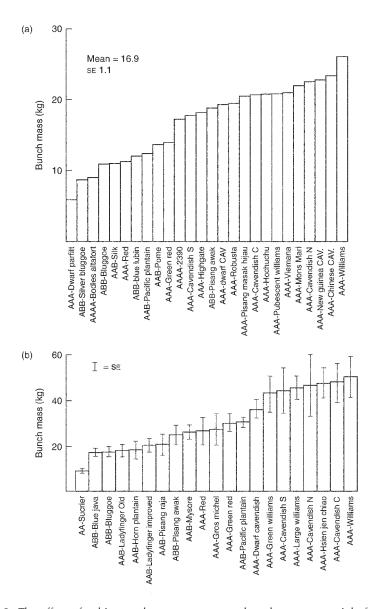
Summary of existing clones

A rough estimate of the total number of existing banana clones was made by Stover and Simmonds (1987). They say an accurate estimate cannot be made since there is a serious shortage of information from Borneo and Indonesia where clones are numerous but not documented. About 130 cultivars have been recognized excluding all synonyms but including some 40 somatic mutants. It is thought that if the bananas of Borneo and Indonesia were better documented, the estimate could increase to 150 primary cultivars, and if it were possible to identify all the presently undetected mutants, there could be 150 of the latter, thus totalling some 300 distinct types. 'Somewhere between 200 and 500' distinct types is the closest one can get to an estimate at this stage. The largest number of primary cultivars is in Papua New Guinea, followed by the Philippines, Malaysia and India. The ratio of pure *M. acuminata* to hybrid types is about two to one over the total range. The main centre of origin of *acuminata* types is Malaysia and that of the hybrid types is India.

Experimental cultivar comparisons

Comprehensive banana cultivar trials involving different genomic groups and ploidy levels were undertaken in Australia by Turner and Hunt (1984) and by Daniells and O'Farrell (1988). The former, in New South Wales, found that AAA bananas of the Cavendish subgroup were the most productive (Fig. 2.3a).

Cultivars from the ABB group used for cooking, yielded only about half that of the Cavendish cultivars. This has important implications when considering the economics of commercializing cooking bananas. 'Pisang Awak' (ABB) was an exception, having a yield similar to 'Dwarf Cavendish' and nearly double that of 'Bluggoe' and other ABB cultivars. The AAB and ABB cultivars had fewer hands per bunch and fingers per hand than the AAA Cavendish subgroup cultivars. 'Williams', the standard commercial cultivar, was significantly superior to all other cultivars and genome groups in respect of yield components. In the North Queensland study by Daniells

Fig. 2.3. The effect of cultivar and genome group on bunch mass potential of a range of banana and plantain cultivars averaged over three cropping cycles. Cultivars are arranged in ascending order of bunch mass. Note that diploids and cultivars containing the *balbisiana* genome are lower-yielding than *acuminata* triploids. Area differences are also indicated, and in this case, cultivars in locality (b) had greater vigour and plant size, which, together with delayed harvest, resulted in bunches twice as large as those in locality (a). Data in (a) redrawn from Turner and Hunt (1984); data in (b) redrawn from Daniells and O'Farrell (1988).

and O'Farrell (1988), precisely the same trend was experienced in which bunch mass, components of bunch mass and harvest index, were all much higher in AAA Cavendish subgroup cultivars than in the diploids or hybrid triploids (Fig. 2.3b). They concluded that none of the cultivars outside the Cavendish subgroup was a satisfactory substitute for the commercial cultivar 'Williams', due to low productivity. However, 'Pacific Plantain' and 'Lady Finger' (both AAB) had some prospects for satisfying an alternative consumer use (cooking and luxury dessert, respectively). Numerous banana/plantain cultivar trials have been conducted by researchers worldwide, and their results are relevant only to the specific climate/soil/cultivar combination of each locality.

BREEDING AND SELECTION

Selection criteria for genetic improvement

The main objectives in breeding bananas and plantains are:

1. Resistance to pests and diseases.
This applies mainly to:

(a) The 'Sigatoka' complex including black Sigatoka (*Mycosphaerella fijiensis* Morelet) and yellow Sigatoka (*Mycosphaerella musicola* Leach).
(b) Fusarium wilt disease, particularly to tropical race 4 (FOC TR4) of *Fusarium oxysporum* f. sp. *cubense* (FOC). This has been the most important effort of breeding programmes in recent years due to the almost total absence of commercial strategies to control this disease effectively.

To a lesser degree resistance breeding applies to:

(c) Viruses, particularly BSV, BBTV and cucumber mosaic virus (CMV). In the case of BSV a major problem for *Musa* breeding is the presence of integrated sequences of this virus in the plant genome. The virus can be activated after stress or tissue culture in hybrids containing the B genome and this inhibits the distribution of B genome cultivars to growers (Escalant and Jain, 2004). Efforts are being made to identify B genome bananas better adapted to drought, and less prone to activation of endogenous BSV (Anon., 2008a).
(d) Banana weevil (*Cosmopolites sordidus*).
(e) Nematodes (especially *Radopholus similis*).
(f) Moko disease, caused by the bacterium *Ralstonia* (*Pseudomonas*) *solanacearum*.

2. Agronomic, postharvest and quality characteristics such as:

    (a) Productivity.
    (b) Fruit quality, addressing finger shape and length, shelf life and market acceptance for dessert bananas, and cooking quality and extended shelf life (for plantains).
    (c) Genetic stability and lack of dwarfism (for tissue culture plants).
    (d) Drought tolerance to reduce dependence on irrigation.
    (e) Resistance to uprooting caused by wind.
    (f) Short ratooning cycles.
    (g) Good sucker production.
    (h) Long bunch peduncle.

For subtropical conditions other specific aspects should be considered including tolerance to low temperature (below 16°C), particularly regarding bunch choking, the response to winter bunch initiation and underpeel discolouration in the fruit.

Unfortunately there has been a certain degree of mutual exclusivity in breeding programmes in that progenies with outstanding disease or pest resistance have mostly failed as horticulturally acceptable cultivars, and vice versa.

The cultivar 'Grand Nain' (*Musa* AAA, Cavendish subgroup) has been proposed as the ideal export dessert banana, regarding horticultural characteristics. Indeed, this cultivar has assumed great importance in the replant programmes of both tropical and subtropical banana-growing countries. The main advantages of 'Grand Nain' are that it has: (i) a relatively short height making it easier to manage and for stability against wind damage; (ii) a shorter ratooning cycle thus increasing yield per annum; (iii) larger bunches and a higher harvest index than other Cavendish cultivars; and (iv) a lower leaf area index permitting higher planting densities. However, 'Grand Nain' is not ideal in all respects because it is not drought or cold tolerant and it is highly susceptible to black Sigatoka, Fusarium wilt race 4, burrowing nematode and BBTV.

Two points are worth noting:

- Currently 'Williams' is matching 'Grand Nain' for popularity since it is more tolerant to drought and cold, its bunch shape is superior for export packing and new, dwarf selections of Williams are now available (see under 'Somaclonal variation' in this chapter).
- With the growing necessity to produce 'environmentally-friendly' cultivars that require minimal pesticide applications, a disease- and pest-tolerant cultivar may be a higher priority than attaining maximum yield and fruit quality.

Breeding improved plantains and cooking bananas has long been neglected in favour of improving commercial bananas for export. However,

two major problems are that all plantain cultivars are highly susceptible to black Sigatoka, and commercially attainable yields are very low compared with dessert bananas (see Fig 2.3). Breeding for resistance to black Sigatoka became a major goal of several plantain breeding programmes, especially at FHIA in Honduras and at IITA in Nigeria, and international funding was provided for this work. Black Sigatoka reached Nigeria as recently as 1986, spreading rapidly, endangering food security and sustainability of plantain production in Africa. Higher yield obtained with some tetraploid plantain hybrids has been attributed to better suckering behaviour compared with their parents, which leads to shorter ratooning cycles. Improved diploids from the FHIA programme have also been used to produce promising new East African cooking banana hybrids (Pillay and Tripathi, 2007).

If the major priority of breeding black Sigatoka-resistant plantains and cooking bananas can be successfully achieved, the other breeding priorities for plantains can be addressed, namely, *Fusarium*, nematode and banana weevil tolerance, genetic stability, improved bunch yield and harvest index, extended shelf life and lastly, shorter ratooning cycles.

A comprehensive review of banana breeding strategies can be seen in the paper by Pillay and Tripathi (2007), but basically five breeding methods are used for banana and plantain improvement, namely: (i) field selection; (ii) conventional breeding; (iii) somaclonal variation; (iv) induced mutation breeding; and (v) genetic engineering.

Field selection

Traditional Cavendish cultivars such as 'Dwarf Cavendish', 'Grand Nain', 'Poyo', 'Valery' and 'Williams', originated through naturally-occurring somatic mutations. The rate of somatic mutation of stable banana clones in the field is very low, in the order of one or two in a million. Recent selection work in the subtropics revealed that the frequency of spontaneous mutations in traditionally-propagated banana fields, not easily identified by obvious morphological differences, is higher than indicated before. A good example of a successful field selection programme is that conducted in the Canary Islands within 'Dwarf Cavendish' plantations, which led to the identification and commercial release of the cultivar 'Gruesa' and other promising selected clones (Cabrera Cabrera and Galán Saúco, 2006).

Evidently the chances of detecting disease resistance in field-selected plants are almost nil, primarily due to the scarce number of somatic mutants occurring in traditionally-propagated banana and plantains. In fact, no plant material of potential interest for disease resistance has been observed so far. The only possible exception may be the identification of 'Dwarf Parfitt' in Australia, which exhibited some *Fusarium* tolerance, but with minimal commercial interest due to its short bunch (Smith *et al.*, 2005).

Conventional breeding

This is based on the production of hybrids from seeds obtained after pollination. There are serious limitations using the conventional method with banana since most modern banana cultivars are sterile. The only way of obtaining hybrids is to use primitive varieties with poor agronomic value but which are able to produce seeds. Even then, only around 0.1% of the seeds are viable. In addition, the process from seed to bunch harvest may take up to 2 years and each plant requires 6 m^2 of space in the field, increasing the operational costs of breeding.

Conventional breeding programmes have been operating since 1922 in Trinidad and 1924 in Jamaica. In 1960 all breeding work was transferred to Jamaica where it continued until 1980 when a lack of funding led to its cessation. Another breeding programme was started in Honduras in 1959 by the United Fruit Company. This continued until 1984 when funding was taken over by FAO (United Nations) for a year and subsequently by USAID (US Agency for International Development) who gave a US$20 million 10-year grant to support the programme. Currently, there is still an ongoing conventional banana breeding programme in Honduras operating under FHIA, which is a private body. Other conventional breeding programmes are being conducted in Guadeloupe (Centre de Coopération Internationale en Recherche Agronomique pour le Développement – CIRAD-FHLOR), Brazil (EMBRAPA), Nigeria (IITA) and India. During the almost 90 years that such breeding work has been carried out, many hybrid progeny have been obtained with commercial interest and resistance to Sigatoka, both for banana, especially at FHIA or EMBRAPA and to a lesser degree for plantain at IITA. Limited commercial success with bananas is explained by the **unusual taste** of the hybrids compared with accepted norms of the Cavendish subgroup. An example of this is the failure of 'FHIA 01'(AAAB) – 'Goldfinger', released in 1989 (Rowe and Rosales, 1993), which otherwise had good agronomic characteristics as well as tolerance to black Sigatoka.

The breeding process at FHIA involves the use of an improved diploid as male parent to pollinate a fertile female triploid resulting in tetraploid progeny which are evaluated and distributed if appropriate. The tetraploid progeny may, if desired, be crossed again with another diploid plant to select triploid progeny coming from the second cross. To avoid problems linked to the utilization of pollen from a tetraploid, triploids can be obtained either through crosses of two diploids (with recombination only in the case of the male parent) or by crosses between a tetraploid and a diploid, both segregating normally.

The potential of conventional breeding to obtain disease resistance is evidently very limited. However, there has been some good progress: (i) in obtaining improved diploids with better agronomic characteristics than the primitive types; and (ii) in taxonomic and cytogenetic studies which may facilitate future long-term success in conventional breeding.

The conventional breeding programmes followed at CIRAD-FHLOR in Guadaloupe, France, or at the Centre de Recherches Régionales sur Bananier et Plantain (CARBAP) in Cameroon, or at IITA (Smith *et al.*, 2005), consist of hybrid production from improved diploids treated with colchicine to obtain tetraploids which are crossed with superior diploids to obtain triploids of dessert bananas. Perhaps the most promising result is the development of the CIRAD selection 'Fhlorban 920' with good-yielding characteristics and a short cycle (Lassoudiere, 2007).

Of particular importance for banana breeding is the fact that hybrids from the major world breeding programmes are being evaluated internationally for both pest and disease resistance and for agronomic improvements. This global evaluation programme has been launched and actively pursued during the past 20 years by the International Network for the Improvement of Banana and Plantain (INIBAP), now called Bioversity International. The recent creation of an international consortium among diverse research centres to sequence the banana genome (Musagenomics, 2010) may impact on all methods for banana improvement including conventional breeding, the only system at present with the potential to produce a cultivar with: (i) good agronomic characteristics; (ii) disease resistance; and (iii) consumer acceptability.

Somaclonal variation

The origin of somaclonal variation in *Musa* shoot tip cultures may be explained by three mechanisms (Novak, 1992). These are: (i) genetic changes already present in the tissue of the explants; (ii) mutagenic action of the tissue culture media; and (iii) variations due to stresses of the tissue culture environment. The first two factors are responsible for genetic changes, whereas the third factor induces morphological changes which revert to the normal characteristic in the field. These variations allow for both non-mutagenic and mutagenic breeding possibilities.

The production of natural mutants during *in vitro* multiplication of banana meristems is called 'somaclonal variation'. Banana meristems propagated through tissue culture may undergo several changes giving rise to the production of 'off-type plants'. With normal, non-irradiated, tissue culture plants, most mutants derive either from a long duration in tissue culture or from an excessive number of cycles (subcultures) in the multiplication phase (Khayat *et al.*, 2004). In contrast with somatic field mutations, the rate of somaclonal variation during micropropagation is much higher, giving considerable scope for selecting a superior mutant clone. The rate of somaclonal variation depends on genotype, propagation media and the number of divisions performed. It may be as high as 70%, although in the best commercial tissue culture laboratories this rate can be lower than

5%. Most frequently-occurring mutations are morphological characteristics like pseudostem height, leaf variegation or mottling, foliar habit (erect or spreading), pseudostem colour, flower persistence or bunch and finger length. By contrast, most somaclonal variants detected in plantains are related to morphology of the inflorescence and fruit (Vuylsteke *et al.*, 1991).

The research institute working most actively in evaluating somaclonal mutants for resistance to FOC is the Taiwan Banana Research Institute (TBRI). Some mutants exhibit lower susceptibility to *Fusarium* and Sigatoka, but lack appropriate agronomic characteristics. The most promising is the cultivar 'Tai Chiao no. 1', moderately resistant to Fusarium wilt, but 10% inferior in yield than normal commercial 'Giant Cavendish', as measured from around 1500 ha planted in Taiwan in the late 1990s. The South African selection 'PKZ' is a somaclonal mutant of 'Goldfinger', with an improved bunch morphology and taste reasonably comparable to Cavendish, although it is very tall, and there are some postharvest disadvantages.

Somaclonal variation is a convenient method for banana improvement due to its simplicity and low cost. Khayat *et al.* (2004) developed a simple laboratory technique to identify height mutants based on different extension responses to gibberellic acid. Recent trials by the same group revealed the potential for selecting elite clones within a relative small *in vitro*-propagated population (300 mats) of 'Grand Nain' derived from a reduced number of selected clones (six). The experiments also showed that clonal selection is clearly influenced by environmental conditions but five clones selected in Western Galilee in the absence of major banana pests and diseases, yielded 18% higher than the standard 'Grand Nain' selection. This clearly illustrates the potential of selecting elite agronomic clones via somaclonal variation.

To take advantage of the well-known fact that *in vitro* propagation increases somaclonal variation, the commercial laboratory Rahan Meristem of Israel, routinely passes its *Musa* AAA 'Grand Nain' selections through tissue culture to identify and evaluate elite new clones. Some elite clones with good agronomic traits produced by Rahan Meristem, include 'Jaffa' and 'Gal', which are planted and evaluated in Central and South America and in other localities (Khayat, 2008). Similarly, from 2001, Du Roi Laboratory in South Africa evaluated in detail every plant in a block of 450 tissue culture plants each of 'Grand Nain' and 'Williams', over three crop cycles. Several elite somaclonal selections were identified of which the best have been named, and new mother blocks of these established using suckers to preserve genetic uniformity and identity. The short 'Williams' selection 'Asdia', has performed very well in international trials in Costa Rica (Chiquita and CORBANA), Honduras (Dole) and Cameroon (CARBAP) compared with local selections, and is currently being commercially distributed in tropical and subtropical localities.

The need to produce large numbers of tissue culture plants to facilitate finding disease-resistant mutants with acceptable agronomic characteristics,

as well as the difficult and time-consuming field testing phase, has made this method unattractive in the past. However, the recently developed double-tray technique (Mak *et al.*, 2004) allows expression of disease symptoms of FOC TR4 on 2-month-old plantlets (10–15 cm tall) under greenhouse conditions with similar reliability to field screening.

Induced mutation breeding

This breeding method is also based on the identification of somaclonal variants, but in this case the frequency of mutations is greatly increased via the use of mutagenic agents like gamma-ray irradiation, neutron bombardments or chemical reagents. Induced mutation breeding enhances the possibility of altering genes by exposing plant parts containing shoot meristems to chemical or physical mutagens. The main advantage of mutation induction in a vegetatively propagated crop is the ability to change one or more undesirable characters in an otherwise outstanding cultivar, without altering the desirable features. This is not possible with conventional breeding. The main disadvantage is that obtaining individuals with resistance to a particular disease is a matter of chance that requires the screening of large numbers of *in vitro*-produced mutant plants. Shoot tips from *in vitro*-grown buds can be irradiated with gamma rays from a ^{60}Co source, and differences in radio-sensitivity are dependent on ploidy level and genome. According to Novak (1992) optimum doses are 25 Gy for diploids, 35 Gy for AAA triploids, 40 Gy for AAB and ABB triploids and 50 Gy for AAAA tetraploids. With the plantain 'Three Hand Plenty' (AAB), the optimal dosage is established as 50–75 Gy (López *et al.*, 2006). Using the chemical mutagen ethylmethane sulfonate (EMS), the optimal mutation response for cultured shoot tips of both diploid and triploid clones was obtained with 0.2% mutagen and 3 h incubation. Other chemicals that have been used include sodium azide and diethylsulphate (Smith *et al.*, 2005).

Mutation breeding with dessert bananas has been conducted in Queensland (Smith *et al.*, 1990) where gamma irradiation of the AAA cultivar 'Dwarf Parfitt' gave rise to several putative mutants. One of them, 'DPM25', exhibited good agronomic characteristics as well as field resistance to *Fusarium* race 4 (although less than 'Dwarf Parfitt'), and this is being tested in the Northern Territory of Australia for tolerance to the more virulent FOC TR4 (Smith *et al.*, 2006).

A similar programme is being conducted jointly by FAO and the International Atomic Energy Agency (IAEA) in Austria where an early-flowering mutant of AAA 'Grand Nain' was produced by irradiation. The mutant (GN-60 Gy/A) was 'fingerprinted' by leaf protein electrophoresis that showed an altered genetic constitution relative to the original GN (Novak *et al.*, 1990). The progeny of this mutant have undergone field testing in

Honduras, Queensland and Malaysia where the plant flowers much earlier than conventional GN (Novak, personal communication, 1993). This mutant of 'Grand Nain' was named 'Novaria' (from Novak and Austria) and it was thought to be relevant in subtropical countries where long cycles due to cold winters are a major disadvantage. However, it has not been extensively planted elsewhere, since its earliness has not been maintained under field conditions. There are, however, some other induced mutants under evaluation which are less susceptible to Sigatoka. They include 'CIBE-1', a somaclonal variant of 'Valery', and the selection 'DPM25' (mentioned above).

Induced mutation breeding as well as any breeding method based on somaclonal variation, requires the testing of large numbers of plantlets to increase chances of success. This can be enhanced, in the case of evaluating disease resistance or environmental stresses, by the development of mass screening methods at the *in vitro* level and further testing of selected plantlets in the greenhouse. But, in addition, treated shoot tips exhibit a high degree of chimerism, which masks the identification of mutated cells from non-mutated cells. It is thus imperative to develop techniques to monitor chimera dissociation after mutagenic treatment, to avoid unexpected results as happened with 'Novaria' (Roux *et al.*, 2004).

The future of induced mutation breeding lies in the use of embryogenic cell suspensions which not only generates large numbers of plants but also avoids chimeras if embryos originate from a single cell (Roux, 2004; Roux *et al.*, 2004). The same authors determined that the optimal irradiation dose for embryogenic cell suspensions of both 'Williams' (AAA) and 'Three Hand Plenty' (AAB plantain), was between 50 and 75 Gy, which is slightly higher than that for shoot tip meristems.

Genetic engineering

This can be defined as the introduction of foreign genes into the plant genome and their expression in a transformed plant (genetically modified organism or GMO – also called a transgenic plant). This can be achieved by transfer of specific genes to morphogenic cell cultures or by protoplast fusion to produce somatic (synthetic) hybrid cells. The possibilities for these genetic modification techniques are extremely exciting as demonstrated in other crops such as potato and tomato, but much work remains to be done in bananas. In principle, this breeding method offers greater potential than conventional routes because: (i) the need to use 'Highgate' or another suitable cultivar in all crosses is bypassed; (ii) the long seed-to-seed cycle is eliminated; (iii) genetic diversity can be increased; (iv) somatic embryos of unicellular origin will minimize chimera problems; (v) the number of potential new genotypes is much higher; (vi) costs are reduced; and (vii) currently available molecular tools can differentiate and identify new genotypes very accurately.

Most of the difficulties mentioned for the different breeding methods can be solved via genetic engineering which also eliminates sterility barriers. The transgenic lines obtained through this process may be further used in breeding programmes or directly utilized by farmers.

Embryogenic suspension cultures to produce somatic embryos of unicellular origin have been successfully produced from various explant types, mostly from immature male flowers (Anon., 2008b). Du Roi Laboratory in South Africa is involved in a cooperative project with the University of Pretoria Biotechnology Department (FABI) in which male flowers from the best elite somaclonal selections are collected and meristems cultured before transferring to FABI for ongoing GMO research. Although embryogenic suspension cultures have been produced from a large number of cultivars, not all the genotypes, particularly plantains, produce male flowers. In addition, a rapid decline in embryogenic potential occurring soon after harvest (Escalant *et al.*, 2004) means this technique is not always appropriate. Other more labour-intensive methods like the 'scalp' method based on using meristem cultures as explants may thus be required. Scalps consist of 3–5 mm explants comprising large numbers of small white meristems with reduced portions of rhizome or leaf tissues. Cultivars with a high initial *in vitro* proliferation rate may produce adequate starting material in standard tissue culture medium, but others may require enriching this medium with different phytohormones (Strosse *et al.*, 2004).

Foreign genes can be transferred to *Musa* via different methods involving either: (i) co-cultivation of cell cultures and tissues with *Agrobacterium tumefaciens*; (ii) protoplast electroporation; or (iii) microprojectile bombardment (see recent revision by Pillay and Tripathi, 2007). Significant advances have been made recently regarding isolation of promoters for use in transformation systems in banana (Smith *et al.*, 2005). For example, work done in Australia where promoters from BBTV satellites S1 and S2 and from the banana vegetative actin gene have been effectively used for expressing genes in transgenic banana plants (Kahl, 2004).

The major emphasis of genetic engineering is directed towards pest and disease resistance, particularly in relation to Panama disease and black Sigatoka. Transgenic lines containing potential resistance genes for various banana viruses and nematodes have already been obtained. Rahan Meristem has developed a technique called 'cytoplasmic resistance' against all banana nematode species, through expressing double-stranded RNA molecules that target nematode genes crucial for completion of the nematode reproductive cycle. Scientists at Rahan have also worked at extending shelf life and metabolic engineering of banana fruits (Khayat, 2008). Australian scientists recently announced the development of a genetically modified banana resistant to Fusarium wilt, at Queensland University of Technology, and field trials were due to start in December 2009 (Anon, 2008a).

HANDLING AND IDENTIFICATION OF BANANA GERMPLASM

Storage and transport of *Musa* germplasm

Long-term *in vitro* germplasm conservation is becoming increasingly important in *Musa* since new genetic material is constantly being discovered or bred, and then fingerprinted. This material has to be stored and then transported to the research and breeding programmes of the world, as required. Obviously seed storage techniques appropriate to many crops do not apply to *Musa*, which has to be stored in clonal form. Field genebanks have been established but these require large inputs of land and labour, and have high risks due to diseases and other hazards. Long-term *in vitro* storage is required but this brings about possible problems such as viability loss over time, genetic instability during *in vitro* storage, and contamination by microorganisms during subculturing. A further problem is that *in vitro* material can still carry viruses and such material cannot be transported to areas free of BBTV, BSV and others, without being indexed first.

These problems and activities are being handled to a large extent by Bioversity International (previously INIBAP). A global *Musa* germplasm exchange system (MGES) was initiated by INIBAP during 1986. Material from all parts of the world, either as conventional suckers or *in vitro*, is received and conserved by the Bioversity International Transit Centre, situated at the Catholic University of Leuven in Belgium, where the International *Musa* Germplasm collection is held. *In vitro* proliferating shoot tips of these plant materials are stored indefinitely under slow-growth conditions at reduced temperature and light, and made available on request to any organization in the world doing research on banana and plantain. In 1988, the International Board for Plant Genetic Resources (IBPGR), now Consultative Group on International Agricultural Research (CGIAR), together with FAO and INIBAP, formulated new guidelines to improve the safety of MGES. All material to be despatched from the Transit Centre in Leuven to the requesting organization must first be sent to virus indexing centres that test for the existence of CMV, BSV and BBTV. The indexing centres are at Montpellier (France) and Brisbane (Australia). For CMV, the enzyme-linked immunosorbent assay (ELISA) method is used, and for BBTV, monoclonal antibodies are used. More recently a DNA probe was developed in Australia to detect BBTV and this is used at the indexing centre to supplement the monoclonal antibody test. After being found virus free at both centres, the required material is multiplied at the Transit Centre and five healthy rooted plantlets are despatched to the requesting body in sealed plastic, gas-permeable bags (Jones and Tezenas du Montcel, 1993).

The *in vitro* storage of clonal *Musa* germplasm material is normally done at low light intensity and at 15°C which necessitates only one subculturing operation/year. However, the problems mentioned earlier in this section

necessitate an alternative storage method. For long-term conservation of banana germplasm, cryopreservation or freeze preservation of meristem cultures in liquid nitrogen at temperatures of -196°C is currently the only practical solution. Initial work on this by Panis *et al.* (1992) was promising, but very time-consuming for *Musa* (Panis, 1995). Presently, up to three cryopreservation protocols for meristem cultures have been developed (Panis *et al.*, 2004):

1. Simple freezing of proliferating meristem cultures.
2. Vitrification of sucrose pre-cultured meristem cultures.
3. Vitrification of apical meristems.

The method of choice will depend mainly on the genome, but approximately 50 banana accessions can be cryopreserved at the Transit Centre per person per year. More than 1100 *Musa* accessions are maintained in this centre, but repositories are also kept in Australia, the Philippines and Taiwan (Smith *et al.*, 2005). In the case of non-organized tissues (i.e. cell suspensions and callus cultures) slow freezing in the presence of cryoprotective agents is still the method of choice.

Complete details about cryopreservation of *Musa* germplasm can be found in a recently published practical manual (Panis and Thinh, 2001).

Biochemical and molecular markers

It is very difficult to study evolution, taxonomy and the extent of genetic diversity in the genus *Musa* by means of morphological, phenological or floral markers. With the wide range of genetic diversity that exists, and the potential for increasing this further by somaclonal variation, mutation breeding and genetic transformation techniques, a more accurate method of identifying banana and plantain cultivars/clones is required. Both biochemical and genetic techniques to accurately identify banana clones ('fingerprinting') have been developed over recent years, creating excellent prospects for new banana cultivars. These techniques will allow for: (i) the accurate identification of species and cultivars; (ii) the determination of evolutionary pathways between clones; (iii) the identification of duplications among accessions in the field and in tissue culture germplasm banks; (iv) the monitoring of genetic stability in micropropagated material for commercial use; and (v) the identification of key markers for use in breeding programmes. Another important advantage of fingerprinting is the ability to police plant patents and to facilitate legal protection of newly-bred cultivars.

Biochemical marker technology was initiated by the use of isozyme polymorphism to differentiate clones. Isozymes of glutamate oxalacetate transaminase (GOT) and malate dehydrogenase (MDH) proved to be reliable

markers for discriminating between *Musa* clones of A and B genomic groups, via the specific banding patterns of the isozyme (Espino and Pimentel, 1990). A different form of the esterase isozyme was found by Novak *et al.* (1990) on the zymogram of a short cycle mutant of 'Grand Nain'. However, other researchers have found that the various isozyme markers are not generally suitable for distinguishing between *Musa* clones of the same genome group and ploidy level.

Restriction fragment length polymorphism (RFLP) analysis is a very useful and sensitive DNA fingerprinting technique to determine close relationships in accessions of similar genome and ploidy level. Kaemmer *et al.* (1992) introduced two new DNA-based fingerprinting techniques to differentiate between different clones within each of the AAA, AAAA, AAB and ABB genomes. One technique, called oligonucleotide fingerprinting, recognizes simple repetitive DNA sequences which are polymorphic in plant genomes. The second technique, called random amplified polymorphic DNA (RAPD) analysis or, alternatively, arbitrarily primed polymerase chain reaction (AP-PCR) is based on the PCR-mediated amplification of arbitrary genomic DNA fragments that may or may not be polymorphic. The authors found that the techniques were somatically stable and did not show differences between individual plants of AAA 'Grand Nain'. However, the techniques could detect bands characteristic of A and B genomes and also differentiated between original and mutant forms of AAA 'Grand Nain'. The DNA markers can be used for 'genetic mapping' techniques in which the segregation of agronomic traits, such as resistance to black Sigatoka, will be identified for breeding programmes.

Although many markers linked to useful characters have been obtained and are utilized in breeding programmes, it is necessary for the success of marker-assisted breeding to define the specific objectives for the use of this technique. Molecular markers in *Musa* breeding can be used for multiple objectives like cultivar identification, studies of phyllogenetic relationships, studies on genome recombination, gene identification, and assisted selection, and are being used to transfer genes among species, but not all serve the same purposes. For example RFLPs of diverse germplasm are useful to study the taxonomy and phyllogeny of *Musa* species, but they are not so suitable to detect differences between more proximal related material, for which PCR and RAPD are more suited. The use of RAPD markers may also be of great value for early detection of dwarf or variegated somaclonal mutants induced during the micropropagation process (Zaffary and Kerbauy, 2006). Recent studies indicate that retrotransposon-derived markers may prove to be very useful for germplasm characterization and cultivar identification. Amplified fragment length polymorphism (AFLP) techniques, on the other hand, may be a potent tool for the molecular breeding of banana and plantains and is now also used together with simple sequence repeats (SSR) microsatellite markers for discriminating fruit parthenocarpy, dwarfism and apical dominance in

edible *Musa*. DNA markers are powerful tools for genetic analysis in *Musa*, but cannot predict progeny performance efficiently (Pillay and Tripathi, 2007). AFLPs and methylation-sensitive amplified polymorphism (MSAP) analysis, based on the differential methylation sensitivity of a pair of isoschizomeric restriction enzymes, have shown good potential to discriminate between closely related cultivars like dwarf and normal-size banana clones at the *in vitro* stage (Engelborghs *et al.*, 2004).

Due to these different applications it is critically importance for banana and plantain breeding programmes to master all these techniques to choose the appropriate method for attaining the desired objective.

Prospects for genetically modified bananas

The benefits for the environment and human health to be obtained through reduced use of pesticides, combined with minimum risks of losing genetic material due to the sterility of commercial banana cultivars, are very important reasons to continue efforts into banana GMO research. This must therefore result in the future utilization of genetically modified bananas in commercial plantings without risks of genetic erosion or damage to the environment and human health. Furthermore, introduced genes may originate from other, wild banana species (cysgenic plants). The earlier-described cooperative effort to map the banana genome by creating the Global *Musa* Genomics Consortium founded by INIBAP in 2001 (INIBAP, 2002) actually integrates 33 institutes from 23 countries. This will permit the localization and activation of candidate cysgenes to express any desirable characteristic, and also to identify promoters for them, thus allowing the production of modified plants using genes only from *Musa* species. Particularly important is the work at Queensland University of Technology to isolate a complete gene sequence from *M. acuminata* ssp. *malaccensis*, a wild diploid banana segregating for resistance to Fusarium wilt disease (FOC race 4). Considerable work towards development of FOC-resistant cysgenic plants at the university is being undertaken (Dale *et al.*, 2004). The product of these methods will not differ from conventional breeding, except that the process is much more rapid. Hopefully, the exclusive use of banana genes in *Musa* GMOs, plus the boost to food security and protection of the environment from pesticides, may eliminate global concerns about transgenic banana plants.

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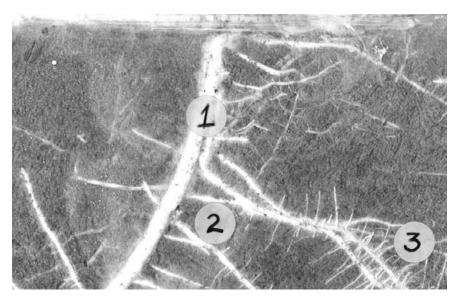
MORPHOLOGICAL CHARACTERISTICS AND PLANT DEVELOPMENT

The banana plant differs considerably from the majority of horticultural plants. It is described as a monocotyledonous, herbaceous, evergreen perennial. It is herbaceous because after fruit harvest the aerial parts die down to the ground and there are no woody components. It is perennial because new suckers grow up from the base of the mother plant to replace aerial parts which have died.

ROOT SYSTEM

In banana plants established vegetatively, the root system is fleshy and adventitious from the beginning. There is no main tap root. Primary roots originate usually in groups of two to four, but normally three, from the surface of the central cylinder within the rhizome. Primary roots are about 5–8 mm in diameter and are white when new and healthy. Later they turn grey or brown before eventually dying. Various reports (Draye *et al.*, 2005) indicate that a healthy rhizome may produce from 200 to 500 primary roots, and this may increase to 1000 if those roots originating from the sucker rhizomes are also included. From each primary root, a system of secondary and tertiary roots develops[1] the latter being progressively thinner and shorter than the primary root (Fig. 3.1). Secondary roots originate in the protoxylem near the root tip and continue to be produced as the primary root extends through the soil. The same applies to tertiary roots emerging from secondaries. For some distance behind the root tip of extending primary and lateral roots, root hairs or feeder roots are produced. These are responsible for most of the water and mineral uptake of the plant. The effectiveness of the plant's uptake potential therefore depends directly on: (i) the number of primary roots produced; and (ii) the vigour of root extension through the soil. In a rhizotron study in the subtropics, Robinson (1987) determined that the functional life of Cavendish subgroup primary roots was from 4 to 6 months and that of secondary and tertiary roots was about 8 weeks and 5 weeks, respectively. Root hairs

Fig. 3.1. Actively growing root system of a banana plant in a rhizotron. (1) Thick primary root originating from the central cylinder of the rhizome, (2) secondary lateral roots, (3) tertiary lateral roots containing root hairs.

remained functional for about 3 weeks before rotting away. Towards flowering, new primary root emergence from the parent rhizome ceases and sucker roots become predominant. However, some roots from the parent rhizome are still functional at harvest as shown by ^{32}P translocation studies.

Root distribution, both horizontally and vertically, is strongly influenced by soil type, compaction and drainage. Heavy, compact or poorly drained soils severely limit root extension and yields are depressed accordingly (Roque Vaquero, 2005). Conversely, lighter soils which are well drained and which have been ploughed to below 500 mm induce more and healthier roots, and there is a good correlation between bunch mass and root volume. A banana adventitious root system is very spreading, and horizontal extension of primary roots can be as far as 5 m although commonly it is 1–2 m. The vertical rootzone is very shallow with about 40% of the root volume in the top 100 mm and 85% in the top 300 mm. The occasional primary root penetrates to below 600 mm. A full discussion of AAA banana root distribution in time and space is given by Draye *et al.* (2005) and Araya (2005). Differences in root distribution are also found between genomes and even between cultivars (Swennen *et al.*, 1986; Blomme, 2000; Blomme *et al.*, 2004; Rodríguez and Lobo, 2008). A detailed study of root development in *Musa* cultivars was made by Swennen *et al.* (1986). They concluded that the proportion of secondary and tertiary roots in plantains was 53 and 46%, compared with 22 and 77%,

respectively, for bananas. They proposed that the relative shortage of tertiary roots, which produce most of the root hairs, was a contributing factor towards poor productivity and rapid yield decline in the plantain group. Plantain root development was also studied by Belalcazar *et al.* (2005) who stress that more research is needed on AAB cultivars.
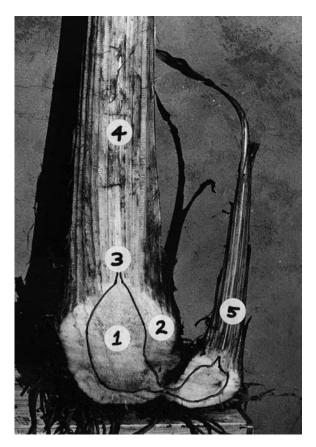
RHIZOME AND SUCKERS

The true stem of the banana plant is partly or wholly underground, and is known technically as a 'tuberous rhizome'. The banana does not have extended horizontal growth like most rhizomes but, nevertheless, suckers grow successively outwards and there is a small amount of horizontal growth before the sucker turns upwards. Thus, it cannot be considered as a true corm and there is much misunderstanding here because certain writers have incorrectly used the term 'corm' quite freely, whereas others have used both terms rhizome and corm together, simply interchanging from one to the other. Finally, others have also used the term 'bulb'. Botanical descriptions of the banana by Cobley (1963), Haarer (1964) and Stover and Simmonds (1987) indicate that the banana stem should be regarded as a short rhizome.

The mature rhizome is about 300 mm in diameter and height although this will vary depending on plant vigour and whether the plant is in a first-cycle or ratoon situation. The rhizome has extremely short internodes covered externally by closely-packed leaf scars. Internally, it is differentiated into the central cylinder and cortex, and the ground tissue is starchy parenchyma (Fig. 3.2). Thus, the rhizome is an important storage organ for sustaining growth of the bunch and the developing sucker. Before flowering, the rhizome contains about 45% of the total dry matter in the plant, but this drops to about 30% at fruit maturity, as reserves are redistributed for fruit growth (see Fig. 5.8).

According to the description by Purseglove (1972) the terminal growing point or meristem of the rhizome is a flattened dome, from the outside of which leaves are formed in spiral succession. Eventually the centre of the meristem is transformed into an inflorescence, and the upper limit of bunch size is set by the size of the meristem at the time of transformation. During leaf production, a vegetative bud is produced 180° opposite each leaf, on the outer surface of the cortex, but only three to five of these buds actually develop into suckers. New roots develop in groups from the outer surface of the central cylinder, and extend through the cortex to emerge through the epidermis of the rhizome (Fig. 3.3).
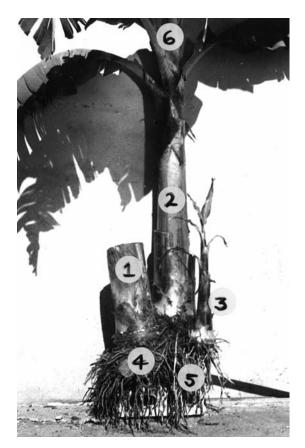
The rhizome should remain completely below the surface of the soil. In cases where the rhizome becomes partly or even wholly exposed, such as commonly found with tissue culture plants that are poorly managed, the entire plant becomes unstable and primary roots dry out after emergence from the exposed rhizome tissue, thus reducing yield potential. This phenomenon

Fig. 3.2. Vertical section through the base of a banana plant. (1) Central cylinder of the rhizome (true stem), (2) cortex of the rhizome, (3) terminal growing point (apical meristem) of the plant, (4) compacted leaf sheaths forming the pseudostem, (5) pseudostem and growing point of a young sword sucker. The position of the growing point, central cylinder and cortex are accentuated with an ink line.
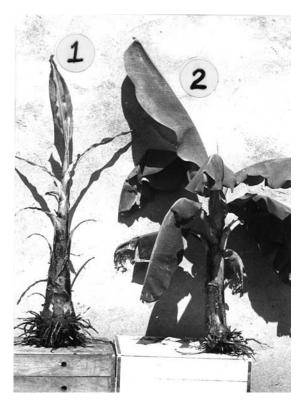
of rhizomes 'climbing out' of the soil to become partially exposed is referred to as 'high mat'.

After harvest, the aerial portions of a banana plant (leaves, pseudostem and fruit stalk) are normally cut down, or else they will die back naturally. The plant propagates itself by producing suckers which are outgrowths of the vegetative buds set on the rhizome during leaf formation (Figs 3.2 and 3.3). In commercial plantings, usually only one of these suckers is selected to grow out and regenerate the plant. Morphologically there are two types of sucker, namely 'sword' suckers which have narrow leaves and a broad rhizome base, and 'water' suckers which have broad leaves and a narrow rhizome base (Fig. 3.4). It is well known that a young sucker is almost entirely dependent

Fig. 3.3. External morphology of a banana plant. (1) Parent pseudostem cut down after harvest, (2) mature pseudostem of ratoon plant prior to flower emergence, (3) newly-selected sword sucker which will develop into the next ratoon pseudostem, (4) parent rhizome with old root system, (5) new adventitious primary roots from ratoon rhizome and its sucker, (6) leaf canopy of ratoon plant. Note: (1), (2) and (3) together form the banana 'mat' and are orientated along the same axis.

on reserves from the parent rhizome, for its initial development (Eckstein and Robinson, 1999). Sword suckers have a strong connection with the mother plant and therefore develop strong thick rhizomes of their own. Leaves are not necessary at this early stage of development, and so they remain as small, thin, bract-like structures. Sword suckers with strong connections usually originate from an axillary bud lower down on the parent rhizome (Fig. 3.2). Water suckers normally develop from shallow buds near the soil surface or even above it, and also from older rhizomes in the 'mat' (planting station). They usually have a thin, weak connection with the parent so that the sucker produces broad leaves very early in an attempt to compensate for the lack

Fig. 3.4. Two common types of suckers growing from the rhizome of a banana plant. (1) Sword sucker with narrow leaves and swollen rhizome, (2) water sucker with broad leaves and underdeveloped rhizome.

of parental support. Such a sucker cannot develop into a strong, vigorous ratoon plant. The proportion of shallow sucker buds is much greater in old plantations than in young ones, therefore the incidence of water suckers is also increased in old plantations.

Sucker development around the parental rhizome is not a random process but they grow out in a specific order, producing up to 15 suckers in a pentagonal pattern (Fig. 3.5). The first five suckers emerge earlier and at shorter time intervals on *in vitro*-produced plants compared with conventional planting material. The reason is that *in vitro* plants have a dense vigorous root system which produces enough phytohormones (cytokinins) to overcome apical dominance and release these suckers at an earlier stage. In a ratoon plantation, the sucker on the side furthest from the harvested mother plant emerges first and grows the fastest. This 'axial sucker' is preferred for follower selection, and it also ensures straight line 'marching' of the plantation to retain the original spatial arrangement. In some cases, particularly in heavy
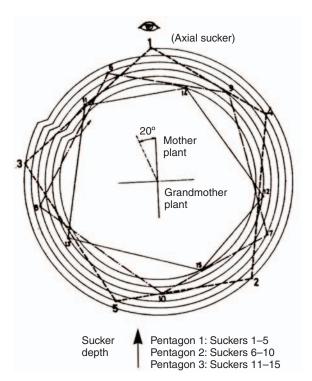
Fig. 3.5. Pentagonal sequence of sucker emergence (after De Langhe, 1961).

soils or unfavourable climatic conditions during sucker emergence, the axial
sucker may not develop well. In such a case it has been recommended to select
the most vigorous sucker nearest to the axial marching line (De Langhe, 1961;
Subra and Guillemot, 1961). Water suckers should never be chosen either
for continuation of the plantation or for removal as planting material (see
Chapter 11).

LEAVES AND PSEUDOSTEM

The first leaves produced from the central meristem of a developing sucker
are scale leaves, followed by narrow sword leaves, and finally broader leaves
with gradually widening laminae until mature, full-sized leaves are produced
after about 6 months. The largest leaves are those emerging prior to flowering.
Leaf sheaths are initially circular, completely enclosing the meristem, but
later the margins of the sheath are forced apart by the growth of new leaves
in the centre of the pseudostem. Leaf sheaths become tightly packed and
thickened to form the 'trunk' or pseudostem of the plant (Fig. 3.2), and the

latter elongates as more leaves emerge, reaching maximum height at flower emergence. Although the mature pseudostem is quite sturdy, and can support a bunch heavier than 50 kg, it is very fleshy, comprising about 95% water. With Cavendish cultivars, artificial propping is usually required to prevent the pseudostem from breaking, which can occur with very heavy bunches and/or strong winds. Pseudostem breakage also depends on the height of the pseudostem itself, which can be as short as 2 m in a plant crop of *Musa* AAA 'Dwarf Cavendish' or as tall as 5 m for a second ratoon crop of *Musa* AAA 'Green Red', and even taller for other cultivars. Pseudostem circumference near ground level can be 1 m on a vigorous ratoon plant, but somewhat less on a mother plant in the first cycle (see Fig. 2.2).
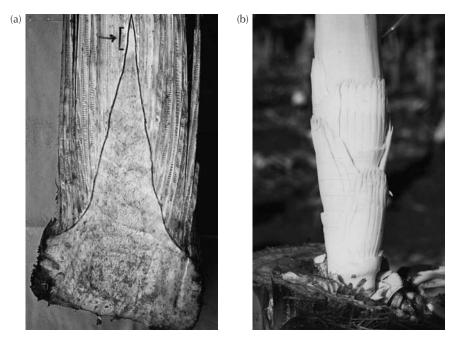
The distal end of the elongating leaf sheath contracts into a narrow petiole of 300–900 mm length depending on cultivar. This is rounded on the underside, channelled above and internally filled with large air pockets. The petiole structure continues into the leaf itself, becoming the midrib which divides the blade into two lamina halves. The mature lamina is entire with a length ranging from 1.5 to 2.8 m in Cavendish cultivars, and a width of 0.7–1.0 m. The lamina often appears shredded into strips between veins because it has very little resistance to transverse tearing in windy conditions (see Fig. 4.10). This is a normal phenomenon but becomes yield-limiting when the strips are less than 50 mm wide (Eckstein *et al.*, 1996). Stomata occur on both surfaces but stomatal density on the abaxial (lower) surface (about 140/mm^2) is about three times that on the adaxial surface. Triploid plants have larger and thicker leaves than diploids.

The lamina develops inside the centre of the pseudostem as a rolled cylinder and while the leaf sheath elongates, the rolled lamina is pushed clear of the leaf crown (the 'cigar' leaf). After emergence it unfolds from the tip taking 6–8 days to open fully. After unfolding, as leaf 1, the lamina is vertical, but as it moves down the leaf profile with further leaf emergence, it gradually becomes more angled, until it is orientated horizontally (about leaf 9). Eventually the petiole collapses, the lamina turns yellow and wilts, and the leaf hangs down against the pseudostem and dies (about leaf 12 or older). While the oldest leaves senesce and die, so younger ones emerge and develop. In the tropics, early leaves produced while the plant is still small may live for about 50 days, but larger leaves produced prior to flower emergence can live progressively longer, up to 150 days. In the cool subtropics, the latter can live for up to 280 days. This ontogenetic longevity, together with the gradual increase in leaf size, ensures that both the number of functional leaves and the total leaf area on the plant, increase progressively until flowering. Thereafter no new leaves emerge, and only leaf senescence takes place. As a general rule there are 10–15 functional leaves on a Cavendish subgroup plant at flower emergence, rather more on a very vigorous plant, and the total leaf area is about 25 m^2. At harvest, there are usually from five to ten functional leaves, rather less if climatic constraints or leaf disease are serious. The total number

of leaves that emerge before the flower is by no means constant but varies widely from as few as 25 to as many as 50. In the Cavendish subgroup, flower emergence occurs after around 24 mature leaves wider than 10 cm have been emitted (Lassoudiere, 2007). Phyllotaxy varies from 1/3 in young suckers to 4/9 in mature plants. Leaf internode length viewed externally along the pseudostem, can vary in the subtropics from about 25 mm for a dwarf cultivar in winter, to 150 mm for a tall cultivar in summer.

INFLORESCENCE AND BUNCH

At a certain critical stage of plant development, the apical growing point at the base of the pseudostem ceases to produce young leaves and starts to develop an inflorescence. The initiation of this transformation is not visible externally nor are there any other characteristic signs of flower initiation. The nature of the flowering stimulus is unknown and remains the subject of considerable speculation. It is unlikely to be temperature or photoperiod related, because flowers are initiated every month of the year in the subtropics, which have wide temperature and photoperiod fluctuations. It is also unlikely to be related to a specific number of leaves because the inflorescence can be initiated after anything from 25 to 50 leaves have been produced. There may be a 'readiness to flower' interaction in which the rhizome must have reached a critical stage of development and a certain 'minimum functional leaf area' must have been produced. The trigger for flower initiation could then be hormonally induced. Recent observations (Hernández *et al.*, 2008) indicate an accumulation of gibberellic acid (GA_3) in the rhizome after emission of leaf 21 (flower initiation at leaf 27) on plantain (AAB cv. Hartón). This may indicate a role of GA_3 in the processes of meristematic change and true stem elongation, but this theory still has to be tested and verified.
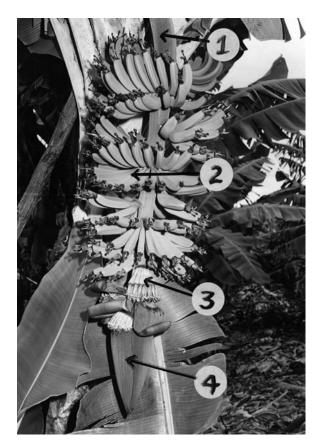
Many studies have been made of the anatomical and morphological changes that occur during flower initiation in banana. These were summarized by Israeli and Blumenfeld (1985) and Stover and Simmonds (1987). The transitional stage begins when the apical meristem rises into a dome and shows intense mitotic activity (Fig. 3.6a). Flower bracts then appear instead of leaves, firstly female bracts followed by male bracts. All bracts enclose axillary, crescent-shaped meristematic cushions from which the flowers differentiate. Male and female flowers are morphologically indistinguishable until the inflorescence is about 120 mm long when it is 1.5 m from the base of the pseudostem. The inflorescence is a complex spike consisting of a stout peduncle on which the flowers are arranged in nodal clusters (Fig. 3.6b), each node comprising normally two rows of flowers set on transverse cushions, and subtended by a bract which protects the young flowers. The flower clusters with their bracts are borne spirally and do not completely encircle the peduncle. The basal (proximal) nodes bear female flowers and there may be from five to 18 of

Fig. 3.6. (a) Apical meristem rising into a point up the pseudostem during reproductive transformation. Flower bracts beginning to appear behind the tip (shown by arrow). (b) Dissected banana inflorescence inside the pseudostem (after flower initiation but before bunch emergence). Note bracts have been cut away from the hands.
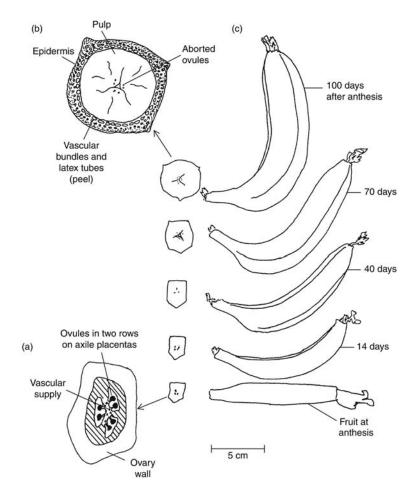
these nodes. The upper (distal) nodes contain male flowers and these remain tightly enclosed in bracts which form a conical structure called the 'bell'. In between the female and male nodes are some nodes containing flowers of an intermediate structure. These are hermaphrodite flowers which have short ovaries and do not develop into edible fruit, but abscise at an early stage after flower emergence (Fig. 3.7).

The developing flower stalk or peduncle extends within the pseudostem until it forces the inflorescence out through the top or 'neck' of the plant, the latter being formed by the petioles of the last few leaves to emerge. A plant containing an inflorescence moving upwards is commonly called a 'pregnant sucker'. There are from ten to 12 leaves still inside the pseudostem at flower initiation, and these leaves continue to emerge while the inflorescence moves upwards. At emergence the inflorescence is initially erect but quickly points downwards due to its own weight, the continued growth of the peduncle and geotropic effects. The bracts rise, exposing double-layered female nodes and tightly packed fruit. In *Musa* AAA cultivars the bracts roll back at their tips (Figs 2.1 and 3.7) and eventually dry out and drop off during early bunch development. As the bracts and flowers in their axils open in

Fig. 3.7. Young Cavendish banana bunch showing fingers in the process of reorientating from a downwards-pointing to an upwards-pointing position. (1) Bunch stalk (peduncle), (2) hands of bananas (female flowers) in double layers arranged spirally around the peduncle, (3) hermaphrodite flowers which usually abscise during bunch development, (4) male flowers tightly enclosed in bracts (bell).

sequence (proximal to distal), the peduncle continues elongating from the meristem in the male bell. The female fruit reorientate themselves from pointing downwards to pointing upwards within a few weeks of inflorescence emergence (Fig. 3.7). This is a negatively geotropic response which is possibly auxin-mediated, and gives rise to curved fruit (Fig. 3.8). In cultivars derived from *M. balbisiana*, this reaction is usually localized in the pedicel and the fruits point upwards but remain more or less straight. In this erect position they continue to swell until harvest. Male flowers remain tightly packed in the bell together with their bracts for the entire bunch life, although in commercial practice the bell is usually broken off to prevent further meristem growth and

Fig. 3.8. Transverse section through (a) young fruit at flower emergence (× 1.5) and (b) mature fruit at harvest (× 0.75) redrawn from Cobley (1963). The diagram showing changes in 'Williams' banana fruit shape and size during development from anthesis to maturity (c) is redrawn from Israeli and Lahav (1986).

elongation of the peduncle axis. Hermaphrodite flowers situated between female flowers and male bell, usually abscise at their base, leaving a callus scar on the peduncle axis.

In commercial terminology the nodal clusters containing double rows of female flowers are called 'hands'. The individual fruits that develop from the female flowers are called 'fingers'. Thus, the edible banana bunch consists of a series of hands of bananas developed from female flowers which are spirally attached to a thick peduncle (Fig. 3.7). The number of hands per bunch and fingers per hand is determined at flower initiation by the number of female

flowers laid down on the transformed meristem. This in turn is controlled by: (i) genome group; (ii) crop cycle; (iii) temperature; (iv) vigour of the plant; and (v) level of management. For AAA Cavendish bananas in the subtropics, flower initiation in the plant crop during winter can result in as few as five or six hands whereas flower initiation on ratoon plants in summer can produce 16 hands or more. Similarly, the number of individual fruit per hand can vary from as few as ten under stress conditions, to over 30 under optimal conditions. As a result of these variations, the mass of a mature Cavendish bunch can vary from 15 to 70 kg. For ratoon bunches of AAA 'Williams', an average number of hands per bunch is 12 and an average number of fingers per hand is 22 giving a mature bunch mass of about 40 kg. The eventual size attained by each finger is a function of conditions prevailing **after** flower initiation, and this is determined by temperature, leaf number and leaf area during bunch development, soil fertility and water supply, and stage of maturity at harvest.

Genome group plays a major role in the potential for number of hands, fingers and bunch mass. With *Musa* AAB 'False Horn' plantain, Swennen and De Langhe (1985) found that seven hands and four fruit per hand were about average for a plant crop, and this gave a bunch mass of about 7.5 kg. Although bunch mass up to 10 kg in the plant crop and 14 kg in the ratoon crop could be achieved, it is clear that AAB Horn plantain has a much lower fruit set potential at flower initiation than AAA 'Williams'.
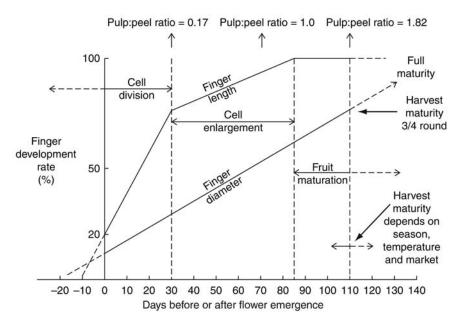
DEVELOPMENT OF THE FRUIT

The banana fruit, despite originating from an inferior ovary, can be botanically characterized as a berry with a pericarp. The exocarp is composed of the epidermis and aerenchyma layer, the mesocarp forms the pulp and the endocarp is limited to the inner epithelium adjacent to the ovarian cavity. In wild, seeded bananas, pollination is essential for fruit development, and the mature fruit contains a mass of hard black seeds, surrounded by a sweetish pulp which develops from the ovary walls and septa. If ovaries of seeded bananas are protected against pollination they do not develop. Edible bananas, on the other hand, are vegetatively parthenocarpic in that they develop a mass of edible pulp without pollination. There are three locules in the ovarian cavity (Fig. 3.8) and most of the pulp develops from the outer edge of the loculus (inner face of the peel where the vascular bundles are situated). Pulp parenchyma also develops from the placental septa. Starch grains are deposited initially in the pulp cells which form in the vicinity of the vascular bundles, and thereafter starch deposition moves centripetally and continues until fruit maturity. The ovules shrivel early but may be recognized in the mature fruit as minute brown flecks embedded in the edible pulp adjoining the central fruit axis (Fig. 3.8).

The seedless nature of most banana fruits is due to specific female sterility genes and a lack of pollen due to triploidy. Thus, while AAA Cavendish subgroup cultivars are highly female sterile, and cannot normally be pollinated successfully, the AAA 'Gros Michel' cultivar gives one or two seeds per bunch if pollinated with diploids. It is therefore not completely female sterile but is regarded as commercially sterile in the absence of pollen. The ABB cultivar 'Pisang Awak', on the other hand, has a rather high degree of female fertility. It will yield edible, seedless fruits if unpollinated, but can bear ten or more seeds per fruit in Malaysia if pollinated by one of the pollen-bearing diploids growing wild or in gardens. In such a case, fruits of this cultivar become inedible.
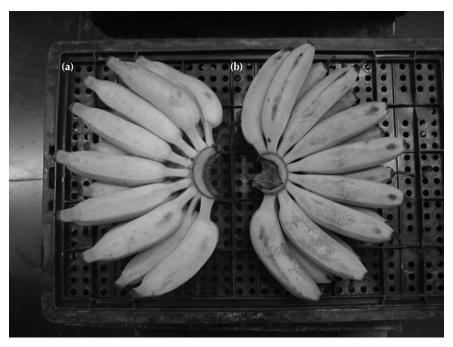
Development of the female fruit falls into two phases, namely, that occurring before inflorescence emergence and that occurring after (Fig. 3.9). The pre-emergence phase is dominated by peel growth; the pulp does not start to develop until fruit reorientate upwards, after emergence. The most rapid development of the inflorescence occurs during the 4–6 weeks prior to emergence. The fruit increases in length rapidly, just before, during and just after inflorescence emergence, suggesting that fruit development is not limited by the process of emergence. Following emergence, the fruit development of AAA (Cavendish subgroup) 'Poyo' was studied in the tropics by Lassoudiere (1978a). There is a rapid increase in finger length for 30 days after which growth in length slows down and is completed in 40–80 days after emergence depending on area and climate. In contrast to finger length, increase in fruit diameter is slower but continuous until harvest. During the phase of rapid finger length increase, average extension rate is 4 mm/day. During the first month after inflorescence emergence, the peel represents 80% of total fruit fresh weight. After this, pulp increases rapidly and pulp:peel ratio increases from 0.17 to 1.82 in 80 days. A fresh pulp:peel ratio of 1.0 is achieved at about 70 days after emergence (Fig. 3.9).

On a cellular level, there are three main stages of growth (Ram *et al.*, 1962). Rapid cell division occurs from 6 weeks before emergence to 4 weeks after emergence. Rapid cell expansion occurs from 4 to 12 weeks after emergence, and fruit maturation from 12 to 15 weeks after emergence. It must be realized that the data of these researchers refer to time periods in the tropics in which fruit are ready for harvest between 85 and 110 days after inflorescence emergence. In the cooler subtropics, fruit development can take up to 210 days before harvest (see Chapter 5 'Flower emergence to harvest duration (E–H)' under 'Phenological Responses'), in which case each component fruit development stage will be correspondingly longer. Furthermore, fruits harvested for commercial dessert purposes are normally cut at 'three-quarters round'. At this stage, the fruit angles are still clearly visible, and the fruit has only about 75% of its potential maximum size and mass. Plantain fruit for home consumption may be kept on the plant for longer in order to increase mass. Fruit development phases are summarized diagrammatically in Fig. 3.9.

Fig. 3.9. Diagrammatic representation of banana fruit development (pre-flowering to harvest) under tropical climatic conditions. This graph is compiled from the data presented by Ram *et al.* (1962) and Lassoudiere (1978a).

The final shape and size of a banana fruit (or hand) should be representative of the cultivar (Fig. 3.10), although there may be an environmental/genetic interaction which determines the eventual size reached at maturity. AAB Horn plantain produces the largest fruits, up to 400 mm long and 0.5 kg in mass. Edible diploids such as AA 'Sucrier' have the smallest fruits, from 60 to 100 mm long. AAA Cavendish subgroup bananas are intermediate, although there are also large fruit size differences within this subgroup such as between 'Dwarf Cavendish' and 'Poyo'. There is also a genetic variability in fruit size within bunches of the same cultivar. Usually, fruit from the distal (bottom) hand are 30–40% smaller than those from the proximal hand. Fruit from the inner whorl of a hand can be 15% smaller than those from the outer whorl. Achieving maximum uniformity of fruit size within a bunch is very important commercially, thus cultivars with a cylindrical bunch shape like 'Williams' or 'Grand Nain' are more sought after than 'Dwarf Cavendish' which has a conical bunch producing smaller distal hands. Also, multinational companies normally remove the (distal) bottom two or three hands early in bunch development in order to maximize finger length on the larger proximal hands.

Fig. 3.10. Morphological differences between (a) a hand of AAB 'Prata Anã and (b) AAA 'Dwarf Cavendish'. Note the longer, thinner pedicels and pronounced knob at the distal end with AAB fruit.

NOTE

1. The term 'primary root' usually refers to the tap root which is derived from the radicle of an embryo. In the banana, roots arising from the rhizome are adventitious. Therefore, in this description, the term 'primary roots' actually refers to first-order adventitious roots, and 'secondary roots' to second-order adventitious roots.

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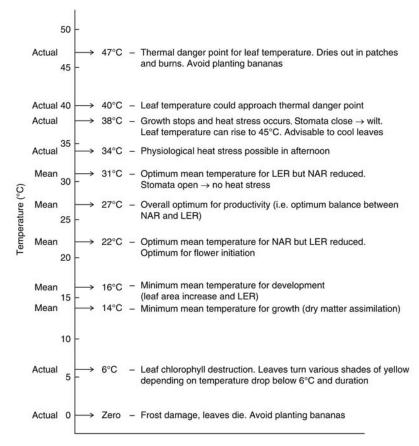
CLIMATIC REQUIREMENTS AND PROBLEMS

GENERAL CLIMATIC REQUIREMENTS

The major banana-growing areas of the world are geographically situated between the Equator and latitudes 20°N and 20°S. Climatic conditions in these areas are mainly tropical, with comparatively small temperature fluctuations from day to night and from summer to winter. The banana-growing areas of the subtropics are situated between 20° and 30° north or south of the Equator. The main climatic characteristics in the subtropics are: (i) wide temperature fluctuations between day and night and between summer and winter; (ii) high and low temperature extremes in summer and winter, respectively; and (c) low annual rainfall which is also poorly distributed.

Where water is not limiting, the rate of banana growth and development is determined by temperature. There is some confusion in the literature as to whether daily means, mean minima and maxima, or actual temperatures are being referred to in correlations with growth. However, the general consensus on mean daily temperature thresholds (i.e. (maximum + minimum) ÷ 2) for banana growth and development is that: (i) new leaf emergence stops below 16°C in the subtropics (corresponding mean minimum = 11°C); (ii) growth (dry matter assimilation) stops below 14°C (corresponding mean minimum = 9°C); (iii) optimum temperature for growth and for flower initiation is 22°C; and (iv) optimum for leaf emergence rate is about 31°C (Turner and Lahav, 1983; Robinson and Anderson, 1991). The overall mean temperature for optimum balance between growth (assimilation) and development (leaf emergence rate) is about 27°C. Various critical temperature thresholds for banana growth and development are shown in Fig. 4.1. These thresholds form the basis of estimating production potential and establishing limiting factors to banana production in different climatic regions, on the basis of temperature alone.

After temperature, rainfall determines where bananas and plantains may be grown. The crop has a high water demand, and 25 mm/week is regarded as the minimum for satisfactory growth. An average annual rainfall

Fig. 4.1. Temperature thresholds for banana growth and development. LER = leaf emergence rate; NAR = net assimilation rate. Actual = the specific temperature at which either heat or cold damage is induced. Mean = mean monthly temperatures related to various growth and development processes (i.e. (mean maximum + mean minimum) ÷ 2). Data taken from Taylor and Sexton (1972), Samson (1980), Turner and Lahav (1983) and Robinson and Anderson (1991).

of 2000–2500 mm evenly distributed throughout the year is considered satisfactory. In some parts of the humid tropics, water requirements of bananas are supplied totally from rainfall, and no irrigation is required. However, in the dry tropics and subtropics, supplementary irrigation is essential to produce bananas economically, and in Mediterranean areas with dry summers, virtually the entire water requirement is supplied from irrigation.

To conclude on general climatic requirements, banana is primarily a crop of the humid tropical lowlands which are areas characterized by less than

10° latitude, less than 100 m altitude, not less than 19°C mean minimum temperature and more than 100 mm rain every month. In the humid tropics, mean temperatures are generally within the optimum growth range of 22–31°C throughout the year; there is no evaporative stress on the plant; no chilling occurs; and irrigation is not necessary to improve production. In the cool subtropics or semi-arid tropics, however, there are usually periods during the year when either cold winter temperatures or excessive heat stress limit production potential. Furthermore, rainfall is low, erratic and seasonal, and must be supplemented by irrigation for maximum production.

TEMPERATURE COMPARISON BETWEEN FOUR BANANA-GROWING AREAS
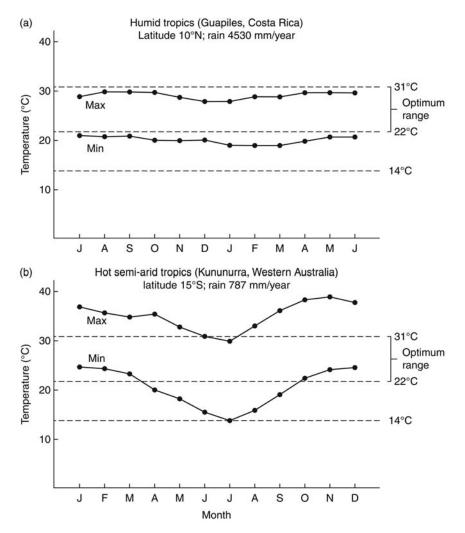
In order to place temperature requirements and responses of the banana plant into perspective, four distinct zones have been chosen which differ widely in their climates, but in which bananas are successfully grown commercially. The four zones to be analysed in relation to Fig. 4.1 are humid tropics (Guapiles, Costa Rica), hot, semi-arid tropics (Kununurra, Western Australia), warm, arid subtropics (Carnarvon, Western Australia) and cool subtropics (Kiepersol, South Africa).

The humid tropics

The mean monthly maxima and minima for Guapiles, Costa Rica (northern hemisphere), are shown in Fig. 4.2a, in relation to lowest daily mean temperature for growth (14°C), optimum daily mean temperature for growth and flower initiation (22°C) and optimum daily mean temperature for leaf area increment (31°C). On the basis of temperature alone, conditions for optimum production exist throughout the year in the humid tropics. Both seasonal and diurnal variations in temperature are minimal and overall mean temperatures achieve the ideal balance between processes of assimilation and leaf area increment. Extremes of temperature are also narrow, resulting in an absence of either chilling or heat stress injury. However, as seen later in this chapter, temperature is not the only factor determining suitability, and there are many climatic disadvantages in the humid tropics.

The hot, semi-arid tropics

The mean monthly maxima and minima at Kununurra, Western Australia (southern hemisphere), are shown in Fig. 4.2b. As in the humid tropics, the average of maximum and minimum temperatures lies within the

Fig. 4.2. Comparison of long-term mean monthly maximum and minimum temperatures in (a) the humid tropics and (b) the hot, semi-arid tropics, in relation to threshold temperatures for banana growth and development. 14°C = daily mean temperature at which growth ceases; 22°C = optimum daily mean temperature for flower initiation and net assimilation rate; 31°C = optimum daily mean temperature for leaf emergence rate.

optimum productivity range for banana throughout the year. However, both seasonal and diurnal ranges of temperatures are much wider than in the humid tropics, resulting in some maxima and minima lying well outside the optimum productivity range. Mean maxima during summer months

of October–January coincide with the temperature at which growth ceases in banana (38°C). Assuming that some daily maxima are well in excess of 40°C, the negative effect on assimilation could be quite serious at these times, while respiratory losses of dry matter could also be very high. However, the maximum temperature itself is of short duration and much of each summer day (the mornings) would be favourable for growth and leaf area increment. The entire summer temperature regime appears to favour leaf emergence rate and cycling of the banana much more than it does net assimilation rate and flower initiation. Flowers which are initiated from September to April result in small bunches, since mean temperatures then are much higher than the optimum for flower initiation.
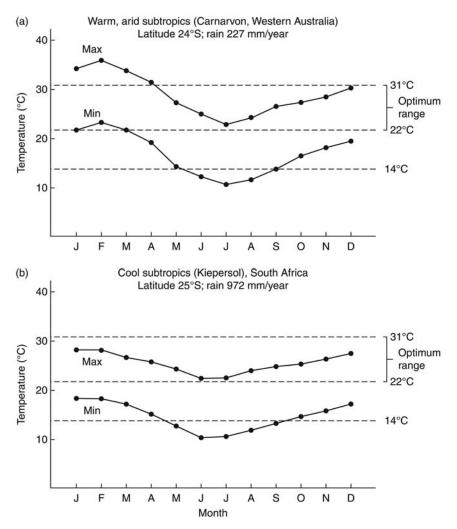
Winter months of May–August at Kununurra appear to be very suitable for net assimilation rate and flower initiation. Considerable dry matter would be accumulated during these months and bunches initiated then are much larger. Leaf emergence rate declines somewhat during winter but not substantially. A distinct advantage in this climate is the almost complete absence of low temperature phenomena that reduce production potential in the cool subtropics.

The warm, arid subtropics

Mean monthly maxima and minima at Carnarvon, Western Australia, are shown in Fig. 4.3a. The averages of monthly maxima and minima lie within the optimum productivity range during summer, autumn and part of spring (i.e. for 8 months of the year). During winter and early spring, the average of monthly maxima and minima fall below the optimum for net assimilation rate, and a pronounced growth and development check occurs at this time of year.

Seasonal extremes of mean minima and maxima are wide at Carnarvon (11°C and 36°C, respectively). This implies that seasonal extremes of absolute temperature are likely to be conducive to heat stress in summer and chilling injury or other cold temperature phenomena in winter. Overall, average yields achieved at Carnarvon (46 t/ha) compared with those at Kununurra (40 t/ha) suggest that bananas benefit more by avoiding the consistently higher summer temperatures prevalent at Kununurra. The winter growth check at Carnarvon is evidently less serious in terms of overall yield potential.

Similar, but less extreme temperatures exist in the Canary Islands. With an annual average temperature of 20.2°C, and winter and summer extremes of 10 and 31.3°C, respectively, very high yields have been reported for bananas. Although numerous microclimates exist in the islands, temperatures seldom go below 14°C in winter or above 30°C in summer, which explains the lack of either chilling or heat stress problems. There are also benefits obtained from protected cultivation (see Chapter 8) which enable the banana to flourish under ideal growing conditions (Galán Saúco, 1992).

Fig. 4.3. Comparison of long-term mean monthly maximum and minimum temperatures in (a) the warm, arid subtropics, and (b) the cool subtropics, in relation to threshold temperatures for banana growth and development.

The cool subtropics

Mean monthly maxima and minima at Kiepersol, South Africa, are illustrated in Fig. 4.3b. Here, overall monthly means lie below the 22°C lower optimum for 8 months of the year and only just above this lower optimum for the other 4 months. On balance, therefore, Kiepersol is considered to be cool for bananas. In reality what happens here is that leaf emergence rate is low, crop cycles are long

and several low temperature phenomena occur such as choke throat, November dump ('May bunch' in the northern hemisphere) underpeel discolouration (UPD), growth cessation and leaf yellowing (see 'Specific Problems due to Climate' in this chapter). On the positive side, heat stress hardly ever occurs, plants are very large, and all flowers initiated from December to May (summer/autumn months) produce very large bunches on these large plants due to ideal prevailing temperatures for flower initiation and assimilation.

Further evidence that Kiepersol can be considered 'too cool' overall for banana growth and development, is obtained from the heat unit concept. Daily heat units above 14°C were cumulated for each month i.e. Σ [(daily Tmax + daily Tmin /2)–14]. Maximum cumulated heat units during any 1 month was 278 in January. It is generally accepted that the optimum mean temperature for bananas is 27°C, which is equivalent to 395 heat units per month above 14°C. Thus, even the hottest month at Kiepersol is below the thermal optimum for bananas. However, productivity achieved in this locality is still comparatively high (see Table 5.1), indicating the wide ecological adaptability of the banana plant. Even in cooler, Mediterranean environments like Israel (around latitude 33°N), where frost occasionally occurs, bananas are commercially cultivated with high yields. Possible reasons for this climatic 'flexibility' of the banana are discussed in the following section, and also in the phenological comparisons in Chapter 5.

IMPLICATIONS OF RAINFALL

From the discussion in the preceding section it is clear that temperatures are more favourable for banana growth and development in the humid tropics than in the cool subtropics. However, rainfall, or the lack of it, has severe implications for physiological, pathological and management aspects of growing the crop. If we take the four banana zones once again, it is evident that annual rainfall differs greatly (Guapiles 4530, Kununurra 787, Carnarvon 227 and Kiepersol 972 mm/year). In Guapiles, up to 500 mm can fall in the wettest months and an average of 200 mm falls in the driest month. Irrigation is unnecessary and, on the contrary, elaborate drainage structures have to be installed to disperse excess rainfall and prevent waterlogging. The soil is nearly always at field capacity, in addition to which relative humidity is high and conditions are mostly cloudy which further reduces evaporative demand on the plant.

At the other rainfall extreme, 227 mm of annual precipitation in Carnarvon is concentrated into the winter months, when growth potential is minimal. In the dry and hot summer climate, virtually no rain falls, relative humidity is low and evaporation rate can rise to an average of 11 mm/day in December and January. The entire water demand is supplied by irrigation, and the key to successful banana production is found in scientific irrigation

scheduling, frequent irrigation cycles and access to large volumes of good quality water. In this environment, evaporative demand frequently exceeds the plant's ability to extract water from the soil at field capacity, translocate it through the plant and into the aerial environment by transpiration. Such a situation causes the plant to lose turgor and enter a 'temporary wilt' phase. This is a physiological problem which seldom develops in the humid tropics or the cool subtropics. In the latter, rainfall provides a portion of the water requirements of bananas but there is overwhelming experimental evidence to support the necessity for supplementary irrigation. Efficient irrigation is often regarded as the single most important factor boosting production potential in subtropical and Mediterranean areas.

It could be generally argued that banana-growing potential in the humid tropics is vastly superior to that in the cool subtropics, since temperatures are ideal and sufficient rain falls to nullify heat stress and the need for irrigation systems. Ironically, it is this constant and heavy rainfall that causes severe constraints to banana production in the humid tropics.

These constraints are as follows:

1. With up to 4000 mm/year rainfall, conditions are predominantly overcast, allowing an average of 3–5 h of sunshine/day. Photosynthesis potential is therefore greatly reduced in comparison with the cool subtropics which average 6–8 h of sunshine/day and Mediterranean regions which average 10–12 h in summer (see Chapter 5 'Photosynthetically active radiation (PAR)' section under 'Physiological Responses').

2. Soils are a major problem due to the hot, humid climate and high rainfall. They are highly leached, with low pH, low cation exchange capacity and rapid breakdown of organic matter. Nutrients are always in low supply and deficiencies of nitrogen, magnesium and boron are common.

3. A complex system of primary, secondary and tertiary drains must be installed to carry off excess water, lower the water table and prevent waterlogging.

4. Since there is no irrigation there can be no fertigation, thus fertilizers have to be applied by hand. This operation must be done up to eight times annually due to the high leaching rate. Not only is hand fertilization labour-intensive, but larger quantities of fertilizer have to be applied to counteract leaching losses of up to 50% of applied nutrients.

The above-mentioned problems relating to soils, organic matter, drainage, leaching and fertilization are uncommon in subtropical and semi-arid localities where rainfall is much less and water and fertilizers are retained within the rootzone by controlled irrigation scheduling.

5. The high humidity and high rainfall lead to rapid infection by the virulent leaf disease black leaf streak or black Sigatoka (*M. fijiensis*). Until such time as a resistant cultivar is commercially recommended, this disease will cost the banana industry millions of dollars in lost production and/or in chemical inputs to control

the disease. In the subtropics, long dry spells do not favour the epidemiological cycle of the black Sigatoka pathogen, and therefore no production is lost from this cause and control measures are unnecessary (the less virulent yellow Sigatoka does occur in the subtropics but chemical control is usually unnecessary).

Although a higher yield potential theoretically exists in the humid tropics than in subtropical or semi-arid production areas, based on temperature, gross margin analysis of commercial production shows a severely reduced economic advantage in the tropics due to: (i) rain-induced problems affecting yields; and (ii) expensive input costs to counteract these problems.

Seasonal influences of temperature on development cycles of the banana plant in the tropics and subtropics are discussed in more detail in Chapter 5 ('Phenological Responses'). The specific effects of climatic factors (temperature, vapour pressure deficit, light, water stress and wind) on the assimilation potential of banana plants are also dealt with in Chapter 5 ('Physiological Responses').

SPECIFIC PROBLEMS DUE TO CLIMATE

As discussed, growing temperatures for bananas in the humid tropics are mostly optimal, with only narrow variations seasonally or diurnally. This means there is an almost complete absence of heat stress on the one hand, and chilling-related problems on the other. Physiological problems typical of colder subtropical climates, such as choke throat, winter flower initiation, underpeel discolouration (UPD) and growth cessation, do not occur in the humid tropics. Furthermore, the general lack of wind, dust, storms, hail or frost in the humid tropics means there are few climate-induced plantation disasters similar to those frequently occurring in the subtropics (except for occasional floods and cyclones). This section on specific problems therefore applies mainly to banana-growing regions outside the humid tropics.[1]

The effect of climatic hazards in the subtropics, semi-arid tropics, or Mediterranean regions, can range from barely noticeable to complete devastation, depending on plantation site and severity of the climatic condition. Quite clearly, the choice of plantation site is vitally important in reducing the impact of these climatic hazards, and this is more fully discussed in Chapter 6 ('Site Selection').

Problems due to cold weather

Frost
Bananas cannot be grown in areas where frost occurs regularly. However, many plantations in the subtropics experience occasional frost damage. Frost

rapidly kills banana leaves and only a few minutes below 0°C during a night are sufficient to ruin a plantation (Fig. 4.4). Frosted leaves rapidly turn brown.

To manage a plantation that has had severe frost damage, the banana farmer must realize that a minimum of four to six healthy leaves are required to fill a young banana bunch (see Fig. 11.6). Each damaged plant must therefore be treated on its merits as follows:

1. A bunch that is nearly mature when frost occurs, can be left on the plant for 1–2 weeks since it may fill out enough from residual reserves in the pseudostem and rhizome to render all or part of it marketable. Protection against sunburn will be necessary.

2. A bunch that is newly emerged or up to 50% developed when the frost occurred, will not fill enough to become marketable, therefore it must be removed and the pseudostem cut off just below the damaged leaf canopy. Nutrients, reserves and water in the cut pseudostem and rhizome will benefit the new follower considerably. The extra light will also enhance sucker growth. This cutting down of the damaged canopy should be delayed until the danger of a follow-up frost is averted.

3. A plant that has not yet flowered should be left until it has produced a bunch. At flowering, the number of functional leaves emerging after the frost should be counted. If fewer than four, the pseudostem should be cut as described in (2) above. If four or more leaves are produced before flowering, the bunch can be

Fig.4.4. Complete dieback of a banana leaf canopy following frost damage during a cold night in the subtropics.

left to develop. However, a bunch developing with only four or five leaves will be smaller than normal, and with a reduced 'green life'.

4. A young plant damaged by frost may continue to grow normally in spring except that flowering will be delayed compared with an undamaged plant.

Winter chill on leaves

These symptoms are seldom seen in the tropics. At winter night temperatures between 6 and 0°C, leaves become progressively more yellow due to chilling and chlorophyll destruction. The degree of leaf chilling depends on actual temperature and the duration of chilling conditions. Although damaged leaves are not killed, patches may become necrotic and physiological efficiency reduced. Such damaged leaves do not recover. Winter yellowing is more pronounced in cooler localities or at the bottom of slopes. In areas with mean monthly minima of 11°C, the absolute minimum will only occasionally fall below 6°C and visible damage will be slight. However, where the mean monthly minimum drops to 8°C, absolute minima can be as low as 3 or 4°C, resulting in severe yellowing on most of the leaf area. With young *in vitro* plants growing through a cold winter, the youngest, tender leaves may die back impeding emergence of new leaves during warmer spring temperatures. Eventually, new leaves form a second pseudostem which pushes out, causing blackened and damaged winter leaves to break away from the plant (Robinson, 2006).

Growth cessation
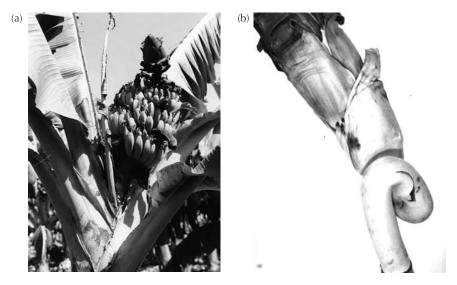
This occurs when the mean monthly minimum temperature falls to 9°C or the mean monthly temperature (i.e. (maximum + minimum) ÷ 2) falls to 14°C. There is no visible damage to the plant, except that negligible dry matter assimilation or leaf emergence takes place and the plant remains quiescent. Extension root growth ceases and existing root hairs die back with no new ones being formed. Absorption of water and nutrients is severely restricted and the plant takes on a wilted look during the day, with sharply folded leaves. Leaf emergence rate drops to between zero and 0.5 leaves/month compared with the normal four to five/month in summer or during every month in the tropics. The period of growth cessation is usually from June to August in the southern hemisphere and from December to February in the northern hemisphere, causing an extension to the total cycle time of the plant which in turn leads to a reduction in annual yield (refer to 'Planting to harvest duration (P–H)' in Chapter 5).

Choke throat

Choke throat in dessert bananas is a well-known phenomenon in high-latitude banana-growing areas. It occurs during winter months when normal leaf emergence is restricted by low temperatures. An inflorescence trying to emerge through the top of the pseudostem is inhibited by leaf petioles with short

internodes which have become compacted and congested at the opening. This problem is most severe with AAA 'Dwarf Cavendish' in which leaves easily become 'rosetted' and compacted at the top of the pseudostem during cold weather. It seldom happens with tall Cavendish cultivars unless temperatures are very low, or due to other production constraints such as drought, flooding or excessive and continuous cloudiness.

There are different degrees of choke throat. In its mildest form, the bunch is thrown clear of the pseudostem but tends to orientate itself horizontally rather than hang vertically, and the peduncle is shorter than usual. In a more severe case, the bunch only just emerges through the pseudostem opening but points directly upwards (Fig. 4.5a). The bunch remains stunted and fingers are directly exposed to radiation burn. Such a bunch is useless and the plant should be cut down. In its most severe form the bunch cannot force its way through the 'throat' of the plant and the elongating peduncle buckles to an 'S' shape within the pseudostem (Fig. 4.5b). The opening bunch may then burst the pseudostem and emerge sideways but is severely damaged in the process.

Under ideal growing conditions, the bunch easily emerges through the 'throat' of the plant which is more flexible due to wider leaf internodes. Growers with 'Dwarf Cavendish' in cool areas should ensure that planting time will not induce peak flower emergence during winter.

(a)   (b)

Fig. 4.5. (a) A choked 'Dwarf Cavendish' bunch in winter which cannot emerge and hang normally due to short internodes and leaf petioles compacted around the 'throat'. The bunch points directly upwards. (b) An extreme case of choke throat in which growth of the peduncle could not force the bunch out, and the peduncle has buckled into an 'S' shape.

Winter flower initiation

This leads to the phenomenon known colloquially as 'November dump' in the southern hemisphere, synonymous with 'May bunch' in the northern hemisphere. It occurs when flower initiation inside the pseudostem coincides with very low night temperatures during midwinter. Bunches initiated at this time emerge from the plant from mid-October to mid-November (southern hemisphere) or mid-April to mid-May (northern hemisphere), some 3–4 months after initiation. Bunches are small and malformed. Fewer hands than normal are set, and individual fingers are variable in size and may be cracked, twisted, joined together, showing a pronounced outgrowth or cigar-end symptom at the distal end, or otherwise adversely affected (Fig. 4.6). Both gross yield and the proportion of first-grade fruit from such bunches decrease drastically. The problem affects all Cavendish subgroup bananas equally but it does not occur in the tropics.

The optimum mean temperature for flower initiation in the banana is about 22°C. When the mean monthly night temperature drops to 10°C and

Fig. 4.6. An unmarketable 'Williams' banana bunch affected with severe 'November dump' symptoms (winter initiation). This effect is caused by cold temperatures at flower initiation. Very few hands are produced and individual fingers are stunted, deformed or split and they develop a protuberance at the distal end. Note the long peduncle and predominance of hermaphrodite hands at the end of the affected bunch.

lower (absolute minima 3–5°C), flower initiation will be strongly influenced by the cold, resulting in a greater or lesser degree of November dump. At Kiepersol, South Africa, it was found that plant crop 'Williams' flowering in August had a mean bunch mass of 37.3 kg compared with 24.2 kg for plants flowering 3 months later in November. Hands per bunch were reduced respectively from 9.3 to 7.2. Mean minimum temperatures during the initiation months were 15.2 and 9.9°C, respectively (Robinson, 1982). Ratoon plants are not as badly affected as parent plants because the growing point in the thick ratoon pseudostem is about 2.5°C warmer than that in the thin parent pseudostem. At Kiepersol, (southern hemisphere) planting in September or in December/January will usually avoid winter initiation, whereas October or November planting will be affected to a greater or lesser degree, depending on the duration and severity of low winter temperatures.

Underpeel discolouration (UPD)

UPD consists of a reddish-brown streaking in the vascular tissue just below the epidermis of the fruit. It is visible in green fruit only by peeling back the epidermis with a knife (Fig. 4.7). UPD usually indicates the fruit has been subjected to chilling temperatures at some stage. Fruit with severe UPD will not ripen bright yellow, but will have a dull grey/yellow colour due to the brown streaks in the peel masking the normal bright yellow colour. In local

Fig. 4.7. UPD under the epidermis of a mature green banana fruit. This is caused by cold temperatures during bunch development. The latex has coagulated in the vascular tissue, and phenols have been oxidized causing brown streaks. Such fruits ripen to a dull grey-yellow instead of a bright yellow colour.

subtropical markets, such fruit tend to be accepted as normal, but commercial export markets will not accept these dull grey/yellow fruit. Eating quality is usually not affected, but the occurrence and appearance of UPD is the main reason why fruit from the cold subtropics cannot be exported to European markets.

UPD from chilling may occur in the field when night temperatures drop below 13°C for several hours, which is a common occurrence in subtropical banana areas. All exposed fruit are affected but fruit approaching harvest stage are the most severely affected. Damage can also occur during postharvest operations (pre-cooling or fruit transport) if the temperature drops below 13°C. Following exposure to chilling temperatures the symptoms appear about 48 h later and they are due to latex coagulation and subsequent browning of the latex by phenolic oxidation. The problem is irreversible.
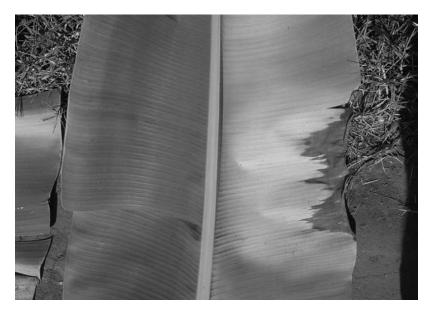
Excessively high temperatures can also cause the same symptoms in fruit. In the semi-arid tropics such as Kununurra, Western Australia, UPD frequently occurs due to maximum temperatures regularly reaching over 40°C. It will only occasionally occur in the humid tropics, when rainfall is lower allowing increased sunshine hours and higher maximum temperatures.

Problems due to hot weather

Hot weather problems are not only limited to the subtropics where high temperature extremes are common, but they sometimes occur in the dry tropics, and even in the humid tropics, when dry periods permit very high temperatures to occur.[2]

Winter leaf sunburn

This phenomenon occurs frequently in subtropical banana areas and should not be confused with 'winter chill on leaves' described earlier. Winter sunburn occurs due to four main factors, namely: (i) high daytime temperatures of more than 30°C; (ii) low relative humidity of less than 25%; (iii) high light intensity; and (iv) a depleted feeder root system due to cold temperature growth cessation. High temperature and low relative humidity combine to produce a vapour pressure deficit (VPD) of more than 35 hPa, which imposes a severe evaporative stress on plants with a depleted root system. The plant responds by wilting very quickly and the leaf temperature rises by 5°C or more above ambient due to a lack of transpiration. With high light intensity the upper surface of the leaf is bleached by the sun to a pale yellow colour, which is apparently a photo-oxidation reaction. This type of damage is easily recognized because it only occurs on the western half of the lamina which is directly exposed to the hot afternoon sun (Fig. 4.8). The eastern half of the lamina, although wilted, remains green due to lower light intensity during periods of high VPD.

Fig. 4.8. Typical leaf symptoms on a banana plant that has been subjected to winter radiation damage. Leaves on wilted plants bleach to a yellow colour, culminating in necrosis, but this only occurs on the western side (right) which is exposed to direct afternoon radiation under conditions of high VPD. The eastern side (left) remains green.

Under normal summer conditions, the humidity is higher and the active, efficient root system allows transpiration to occur normally which cools the leaf and prevents burning under high light intensity.

Summer heat stress

Under normal summer conditions of up to 33°C and with well-watered soil, the banana plant functions efficiently and does not suffer excessive wilting or heat stress. However, if the ambient temperature rises to 38°C, then a 'temporary wilt' is initiated in which the evaporative demand and transpiration loss exceeds the ability of the plant to extract water from a soil at field capacity. The plant wilts, transpiration decreases, leaf temperature rises due to lack of cooling, and photosynthesis is decreased. If the ambient temperature rises above 40°C and the leaf temperature reaches the thermal danger point of 47°C (Taylor and Sexton, 1972), patches of leaf tissue dry out completely and become necrotic. The rolled-up 'cigar' leaves on young tissue-cultured plants also exhibit burning on the western side because VPD stress is greater in the afternoon. Vertical yellow/brown streaks remain when the leaf unfolds. Exposed bunches can also burn, showing necrotic patches on upper fruit surfaces and peduncle.

Mixed-ripe fruit

'Mixed ripe' occurs when harvested fruit ripen prematurely and spoil a carton by rotting and stimulating other green fruit to ripen prematurely. Many factors contribute to mixed ripe and one of the main factors is heat stress on fruit before and after harvest. High temperatures during field transport, packing, storage and road transport must be avoided in order to slow down physiological processes in the fruit after the latter have reached harvest maturity. High field temperatures coupled with picking fruit that are overmature can lead to a high incidence of mixed ripe in the subtropics. Fruit should be kept cool during all stages of postharvest management, and cartons should be pre-cooled to 13°C before transporting them long distances (see Chapter 14 section 'Cooling of Fruit from the Field'). This problem can also manifest itself in tropical banana areas, but is much less common due to the early harvesting stage for export.
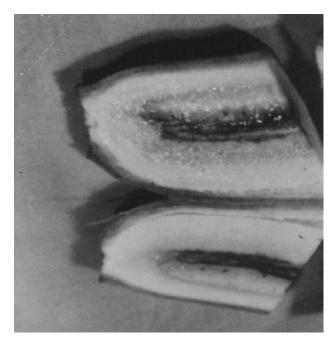
Ripe fruit breakdown

This phenomenon may be related to 'yellow pulp' in the tropics which is attributed to various stress conditions in the plantation. In the subtropics, the physiological problem of ripe fruit breakdown is due to exceptionally high maximum temperatures of between 40 and 45°C occurring from just before to just after flower emergence. Exposed banana bunches in a weak, poorly managed plantation are the most severely affected. Fruit develop normally on the plant, but, after ripening, they have an exceptionally short shelf life of only 2 days before the pulp collapses into a liquid mushy consistency and the fruit is inedible. Normal fruit would have a shelf life of about 1 week after ripening. There are no visible symptoms externally on mature green fruit, but after ripening the problem is manifested internally as a ring of dark, mushy tissue surrounding the central core of the fruit. This is the most sensitive region in a young developing fruit (Fig. 4.9).

It is thought that excessively high temperatures cause cell damage (biochemical changes and cell wall rupture) in the area surrounding the ovules, specifically during the cell division stage (see Fig. 3.9). These ruptured cells would then collapse and disintegrate during the cell expansion phase and become mushy during the ripening phase. The problem is not commonly encountered but it can be reduced by optimum management, high density and by evaporative cooling with sprinklers during such exceptionally high temperatures in summer.

Other climatic problems

Hail

Hail is a major recurring problem in most subtropical banana-growing areas which experience afternoon convectional thundershowers. Hail damage may vary from slight downgrading of fruit to complete devastation of the

Fig. 4.9. Ripe fruit breakdown caused by very high temperatures just before or after flower emergence. Tender core tissue is damaged physiologically, turning mushy and black during ripening.

plantation. The problem that faces the banana farmer after a severe hailstorm is to decide on a plan of action which will enable the salvage of as much fruit as possible and return to full production in the shortest possible time. Similar to the recommendation for a frost-damaged plantation, each plant must be evaluated individually after hail damage since plants are at all stages of development in a ratoon plantation. The following recommendations should be followed after a hailstorm:

1. Immediately remove all bunches from toppled plants and pack any marketable fruit.
2. For standing plants, wait until at least 1 week after the hailstorm before assessing damage.
3. Plants with severely damaged bunches and no leaf area should be cut down completely.
4. Plants with partly damaged bunches and some surviving green leaf area should be left so as to salvage some marketable fruit.
5. Plants which have not yet flowered must produce four or more leaves before it is decided whether to leave them to develop after flowering (as with frost damage).

Hail damage to banana bunches can be partly offset by the use of polyethylene covers, depending on severity of the hail and thickness of the cover. During a light hail, thicker covers certainly afford some protection, thus perforated covers of 40 μm thickness or more should be used over summer, for both hail and wind protection.

Wind

Wind can cause different types of damage in a banana plantation. Gale force winds or hurricanes of more than 15 m/s (54 km/h) frequently cause blowdowns in tropical banana plantations. At wind velocities of more than 20 m/s, between 50 and 100% of the plants can be blown down. A taller cultivar such as 'Valery' will experience a much higher percentage blowdown than a shorter cultivar such as 'Grand Nain', which in turn will be worse than 'Dwarf Cavendish'. Recovery of the plantation will be very much faster where the pseudostems snapped, thereby retaining the rhizome, roots and sucker underground, compared with plants that were entirely uprooted, necessitating replanting.

Regular, strong seasonal winds in the subtropics (5–10 m/s) cause leaf tearing which may reduce productivity when severe (Fig. 4.10 – see also Chapter 5 'Wind' section under 'Physiological Responses'). Windbreaks are recommended if such severe winds are experienced regularly, such as in coastal plantations. Winds between 2.5 and 5 m/s can reduce fruit quality by enhancing leaf and dust abrasion. Finally, hot, dry winds induce water stress and temporary wilting by increasing VPD and disturbing the leaf boundary layer, thus damaging the plant physiologically.

Drought

In banana areas where plantations are normally irrigated, drought periodically reduces or removes the source of irrigation water, resulting in plant damage. The initiation of yield reduction, caused by a physiological reduction of assimilation, occurs long before any visible symptoms of drought injury become evident (see Chapter 5 'Water' section under 'Physiological Responses'). When symptoms appear, drought injury is already severe.

The first response to drought is a reduction in leaf emergence rate, but visible signs of drought stress are prolonged wilting of the leaves, followed by yellowing of the leaves, marginal necrosis and leaf burn symptoms. Prolonged drought produces small, stunted plants, severely-reduced leaf emergence, choked bunches (even in summer and on tall cultivars), short fingers and, in the worst case, small bunches with shrivelled, blackened fingers.

In a situation whereby only say 30% of the normal irrigation requirement is available, it is preferable to irrigate 30% of the best bananas with their full water quota and abandon the rest, than to irrigate all the bananas with only 30% of their water quota. The latter policy results in a drastic yield reduction and a lack of response to other expensive inputs, such as fertilizers and labour.

Fig. 4.10. Severe leaf tearing caused by strong seasonal winds. Leaf strips hang down and become desiccated at their tips, causing reduced light interception and photosynthesis (see Table 5.3).

According to Stover and Simmonds (1987), AAB bananas and plantains are more drought tolerant than pure *acuminata* clones, and the ABB cooking bananas are the most drought tolerant of all. This drought tolerance seems to be linked to the B genome as indicated by *M. balbisiana* wild types compared with lower tolerance of *M. acuminata* (Infomusa@, 2009).

Floods

Flooding is most often associated with tropical banana regions experiencing severe storms, thus wind damage and flooding may occur simultaneously. Bananas will tolerate about 72 h of flooding with flowing water, provided the water table falls rapidly along with the flood waters. Under stagnant, static flood waters, only about 24–48 h of flooding can be tolerated before oxygen starvation causes root dieback and eventual leaf yellowing.

Radiation damage

Insufficient photosynthetically-active radiation (PAR) is a problem in some tropical banana areas which experience heavy rains and continuous overcast conditions. This is not normally a problem in production areas outside the tropics due to: (i) longer summer days; and (ii) more sunshine hours per day. The physiological influence of cloud and shade on assimilation potential is described under 'External controls of photosynthesis (Ps) and transpiration (Tr)' in Chapter 5. At the other extreme, excessive radiation can cause

sunburn under certain conditions. Excessive light can bleach leaves in a subtropical winter (see earlier in this chapter under 'Winter leaf sunburn'). Exposed bunches along roadways, in open plantations or in protected cultivation under plastic covers, can be burnt on the top hand and bunch stalk. The fruit peel bleaches yellow/white with mild sunburn and becomes necrotic with severe burning. Clear polyethylene covers can enhance the sunburn on exposed fruit due to increased temperatures within the cover. In areas prone to radiation burn, the canopy cover must be dense enough to protect hanging bunches from direct sunlight, especially those with covers. Also, white bunch covers with perforations should be used.

Lightning damage

This is a rare phenomenon in the tropics but not so rare in the subtropics where convectional thunderstorms occur. When lightning strikes a plantation, a dozen or more plants may be affected in a patch, within an area of otherwise healthy plants. There is initially a yellowing, browning and dieback of the leaf tips and the midrib may collapse half-way down the lamina. The entire leaf eventually becomes discoloured and collapses around the pseudostem. The pseudostem then begins to rot from the top downwards. This process takes about 10 days from the strike, and the affected patch should be replanted.

NOTES

1. There is a full chapter on various climate-induced problems in banana (Chapter 10), in the book edited by Jones (2000).
2. Most overheating problems in the subtropics may be minimized by appropriate cultural practices including a complete canopy cover in hot areas, higher planting densities, or by exploiting evaporative cooling with overhead sprinklers during the hottest hours of the summer days.

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5

PHENOLOGICAL AND PHYSIOLOGICAL RESPONSES

PHASES OF PLANT DEVELOPMENT

The two visible phases of development in a banana plant, are **the vegetative phase**, characterized externally by the emergence of leaves, and the **reproductive phase**, easily identified by emergence of the bunch. This is, however, a very simplistic approach, since at the end of the vegetative period, when leaves are still emerging, the apical meristem has already changed from a vegetative to a reproductive stage, forming the inflorescence which grows inside the pseudostem until it becomes visible from the outside. The process is even more complex in a ratoon cycle, due to the dominance of the mother plant over the selected sucker of the ratoon crop. To be more precise, the developmental phases of a ratoon banana plant (Cavendish subgroup) can be described as follows.

Vegetative phase

Juvenile phase
This is also called the 'dependant sucker' phase, in which the sucker is under the dominance of the mother plant. It is characterized by the emission of short, lanceolate leaves with narrow laminae, successively increasing in size from almost a simple central midrib until at least 10 cm wide. F_{10} (leaf is *feuille* in French) is the first leaf with a width equal to or greater than 10 cm. Although partial dominance of the mother plant remains until close to harvest, its influence on the sucker diminishes progressively over time.

Vegetative independent phase
Early studies on banana development (Dumas, 1958; Galán Saúco *et al.*, 1984) indicate that complete independence from the mother plant is reached when the first fully-developed leaf is emitted. This coincides with the stabilization of the leaf length:width ratio which is easily recognized in the

Cavendish subgroup by the orthogonal angle at the junction of sheath and petiole seen from the underside. This is why this first fully developed leaf is named orthogonal leaf (F_0). For practical phenological studies F_{10} is considered as the start of the independent phase (leaf 10 cm wide) and for production purposes it is important that sufficient leaves with less than 10 cm width are produced before this phase starts (Lassoudiere, 2007). If it happens too early, as occurs with water suckers (see Chapter 3), the sucker has insufficient root development or reserves to reach its full potential.

Vegetative apparent phase
At flower initiation, around 11–12 leaves are still inside the pseudostem and will successively emerge from the top of the plant while the inflorescence pushes upwards inside the pseudostem (vegetative apparent = no indication of floral development).

Studies on **plantain**, *Musa* AAB cv. Hartón (Nava and Sosa, 2006) also indicate the existence of a juvenile phase with the emission of 12 non-functional leaves and a vegetative phase with the emission of 28 functional leaves (27–30 for the dwarf *Musa* AAB cv. Hartón enano; Hernández *et al.*, 2006), until the emergence of the inflorescence. (The total is thus 40 ± 2, which is similar to Cavendish subgroup cultivars.)

Reproductive phase

The fact that male flower differentiation continues even after bunch emergence means the total period from flower initiation to harvest can be regarded as one phase. However, for practical purposes, it is more convenient to subdivide the reproductive phase into two component phases, namely the **floral phase** which is actually the vegetative apparent phase, and the **fruit phase** which is clearly delimited by emergence of the inflorescence. For practical phenological studies, the stage of inflorescence emergence (**E**) is defined as when the first hand of the bunch becomes visible after the unfolding of the floral bract (Kuhne *et al.*, 1973).

PHENOLOGICAL RESPONSES

The term 'phenology' refers to the vegetative and reproductive development cycles of a plant as determined by climate, and in particular, temperature. Detailed knowledge of phenological cycles of the banana plant in a particular area enables the farmer to do the following:

1. Intensify level of management when developmental rates are at their highest, and scale down management to coincide with a slowing down of phenological phenomena in cooler weather.

2. Plan the planting date and first sucker selection date, in order to time the harvest during an optimum marketing period.
3. Forecast the volume of crop harvested and seasonal spread of harvest according to frequent flower date counts.

For most citrus, deciduous and tropical tree fruit species, phenological studies are facilitated by specific, short, flowering and harvesting periods which are determined seasonally, and which vary only marginally from year to year. With banana and plantain, however, floral initiation is controlled by internal mechanisms and appears to be totally independent of external factors such as temperature and light. Thus, both flowering and harvesting can occur at any time during the year. Reproductive phenological cycles with banana are thus more complicated than with other crops. In addition, phenological characteristics of banana in the subtropics are more variable and difficult to study than in the humid tropics due to wider temperature variations.

A few years after establishing a plantation in the humid tropics, phenological cycling settles into a uniform pattern. The monthly leaf emergence rate (LER) remains approximately the same throughout the year, flower emergence occurs uniformly throughout the year, and the interval between flower emergence and harvesting remains similar irrespective of flower date. Therefore, fruit should be harvested regularly with no seasonal gluts or shortages. Conversely in the subtropics, such as New South Wales in Australia, or South Africa, there are wide seasonal variations in LER, time to flower emergence and flowering to harvest duration. These are mostly temperature-induced variations which usually result in shortages of fruit in autumn and winter, and gluts in spring and summer. Nevertheless, some flowering occurs, and some bunches are harvested, every month of the year. In Israel, which has long, hot summers and very cold winters, phenological cycles are even more pronounced, as described by Israeli *et al.* (1988a). In that country, 80% of bunches emerge during the 3 summer months of July, August and September, the balance emerging in May/June or October. Earlier flowering coincides with winter flower initiation and a high incidence of 'May bunch' which must be avoided (see Chapter 4 'Winter flower initiation'). Later flowering delays phenological events and causes young bunches to be poorly filled and damaged over winter. Consequently, harvesting period in Israel is limited to 7 months from October to April, with negligible fruit production during May–September. The severe climate has forced Israeli growers to manage bananas carefully as an annual crop. Phenology, as a tool to help the banana farmer, therefore becomes more important as climatic conditions become more variable and extreme. In the mild subtropical climate of the Canary Islands, and particularly under greenhouse cultivation, differences between winter and summer LERs are less important and harvest may be planned to either have a concentrated harvesting period in winter when prices are high, or to spread it more evenly over the year (Galán Saúco and Cabrera Cabrera, 2006).

Phenological studies have not received much serious attention in the tropics due to a lack of relevance, whereas in subtropical and Mediterranean countries, detailed studies have been made for the last 30 years. The most important phenological parameters are: (i) planting to harvest duration (P–H) for different planting dates and localities; (ii) LERs; (iii) primary root extension rates (RERs); and (iv) variations in flower emergence to harvest duration (E–H).
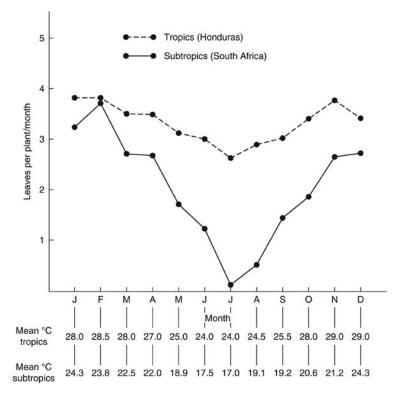
Planting to harvest duration (P–H)

In the humid tropics, the plant crop developmental cycle (P–H) is of little relevance because most dessert banana plantations are very old, replanting is rare (although certainly more frequent during the last 15 years, using vitroplants) and the export market requires that fruit are produced throughout the year. In the subtropics and Mediterranean areas, however, modern plantations are regularly replanted after 5–10 years. Certain phenological events must be carefully timed to avoid climatic constraints and fruit must be harvested at specific periods for high prices on the local markets. Thus, knowledge of planting to flower emergence (P–E) and P–H are of great importance.

In the humid tropics of Costa Rica or Honduras, the time from P–E and P–H of *Musa* AAA Cavendish subgroup cultivars is 7 months and 10 months, respectively. In the warm subtropics of Komatipoort, South Africa, it is 9 and 13 months, and in the cool subtropics of South Africa, Israel or the Canary Islands, it is 12 and 16 months, respectively (when planting at the beginning of summer). In the latter localities, late planting at the end of summer induces long cycles of 13 and 20 months, respectively, due to the total development cycle extending over two winter periods. These comparisons illustrate the cycle time and yield/annum advantages inherent in tropical countries. Optimum planting dates in subtropical localities are discussed in more detail in Chapter 7. Planting under greenhouse protection in the Canary Islands induces shorter ratoon cycles (see Table 8.1) although AAA Cavendish cultivar differences were also shown in that 'Gruesa' had a consistently longer P–H than either 'Grand Nain' or 'Zelig' (Cabrera Cabrera and Galán Saúco, 2005).

Leaf emergence rate (LER)

LER is a useful index of the vegetative development rate of a banana plant and it has been established experimentally that LER is closely correlated to temperature conditions (Turner and Hunt, 1983; Galán Saúco *et al.*, 1984; Robinson and Nel, 1985). There may also be differences between cultivars, even closely-related cultivars of the Cavendish subgroup (Cabrera Cabrera and Galán Saúco, 2005). To measure LER, the midrib of the youngest fully emerged leaf is painted at the beginning of each month to identify it. Monthly LER is the number of fully opened leaves emerging between two painting dates. Monthly LER is reflected

Fig. 5.1. Seasonal variations in the monthly leaf emergence rate (LER) of Musa AAA in the cool subtropics ('Williams', South Africa) and the humid tropics ('Grand Nain', Honduras). Monthly LER values are for established ratoon plantations and are correlated with corresponding monthly mean temperatures (i.e. (maximum + minimum) ÷ 2). Honduras data have been shifted by 6 months to equate seasonally with southern hemisphere data (Stover, 1979; Robinson and Nel, 1985).

in Fig. 5.1 for ratoon bananas in a tropical and subtropical banana-growing locality (AAA Cavendish cultivars 'Grand Nain' and 'Williams', respectively).

The highest ratoon LER in the two localities is about 3.8 leaves/month. This coincides with a summer mean monthly temperature of 24°C in South Africa and 28°C in Honduras. During the 'cooler' period in Honduras when the mean monthly temperature is 24–25°C, the LER declines to just under three leaves/month. Therefore, the peak LER appears to be higher in the subtropics for a given mean temperature, due to longer days and more radiation/day. This also explains the high monthly LER of 4.14 recorded in August in the Canary Islands with long, hot days and few clouds (Galán Saúco *et al.*, 1984). However, the subtropical winter period causes a severe reduction in LER. The lowest value of 0.1 leaves/month in Fig. 5.1 occurs at a mean monthly temperature of about 17°C and the LER remains under two leaves per
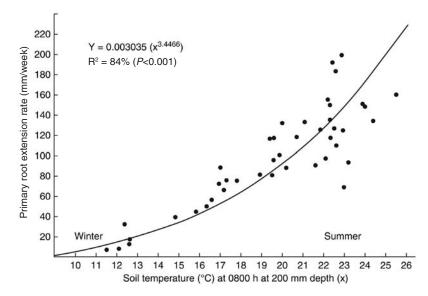
month for 6 months of the year, drastically slowing the annual development rate. These two ratoon plantations were both mature, with similar densities and with maximum leaf area index. Ratoon LER is considerably reduced under high plant-to-plant competition, whereas for an open plant crop in the subtropics, young vigorous vitroplants can attain an LER as high as seven leaves per month during a hot summer.

In the subtropics, the LER is important to the farmer because it indicates when management must be optimal, especially irrigation, fertilization, desuckering, nematode and weed control. During summer, vegetative development potential as expressed by a high LER will be considerably reduced if management inputs are lacking. However, even excellent management inputs in winter will not improve the low LER, because temperature is the major constraint. Thus, management can be scaled down accordingly. In the tropics, or under greenhouse cultivation in Mediterranean countries, optimum management should be applied every month of the year. The long P–E interval in the cool subtropics (12 months) compared with the humid tropics (7 months) is due to the 5 or 6 cooler months of the year, when the LER is less than two leaves per month.

Primary root extension rate (RER)

Primary RER is another vegetative index of banana plant development. Root development is closely correlated with soil temperatures just as LER is correlated with aerial temperatures. In a rhizotron study in South Africa, RER of AAA 'Williams' was measured weekly and related to minimum soil temperatures at 200 mm depth (Robinson and Alberts, 1989). The sensitivity of RER to variations in minimum soil temperature in the subtropics can be seen from data in Fig. 5.2. Extension ranged from 10 mm/week at 11°C to 200 mm/week at 25°C. Below 11°C RER ceased entirely. At higher soil temperatures, RER became variable with some roots growing 70 mm/week and others 200 mm/week at 23°C. This variation was much less when minimum soil temperatures ranged between 12 and 20°C.

Seasonally, peak RER occurred during February in South Africa, coinciding with highest soil temperatures. Some individual roots extended at a rate of 275 mm/week (peak RER in the tropics of the Ivory Coast was 245 mm/week (Lassoudiere, 1978b)). RER was terminated completely during a 2-month period in winter when minimum weekly soil temperatures dropped below 11°C. In spring, soil temperatures were slower to increase than aerial temperatures, thus a short lag phase occurred in which RER remained inhibited while LER increased. Rapid RER was initiated in mid-September. Feeder roots were produced on new primary root extension growth and also on new lateral roots (secondary and tertiary roots) within 7 days, but feeder roots remained functional for only about 3 weeks. The efficiency of root absorption

Fig. 5.2. Fitted regression line representing the correlation between mean minimum weekly soil temperature (0800 h) at a depth of 200 mm, and the weekly rate of primary root extension (RER). Each point is a mean of from eight to 25 primary roots seen extending within the rhizotron observation windows. Data were taken weekly for 10 months and no extension growth was recorded in July and August when mean minimum soil temperatures were below 11°C (Robinson and Alberts, 1989).

thus depends on the production of new lateral roots, which in turn, depends on primary RER.
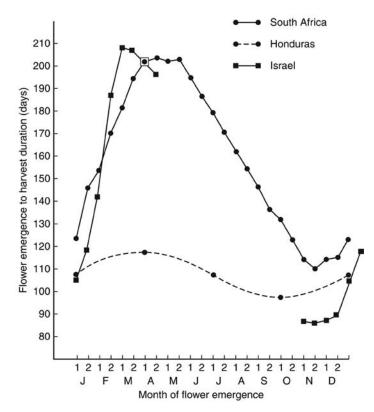
Knowledge of RER has practical value to the banana farmer in the subtropics. Due to root development cessation during winter, there is no need to fertilize during this period and irrigation can be reduced considerably. Feeder root volume and efficiency are drastically reduced and low soil temperatures limit root development rate, irrespective of management. Conversely, it is important to have water and nutrients in the soil to coincide with the root development flush in spring, and to increase these inputs gradually until peak RER occurs in late summer. For young tissue culture plants established in summer, primary roots may extend up to 2 m from the plant by 2.5 months after planting. Accordingly, fertilizers and water should be applied up to this distance and not only in a narrow band close to the stem.

Flower emergence to harvest duration (E–H)

E–H is the main **reproductive** index of banana development. From practical phenological studies in the subtropics, 'flower emergence' is when the

proximal (top) female hand is first visible on the hanging bunch, and 'harvest' is when the fingers are at the three-quarters round stage of maturity. At Burgershall research station, Kiepersol, South Africa, seasonal variation in mean E–H of 'Williams' according to 15-day flowering periods, is shown in Fig. 5.3 (Robinson and Human, 1988). The variation was wide, ranging from 110 days (late November flowering) to 204 days (late April flowering).

Autumn flowering in South Africa (March/April) causes an extended E–H due to bunches developing over winter when mean temperatures are low (see

Fig. 5.3. Seasonal variations in flower emergence to harvest duration (E–H) of *Musa* AAA in cool subtropics ('Williams' at Kiepersol, South Africa), humid tropics ('Grand Nain' in Honduras) and Mediterranean climate ('Williams' in Jordan Valley, Israel). For each month, period 1 = 1st to 15th of the month; period 2 = 16th to the end of month. Subtropical data from Robinson and Human (1988), tropical data from Stover (1979) and Israel data from Israeli *et al.* (1988a) and Israeli (personal communication). Note: Israel data are shifted 6 months to equate seasonally with southern hemisphere subtropical data. A total of 2570 bunches was used in the South African study. In Israel, few flowers are produced in November, March and April and none at all from December to February (June to August on this graph).
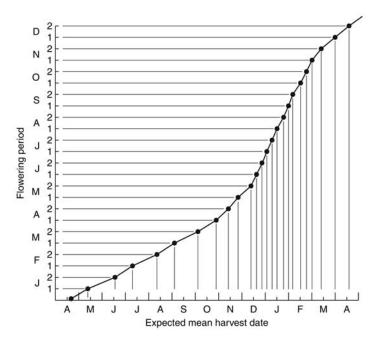
Fig. 4.3b). Conversely, flowering in spring/early summer (October–December) induces a short E–H due to rapid fruit development over the hot summer months. A completely different pattern occurs in the tropics of Honduras (Stover, 1979), where extremes of mean E–H for AAA 'Grand Nain' were 98 days for hot weather fruit development, to 117 days for 'cool' weather development (Fig. 5.3). The longest mean E–H in the humid tropics is thus only slightly longer than the shortest E–H in the cool subtropics. In the extreme climate of Israel, the variation in E–H is very wide, from 86 days for late May flowering to 208 days for flowering only 3.5 months later in mid-September (Israeli *et al.*, 1988a; Fig. 5.3). These later-flowering bunches are retarded by the cold winter (mean monthly temperature in January is 13.5°C in the Jordan Valley). However, early-summer bunches develop even quicker than those in the tropics due to long summer days, absence of cloud, and high mean temperatures (30°C for August in the Jordan Valley). Few flowers emerge from November to April (May–October in Fig. 5.3). In parts of the Canary Islands where summer temperatures are milder than Israel (<30°C) and winter temperatures remain below 20°C on northern slopes, E–H intervals are long, ranging from 150 to 230 days (Galán Saúco *et al.*, 1984).

The mean harvest date for each 15-day flowering period in the subtropics of South Africa is illustrated in Fig. 5.4. From this it is evident that a 7-month flowering period (May–November) is concentrated into a 3-month harvest period (December–February – summer). Conversely, a 4-month flowering period (January–April) is extended into a 7-month harvest period (May–November). This phenomenon partly explains the glut of fruit commonly experienced in summer, and the shortage during autumn/winter in the southern hemisphere. In Israel, the severe climate (combined with management) forces nearly all the fruit to be harvested from October to April, very little during September and May and none from June to August. Due to the less extreme subtropical climate of the Canary Islands, production is also slightly more uniformly distributed than in South Africa or Israel. Contrasting with these localities, production in the humid tropics is continuous and uniformly distributed throughout the year.

The concept of heat units is another way of illustrating the effect of temperature on fruit development. Studies in South Africa (Robinson, 1992) showed that an average of 1000 heat units or degree days above 14°C are required to develop a 'Williams' banana bunch from flower emergence to harvest maturity (range 950–1050). Cumulative E–H heat units are determined from the formula:

$$\Sigma \left[(\text{daily } T\text{max} + T\text{min})/2 \right] - 14)$$

This heat unit range needed in the subtropics is relatively constant irrespective of flower date, but only about 100 days are required to accumulate them over summer compared with about 200 days over winter. Using the same base
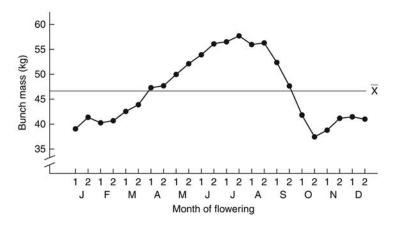
Fig. 5.4. Predicted mean harvest date of *Musa* AAA 'Williams' according to 15-day flowering intervals in the subtropics. Vertical lines represent predicted mean harvest date as derived from seasonal E–H data shown in Fig. 5.3 (Robinson and Human, 1988).

temperature of 14°C, Ganry (1978) found that 900 degree days were required to complete fruit development in the French West Indies. Possibly the criterion for determining the H stage for export harvest maturity in the French West Indies is earlier than that selected for the local market in South Africa, and/or the criterion to define the E stage is later.

Seasonal variations in bunch mass

For a single vigorous ratoon banana plantation in the subtropics, bunch mass can vary greatly according to flowering date. Seasonal variation in bunch mass of 'Williams' banana according to 15-day flowering intervals is shown in Fig. 5.5. The sensitivity to flowering date is obvious at this locality, where mean bunch mass decreased from 57.8 to 37.2 kg as flower date was delayed 3 months from late July (winter) to late October (spring). Ratoon plantations from which these data were taken were all similar in soil type, density, plant vigour and management, and were situated next to each other, thus differences were climate related. Using prevailing LERs and the accepted norm

Fig. 5.5. Seasonal variations in bunch mass of *Musa* AAA 'Williams' in the subtropics according to 24 flowering periods of 15 days each. For each month, period 1 = 1st to 15th of the month; period 2 = 16th to the end of month. The horizontal line at 46.7 kg represents a high overall mean bunch mass achieved from 2570 experimental bunches at Burgershall research station in Kiepersol, South Africa (Robinson and Human, 1988).

of 11 leaves emerging between flower initiation and flower emergence (Stover, 1979), the approximate date of flower initiation could be retrospectively estimated. Thus, November-flowering bunches with lowest bunch mass were initiated during cold temperatures of July (see Chapter 4 'Winter flower initiation'), whereas July/August flowering bunches with the highest bunch mass were initiated during the optimum warm period of March.

Stover and Simmonds (1987) report a similar wide variation of bunch mass from 72,000 'Valery' bunches recorded in Honduras. Of these bunches, 7% weighed 57–68 kg, 40% weighed 46–56 kg, 41% weighed 35–45 kg and 11% weighed 24–34 kg. These data were taken over a wide range of plantations thus the wide variation can be ascribed to both seasonal and management effects. Bunches initiating from April to September in Honduras are smaller because mean temperatures are over 28°C which is in excess of the 22°C optimum for flower initiation. Largest bunches arise from flowers initiating in the Honduran 'winter' from December to February, when mean daily temperatures are around 24°C. Bunch mass variations quoted by Stover would also include the influence of soil type, fertility, water stress and other management factors. If initiation date, soil type and management level interactions are considered for ratoon plantations of *Musa* AAA (Cavendish subgroup) in the subtropics, then the best scenario can produce a bunch mass in excess of 70 kg for 'Williams' and the worst scenario will produce a bunch mass as low as 15 kg, but these extremes are evidently rare in the humid tropics.

Crop forecasting

Using experimental data shown in Figs 5.3, 5.4 and 5.5, it is possible to forecast the volume and spread of a banana farmer's future harvests in the subtropics. It is important to inform the banana marketing organizations of expected yields so that orderly ripening, distribution and marketing of fruit can take place. The farmer benefits in that he/she can plan their packshed and labour requirements in advance. A practical crop forecasting model was constructed by the Agricultural Research Council Institute for Tropical and Subtropical Crops (ARC-ITSC) in Nelspruit, which is based on new flower counts every 15 days and the overall box per bunch potential of the grower. From historical experimental data, the total boxes are then forecast using seasonal yield adjustment factors to allow for the variations in bunch mass due to flower date. Harvest spread into different monthly periods is forecast according to the historical pattern of harvest distribution for experimental bunches in each flowering period (Robinson and Human, 1988). Any grower can make use of this forecasting facility by submitting his/her flower counts every 15 days together with an estimate of their average annual box per bunch ratio. Such forecasting exists for 'Williams' and 'Dwarf Cavendish' in two South African localities.

Harvest dates can also be forecast from flowering dates, using the heat unit summation or degree day technique described under E–H intervals. Many attempts to do this have been tried in tropical countries using historical temperature data (e.g. Hord and Spell, 1962). Since it is not possible to predict temperatures in advance, the use of degree days is not accurate enough in predicting harvest dates for commercial purposes. However, at any stage in the E–H cycle, heat units can be cumulated to determine the proportion of the development cycle completed to date. This could help in determining if bunches are developing slower or faster than normal. A similar disadvantage of the technique described for the subtropics is that historical experimental data for E–H are also used which may not be accurate for the current season. Any forecasting technique is destined to be somewhat inaccurate, not only due to unknown future variations in temperature, but also due to other climatic variables and management differences which change E–H, and the occurrence of natural bunch losses due to cyclones, hail, wind or frost.

Phenological summary of a tropical versus subtropical locality

The main phenological differences between bananas in a humid, tropical locality (Honduras), a cool, subtropical locality (South Africa) and a Mediterranean locality (Israel) are summarized in Table 5.1. In Israel, peak monthly LER in summer is higher than in the subtropics which in turn is higher than in the tropics due to progressively shorter daylength and reduced

sunshine hours per day. Annually, however, total leaf production in the tropics is much higher due to consistently high LER at other times of the year. Resulting from shorter vegetative cycles and shorter E–H in the tropics, total cycle time is considerably shorter, which enhances yield/annum compared with the subtropics. Mean bunch mass is progressively reduced from tropical to subtropical to Mediterranean climate, due to increasing severity of temperature extremes in both winter and summer. Accordingly, bunch mass range is also less variable in the tropics than in the other two localities. The wide bunch mass range in South Africa (Fig. 5.5) is accentuated by flower initiation in the cold winter resulting in stunted and small bunches, with few hands and fingers. This, however, is for a limited duration only.

The net result of three processes, namely, growth (net assimilation of dry matter (DM)), development (leaf area increase) and initiation (the setting of hands and fingers on the young inflorescence) is that yield per annum potential in the tropics is about 40% higher than in the cool subtropics. As explained in Chapter 4, however, the difference in gross margin to a grower would not be so great, since production costs are very high in the tropics as a consequence of the high rainfall and leaf diseases.

Table 5.1. Summary of phenological differences and annual yield potential between Cavendish subgroup banana ratoon plantations in the humid tropics (Honduras; cultivar 'Grand Nain'), the cool subtropics (South Africa; cultivar 'Williams') and the Mediterranean (Israel; cultivar 'Williams') (from Stover, 1979; Robinson and Nel, 1985; Stover and Simmonds, 1987; Israeli *et al.*,1988b; Robinson and Human, 1988; E. Lahav personal communication).

Phenological parameter	Honduras (latitude 15°N)	South Africa (latitude 25°S)	Israel (latitude 32°N)
Mean number of new leaves per month (summer–winter)	3.5–2.5	4.0–0.5	5.5–0
Total leaf production per year	40	25	30
Planting to harvest (months)	9–11	15–20	15
Harvest to harvest (months)			
1666 plants/ha		11–13	
1800 plants/ha	6–8		12
Flowering to harvest duration (summer–winter) (days)	98–117	110–204	86–208
Mean bunch mass (kg)	35	30	25
Normal bunch mass range (kg)	30–40	20–40	15–35
Yield per annum (packed boxes) average to high (t/ha/year)	45–65	30–50	
Yield per annum (bunches) average to high (t/ha/year)			35–50

PHYSIOLOGICAL RESPONSES

While developmental processes in the banana plant are best described by morphological and phenological responses (Chapter 3 and the previous section of this chapter, respectively), the processes of growth (assimilation of DM) are described by physiological responses. To determine crop yield potential under different environments it is important to measure, analyse and interpret carbon assimilation levels quantitatively and to identify environmental constraints on the physiological efficiency of the plant.

In this section of Chapter 5 it is proposed to summarize experimental knowledge in the field of banana crop physiology, and to highlight management practices that can be modified by growers as a result of this knowledge. Since the basis of assimilation is photosynthesis (Ps), the factors influencing this process are vitally important and will be discussed. Similarly, knowledge of transpiration (Tr) responses is essential to monitor the extent of physiological stress imposed on the plant by the external environment. Whereas phenological studies involve measuring developmental responses over a long seasonal period, physiological studies measure instantaneous reactions of the plant to the prevailing environment. Thus, valuable information on the adaptability and physiological status of the plant can be gathered over a diurnal time course, over an hour, or at any specific moment. Sophisticated and expensive equipment is needed to conduct these studies in the field, and the organ normally used to represent the physiological condition of the whole plant is the main 'source' organ of photo-assimilation, namely the leaf.

Internal controls of photosynthesis (Ps)

Leaf characteristics

The most efficient leaves on a banana plant growing vegetatively, are leaves 2 to 5 down the profile (Table 5.2, top row 'Leaf profile'). This was determined for Ps by Kallarackal *et al.* (1990) and Eckstein and Robinson (1995a) and for Tr by Robinson and Bower (1988). For standardized physiological measuring techniques, any of these leaves can thus be chosen, but leaf 1 is still in a 'sink' growth stage when stomata on its tender surface are not fully operational and assimilates are imported rather than manufactured. Conversely, leaves 6 to 12 are regarded as progressively ageing and ultimately senescing, thus Ps **efficiency** is reduced. Additionally, Ps **capacity** is reduced on these older leaves since light penetration to the lower canopy levels is progressively reduced.

Leaves 2 to 5 are not static and in a vigorous plantation with four new leaves per month appearing, the most efficient leaf area is thus renewed monthly. It is important that the most efficient leaf area remains free of

Table 5.2. Summary of some internal plant factors affecting the rate of photosynthesis (Ps) in AAA Cavendish subgroup banana leaves in a subtropical climate.

Internal plant factor		Photosynthesis rate (μmol $CO_2/m^2/s$)	Reference
Leaf profile (summer)	Leaf number 1 (youngest)	11.7	Eckstein and Robinson (1995a)
	2	18.7	
	3	21.0	
	4	20.6	
	5	19.4	
	6 (mid-profile)	17.3	
	7	15.8	
	8	13.4	
Leaf surface (leaf 3, 4 or 5)	Abaxial/adaxial (spring)	24.1/7.7	Eckstein and Robinson (1995a)
	Abaxial/adaxial (summer)	33.2/21.6	
	Abaxial/adaxial (autumn)	20.6/7.9	
	Abaxial/adaxial (winter)	18.8/6.1	
	Abaxial/adaxial (winter sunburn)	13.4/2.5	
Ontogenetic stages (summer)	Prior to flowering (leaf 3, 4 or 5)	18.4	Eckstein and Robinson (1995a)
	Mid-fruit development (leaf 3, 4 or 5)	13.0	
	At harvest (leaf 3, 4 or 5)	8.2	
Cultivar (all AAA, during summer)	'Chinese Cavendish'	29.5	Robinson *et al.* (1993b)
	'Dwarf Cavendish'	29.1	
	'Grand Nain'	28.6	
	'Valery'	27.5	
Type of planting material	Suckers (2 months after planting)	15.0	Eckstein and Robinson (1995c)
	In vitro (2 months after planting)	18.6	
	Suckers (3 months after planting)	23.1	
	In vitro (3 months after planting)	26.2	
	Suckers (4 months after planting)	27.9	
	In vitro (4 months after planting)	28.8	
	Suckers (5 months after planting)	28.7	
	In vitro (5 months after planting)	28.7	
Compensatory response 9 days after leaf pruning	Leaf 3 (12 leaves present)	11.8	Robinson *et al.* (1992)
	Leaf 3 (four leaves present, eight removed)	15.4	

leaf disease, severe leaf tearing and excessive shade, otherwise assimilation potential is greatly reduced.

There are approximately 140 stomata/mm^2 on the abaxial (lower) surface of banana leaves, compared with 55 on the adaxial surface (Eckstein and Robinson, 1995a). Ps and Tr are increased accordingly on the abaxial surface. The abaxial/adaxial Ps ratio is 1.5:1 in normal summer conditions, but in a subtropical winter the ratio increases to 3.1:1 and where winter photo-oxidation bleaches and damages the adaxial surface physiologically, this ratio increases to 5.4:1, and overall Ps is also greatly reduced (Table 5.2, row 'Leaf surface').

Ontogenetic stage of development

This is particularly important in the subtropics where critical growth phases have to be synchronized with favourable external conditions. Highest physiological activity on banana plants was measured in the vegetative growth phase during late summer (Eckstein and Robinson, 1995a) since, in this phase, the most efficient leaves (2 to 5) are replaced every month and temperature conditions are nearest to the optimum for Ps (Turner and Lahav, 1983). In winter, plants growing vegetatively have higher Ps than those carrying a bunch, due to the younger leaf area, but overall activity is much lower than in summer, due to limiting winter temperatures. Plants still growing vegetatively in the second summer can renew their leaf area which has physiologically aged over the winter, thus photosynthetically-active young leaves can support the bunch after flowering. It is important to utilize this advantage in the subtropics and avoid flowering during winter and spring when older leaf area which has not had a chance to renew itself cannot contribute so efficiently to later bunch filling. The Ps inefficiency of old leaf area (at harvest) compared with young leaf area (prior to flowering) can be seen in Table 5.2 (row 'Ontogenetic stages').

Cultivar

Physiological differences between cultivars within the AAA Cavendish subgroup are not great and yield differences cannot confidently be explained on the basis of Ps efficiency. In a study by Robinson *et al.* (1993b), 'Chinese Cavendish' appeared to be the most efficient with a summer Ps rate 7% higher than that of 'Valery' (Table 5.2, row 'Cultivar'). This may have been due to the 13% increase in stomatal density (Ps capacity) on leaves of 'Chinese Cavendish'. In terms of CO_2 assimilation per 10,000 stomata, 'Dwarf Cavendish' was actually more efficient than the other cultivars. In Australia, it is thought that the susceptibility of 'Williams' to infection by Fusarium wilt may be related to its cold susceptibility and decline in Ps during winter (Whiley *et al.*, 1993). AAAB 'Goldfinger', which is tolerant to cold and has higher chlorophyll and Ps during winter, is more tolerant to Fusarium wilt infection. The possibility of a relationship between Ps efficiency in winter and resistance to Fusarium wilt needs further investigation with different cultivars.

Type of planting material

The increase in vigour, plant size, bunch mass and yield from using *in vitro* planting material compared with suckers has been well documented in the literature (see Chapter 7). The physiological basis for these differences was studied by Eckstein and Robinson (1995c). *In vitro* plants, with a juvenile rhizome, produced 77% higher root DM than conventional suckers by 5 months after planting in spring. Additionally, new leaf growth on *in vitro* plants had an average of 18% higher Ps rate than on new leaves of suckers, for the first 3 months of development (Table 5.2, row 'Type of planting material'). Increased root vigour and Ps efficiency of *in vitro* plants led to a doubling of functional leaf area and total plant DM after 5 months of development, compared with conventional suckers. It is thought that increased Ps efficiency and rooting vigour of *in vitro* plants are caused primarily by: (i) the physiological juvenility of the tissue; (ii) increases in dry mass being enhanced by the extra water and nutrient uptake capability of the dense root system; and (iii) the extra Ps capacity of the larger leaf area (Fig. 5.6).

The physiological advantages of *in vitro* plants have encouraged interesting avenues of intensive management relating to: (i) critical irrigation and nutrient needs of the young plants; (ii) efficient weed and nematode control to protect the vigorous root system from competition; and (iii) mycorrhizal and endophyte supplements to boost nursery/early field growth.

Fig. 5.6. Sucker and tissue culture planting materials after 1 month growth in the field. (1) Sucker growth with degrading rhizomes, scarce new roots and small leaf area; (2) tissue culture vigour showing prolific root growth and large leaf area.

Photosynthetic compensation

A banana plant has the internal capability to partly compensate for lost assimilation capacity due to leaf area destruction or removal. Provided that some of the leaf area from leaves 2 to 5 is retained, the Ps rate on these leaves is increased in compensation for the lost leaf area. Robinson *et al.* (1992) measured a 30% increase in Ps on leaf 3 of pruned banana plants (leaves 1 to 4 retained) compared with unpruned plants (12 leaves present; Table 5.2, row 'Compensatory response'). However, this compensation did not allow any benefits of yield or cycle time to accrue to the pruned plants, compared with unpruned plants, due to the severe depletion of gross leaf area.

The higher Ps rate measured on *in vitro* plants (Table 5.2, row 'Type of planting material') may also be partly due to a compensatory mechanism whereby vigorously-growing plants exert a high assimilate demand on young leaves. In comparison, sucker plants have an assimilate reserve in the large rhizome which can support the young leaves thus placing minimal assimilate demand on the latter until several months have elapsed.

Physiological interaction between parent and sucker

A study to demonstrate the influence of the mother plant on sucker growth, development and Ps, was undertaken in the subtropics of South Africa (Eckstein and Robinson, 1999). Removing the leaf canopy and newly-emerged bunch from the parent at sucker selection stage, doubled total dry mass and leaf area of the ratoon sucker 6 months later, compared with a sucker attached to a normal bunched parent. Evidently assimilates meant for the bunch were relocated to the sucker, and this was boosted by extra light on the sucker leaves. In contrast, severing the vascular connection between a newly-selected sucker and its parent, reduced sucker dry mass after 6 months to only 20% of that achieved by a normal attached sucker. The heavy dependence of the young sucker on its parent is thus clearly evident.

External controls of photosynthesis (Ps) and transpiration (Tr)

Seasonal effects in the subtropics

External influences of the subtropical environment on Ps in banana have been studied by Ke (1980), Eckstein and Robinson (1995b, 1996), Eckstein *et al.* (1996, 1997), and on Tr by Robinson and Bower (1988) and Hoffman (1990). These field studies describe influences of the gross environment (integrated effect of all climatic factors) on banana physiological response. Although correlations between physiological response and either photosynthetically active radiation (PAR), temperature or vapour pressure deficit (VPD) have been made in the field, it is obvious that these correlations indicate trends only and are not accurate since other climatic factors were not controlled. As pointed out by Turner (1995), reliable correlations between Ps and any particular

climatic parameter must be done in a growth chamber with strict control of all other variables. However, the advantage of the field approach is that it is commercially important to know how the banana plant responds to the typical gross environment of a locality and not just its component parts.

In a study by Eckstein and Robinson (1995b), diurnal time courses were conducted to relate Ps and Tr of AAA 'Grand Nain' to prevailing climate during summer, autumn, winter and spring. Highest annual Ps levels were measured during early morning of the summer months, and lowest midday values were during winter following low night temperatures. Whereas peak diurnal Ps occurred always before noon, Tr peaked at noon or in the afternoon. Seasonally, summer early mornings (0800 h) had the highest Ps (Table 5.3, top row 'Seasonal/diurnal climatic factors') due to a combination of high PAR, optimum temperature, low VPD and a vigorous root system. In the afternoon, Ps was reduced due to high temperature and VPD causing stomatal closure. During winter, low night temperatures below 8°C, high daytime VPD and a depleted root system which was unable to cope with evaporative demand, were the causes of low Ps and Tr. While diurnal variations in these responses during winter were related mostly to VPD, the mean daily Ps was strongly related to minimum temperature the previous night (Table 5.3, 'Seasonal/diurnal climatic factors'). Low winter night temperatures in general induce a functionally-depleted root system which cannot respond to high daytime VPD (Robinson and Alberts, 1989). Following particularly cold nights, however, the daytime Ps and Tr are severely reduced, probably due to increased viscosity of latex (Hoffman, 1990).

Tr response curves of banana to seasonal diurnal cycles of VPD were found to be very similar in Western Australia (Hoffman, 1990) and South Africa (Robinson and Bower, 1988), as shown in Fig. 5.7. These data emphasize that management of subtropical banana plantations must be optimal in summer and autumn to maximize physiological potential. However, in winter and to a lesser extent in spring, the climate imposes constraints within the plant which cannot be compensated by improved horticultural management, except by artificial amelioration of the environment like under greenhouse cultivation (see Chapter 8).

Photosynthetically active radiation (PAR)

Although a light/Ps response curve cannot accurately be measured in the field, it is certainly possible to measure the diurnal reduction in PAR and Ps on a cloudy day compared with a sunny day, and also the reduction in Ps due to shade from a leaf canopy or windbreak. These are the practical realities of growing bananas and the loss of assimilation potential from cloudy conditions or plant competition needs to be quantified.
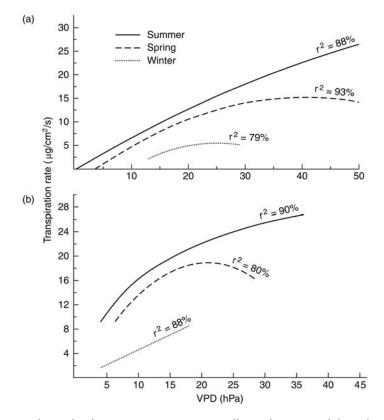
Eckstein and Robinson (1995a) measured the average diurnal intensity of PAR on a cloudless summer day as 1974 μmol/m^2/s compared with 477 μmol/m^2/s on a fully overcast summer day. Ps rate of AAA 'Williams' banana

Table 5.3. Summary of some external factors affecting the rate of Ps in AAA Cavendish subgroup banana leaves in a subtropical climate.

External factor		Photosynthesis rate (μmol $CO_2/m^2/s$)	Reference
Seasonal/diurnal climatic factors (leaf 3,4 or 5; standard 1 m plant)	Summer diurnal maximum/mean	23.4/19.6	Eckstein and Robinson (1995b)
	Autumn diurnal maximum/mean	19.4/16.4	
	Winter diurnal maximum/mean	9.2/7.3	
	Winter diurnal following cold night (6.2°C minimum)	10.4/2.8	
	Spring diurnal maximum/mean	16.8/10.5	
PAR[a] (summer)	500 μmol/m²/s	12.2	Whiley *et al.* (1993)
	1000 μmol/m²/s	17.3	
	1500 μmol/m²/s	19.5	
	2000 μmol/m²/s	20.3	
Overcast weather	Summer sunny day (PAR = 1974 μmol/m²/s)	17.2	Eckstein and Robinson (1995a)
	Summer overcast day (PAR = 477 μmol/m²/s)	11.4	
Shade from leaf canopy (summer)	Leaf 3 sunlit (PAR =1652 μmol/m²/s)	20.9	Robinson *et al.* (1989)
	Leaf 4 shaded (PAR = 80 μmol/m²/s)	6.8	
SWP[b] (autumn)	(a) Unstressed plants	26.4	Eckstein and Robinson (1996)
	Stressed for 4 days (-12 kPa)	24.2	
	(b) Unstressed plants	22.6	
	Stressed for 6 days (-25 kPa)	18.6	
	(c) Unstressed plants	20.8	
	Stressed for 9 days (-53 kPa)	11.7	
	(d) Unstressed plants	18.0	
	Stressed for 12 days (-70 kPa)	3.3	
Experimental leaf tearing (inside a shadecloth windbreak)	Control leaves (untorn)	20.5	Eckstein *et al.* (1996)
	100 mm lamina strip width	20.4	
	50 mm lamina strip width	18.3	
	25 mm lamina strip width	16.5	
	12 mm lamina strip width	13.7	
	~130 mm strips (outside windbreak)	16.7	

[a] PAR, photosynthetically-active radiation;

[b] SWP, soil water potential.

Fig. 5.7. Relationship between Tr rate in AAA 'Williams' banana and diurnal changes in vapour pressure deficit (VPD) during summer, spring and winter, at (a) Carnarvon, Western Australia and (b) Kiepersol, South Africa. The regression lines of best fit are very similar between these two subtropical localities. Data indicate that for a specific level of VPD, transpiration efficiency was greatest in summer, somewhat less in spring and very suppressed in winter, due to internal plant constraints resulting from low night temperatures. r^2 = Correlation coefficient. Data for (a) and (b) redrawn from Hoffman (1990) and Robinson and Bower (1988), respectively.

leaves was reduced from 17.2 to 11.4 µmol CO_2/m²/s, respectively (Table 5.3, row 'Overcast weather'). This emphasizes the loss in assimilation potential (34%) occurring during overcast conditions, and is relevant to the humid tropics where it is predominantly overcast, allowing only 3–5 sunshine h/day on average. Conversely, Mediterranean climates with long, cloudless summer days have a distinct advantage, not only in terms of sunny conditions but also due to increased sunshine hours per day. Differences in PAR between different greenhouse covers and an open air locality were shown by Galán Saúco *et al.* (1998). Maximum open air values around 1500 µmol/m²/s, were higher than

those registered under any greenhouse cover (polyethylene had the highest PAR), with a maximum value around 1100 μmol/m^2/s. However, the lower PAR under polyethylene covers was more than compensated by: (i) a higher growing temperature compared with the open site; and (ii) a higher leaf area index to intercept more incoming radiation than on open air plants.

The loss of Ps activity on a banana leaf in the shade of another leaf is greater than the loss due to full overcast conditions. This is due to the more severe reduction in PAR on a leaf in canopy shade (Table 5.3, row 'Shade from leaf canopy'). Robinson *et al.* (1989) measured a PAR reduction from 1652 to 80 μmol/m^2/s from leaf 3 (exposed) to leaf 4 (shaded) and this corresponded to a reduction in Ps from 20.9 to 6.8 μmol CO_2/m^2/s (67% reduction). The poor performance of individual banana plants at very high density is mainly due to this severe reduction in PAR over a large portion of their functional leaf canopy.

The effect of three levels of artificial windbreak shade (30, 60 and 80% reduction of normal PAR, respectively) was investigated on 'Williams' by Israeli *et al.* (1995b). During the second cycle, bunch mass was reduced by 8, 21 and 55%, respectively, and yield/annum was reduced even more due to extended cropping cycles. Eckstein *et al.* (1997) studied the effect of windbreak shading on banana physiology and showed that shadecloth windbreaks reduced average PAR by 69%, and Ps rate by 27%, compared with plants in full sun. This in turn led to a 10.6% extension in cycle time over two crop cycles and a cumulative yield reduction of 13%. Thus windbreaks may have advantages but also many disadvantages.

With 'Williams' banana in Queensland, Whiley *et al.* (1993) determined Ps/light response curves in summer. For increases in PAR from 500 to 1000 to 1500 to 2000 μmol/m^2/s they measured incremental increases in Ps of 42, 13 and 4%, respectively, suggesting that PAR should be between 1500 and 2000 μmol/m^2/s, and confirming that Ps becomes severely reduced at under 1000 μmol/m^2/s quanta PAR (Table 5.3, row 'PAR'). Similar results were obtained by Thomas and Turner (2001) showing the optimum PAR for banana at about 2000 μmol/m^2/s and a sharp reduction in Ps at 500 μmol/m^2/s and below. Conversely, they also measured photochemical damage caused by reduced chlorophyll fluorescence at high PAR.

Water

Sensitivity of the banana plant to water stress is broadly described in Chapter 10. Physiologically, however, it is evident that the initiation of water stress can be detected when soil water potential (SWP) is still relatively high, especially under environmental conditions of high VPD. This occurs well before any visible signs of water stress are apparent such as leaf folding or wilting. Thus, under controlled glasshouse conditions, Robinson and Bower (1987) found that banana plants responded physiologically very slowly to a SWP decreasing to -80 kPa, when evaporative demand was negligible (VPD = 5 hPa). Conversely, when VPD was increased to 20 hPa, the Tr rate of plants

was rapidly reduced by 39% at an SWP of -47 kPa. Similar relationships were detected in the field, and these show that a sensitive and dynamic interaction exists between plant stress reactions, SWP and VPD. In field studies by Eckstein and Robinson (1996), physiologically healthy and active plants growing in autumn were subjected to a single extended water stress cycle. After 6 days without water when SWP was -25 kPa, the level of Ps was reduced by 19%, and after 12 days without water, at a SWP of -70 kPa, Ps was reduced by 80%, compared with well-watered plants (Table 5.3, row 'SWP'). Severe water stress on banana is additionally damaging in that more than 3 days elapse before the plant recovers its normal level of physiological activity, after re-irrigation. This is due presumably to the need to re-establish functional roots and, thereafter, normal plant turgor. Such a delayed recovery of banana plants subjected to severe water stress was also observed by Kallarackal *et al.* (1990). In addition, Thomas and Turner (2001) measured a higher level of photochemical damage to chlorophyll when drought conditions were present, which is a non-stomatal response. Thus, to avoid water stress damage from either stomatal closure or PAR-induced chlorophyll damage, it is recommended that SWP does not become lower than -20 kPa between irrigations.

Wind

Wind has both mechanical and physiological effects on banana plants, and the mechanical effects were described in Chapter 4 (see section 'Wind'). Physiological effects of wind on a banana leaf canopy are less visible but can be severely damaging. In an open, plant crop canopy at low density, these effects are more pronounced than in a ratoon crop at high density, due to mutual plant protection reducing wind speed in the latter. Thus, relative to a wind-protected plantation, wind reduces yield on a plant crop much more than it does on a ratoon crop (Eckstein *et al.*, 1996). Wind modifies the physiological functioning of the plant through its effect on the boundary layer of undisturbed air adjacent to the leaf surface, and on leaf temperature (Turner, 1995). Thus, if wind speed is high and humidity low, the boundary layer quickly disperses, leaf temperature rises and the plant suffers physiological stress. However, a slight wind and high humidity benefit the plant physiologically by cooling leaf surfaces and reducing the vapour pressure gradient between leaf and air, thus reducing Tr loss.

The influence of mechanical damage from progressive leaf tearing on banana physiology and yield was investigated experimentally by Eckstein *et al.* (1996). Under protection of a windbreak, leaves of AAA 'Dwarf Cavendish' were torn with combs into strips of 100, 50, 25 and 12 mm width, or left untorn (control). Ps efficiency per unit of leaf area was reduced by only 11% on leaves torn to 50 mm strips, but with 25 and especially 12 mm tears, representing a severe windstorm, Ps was reduced by 20 and 33%, respectively, compared with untorn leaves (Table 5.3, row 'Experimental leaf tearing'). Since experimental ratoon plants were protected from detrimental boundary-

layer and VPD effects by the windbreak, the reduced Ps with tearing is ascribed to a measured increase in relative leaf folding and reduced interception of PAR. However, leaves on plants outside the windbreak, which at one stage were only mildly torn by wind into ~130 mm strip widths, had reduced Ps and yield equal to the 25 mm tears inside the windbreak. In this case, microclimate effects of the prevailing wind itself were detrimental to physiological efficiency, irrespective of tearing. An earlier reference to this topic was made by Lorch (1958) in which increased leaf tearing in Israel was correlated with reduced bunch mass. However, a possible advantage of leaf tearing, as determined by Taylor and Sexton (1972), is that leaf strips narrower than 100 mm are more tolerant than whole leaves to permanent heat damage at or near the thermal danger point of 47.5°C. In hot, dry periods when leaf resistance to water loss is high, leaf temperature can be 6°C higher on entire leaves than on narrow leaf strips.

Although it is recommended that windbreaks should be used in areas where prevailing winds are strong enough to tear leaves into strips narrower than 50 mm, this has to be balanced against the negative effects of windbreak shading which can significantly reduce the LER, extend cycle duration and reduce yield per annum (Israeli *et al.*, 1995b; Eckstein *et al.*, 1997; and see section 'Photosynthetically-active radiation (PAR)' above). Artificial windbreaks, like those used in Israel and the Canary Islands, are not solid blocks, but have permeability levels between 35 and 50%, not only to avoid excessive shading, but to be more efficient as windbreaks (Rodrigo López, 1973).
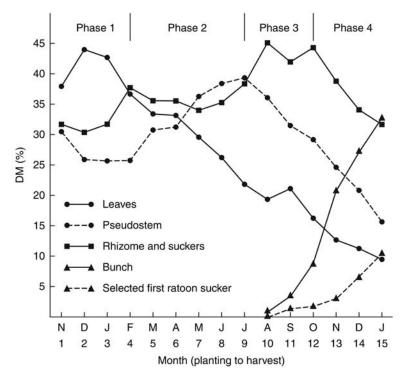
Dry matter (DM) accumulation and distribution

Accumulation of DM and source/sink relationships in a banana plant need to be evaluated over a complete crop cycle in order to understand how the allocation of assimilates relates to different developmental stages of the plant. Once this is known, it can be possible to modify management to ensure that different sink organs of the plant do not compete for assimilates at critical periods, to the detriment of economic yield. This refers particularly to the competitive effects between parent bunch and organs such as the pseudostem and ratoon sucker.

In a study by Veerannah (1988) the DM accumulation and distribution of seven cultivars of different genome and ploidy level were recorded through a crop cycle. Total DM per plant was highest when the *M. balbisiana* genome was predominant, for example ABB 'Karpuravalli'. However, production efficiency as measured by 'harvest index' (bunch DM/total DM) was highest when only the *M. acuminata* genome was present (e.g. AA 'Ney Poovan' and AAA 'Robusta'). Within the *M. acuminata* genome, ploidy level also plays a role in that AAAA 'Bodies Altafort' had a lower harvest index than AAA 'Robusta'.

The latter also had a higher yield per hectare than AA 'Ney Poovan' because excessive DM was allocated to structural organs instead of the bunch with 'Ney Poovan'.

A comprehensive study on seasonal DM distribution in AAA 'Williams' was made by Eckstein *et al.* (1995; Fig. 5.8). Sink strength of the leaves was greatest during the first 4 months after planting (phase 1) after which DM allocation to the leaves declined. For months 7–9 after planting (phase 2) the pseudostem had the greatest sink strength which enabled development of a structural support for the bunch. For months 10–14 after planting (phase 3 and early phase 4), DM was mainly allocated to the rhizome and young suckers. After flowering (month 11), DM from the rhizome was reallocated simultaneously to the developing bunch and selected sucker (phase 4). Throughout the bunch development phase, DM percentage in rhizome, pseudostem and leaves fell rapidly while that of bunch and first ratoon (R1) sucker increased. At month 15 (harvest) the bunch achieved the highest

Fig. 5.8. Seasonal distribution of total dry matter (DM) in a Musa AAA 'Williams' banana plant over a complete plant crop cycle in the subtropics. The planting date was 15 October. Six new data plants were removed and analysed each month. Redrawn from Eckstein *et al.* (1995).

proportional DM in the plant (harvest index = 33%). In this study, specific movement of assimilates was monitored with ^{14}C incorporated into leaf 3 on two occasions. During vegetative growth the most important primary sink for ^{14}C was leaf 1 together with the rhizome. After flowering the developing bunch was the primary sink for ^{14}C assimilates.

In terms of management efficiency to optimize source/sink interactions, it is logical that the first ratoon sucker should have been selected in April, 6 months after planting instead of at flowering in September (11 months). In the former, peak sink strength of the sucker would have coincided with that of the rhizome. The sucker would then be physiologically independent by flowering, and not compete directly with the developing bunch for available assimilates.

Net assimilation rate (NAR), crop growth rate (CGR) and relative growth rate (RGR), which are indices of growth analysis and DM accumulation in the whole plant, are all highest on young, vegetative banana plants during late summer in the subtropics. Seasonal NAR, CGR and RGR correlate closely with seasonal levels of Ps and decline rapidly in autumn, winter and spring. This is due to combined effects of temperatures falling below the optimum for Ps, and plantation leaf area index increasing, thus causing mutual shading and lower Ps efficiency. During the summer of the second growing season, NAR and especially RGR are much lower than the levels achieved in the summer of the first (vegetative) cycle. This is because: (i) leaf area has become physiologically older after flowering (see Table 5.2, row 'Ontogenetic stages'); and (ii) at maximum leaf area index (flowering) a greater portion of the leaf area is shaded and thus less Ps efficient.

A recent detailed review of environmental physiology in the banana plant was compiled by Turner *et al.* (2007).

6

SITE SELECTION, SOIL REQUIREMENTS AND SOIL PREPARATION

SITE SELECTION

The important prerequisite of optimum site selection for bananas has different criteria according to whether the site lies within the humid tropics or the subtropics. In the humid tropics, with flat topography and uniform warm climate, site selection is mainly based on soil classification and drainage. The best banana soils are deep, well-drained loams with high inherent fertility and organic matter content, and an absence of compaction, excessive clay, acidity or salinity. It is mainly soil type and not climatic factors which determines site selection in the tropical lowlands of Central America, and any new site has to conform to certain minimum physical and chemical requirements in the soil. Consequently, in Costa Rican plantations, 67% of the variance in gross yields could be directly attributed to variations in soil type (Veldkamp *et al.*, 1990).

In subtropical and Mediterranean banana areas, site selection for bananas is only partly determined by soil type. Due to climatic extremes, suitable areas have to be carefully selected on the basis of long-term temperature data. As seen in Chapter 4, minimum winter temperatures below 10°C and maximum summer temperatures regularly above 38°C induce growth cessation and a wide range of physiological problems. Therefore, areas with warmer winters and cooler summers are sought. Despite this, however, bananas can be grown successfully in Western Australia and Saudi Arabia, at peak summer temperatures between 40 and 45°C, and also in Israel where winter temperatures of 1–8°C occur. This is achieved by modifying management, in particular through protected cultivation (see Chapter 8).

Within broadly suitable temperature zones in the subtropics, specific site selection has to be based on many other factors, as follows:

- sufficient elevation for frost protection;
- shelter from prevailing winds;
- avoiding known hail belts or storm areas;
- avoiding areas prone to waterlogging or salinity;
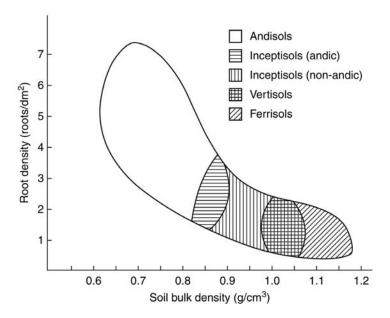
- ensuring proximity to perennial water supplies for supplementary irrigation;
- a suitable fertile and well-drained loamy soil;
- an appropriate aspect and slope according to hemisphere and latitude.

Regarding aspect and slope, Bozalek (1980) demonstrated that banana sites in South Africa at 25°S, orientated northwards with a 20° slope, received 47% more solar radiation in midwinter than was received by a horizontal surface, and 220% more than a southerly aspect, also with a 20° slope. This effect is more pronounced at higher latitudes, and in winter rather than summer, and it has considerable implications for increased banana productivity in the subtropics.

TROPICAL SOIL CLASSIFICATION

There are a wide variety of soils in tropical banana areas which vary in their suitability for growing the crop. According to Stover and Simmonds (1987), soil types include ferruginous, leached ferralitic, weathered ferralitic, ferrisols, eutrophic brown soils, humic latosols, lowland tropical podzols, andisols, arenosols and regosols, vertisols, halomorphic soils, gleys, organic soils, alluvial soils, acid sulfate soils and paddy soils.

The most important and productive tropical soils are the alluvials (mainly classified as inceptisols) but they constitute only 8% of the area. Textures range from sand to heavy clays, although loams and clay loams should be preferentially chosen. Most of the world's export bananas are produced on alluvial loams in Central and South America. However, intensive drainage provision is still required in high rainfall areas. Unlike most tropical soils, the alluvials are highly fertile, and usually only require fertilization to replace the nutrients removed by the fruit. These soils can sustain continuous high banana production for many years. Another good soil type is the eutrophic brown soils which are very productive and have high organic matter content. Bananas and plantains for local use are widely grown on these soils. Andisols are volcanic soils of high natural fertility and low compaction potential (Fig. 6.1) which also favour banana and plantain production. Organic soils contain more than 20% organic matter and will sustain good banana growth provided the water table is below 1 m deep. Less than 1% of tropical soils are classified as organic. The other soil types mentioned are either unsuitable or only marginally suited for banana production and should be avoided if possible. For example, the ferralitic soils are highly weathered, leached and acid. Their fertility decreases rapidly after forest clearing, resulting in multiple nutrient deficiencies. Intensive banana production on these soils requires heavy fertilization and liming, whereas traditional plantain production requires much human and animal refuse, together with frequent bush fallow rotations.

Fig. 6.1. The relationship between soil classification, soil bulk density and rooting vigour (root density) in vertical plans of the root profile under banana plants at flowering stage in Martinique. Adapted from Delvaux (1995).

SOIL PHYSICAL REQUIREMENTS

According to Delvaux (1995), soil physical factors important for vigorous root growth of bananas and plantains are porosity and mechanical impedance (related to compaction), aeration and natural drainage (related to waterlogging), water-holding capacity (WHC) and soil temperature. Stover and Simmonds (1987) refer to a grading system for the physical evaluation of tropical alluvial soils in terms of banana production. Grade 1 soils (very good) have no limitation to sustained high production. They are flat (no runoff), well drained, deep, medium textured (loam), well structured and permeable. There are no stones, and there is no danger of flooding or salinity. Grade 2 soils (good) have one or more minor limitations as follows: slightly sloping, tendency to light sandy or heavy clay texture, moderate structure, slightly stony, moderate drainage, reasonably permeable, slight risk of flooding. Grade 3 soils (fair) are only marginally useful for bananas because one or more of these physical attributes can be severely limiting. Grades 4 and 5 are totally unsuitable for bananas due to severe physical deficiencies that lead to uneconomic yields.

Porosity and compaction

The high sensitivity of banana roots to compaction has been well documented by many researchers and experienced by many growers to their cost. Plantation longevity and sustained high production are dependent on porous, loose soils allowing unimpeded root extension. Macroporosities lower than 5% caused root deformation and limited development (Avilán *et al.*, 1982). Horizontal and vertical root spread are severely restricted in compacted soil, and plant vigour and yield are reduced accordingly. In soils not limited by poor drainage, banana root density and soil bulk density are inversely related (Fig. 6.1).

Although soil compaction can be alleviated by deep ploughing or ripping, it is not recommended to do this in an existing plantation otherwise the benefits of reduced compaction can be offset by severe root damage. Deep soil tillage (cross-rip to minimum 800 mm depth) is usually carried out before replanting and thereafter recompaction must be avoided by keeping heavy equipment out of the plantation. When checking compaction with a digital penetrometer, the soil strength should not exceed 1500 kPa down to 800 mm depth. Organic matter can improve soil structure and porosity, but the benefit is short lived in tropical soils due to rapid decomposition.

Aeration and drainage

Waterlogging, enhanced by compaction, causes a depletion of air spaces in a banana soil, and then oxygen starvation and root death can quickly follow. There is an optimum air:water ratio in the pore spaces below which banana roots suffer from oxygen deficiency. Compaction has the effect of increasing the micropore:macropore ratio, which in turn induces quicker water saturation and oxygen starvation when waterlogging occurs.

A naturally well-drained soil improves air-filled porosity, and this is more pronounced when the soil has a low bulk density, making waterlogging unlikely or, at worst, only temporary. A banana root profile dug in a soil with compaction/waterlogging problems shows a low root density and individual primary roots have a dull grey colour with necrotic patches on them and a lack of lateral roots. In a well-drained, porous soil of low bulk density, primary roots are numerous, thick and white, with prolific lateral branching (see Fig. 3.1).

In the humid tropics, the best soils for banana production should have a water table below 1200 mm and drainage must be provided to allow for this. Numerous research studies conducted on bananas and plantains relate increased plantation vigour and yield to depth of water table. Avilán *et al.* (1979) recorded banana yields of less than 6 t/ha in an undrained soil with the water table at 350 mm. Where subsoiling and terrace drainage were applied, yields increased to 33 t/ha. With plantains, Irizarry *et al.* (1980) showed how

yields increased from 5 to 25 to 38 t/ha, as water table depth increased from 120 to 240 to 360 mm, respectively.

According to Stover and Simmonds (1987), provision for extra drainage is the single most important infrastructure for maximum banana production in the humid tropics. Complex drainage systems are a feature of most tropical plantations, the objective being to lower the water table from around 700 mm to 1200 mm. A shallow network of small furrows is dug between plants, and these lead into a more systematic pattern of tertiary and secondary drains, and finally into a deep, wide primary drain along the plantation perimeter. Excess water is effectively removed this way, but must sometimes be pumped out of the primary drain. In places where temporary flooding may occur, pre-plant drainage ditches must be prepared. In North Queensland (3000 mm rain/year), waterlogging is a common problem on certain soil types and either tile drains, mechanically dug trenches or ridge-and-furrow planting systems are used to counteract this problem. Ridges are more appropriate for tramline (double-row) plantings with two narrow rows on a raised ridge and with plants tied together with twine to secure them. In the subtropics, lower rainfall reduces the need for elaborate drainage, but temporary waterlogging problems do occur on certain coastal soils or inland during heavy summer rain. In dry Mediterranean areas, like Israel and Canary Islands, waterlogging is not a problem. On the contrary, the scarcity of water causes salinity problems in the soil, and heavy winter rains or periodic over-irrigations are required to leach salts out of the rootzone.

Water-holding capacity (WHC)

While it is clear that waterlogging can be a severe limiting factor, it is nevertheless important that the soil is able to retain a large volume of water at field water capacity, which still allows for adequate air-filled porosity. Banana roots utilize water only at high water potential values in the soil, while regular and severe decreases in soil water potential restrict the volume and growth rate of roots. A light sandy soil requires more frequent water replenishment to maintain field water capacity than does a loam soil. In a subtropical or Mediterranean area, the maintenance of field water capacity becomes a vitally important management factor, and this will be dealt with in more detail in Chapter 10.

Soil temperature

Optimal day/night temperatures for banana developmental processes (LER and RER) are in the region of 33/26°C (Turner and Lahav, 1983; Robinson and

Alberts, 1989). Conversely, as seen in Fig. 5.2, minimum soil temperatures of 10–15°C severely restrict RER, suggesting that soils should be exposed as much as possible to direct sunlight in a subtropical winter.

Soil texture

Sandy–clay loam soils are best suited for banana cultivation. The optimum soil texture for bananas and plantains should be around 30:10:60 (clay:silt:sand) since these ratios provide for better aeration, increased water infiltration and drainage, while also presenting the best balance between WHC and cation exchange capacity (CEC).

SOIL CHEMICAL REQUIREMENTS

There are three main aspects here, namely cation balance, soil acidity and soil salinity. Pre-plant soil sampling and analysis to determine soil chemical characteristics and pH, are essential prerequisites for intensive banana production, appropriate fertilizer recommendations and high yielding plantations.

Cation balance

The most important cations in a banana soil are potassium (K), calcium (Ca), magnesium (Mg) and phosphorus (P). In certain soils there may be a specific shortage of minor elements such as zinc (Zn) or boron (B). The banana crop is very demanding on K and large quantities of this element are removed from the soil. K has been the most widely researched element in banana soils, and it is very sensitive to cation imbalances (Lahav, 1995). In particular, the K:Mg and Ca+Mg:K ratios are very important, and K deficiency symptoms may be observed when soil Mg or Ca reserves are high, relative to K. The correct cation balance must be achieved by judicious use of applied Mg, Ca and K. In South Africa, good growth on sandy soils can be achieved if the ratio of K to Mg is approximately 0.25, whereas on heavier soils a ratio of 0.5 is required. A soil content of 200–350 mg/kg K is usually sufficient for normal growth of bananas, but if large quantities of Mg or Ca are present, a K deficiency may still develop. In the case of high K:Mg ratio, Mg should be applied as magnesium sulfate, and in the case of low K:Mg ratio, both Ca and K should be applied to replace Mg in the exchange sites. The optimum proportion of different cations in the total CEC is Ca 55–75; Mg 18–30; K 6–10 and Na less than 2 meq %.

The P requirement of the banana plant is not very high and it would seem that the plant can absorb P readily. A soil P status of less than 10 mg/kg

is regarded as deficient and P fertilization then becomes essential. It is then advisable to apply any source of P at pre-planting stage, like superphosphate or, in the case of organic cultivation, rock phosphate, and to work it in deeply.

Soil acidity

For optimum productivity, the soil pH, measured in water, should be between 5.8 and 6.5 (5.0 and 5.8 if measured in KCl). If the soil is too acid, dolomitic or calcitic agricultural lime can be added, depending on the Ca:Mg ratio in the soil. Lime should be applied pre-planting and worked in deeply, well before planting. After planting, lime cannot be incorporated effectively since mechanical cultivation causes excessive root damage. Soil pH usually shows a downward trend with regular nitrogen application and irrigation. An initial water pH of 5.8 may thus decrease in the rootzone after a few years of cultivation. One effect of high soil acidity (low pH) is to cause Ca and Mg deficiencies. Another negative effect is to increase the content of exchangeable aluminium (Al) and the availability of some minor elements up to toxic levels (e.g. manganese). High exchangeable Al may be toxic in itself or else reduce the accessibility of Ca and Mg on exchange sites, upsetting the K:Mg balance. Liming is needed to rectify these imbalances. It is usual to add up to 6 t/ha lime on pre-plant land with a low pH, but it may take 2 or 3 years to register on pH levels.

Soil salinity

Salinity is usually only a problem in dry Mediterranean climates (Israel and the Canary Islands) with saline soil, an absence of summer rain and poor quality irrigation water. Excessive salinity increases the sodium (Na) content of the soil which reduces K uptake and decreases yield. The optimum ratio for soil K:Na is 2.5 and Na should ideally be less than 2% of the total exchangeable cations on a milli-equivalent % basis. Values of electrical conductivity in the soil solution higher than 2.5 dS/m are also detrimental for root development (Rodríguez and Lobo, 2008).

SOIL BIOLOGICAL LIMITATIONS

In addition to physical and chemical properties of soils suitable for banana cultivation, certain biological limitations exist in some soils which can make the soil unsuitable for the crop. For example, the plant parasitic nematodes *Radopholus similis*, *Pratylenchus coffeae* and *Helicotylenchus multicinctus* can proliferate in sandy soils, and banana cultivation may become impossible

unless expensive chemicals are applied. The soil-borne pathogen *Fusarium oxysporum* f. sp. *cubense* (FOC), which causes Panama wilt disease, is present in many soils, especially in subtropical localities. Race 4 of this pathogen has infected many soils in Taiwan, Queensland, the Canary Islands and South Africa to the extent that such soil must be abandoned for banana use, or in the case of the Canary Islands, completely renewed. Chemicals cannot be applied and the definitive solution for infected soils is to develop commercially-acceptable resistant or tolerant cultivars, which is proving very difficult. In the meantime, soil inoculation with mycorrhizae (Borges *et al.*, 2007) may help to reduce the infection index of FOC. In virgin soil, it can be expected that there are no plant-pathogenic organisms to inhibit banana production. However, in banana replant soil, it will eventually become necessary to fallow the soil or rotate the cropping for a year or more to starve out nematodes and banana weevil. The influence of soil-borne disease and nematodes will be discussed in more detail in Chapters 12 and 13, respectively.

SOIL PREPARATION

Soil sampling

A representative soil sample is an essential prerequisite before planting bananas for intensive commercial management. This applies irrespective of whether the site is a virgin soil, banana replant soil or in a rotation cropping system. The analysis of such a soil sample will determine the pH and chemical composition of the soil, and indicate whether any remedial applications are necessary, usually either lime, gypsum, superphosphate or K. Relationships between soil chemical analysis, leaf analysis and yield in banana have been shown by Turner *et al.* (1989). To be representative, the sample should comprise at least ten subsamples taken from a depth of 100–300 mm for top soil and 300–600 mm for subsoil and from sites spread systematically over the proposed planting area. Not more than 3 ha should be used per main sample, and less if the soil type changes significantly. In addition, a soil sample should be taken to indicate whether a pre-plant nematicide treatment is necessary.

Mechanical preparation

Soil preparation for planting depends largely on topography and soil type. On flat land, soil should normally be ploughed first, then ripped before planting, to reduce compaction within the rooting profile and to produce a suitable tilth for planting. Clay soils require a more thorough preparation than ferralitic soils.

Ploughing should occur to a depth of 200–300 mm while the soil is moist. Any lime, P or K requirement, as determined from the soil sample, should

be incorporated deeply with this operation. After ploughing, cross ripping to 1 m depth has been effective in South Africa where compaction or impeding layers were present. Following these operations, only small planting holes or 300 mm deep planting furrows are required for tissue culture plants. The importance of soil preparation for plantains was demonstrated by Irizarry and Rodriguez (1981) who found pre-plant ploughing and harrowing increased plant crop 'Maricongo' plantain yields to 41 t/ha compared with 26 t/ha on non-tilled plots.

On sloping land a different preparation strategy is required, primarily to prevent surface erosion. Effective conservation planning is essential in order to retain topsoil but dispose of excess water safely. Phased development of a sloping banana site involves establishing grassed waterways, digging storm water drains and designing a conservation structure. On slopes of 25% or greater, bench terraces should be constructed for single or double rows of bananas. On slopes less than 25%, contour channel banks may be sufficient. Construction of these is easier than with terraces, but the banks should be covered with a binding grass, and trash lines provided in the channels.

Where slope or rocks or lack of access to equipment prevents mechanical cultivation, large planting holes must be prepared by hand. The dimensions of the planting hole should be about 400 mm^3. Pre-plant fertilizers and nematicides are then calculated per planting station and incorporated with the topsoil in the bottom of the hole. With small-scale, limited-resource farmers, household refuse and organic matter can be mixed with topsoil in the planting holes. Provision for adequate drainage is a vital aspect of soil preparation in the humid tropics and this is discussed earlier in the chapter.

The volcanic origin and steep slopes of the Canary Islands forced growers in the past to build bench terraces (*sorribas*) in order to maximize available land This laborious and costly operation involves construction of gravity retaining walls (either concrete or mortarless stone), usually topped with cinder-block windbreak fences around 2.5 m in height. The bedrock of these plots is covered with a 0.3–0.4 m layer of coarse aggregate to facilitate drainage, followed by 0.80–1.00 m of suitable soil which has been transported from higher elevations (Fig. 6.2). Once levelled, organic matter (manure) is incorporated at 60–80 t/ha, together with standard mineral fertilizers (usually 1.5–2.0 t/ha superphosphate and 0.8–1.0 t potassium sulfate) and other mineral amendments depending on soil analysis (Galán Saúco, 1992). Not many new terraces are built nowadays since land at low altitude is scarce due to tourist or urban development.

Fig. 6.2. Soil preparation in the Canary Islands. Note retaining walls and good quality soil imported from higher elevations on the islands.

7

Establishing a Plantation

TYPES OF PLANTING MATERIAL
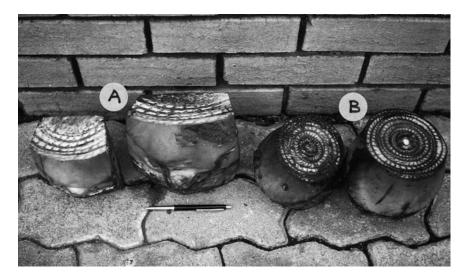
There are two broad groups of banana planting material, namely conventional and *in vitro* (tissue culture). Currently, tissue culture material is used almost exclusively in commercial plantations worldwide.

Conventional planting material

This group comprises mainly suckers and bits. The term 'sucker' refers to a detached rhizome in which the central growing point forms the new plant while all axillary buds are removed (Fig. 7.1b). The term 'bit' refers to a rhizome in which the central growing point is either naturally absent (post-flowering plants), or mechanically removed, leaving an axillary bud to grow out and produce the new plant (Fig. 7.1a). These types can also differ in size, with varying amounts of rhizome storage material to sustain new growth.

Suckers can be either young 'peepers' which have just emerged through the soil surface; large 'sword' suckers (or spearpoints) which have narrow leaves, tapered pseudostem and large rhizome (see 1 in Fig. 3.4); 'water' suckers which have broad leaves, narrow pseudostem and a small rhizome (see 2 in Fig. 3.4); or suckers with large mother rhizome attached for extra sustenance. Water suckers lack vigour and are to be avoided as planting material because they have a weak connection with the parent, minimal storage reserves and weak rooting potential. Sword suckers, on the other hand have a strong physical and physiological connection with the parent and a large volume of storage reserves to boost growth. In general, tropical banana growers still using suckers prefer tall sword suckers which have large rhizomes. Such large units are used in order to achieve a higher establishment rate in wet conditions.

Bits are derived either from dividing large parent rhizomes after bunch harvest, or by gouging out the central growing point of a smaller pared sucker

Fig. 7.1. Conventional banana planting materials. (A) Small and large 'bits' with axillary bud on the side. (B) Small and large 'suckers' which grow from the central growing point, and axillary buds are removed.

in favour of an axillary bud. Large rhizomes can be split into several bits, each with a prominent side bud. Conventional planting material is still occasionally used in the subtropics, and here it usually comprises cut and pared suckers or bits of 1–2 kg mass which are treated for nematodes before planting below soil level. During the past 25 years, conventional planting material has declined steadily in favour of *in vitro* plants. Currently in South Africa, Taiwan, Israel and the Canary Islands, there is virtually no commercial use of conventional planting material, and this is becoming the case in the tropics as well. With traditional banana growers in poor countries, conventional planting material is still widely used due to lack of access to or finance for *in vitro* plants. However, this practice has many associated risks, especially in relation to plant and soil hygiene.

In vitro plantlets

This process involves the micro-propagation of a sucker growing point under sterile conditions (Israeli *et al.*, 1995a). Since about 1985, banana planting material derived from *in vitro* techniques has been used commercially in most countries as an alternative to conventional planting material. *In vitro* planting material is now widely used in certain Mediterranean and subtropical countries (Israel, the Canary Islands, Taiwan, South Africa, Australia and

Morocco) which have developed the laboratory technology and field testing to the point where commercial acceptance has become almost automatic. Latin American countries which export dessert bananas have not yet completely adapted to *in vitro* plantlets but their use is more and more frequent.

Advantages of using in vitro-propagated banana plants

There are many practical advantages of using *in vitro* plantlets, which have fully justified the intensive research and high capital investment costs necessary to establish this technique as a major breakthrough in banana production technology.

- The ability to deliver large numbers of plants rapidly, hygienically and safely, to any destination in the world. This logistical advantage is particularly useful for starting an industry in a new area.
- Advantages at planting out in the field – *In vitro* plants in bags have 100% establishment rate, therefore no replacements are necessary except for somaclonal variants discovered after planting. There is no disturbance of the root system so growth continues immediately after planting. Thus, an *in vitro* plant in the field will have about ten functional leaves before a planted sucker has emerged through the soil surface. *In vitro* plants can be established successfully in the field during every month of the year, whereas conventional suckers cannot establish properly during a cold winter, and many deaths occur if planting coincides with wet summer conditions.
- Uniformity and harvest timing – *In vitro* plants in bags can be specially selected for uniformity of size and shape. These plants then grow and flower uniformly and can all be harvested over a very short period, making crop timing more accurate.
- Precocity and high production – It has been widely reported from research that *in vitro* plants grow larger pseudostems and give heavier bunches than conventional suckers in the first crop cycle (Table 7.1). Carry-over effects into the second cycle have also been reported in which follower suckers from *in vitro* mother plants gave larger plants and bunches than suckers from conventional plants (Table 7.1). Increased vigour and yield with *in vitro* plants is expressed by taller and thicker pseudostems, larger leaf area, more hands per bunch, and shorter time to harvest, than with conventional suckers. The physiological superiority of *in vitro* planting material is described fully in Chapter 5.
- Pest- and disease-free plants – *In vitro* plantlets are guaranteed free from nematodes, and fungal and bacterial pathogens. If planted out on 'clean' soil, *in vitro* material ensures a reduction in the use of nematicides and fungicides. Conventional material cannot be guaranteed hygienically clean.
- Rapid multiplication – If a new cultivar, a horticulturally-superior selection or a disease-resistant mutation is discovered, this can very rapidly be distributed through the industry by *in vitro* methods. Up to 2000 individual

plants can be produced from a single growing point in 1 year of subculturing. With the nursery sucker method, only about ten suckers can be produced from one plant in a year.

- Plant breeding by somaclonal variation – While somaclonal variants are normally visibly identified as undesirable mutations, this phenomenon also offers the possibility to select elite plants, horticulturally superior to the parent plant, or with disease resistance. Many thousands of *in vitro* plants have to be screened over several crop cycles, but by this technique, some reputable tissue culture laboratories have identified superior stable selections of common Cavendish subgroup cultivars, which are being commercially distributed.

Disadvantages of using in vitro-propagated banana plants

There are several disadvantages, some of which have prevented the universal acceptance of *in vitro* material in some countries.

- Increased costs – It is expected that a grower will have to pay more for a field-ready *in vitro* plant in a bag than for a normal sucker. This creates the perception that establishment costs are much higher in a plantation of *in vitro*-grown plants. This may be true but the use of *in vitro*-grown plants is normally more cost-effective in that the farmer is paying for established, uniform, pathogen-free plants that produce up to 20% increase in annual yield per hectare (Robinson *et al.*, 1993a).
- Extra care at planting and establishment – Young *in vitro* plants are very tender and sensitive to stress after establishment. They have no nutrient or carbohydrate reserves and they have to receive optimum management to ensure that neither the tender leaf area nor the root volume is damaged or stressed in any way. This entails extra attention and added costs at this critical stage. After about 5 months they can be treated the same as normal sucker plants.
- Somaclonal variation – The occurrence of off-type plants during *in vitro* propagation of bananas has been widely reported and discussed. The frequency ranges from 50% (Daniells, 1988a), 25% (Stover, 1987) and up to 20% (Israeli *et al.*, 1988b), to the more common lower levels of 3% (Hwang and Ko, 1987; Drew and Smith, 1990), 1% (Arias and Valverde, 1987) and 1.8% (Robinson *et al.*, 1993a) (Table 7.1). With plantains, large differences in the degree of somaclonal variation were found by Vuylsteke *et al.* (1991). French plantains were stable, with off-types barely exceeding 2%. However, 'False Horn' plantains ranged from moderately stable (5%) to highly unstable (25% mutations). These values contrast with the very low 0.0001% somatic mutation rate estimate for conventional plantations. The most common types of somaclonal variant are: (i) stature variants (dwarfism) which are most prevalent in the Cavendish subgroup; (ii) foliage variants (mosaic, rubbery or mottled-green thin leaves resembling virus infection);

Table 7.1. Field comparison between *in vitro*-derived Cavendish banana plants and conventional suckers, in terms of pseudostem height and bunch mass (plant crop) and bunch mass (first ratoon), according to various researchers. The rate of occurrence of somaclonal variants (off-types) is also presented.

	Planting material					
	'Giant Cavendish' (Hwang *et al.*, 1984)	'Grand Nain' (Arias and Valverde, 1987)	'Williams' (Daniells, 1988a)	'Williams' (Israeli *et al.*, 1988b)	'New Guinea Cavendish' (Drew and Smith, 1990)	Three Cavendish cultivars (Robinson *et al.*, 1993a)
Plant height (m)						
In vitro	2.56	2.48	2.77	2.68	2.37	2.72
Suckers	2.57	2.83	2.46	2.39	2.20	2.49
Bunch mass – PC (kg)						
In vitro	26.0	31.7	34.7	35.1	35.9	40.7
Suckers	25.5	30.2	32.3	31.8	30.6	35.3
Bunch mass – R1 (kg)						
In vitro	N/A	N/A	N/A	36.4	34.1	44.9
Suckers	N/A	N/A	N/A	30.7	33.3	39.9
Off-types (%)						
In vitro	3.0[a]	1.0	50.0	Up to 20	3.0	1.8

N/A, data not available; PC, plant crop; R1, first ratoon.
[a] Hwang and Ko (1987).

(iii) pseudostem variants (black, red or pale green stems); and (iv) bunch variants (affecting peduncle, fruit, sex ratio of flowers, bracts and male bud).

In order to reduce the proportion of somaclonal variation to a commercially acceptable level, it is recommended that: (i) only vigorous sword suckers be selected from superior mother plants; (ii) subculturing and multiplication should be limited to only 1000 plants per explant; (iii) plants should be screened in the nursery for early detection of variants; (iv) only genetically-stable parent clones should be used; and (v) there should be a constant feedback from nursery to laboratory on variant counts. The main disadvantage is when variants pass through the nursery screening and later have to be culled from a field plantation.

- Transmission of viruses – Since banana viruses are not eliminated during laboratory multiplication, there is a risk of transmitting the virus from infected to non-infected areas of the world via *in vitro* material. Wherever possible, mother blocks for *in vitro* propagation should be located in virus-free conditions and, in addition, mother plants should be indexed with a monoclonal antibody or DNA probe test to confirm freedom from viruses. In reputable laboratories, this has become standard procedure for *in vitro* consignments from one country to another, and even from laboratory to field within the same country.
- Physical instability of *in vitro* plants in the field – Due to the vigour of *in vitro* plants and the rapid and early production of suckers with swelling rhizomes, the mother plant rhizome is often pushed above soil level where it becomes unstable (condition called 'high mat'). After flowering, the plant can easily be blown over by wind, and stringent propping is required. This disadvantage may be perpetuated if the selected sucker is also set above soil level. The problem can be minimized with strict sucker management (see Chapter 11, section 'Sucker Management').

MULTIPLICATION AND PREPARATION OF PLANTING MATERIAL

Conventional planting material

There are three main sources for multiplying conventional banana planting material for commercial purposes. First, a nursery area can be established solely for the purpose of raising the maximum number of suckers per unit area. Second, extra suckers can be allowed to grow in a commercial plantation, for later excavation when required for planting. Thirdly, suckers and bits can be prepared from a plantation that is to be removed.

Nursery production
A banana nursery differs from a commercial planting in that: (i) planting density is much higher; (ii) desuckering is unnecessary; and (iii) parent plants

are decapitated at flowering so that reserves in the pseudostem and rhizome are available for the crop of suckers, and to ensure that maximum light is received by these suckers. In this way it is possible to obtain up to ten vigorous planting material suckers per parent plant per year (possible 25,000 suckers/ha) although both number and vigour of emerging suckers tend to decline with each ratoon cycle. One vigorous sucker per plant must be left to grow fully and continue the nursery cycle. For plantains, Wilson *et al.* (1985) reported a technique to boost nursery sucker production around a parent plant. This consisted of destroying the apical meristem through a hole in the pseudostem, but leaving the foliage intact. By suppressing apical dominance but retaining the foliage, 70% more suckers were produced 2 months earlier than when the parent foliage was removed as normal.

A nursery site should be established on clean land, planted with clean planting material and watered with 'clean' irrigation water. It is very important to maintain the nursery in a healthy and disease-free condition. The nursery area should be fenced so that it is accessible only via a foot dip. All materials, equipment and implements used in the nursery should be disinfected and retained within the fenced area at all times.

Suckers from a commercial plantation

The cropping of suckers from a commercial plantation is widely practised although certainly not to be recommended. The implications are that: (i) fruit yields from the plantation are reduced; (ii) the process of sucker excavation damages the roots of the mat; and (iii) sucker removal becomes a systematic method of spreading nematodes and soil-borne diseases between mats. Robinson and Nel (1990) tested the effect of retaining and later excavating one large nursery sucker per mat on the plantation yield of AAA 'Williams'. When the height of the nursery sucker was allowed to reach 1.0 m before excavation, yield of the selected ratoon follower was reduced by 7.9% compared with a follower having no competing nursery sucker. When the height of the nursery sucker was allowed to reach 1.5 m, yield of the selected follower was reduced by 12.6%.

Plantation to be removed

A more acceptable source of supply for conventional planting material is from an old plantation due to be removed. In this case all suckers can be left to grow for several months before removal date. When required, all these suckers can be excavated with no adverse effects, and the parent rhizome can also be cut up into two or three 'bits'. Nematode levels could be high in such an old plantation, thus all planting material from this source must be carefully pared, inspected and dipped in nematicide before use.

Preparation of planting material

After excavation, it is important to divide the available plant material into groups of uniform size to ensure uniform growth in blocks so that each plant

will derive equal benefit from the available sunlight. In practice the uniform growth seldom occurs. Delays between excavation and planting should be avoided because Patel and Chundawat (1988) found that banana suckers planted fresh from lifting gave better establishment, faster cycle and larger bunches than suckers stored for 10 days before planting.

For optimum hygiene, roots should be removed and the rhizome pared to expose any possible nematode infestation or disease infection (Fig. 7.1). As a further precaution, pared material can be dipped in hot water at 53–55°C for 20 min, although the sucker mass should be greater than 1 kg for this. Despite these precautions, it is unwise to move conventional planting material between designated banana-growing areas. Such movement is in fact prohibited in Queensland due to Fusarium wilt and bunchy top virus, in South Africa due to Fusarium wilt and *Radopholus similis* nematode and in the Canary Islands due to *Cosmopolites sordidus* (banana weevil).

In vitro planting material

A nursery similar to that described under 'Nursery production' above is also the option of choice for an *in vitro* banana mother block, in which all the same specialized management and hygiene precautions are strictly followed. In addition, superior genetic material is established in the mother block from the breeding programme of the laboratory, and the entire area may need to be covered by aphid-proof netting for virus protection.

Multiplication of plantlets
The use of *in vitro* planting material has opened up the possibility of rapid and large-scale multiplication of bananas, with a minimum of risk attached. It is possible to produce 2000 *in vitro* plantlets from one original explant within a year. However, some laboratories are adopting a safer procedure of limiting the progeny of one explant to 1000 plantlets or fewer. In this way it is possible to reduce the number of somaclonal variants that tend to occur with excessive subculturing. Thus, 1000 nursery suckers have the potential to produce up to one million plants in 1 year which is enough to establish 500 ha of new plantations (at 2000 plants/ha). Using the *in vitro* route, the banana farmer does not need to construct his or her own nursery, deplete productive plantations or buy in suckers from a place of dubious origin.

Preparation of planting material
Meristem shoot tips are taken from vigorous sword suckers on selected plants in the mother block, as the source for explants. Under aseptic conditions the shoot tips are trimmed to cubes with 5 mm sides and transferred to a culture medium (Fig. 7.2). Various culture media are described in the literature and cultures are maintained at 28°C and 70% relative humidity in a 16 h light

Fig. 7.2. Initiation plug from inside a nursery sucker being dissected under sterile conditions. This plug contains the apical meristem.

Fig. 7.3. Separating proliferating shoots for re-establishment on fresh agar (a process called subculturing).

cycle. Subculturing of small green shoots is done after 4–6 weeks and repeated at similar intervals (Fig. 7.3), placing the propagules on a medium enriched with cytokinin. For rooting, the propagules are placed on a different medium with reduced cytokinin and increased auxin. Rooting takes 6–8 weeks, and for removal from *in vitro* conditions, the plantlets should be about 50 mm tall with four or five leaves and a well-developed root system. The plantlets must first be acclimatized to *ex vitro* conditions (weaning) and then grown out to size (nursery hardening) for planting in the field.

For weaning, plantlets are transferred to polystyrene trays with small planting cells containing sterilized potting mixture, inside a plastic tunnel (Robinson and Galán Saúco, 2009a). Plants must receive optimum temperature (25–32°C), reduced light and high humidity (>90%). Frequent misting is beneficial in the first 7–10 days, after which new roots and leaves will have developed. At this stage foliar feeding can be applied. After 5–6 weeks, weaned plantlets are transferred to a potting medium in polyethylene bags of from 1 to 5 l volume, and placed under a nursery shade net protection for hardening (Robinson and Galán Saúco, 2009b). At optimum temperatures, the plants take 6–8 weeks to reach field-establishment stage. During the first part of this nursery growing-out stage, plants should be under 50% shade and later, placed in the open to harden them before field establishment. Watering and fertilizing should be regularly and carefully applied, and somaclonal variants must be eliminated before transfer to the field. For optimum establishment, plants of 300 or 400 mm height in 2 or 3 l bags, respectively, give the best results (Fig. 7.4). The use of old, pot-bound plants should be avoided.

For up-to-date reviews on the weaning and nursery hardening of *in vitro*-produced banana plants refer to Robinson and Galán Saúco (2009a) and (2009b), respectively.

Fig. 7.4. Vigorous and uniform *in vitro*-derived nursery plants in 3 l bags, ready for establishing in the field. Plants are about 400 mm tall from soil level to the junction of the two youngest leaves and they each have about six functional, healthy leaves. The plants are ideal specimens which are not stressed, etiolated, lanky or pot bound in any way, and somaclonal variants can easily be detected before planting out.

METHODS OF PLANTING

Conventional planting material

With adequate soil preparation as described in Chapter 6, it is only necessary to dig a planting hole slightly larger than the planting material, or even a furrow in which the suckers or bits are placed according to the required spacing. Larger holes are required where no uniform soil preparation took place, since growth and yield are improved with deeper planting. With pared suckers or bits, between 100 and 200 mm of soil should cover the cut pseudostem surface. The side bud on bits should thus be 200–300 mm below the soil surface and all buds should face the same direction to facilitate 'marching' of the subsequent ratoon cycles. Extra suckers or bits should be planted into large black polyethylene bags (about 1% of the number planted in the field). These potted plants can later be used to replace any that die in the field, with minimal disruption of plantation uniformity.

In vitro plants

Planting depth and method have become vitally important issues with *in vitro* plants due to the problem of rhizomes forcing their way above soil level (see earlier under 'Disadvantages of using *in vitro*-propagated banana plants'). First, the polyethylene bag should be cut and removed carefully so that the entire root ball can be planted without the soil breaking up. Collapsing soil exposes and damages the roots, causing a lag phase before growth recommences. When planted, soil level in the bag should be at least 100 mm below the surface level of the field. With infilling, the young pseudostem can be further supported by mounding up soil around it. More soil can be heaped up around the pseudostem 2 months after planting. Despite these precautions some developing rhizomes still emerge above soil level, due to pressure from developing suckers. Currently the recommended method is to excavate the planting hole at the bottom of a prepared furrow (300 mm deep). After the first flush of suckering has occurred and the plant has stabilized its position, the furrow is filled in to the normal soil level, with the rhizome stabilized underground.

Post-plant management of young *in vitro* plants is extremely important (Galán Saúco and Robinson, 2010). The first 3 months is when these plants are physiologically very active (see Chapter 5 section 'Type of planting material') and when root and leaf growth is at a maximum. There must be no stresses on the plant, or any constraints whatsoever during this stage, otherwise the inherent advantages of juvenile tissue culture vigour could be lost to a large degree. The following aspects must receive particular attention:

- Nitrogen fertilization should be applied frequently to stimulate leaf area and increase photosynthetic **capacity** at a time when photosynthetic **efficiency** is very high.
- Foliar sprays of zinc and boron should be applied twice within the first 4 months.
- Frequent watering in the immediate rootzone of the planting bag should take place for the first 2 weeks.
- Evaporative cooling of the leaf area should be achieved by sprinkling with water once or twice a day during peak evaporative demand (1200–1700 h) until the leaves have acclimatized. This can prevent wilting and leaf burn. Microspinner systems are best for this essential process.
- Somaclonal variants should be removed and replaced immediately with normal plants.
- There should be no gouge or chemical desuckering for the first 3 months. Suckers should simply be cut off at soil level. However, growing points should be destroyed before the sucker rhizomes have enlarged and start to push the parent rhizome upwards.

- There should be effective weed control by hand. Weeds compete with young *in vitro* plants which have a strong root system but no reserves. Avoid contact or hormone weedkillers.
- Nematodes should be completely controlled.

Early post-plant management of *in vitro* plants is discussed in more detail by Robinson (1994) and Galán Saúco and Robinson (2010).

TIME OF PLANTING

Optimum planting time for bananas is dictated by two major factors, namely: (i) timing the crop harvest to coincide with high market prices; and (ii) timing the planting date to benefit from, or to avoid, certain climatic conditions. Very often these two factors interact to severely limit the planting date range (Table 7.2). Timing for markets is usually only effective for the plant crop and possibly for the first ratoon cycle, after which natural harvest spread nullifies this benefit.

Tropical localities

In the humid tropics of Central America, planting date is not usually related to crop timing since replanting is infrequent, and annual production is fairly evenly distributed for export. However, planting cannot occur during the peak rainy season due to rotting of young plants. Where there is a dry season but no irrigation, planting time is just before the rainy season. In the semi-tropics of North Queensland, planting is limited to winter (May–June) and spring (August–October). Summer (November–April) is either too hot or too wet for successful vitroplant establishment, and rotting may occur. Furthermore, winter/spring plantings coincide with winter/spring harvest when prices are generally high. In north-west Australia, which has extremely hot summers, planting is strictly limited to winter (June/July) because newly-established plants do not perform in the intense heat at other times of the year. For plantains in Nigeria, wind damage is the main limiting factor (Obiefuna, 1986). August–December plantings gave optimum yields, whereas January–May plantings mature in the windy, dry season resulting in 25% yield decline from wind damage.

Subtropical localities

Time of planting has different constraints in subtropical and Mediterranean localities, which have cold winters. In Israel, winters are very cold and planting

Table 7.2. Analysis of the advantages and disadvantages of planting tissue culture bananas during different months of the year in a subtropical locality which has hot summer and cold winter extremes of temperature (Komatipoort, South Africa).

Month of planting	Advantages	Disadvantages	Overall suitability for planting
December/January (summer)	None	Young *in vitro* plants burn from heat stress. December/January planting causes winter flower intiation. Harvest in summer (lower prices)	Very poor
February (summer)	Avoids winter flower initiation. Harvest in autumn (higher prices)	Young *in vitro* plants damaged in hot conditions	Good
March/April/May (autumn)	Ideal establishment weather for *in vitro* plant. Spring flower initiation. Large bunches produced. Harvest in autumn/winter (high prices)	Small plants may be chilled if winter is cold	Very good
June/July /August (winter)	Average-sized bunches (average prices)	Harvest winter/spring. Young *in vitro* plants can be chilled or burnt. Midsummer flower initiation (too hot)	Average to poor
September/October/November (spring)	Ideal establishment weather. Average-sized bunches	Winter flower emergence may cause choke throat. Harvest spring/summer (lower prices)	Average to good

occurs in March (spring). The plant crop is small, so the objective here is to time for optimum first-ratoon sucker selection in June (summer), 3 months after planting. This in turn allows flower initiation and flower emergence to occur in the warm weather of spring/summer the following year, and harvest

in November/December (autumn/early winter) which is ideal for good quality
and high prices. In the cool subtropics of Kiepersol, South Africa, and also in
New South Wales, summer planting (December/January) has been identified
as the optimum. Winter is too cold for plant establishment whereas spring
planting causes winter flower initiation and subsequent fruit quality problems
(see Chapter 4 'Winter flower initiation'). Autumn planting induces a very
long cycle over two winters, with low yields per annum and poor prices during
the spring harvest. Summer planting, however, gives high yields, good quality
and high local market prices from an autumn/winter harvest. This cool-area
planting date scenario differs completely from that in a warm subtropical area
which has hot summers and shorter cycle duration such as in Komatipoort,
the main production area in South Africa (Table 7.2).

PLANTING DENSITIES AND SPATIAL ARRANGEMENTS
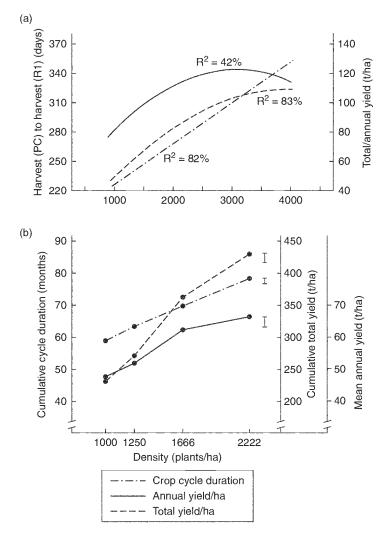
General principles

Spacing of banana plants is a subject of extreme complexity and no general
recommendations can be made to suit all situations. However, it is vitally
important that the appropriate planting density be chosen, first, because it
is one of the major determinants of annual yield per hectare, and, secondly,
once the density is initially chosen, it cannot easily be adjusted at a later
stage. Therefore, for the highest possible yields of good quality fruit, there
is an optimum plant density which should be maintained for the life of the
plantation. This optimum varies according to each particular locality, cultivar,
soil type and management level. These factors in turn influence the more
specific determinants of density choice which are: (i) prevailing climate; (ii)
level of plantation vigour; and (iii) expected plantation longevity.

   An important principle to consider with bananas and plantains is that
the harvest-to-harvest cycle is not specifically annual, as it is with tree crops
in which flowering is determined seasonally. With bananas, the cropping cycle
can be much shorter or much longer than a year. Therefore, optimum density
for either high yield or good fruit quality involves a compromise between
several components. For example, high density will induce a longer crop cycle,
smaller bunches and a smaller fruit size (Fig. 7.5), but total yield per hectare
will increase due to the greater number of bunches (Robinson and Nel, 1988,
1989a). On the other hand, production costs per hectare increase drastically
at high density (Robinson *et al.*, 1994). The optimum density can therefore be
defined as '**the density at which cumulative gross margin per hectare
per annum is maximized over the entire plantation life**'. This definition
integrates: (i) input costs; (ii) fruit prices received; (iii) yield per hectare per
annum; and (iv) market grades achieved, over the long term (Fig. 7.6).

Fig. 7.5. Long-term planting density effects with 'Williams' banana in the subtropics. Treatments 1, 2, 3 and 4 represent planting densities of 1000, 1250, 1666 and 2222 plants/ha, respectively. (a) Cumulative planting to harvest duration (P–H) for four successive cropping cycles: plant crop (PC) and successive ratoons R1, R2 and R3. Note competitive effects in first (PC) cycle are minimal but plant-to-plant competition becomes progressively more pronounced at high density, with plantation age. Total cycle duration for three cycles at 2222 plants/ha was equal to four cycles at 1000 plants/ha. (b) Variation in mean bunch mass between planting densities and cropping cycles. Bunch mass potential of ratoons compared with plant crop can be clearly seen. At low densities (1000–1666 plants/ha) bunch mass remained stable through four successive ratoon cycles, but at 2222 plants/ha, a progressive decline was evident. Vertical bars represent least significant difference at $P = 0.05$ and NS indicates non-significance. Data redrawn from Robinson and Nel (1988, 1989a).

Fig. 7.6. Interaction between crop cycle duration (-·--·--), total yield per hectare (– – – –) and annual yield per hectare (——) in a 'Williams' banana density trial in (a) Queensland, Australia, and (b) Kiepersol, South Africa. Queensland data are for the first ratoon cycle and show optimum density at that stage to be around 3000 plants/ha on an annual yield basis alone. Data for South Africa are cumulated for five successive cropping cycles, and show the optimum long-term density for annual yield to be 2222 plants/ha (66.2 t/ha) which is slightly more than at 1666 plants/ha (62.6 t/ha). However, according to the stated definition of optimum density, 1666 plants/ha is the recommended optimum density for this locality due to reduced input costs and higher overall gross margin per hectare. Vertical bars represent least significant difference at $P = 0.05$. Data redrawn from Daniells *et al.* (1985) and Robinson and Nel (1989a).

Determinants of density choice

Prevailing climate

Climate is the main determinant of planting density. A hot, dry locality with excessive heat units and regular heat stress, requires that a high ratoon density be used (2500–3000 plants/ha) to: (i) obtain maximum benefits from extra light and heat units; and (ii) to provide shade and microclimatic protection. On the other hand, a mild, subtropical climate with cold winters requires that a lower ratoon density be used (1500–2000 plants/ha) to: (i) allow light penetration; (ii) enhance growing temperatures; and (iii) accelerate the cycle time. Under the hot conditions and cloudy environment of tropical banana export countries, lower densities of around 1750 plants/ha are generally used to maximize the proportion of export fruit quality.

Plantation vigour

This is a major factor influencing density choice, and vigour itself is determined by many other components (cultivar, soil physical and chemical characteristics, level of management and water supply). Canopy characteristics such as leaf area index and transmission of PAR can be used to correlate with yield levels to determine optimum density for a given level of plantation vigour (Stover, 1984). In general, plantations of high vigour can have a lower density for optimal gross margin. High vigour can also accommodate a much higher density. However, a plantation of medium to low vigour cannot tolerate a high density in an attempt to increase total canopy area and compensate for the low vigour. Individual plants and bunches then become too weak and stunted for commercial purposes (Robinson and Nel, 1989b). Increased plant-to-plant competition simply aggravates the initial reason for the low vigour, therefore a much lower density must be chosen for each plant to grow unhindered to produce marketable fruit.

Plantation longevity

The intended life of a plantation plays a major role in density choice. It has been clearly demonstrated in South Africa, Israel and elsewhere, that bananas planted for a single crop cycle can tolerate a density of about double that recommended for a long-term ratoon plantation. This is due to the absence of an overhead canopy and shade in the plant crop. Bananas planted for a two- or three-cycle plantation should have a density intermediate between that recommended for a single-cycle and a long-term ratoon plantation. In a high density study at Kiepersol, South Africa, using AAA 'Chinese Cavendish' (Robinson *et al.*, 1994), the following conclusions were made:

- For one cycle, 3333 plants/ha gave the highest gross margin. At higher densities than this, the increased yields of marketable fruit did not compensate for the increased costs of production, and gross margin declined.
- For two cycles, 2777 plants/ha gave the highest combined gross margin.

- For three or more cycles 2222 plants/ha gave the highest long-term gross margin.
- It proved much better to start a long-term plantation at 2222 plants/ha and continue at this density. It was uneconomical to start at 4444 plants/ha and thin out after one cycle. Not only did the higher density have a lower gross margin than 2222 plants/ha in the first cycle, but the second-cycle suckers were suppressed under the heavy canopy of the plant crop, thus lengthening ratoon cycle time.
- For the larger plants of cultivar 'Williams', a long-term density of 2222 plants/ha gave the highest cumulative annual yield per hectare but 1666 plants/ha gave the highest gross margin (Fig. 7.6b); the lower density has therefore been recommended for this cultivar (Robinson and Nel, 1989a).

Commercial practices worldwide

There is a wide range of commercial practices regarding Cavendish banana plant densities and spatial arrangements worldwide, and these reflect the determinants of density choice discussed earlier in this chapter. A summary of commercial practices is presented in Table 7.3. In the humid tropics of Costa Rica and Honduras, plantations are regarded as permanent, therefore densities are low, averaging 1750 plants/ha (range 1500–2000 plants/ha). Densities in the French West Indies also vary between 1500 and 1900 plants/ha (Lassoudiere, 2007). Another reason for the low densities chosen is that large fruit size is essential for export and a better size grade is achieved at lower density. According to Stover (1984) the objective with planting densities in Central America is to achieve a ratoon leaf area index of about 4.5 and a percentage of light transmission to the ground from 14 to 18%, the remainder being intercepted by foliage. This assumes that plantation vigour is adequate, otherwise the optimum balance between annual yield and the proportion of A-grade packout cannot be maintained. Nearly all plantings are made on a systematic hexagonal system which makes efficient use of the area initially, but which becomes more random in ratoon plantations.

In the semi-tropics such as North Queensland, plantation life is short (about 5 years) and optimum ratoon densities therefore tend to be higher at around 2100 plants/ha (Daniells *et al.*, 1987a). Planting arrangement is either in single rows with double suckers per mat and wide interrows (5.5 × 1.8 m) or else in double rows with single suckers, also with wide interrows (5 × 1.5 × 1.5 m). Although these wide interrow systems are physiologically less efficient than square or hexagonal plantings, they are used for practical advantages related to accessibility and mechanization. Maintenance of these spatial arrangements is difficult, hence the short life span of the plantations.

In the hot, semi-arid tropics of north-west Australia, where summer

Table 7.3. A summary of commercial practices in common use, relating to plant crop densities, initial spatial arrangements, number of followers selected and ratoon densities, for banana and plantain.

Country	Cultivar	Plant crop density (plants/ha)	Initial spatial arrangement (m) and number of R1 followers	Ratoon density (plants/ha)
New South Wales, Australia	Williams	1666	3 × 2; one follower	1666 – ≥ random[a]
North Queensland, Australia	Williams	2050	5 × 1.5 × 1.5;[b] one follower	2050
Kununurra, Western Australia	Williams	1666	3 × 2; two followers	3333
Carnarvon, Western Australia	Williams	1111	3 × 3; three followers	3333
Kiepersol, South Africa	Williams	1666	3 × 2; one follower	1666
Komatipoort, South Africa	Grand Nain	2222	3 × 1.5; one follower	2222
Taiwan (one cycle)	Pei Chaio	2250	2.1 × 2.1; –	–
Taiwan (two cycles)	Tai Chaio no.1	2250	3 × 1.2 × 2.1; one follower	2250
Jordan Valley, Israel	Williams and Grand Nain	1111	3 × 3; two followers	2222 – >1800
Coastal plain, Israel	Williams and Grand Nain	950	3 × 3.5; three followers	2850 – ≥1900
Canary Islands (north slope – old plantations)	Dwarf Cavendish	1600	2.5 × 2.5; one follower	1600 – > random
Canary Islands (south slope – old plantations)	Dwarf Cavendish	2000	2.24 × 2.24; one follower	2000 – ≥ random
Canary Islands (new plantations)	Grand Nain	2400–2500	5 × 1.67 (two plants per mat) one follower each or 3 × 1.3 (one follower)	2400–2500
Egypt	Maghraby	816	3.5 × 3.5; three followers	2450
Central America (fertile soil)	Valery and Grand Nain	1730	2.59 × 2.23 (hexagonal)	1500 (variable and random)
Central America (poor soil)	Valery and Grand Nain	1730	2.59 × 2.23 (hexagonal)	2000 (variable and random)
Windward Islands	Plantain	1680		1680
Virgin Islands	Plantain	1852	3 × 1.8; one follower	1852
Honduras	Plantain	2000–2100		
Puerto Rico (intensive)	Plantain	3460	1.7 × 1.7; one follower	3460
Nigeria	Plantain	1600	2.5 × 2.5; two followers	3200
Colombia (normal)	Plantain	1600	2.5 × 2.5; one follower	1600
Colombia (intensive)	Plantain	5000		

[a] Random means that plantations are long term and rapidly lose their initial spatial arrangement.
[b] Three figures indicate a double-row planting system.

temperatures are extremely high (see Fig. 4.2b), microclimatic protection is facilitated by very high ratoon density and for 'Williams' this is usually 3333 plants/ha on a rectangular system (3 × 2 m with two suckers per mat after the plant crop). In the Mediterranean climate of Israel, bananas are managed as an annual crop due to the very cold winter, and densities are selected purely to achieve the degree of competition needed to sustain the annual cycle. Initial plant crop density is 950 plants/ha. Three suckers are then selected to give 2850 plants/ha in the first ratoon, decreasing to 1900 plants/ha in the second ratoon and maintained thereafter. In the Canary Islands, densities are climate related, ranging from 1600 plants/ha in the cooler climate of the north, to 2400–2500 plants/ha in the warmer regions of the south. In older plantations there is no longer any systematic spatial arrangement.

Subtropical banana-growing areas such as New South Wales, and Kiepersol, South Africa, generally have low ratoon densities (Table 7.3) due to a mild climate with cold winters, the large vigorous plants and the long plantation life. The optimum long-term density for 'Williams' is 1666 plants/ha in a rectangular 3 × 2 m configuration (Robinson and Nel, 1989a). Careful sucker selection is practised to retain this row structure into the later ratoons. Lower planting densities, (between 1234 and 1600 plants/ha) for other dessert banana plants like 'Prata Anã', are used in Brazil (Rodrigues *et al.*, 2008).

With **plantains**, experiments have, to a large extent, confirmed the trends found with AAA dessert bananas, namely that high density increases yield per hectare but gives smaller fruit and longer cycles. However, it appears that optimum densities for plantains are rather higher than those for Cavendish bananas. Higher densities (2500 plants/ha) proved very successful in Venezuela (Gómez *et al.*, 2006) for intensive cultivation of plantain 'Hartón Gigante' (AAB). Irizarry *et al.* (1981) found that densities of high-yielding plantain cultivars could be held at 3500 plants/ha without fruit size dropping below the minimum commercial standard of 270 g per fruit. In Nigeria, Obiefuna *et al.* (1982) reported that 3200 plants/ha over three crop cycles produced the best combination of high yields and marketable fingers above 270 g for plantains. At 6000 plantains/ha, overall yield was higher, but an unacceptable fruit size of 170 g was produced. Such studies with plantain were conducted with commercial markets in mind, in which fruit size plays a greater role than in traditional production systems. Belalcazar *et al.* (1994) determined that for farmers who have to buy land in Colombia, the most cost-effective density for plant crop plantains was 5000 plants/ha. In contrast, densities around 1500 plants/ha are used for plantain under traditional cultivation systems (Norgrove and Hauser, 1998; Tazán, 2006).

General disadvantages of high or low densities

High density banana plantings have a wide range of disadvantages which the prospective grower should be aware of:

- Yield per annum becomes progressively lower as the plantation ages (Fig. 7.5).
- Harvest spread widens very quickly as the plantation ages thus crop timing potential is rapidly lost (Robinson and Nel, 1989a).
- As density increases, input costs per hectare rise due to increased use of planting material, props, bunch covers, fertilizers, nematicides and labour. Gross margin analysis has to take this into account.
- There is a progressive scarcity of healthy follower suckers at high density as the plantation ages. As a result, spatial arrangement can degenerate from a systematic to a random situation in which both accessibility and physiological efficiency are reduced.
- Reduced plantation accessibility causes increased management problems.
- Finger length and mass, especially on the distal hands, become undersized as density increases (Robinson and Nel, 1989a).
- Economic life span of the plantation is reduced.
- Development of fungal diseases is promoted in a dense canopy and control is more difficult.

Conversely, there are also some disadvantages of densities which are **too low**, although these are fewer than those at high density:
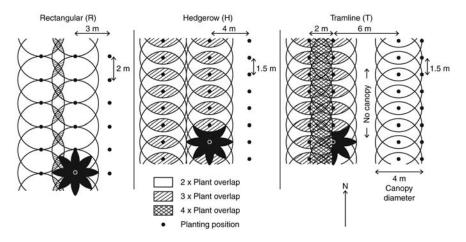
- Bunches are larger which makes them more difficult to harvest and transport.
- Greater sunlight penetration causes increased weed growth.
- Wind penetration is easier thus increased mechanical damage of leaves and fruit is likely to occur.
- In areas with heat stress, evaporative water loss is increased and micro-climatic protection is reduced.
- If density is below the optimal, light is wasted on the soil surface thus annual yield per hectare and gross margin per hectare are reduced.

On balance therefore, it is better to choose a density which is too low rather than one which is too high, but bearing in mind the various principles discussed in this chapter, an appropriate optimal density can and should be chosen to suit each plantation situation.

Spatial arrangement

It is not only the density of plants per hectare which is important but also the way they are spaced in relation to each other. A long-term study on this was made by Robinson *et al.* (1989) in the subtropics. At the standard recommended density of 1666 plants/ha for AAA 'Williams', the influence of rectangular (3 × 2 m), hedgerow (4 × 1.5 m) and tramline (6 × 2 × 1.5 m) spatial arrangements was investigated over five successive crop cycles. A

diagrammatic view of the canopy overlap pattern in these three spacings
is shown in Fig. 7.7. Overall productivity was highest at the rectangular
spacing and this was reduced by 4.6% at the hedgerow spacing and by 7.4%
at the tramline spacing. There was thus a loss of physiological efficiency as
the interrow became wider. Modern plantings in the Canary Islands have
plantations with wide interrows and two to three plants/station at 2000–2400
plants/ha (Galán Saúco, 2005). 'Grand Nain' at 5.0 × 1.67 m and two plants/
station is the most popular, but these arrangements are inherently inefficient
physiologically. More efficient rectangular designs (3.0 × 1.3 m) with one
plant/station are preferred for Dwarf Cavendish cultivars like 'Gruesa'. In
the tropics, bananas are usually planted in hexagonal patterns at between
1500–2000 plants/ha, leaving a single sucker for the first ratoon. Planting
distances are around 2.60 × 2.23 m (Table 7.3). This is initially the most
efficient arrangement possible, but spacing degenerates in later ratoons due to
random sucker selection which favours the most vigorous sucker, instead of
directional marching.

    Choice of tramline, hedgerow or rectangular planting patterns for
banana should depend on the circumstances of the grower, since losses in
productivity are fairly small at a specific density level chosen. Where labour is
not a limiting factor, rectangular-spaced plantations can be used as they make
more efficient use of the available radiation. Where the need for labour-saving
or mechanization is paramount, tramline (double-row) plantations afford the
greatest accessibility but with a long-term yield reduction of about 7%. The
tramline arrangement has distinct advantages relating to easier and cheaper

Fig. 7.7. Diagrammatic representation of canopy overlap patterns for rectangular,
hedgerow and tramline (double-row) spatial arrangements (all at the same density of
1666 plants/ha). From Robinson *et al.* (1989).

plant support, less mechanical damage to bunches, easier irrigation control, more efficient monitoring of bunch development and complete accessibility to each plant by tractor and trailer.

Three points are worth noting for tramline (double row) plantations:

- Tramline plantations are not recommended for very hot areas due to the need to achieve a total canopy cover for microclimatic protection.
- As a general rule, an 'in row' plant spacing of less than 1.5 m is not recommended for any density scenario, since the emerging bunch on one plant may clash with the emerging bunch and/or the selected sucker on the neighbouring plant.
- In higher latitudes, tramline plantations should be orientated N–S to achieve equal light interception and development rate on both rows.

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Systems of Cultivating Bananas and Product Certifications

SYSTEMS OF CULTIVATION

Traditional and conventional cultivation

Cultivation of bananas was historically initiated as isolated plants in home gardens. They were planted to satisfy family consumption needs, and any surpluses were exchanged for other goods in nearby villages. Bananas were also usually associated with a range of other subsistence crops for family use. Crop and animal residues and ashes were the only source of fertilizers.

Cultivation of bananas evolved towards cultivation systems in association with other crops, or to shifting cultivation within the natural bush. Bananas planted at low density were used as shade plants for shorter perennial crops. Associated multicrop fields are still the most extensive systems of cultivation in the tropics for non-Cavendish banana cultivars.

When bananas started to become an important source of income by selling them at the local market, there was a progressive reduction of other crops and an intensification of banana cultivation that became a monoculture. In the second half of the 20th century, the market for bananas increased substantially, requiring production of maximum yields in minimum time. In order to achieve this objective, cultural practices (soil preparation, establishment, planting densities, choice of planting material, desuckering, fertilization and irrigation) were all improved. Yields increased significantly up to the 1990s when this intensification of conventional cultivation caused soil degradation and an increase in pests and diseases. In turn, this necessitated important changes in cultural techniques to ensure: (i) sustainable banana cultivation; (ii) environmentally-safe practices; and (iii) respect for human health. In this context, modern systems of cultivation evolved.

Integrated cultivation

This can be defined as a system of cultivation that maximizes the use of natural resources and avoids, wherever possible, external inputs in order to: (i) ensure a final product of high quality; (ii) provide full protection of the environment; (iii) be socially acceptable; but (iv) without compromising economic farm profit. Integrated cultivation includes both integrated crop management (ICM) and integrated pest management (IPM). Technical regulations for integrated cultivation in general and for specific crops in different countries, have been established. However, no generic or specific regulation for bananas has been established globally. Country regulations for integrated certification include specific requirements, some compulsory, some forbidden and some recommended for different cultural techniques. A complete discussion of these practices is outside the scope of this book, but a few of them are mentioned to better understand this system of cultivation.

1. Soil preparation – Chemical disinfection is forbidden as well as planting in soils with a clay or sand content higher than 60%.
2. Water control – This should be achieved using appropriate technical management. This includes avoiding the use of saline water (the sodium absorption ratio (SAR) should be less than 6).
3. Protected cultivation – All cover materials must be recyclable and any cover residues or other scrap materials used in construction of greenhouses should be removed and carried to special refuse sites designed for this purpose.
4. Planting – Planting should use only tissue culture plants or conventional plant material from the same farm. A suitable plant density (lower) should be chosen that will delay the need for replanting.
5. Fertilization – This should be applied according to foliar and soil analysis. Applications of nutrients must not exceed a fixed limit. For example in the Canary Islands, the following quantities (g/plant/year) cannot be exceeded: N (280); P_2O_5 (125); K_2O (450); and CaO (140).
6. Integrated pest management – Biological and cultural methods should be used rather than chemical pesticides, but if pesticide use is necessary, only authorized products should be used and at recommended dosages. Particularly important is to plant in areas unfavourable for Sigatoka disease and to practise weekly removal of necrotic leaves.
7. Harvesting and field transport – Integrated fruit produce should be kept separate from conventional produce. Clean protective materials should be used for the bunch during harvesting and transport. Exposure to sun or other damaging climatic factors should be avoided.
8. Reception of fruit at the packshed – There should be entrance control systems to register incoming produce. Use of non-chemical postharvest treatments is preferable. Recycling and treatment of water from the packshed is compulsory.
9. Record keeping – Traceability is a key factor for integrated production, which obliges participating farms to keep accurate field and packshed records.

In combination, these integrated practices aim to:

- maintain or improve soil fertility;
- limit external inputs to real plant needs;
- ensure efficient water use to control erosion, avoid water waste and reduce toxicities;
- utilize cultural practices rather than chemicals, to reduce biotic risks;
- produce good fruit quality that is as homogeneous as possible;
- improve traceability and protect the environment.

Organic cultivation

Organic cultivation (also called biological or ecological cultivation) is described in the FAO *Guidelines for Production, Processing, Labelling and Marketing of Organically Produced Foods* according to Codex Alimentarius (FAO, 2001b). This is a holistic management approach which improves health of the agrosystem, particularly biodiversity, as well as the biological cycle and biological activity of the soil. It offers the consumer healthy and natural products with authentic taste. Technical regulations, such as those given by the International Federation of Organic Agriculture Movements (IFOAM, 2009) have been established for organic cultivation in general and for specific crops in different countries. They are more restrictive than with integrated cultivation and put special emphasis on sustainable systems of cultivation from social, ecological and economic perspectives. Maximizing yield is not especially important and can be sacrificed to achieve long-term sustainability. All these regulations must be complied with to certify banana production as being 'organic'. Several EU Directives (2092/1991, 392/2004, 834/2007 and 889/2008; EUR.lex, 2010a) regulate organic cultivation. Certification in many countries is done by official bodies (e.g. Regulatory Council for Ecological Agriculture (CRAE) in Spain) or by organizations authorized in each country, like Écocert, Qualité France or Afac-Ascert in France (Lassoudiere, 2007).

As with integrated cultivation, a complete analysis of regulations required to certify banana production as organic, is outside the scope of this book, but a few general principles and specific regulations are worth mentioning here to better understand the nature of organic cultivation.

1. A period of conversion from conventional to organic production (2–3 years) is compulsory.

2. Complete separation of organic from other systems of production, both for field operations and for fruit storage, is compulsory.

3. Only organic products or specially-approved products for organic cultivation can be applied. This refers to fertilizers, pesticides, manures and other inputs. All synthetic products are forbidden.

4. Applied nitrogen must not exceed 170 kg N/ha/year.

5. Transgenic planting material is forbidden.
6. Planting of legumes, green manures and incorporation of organic matter is encouraged. The use of certain natural fertilizers specifically authorized to maintain or improve soil health and fertility, is permitted.
7. All organic products should be labelled as such and the name of the certification body should be included.

Obviously, many general recommendations given for integrated cultivation, like those for soil preparation, use of vitroplants and judicious irrigation control, are also applicable to organic cultivation. Major problems for organic banana cultivation derive from the incidence of leaf diseases, nematodes and banana weevil, for which toxic chemicals cannot be used. Consequently, the search for resistant cultivars continues (see Chapter 2).

The key issue of maintaining appropriate soil fertility should be based, as in any system of banana cultivation, on soil and foliar analysis. Since organic materials (manures, compost, bokashi[1] and others) are the most commonly used fertilizers, attention must be given to their manufacture in terms of microbial activity, internal temperature and the C:N ratio. Packing procedures require special attention, especially regarding fruit washing, water quality, recycling procedures and biological water treatments.

Protected cultivation

During the 1980s, protected cultivation of banana gained in popularity especially in Morocco and the Canary Islands, which are Mediterranean countries characterized by cold winter temperatures. From 1984 to 1990, banana production under plastic greenhouses in Morocco increased from 5 to 1300 ha and then to 4000 ha by 2009. In the Canary Islands, protected cultivation started in the late 1970s reaching 3000 ha by the end of the 20th century. Protected banana cultivation is also gaining importance in Turkey with 2500 ha out of a total area of 4000 ha being under greenhouse cultivation. In Israel, after experimental plots were planted in the early 1990s, around 1250 ha are now planted under net which represents about 30–40% of the total surface (Galán Saúco and Damatto Junior, 2010). Experimental work in the Canary Islands by Galán Saúco *et al.* (1992) demonstrated clearly that banana plants were larger, bunches heavier, cycle intervals shorter and annual yield per hectare was highly significantly increased under plastic compared with open cultivation (Table 8.1). These effects were particularly pronounced on cool, north-facing slopes where climatic constraints are more severe. With such large increases in yield (up to 77%), the use of a plastic greenhouse was shown to be cost-effective, and may pay for itself within 5 years.

Table 8.1 The influence of environmental modification (greenhouse versus open air) and aspect (north versus south slope) on morphology, crop duration and yield of AAA 'Dwarf Cavendish' bananas in the second (R2) and third (R3) ratoon cycles in the Canary Islands. Banana productivity under greenhouse protection is significantly greater than in open air, especially on cooler north-facing slopes (Galán Saúco *et al.*, 1992).

Environment	Aspect	Plant height (m) R2	Plant height (m) R3	Stem circumference (m) R3	Harvest (R2) to harvest (R3) (days)	Bunch mass (kg) R2	Bunch mass (kg) R3	Annual yield (t/ha) R2	Annual yield (t/ha) R3
Greenhouse	N	2.61[2]	2.42[2]	0.86[2]	339	51.0[1]	40.7[1]	83.7	78.4
Open air	N	2.32[3]	2.36[2]	0.80[3]	383	31.5[3]	32.7[3]	47.3	49.9
Greenhouse	S	2.76[1]	2.68[1]	0.96[1]	331	50.3[1]	35.9[2]	86.7	62.5
Open air	S	2.38[3]	2.21[3]	0.86[2]	379	44.7[2]	35.9[2]	68.9	55.3

Different superscript numbers indicate that means differ significantly ($P = 0.05$).

The general advantages of greenhouse cultivation in the subtropics have been studied in depth in the Canary Islands (Galán Saúco *et al.*, 1992, 1998, 2004; Galán Saúco, 2002; Galán Saúco and Cabrera Cabrera, 2002). These advantages include:

1. Increased number of days with mean temperature above 16°C, considered the threshold below which leaf area development stops and cannot be initiated by any cultural technique (see Fig. 4.1).
2. Protection against wind and other weather conditions (sunburn, hail).
3. Reduction in water consumption, since evapotranspiration is reduced by up to 25%. This is also the main objective for Israeli plantings under net where water savings of 25–40% (6000–7000 m³/ha/year) are reported (Y. Israeli, 2008, personal communication).
4. Increased leaf surface area leading to higher photosynthetic capacity.
5. Shortened crop cycle of the plant to less than 13 months from planting to harvest; thus creating the possibility of three cycles in 2 years.
6. Production of larger and heavier bunches.
7. Additional advantages include: (i) increased size of banana fruit; and (ii) theoretical prevention of yellow Sigatoka spread since the two inoculum types (conidiospores and ascospores) are spread mostly by wind (Carlier *et al.*, 2000). Although this is not important in Mediterranean countries, it may be relevant in the tropics.

All these factors point towards reduced costs and increased yields (= higher gross margin). In some parts of the Canary Islands, bunch weights have increased by 62% (Galán Saúco *et al.*, 1998), leading to average yields exceeding 80 t/ha (exceptionally 100 t/ha/year) in comparison with 60 t/ha/year, the average for well-managed open air plantations.

Greenhouse costs vary according to countries and climatic conditions, particularly wind intensity. Values for 2009 are 12 €/m² in the Canaries, 10.4 €/m² in Turkey, not including the plastic cover (H. Gubbuk, 2009, personal communication), 1.5–3 €/m² in Morocco and 3 US$/m² in Israel. The high cost of greenhouses is a serious constraint for protected cultivation, but in Israel, as previously in the Canary Islands, all new banana plantings under net are government subsidized by 50% of the cost difference between open-air versus net protection (Y. Israeli, 2009, personal communication). In the Canaries where tourism is very important, greenhouse cultivation is thought to have a negative aesthetic impact and is forbidden in some locations. Greenhouse cultivation is also forbidden in the Madeira Islands for the same reason.

Different types of greenhouse are used for banana cultivation. In the Canary Islands (Galán Saúco, 1992; Galán Saúco *et al.*, 1998), a frame of galvanized steel pipes (5–10 cm in diameter and 6–7 m in height) embedded in concrete bases, is used. Such structures last for more than 20 years but polyethylene (PE) covers should be replaced every 2–3 years while netting may

last 5 years. Different types of greenhouse covers have been evaluated in the Canaries (Cabrera Cabrera and Galán Saúco, 2003, 2005). Some interesting observations from these studies are:

1. Important differences exist between ultraviolet (UV) light penetrations (Fig. 8.1). UV penetration is lower under covers.
2. Temperatures are higher under PE covers than under net covers.
3. Incidence of white flies (*Aleurodicus dispersus* and *Leucanoides floccissimus*) is lower under PE cover. This is explained by UV reduction as reported for other crops (Antignus *et al.*, 2001).
4. PE covers of (750 gauge) (190 μm) give the most favourable conditions for banana growth and development, reducing cycle duration and increasing bunch mass.
5. New PE materials, like Celloclim®, are of special interest as they combine the best characteristics of PE with long-lasting characteristics (minimum of 4–5 years against 2–3 years with normal PE types).
6. Cultivation of banana under PE covers requires careful ventilation management to avoid temperatures above 30°C which may burn banana leaves. This is why many farmers prefer to use nets instead of PE to cultivate bananas in the warmer areas. Also, the use of PE covers is not appropriate for protected banana cultivation in Israel, due to very high summer temperatures.
7. Up to now, no greenhouse cover used for banana cultivation is fully biodegradable.
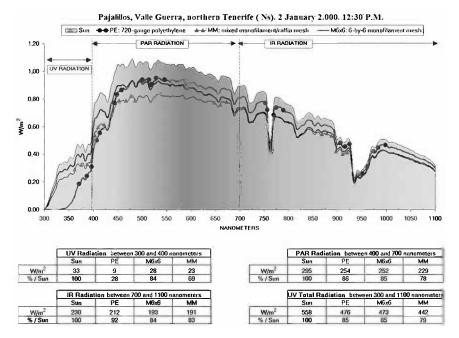
Some trials have also been done in Israel with different coloured nets, but none of them are better than the transparent cover normally used. Furthermore, the red colours are detrimental since they induce longer and narrower leaves which have lower photosynthetic efficiency (Y. Israeli and E. Lahav, 2009, personal communication).

'Grand Nain' is the most widely planted greenhouse cultivar, both in Israel and in Turkey (100%), in Morocco (92%) and in the Canary Islands (roughly 75% of the surface under cover; Galán Saúco *et al.*, 2004). 'Dwarf Cavendish' is second in importance in Morocco and the Canary Islands, with only token plantings of the tall 'Williams' and 'Poyo' in Morocco (<2%). Many new plantings in the Canaries, under greenhouse and in the open air, are being done with 'Gruesa', a locally-selected 'Dwarf Cavendish' clone (see Chapter 2).

Cultural techniques for greenhouse cultivation do not differ much from open-air cultivation, but the excessive leaf surface under greenhouse cultivation requires leaf removal to avoid excessive shade and consequently cycle delay. Leaf removal is carried out shortly after bunch emergence retaining a minimum of eight leaves per plant (the eight youngest leaves). Greenhouse cultivation also allows the aerial tying of bunches to the internal pipes of the roof structure thus eliminating the need for props. Phytopathological problems under greenhouses are similar to open-air conditions, while pest exclusion measures, biological control, and integrated or organic plot management are easy to apply.

Fig. 8.1. Light radiophotometric spectrum under three types of greenhouse covers: polyethylene (720 gauge); mixed monofilament/raffia mesh; and mixed 6 × 6 monofilament mesh. IR, infrared; PAR, photosynthetically-active radiation; UV, ultraviolet. From Cabrera Cabrera and Galán Saúco (2005).

PRODUCT CERTIFICATION SCHEMES

Consumer demand for production and marketing details of fruits reaching the market (traceability), has given rise to different certification schemes that consider internal and external quality of the product, as well as social and environmental aspects of the cultivation system.

Although the process of certification is voluntary, practically all export markets are demanding stricter certification that helps to determine the status of banana producers. The certification process which verifies that a product, a service or an organization fulfils a given number of rules, is discussed below.

The International Standards Organization (**ISO**) is an NGO founded in 1976 which operates in 140 countries. **ISO 9000** is directed towards improving the quality of the production process, whereas **ISO 14000** relates to environmental management and **ISO 22000** controls food safety for human consumption. These norms deal with systems of management rather than the result, although obviously they have an indirect bearing on the final product.

The procedure for obtaining ISO certification, which is given by different organizations in different countries, usually comprises the following steps:

1. The applying organization (AO) requiring the certification label, completes a questionnaire sent by the certifying organization (CO).
2. The CO sends the AO a contract together with a reference guide, questionnaire of evaluation and an audit guide.
3. The CO requests from the AO an evaluation about their system of quality.
4. The CO sends an audit report and following the response by the AO, a supplementary audit may be necessary.
5. The dossier is examined.
6. If positive, the CO issues a corresponding certificate, valid usually for 3 years, but with interim inspection visits.
7. Renewal of contract if everything goes according to ISO norms.

ISO 14000, compatible with ISO 9000, must ensure that the AO makes every effort to eliminate/reduce any negative impact on the environment. The certification extends through a 3-year cycle (a complete audit in the first year and two supplementary audits the other 2 years, starting a new cycle in the fourth year). Since it is the process and not the product which is certified by the ISO body, the latter need not carry a label indicating 'product certified by ISO ...'.

ISO 22000, published in September 2005 is a new norm, with the same structure as ISO 9000 and ISO 14000. This new norm specifies requirements for a food safety management system to which any company involved in any part of the food chain, must conform. The company must clearly demonstrate its ability to control food safety hazards and that its product is safe for human consumption.

ISO 22000 fulfils all the principles established by the Codex Alimentarius regarding the development of a **HACCP** (Hazard Analysis of Critical Control Points). This system involves: (i) risk analysis; (ii) identification of Critical Control Points; (iii) establishment of Critical Levels; (iv) establishment of Corrective Measures; and (v) system verification. These methodologies are outside the scope of this book, but they well exceed obligatory levels of food safety required for national legislations. Such certification is accepted worldwide and effectively facilitates access to international markets.

Another certification, **EUREPGAP** (now **GLOBALGAP**), establishes minimum acceptable norms for distribution of fruits and vegetables and is considered the international reference for these commodities. Essentially this is a certificate of 'good agricultural practices' (GAP) created in 1997 under the initiative of the Euro Retailer Produce Working Group (Eurep), responsible for the huge distribution channels in Europe. This norm is orientated to satisfy consumer concerns about food safety, environmental protection and improved working conditions, and it integrates the concerns of producers, selling agents and consumers.

EUREPGAP relied on five main principles:

- Stimulating safe and economically viable systems of agriculture while discouraging the use of chemicals.
- Developing the concept of 'GAP'.
- Developing ways to continuously improve the system.
- Establishing a universally-recognized system of verification.
- Maintaining a communication channel between producers, exporters, importers and consumers.

GLOBALGAP is not really a label, but a certification required for commercial companies and used by them in their information to consumers. As with ISO 22000, it utilizes principles of the HACCP system to ensure food safety. Protection of the environment at production level is addressed by the practices of IPM and ICM. A global evaluation of worker protection (health and safety) is also proposed by GLOBALGAP, but the final responsibility for this lies with the producer.

GLOBALGAP certification can be given either to individual producers, commercial companies or to professional organizations. The main requirements to obtain this certification are:

- Traceability of the product back to its origin (the producing farm).
- If GMOs are used they must conform to the norms concerning these products both in the country of origin and in the receiving country.
- An historical and management register of each production site is made including previous crops and neighbouring crops.
- Storage of fertilizers must be in a place separate from fruits or vegetables.
- Use of non-treated used water for organic manure preparation or for irrigation is forbidden.
- Use of chemical products must be registered for the specific crop, and be recommended by a competent person. Protection measures such as protective clothes and withholding periods should be followed, and residue analyses must be conducted.
- Postharvest treatments must conform to country regulations.
- Postharvest washing should preferably be with drinking water, but adequately treated recycled water may also be used.

The **Rainforest Alliance** is an NGO established in the USA in 2003 with the aim of safeguarding nature and substituting for the already existing labels SA norm, Better banana and Eco-OK. This certification relies on principles similar to those previously cited in this chapter, for example:

- Prohibiting destruction of the primary forest.
- Establishing specific norms for the management of soil and water.
- Establishing buffer zones.
- Management of pesticides according to IPM principles.

The SA 8000 norm, concerning Social Accountability, was elaborated by another NGO, Social Accountability International (**SAI**) also founded in the USA in 1998. While the **SAN** norm respects the Conventions of the International Labour Organization and other human rights, **SAI** implies a system of social management. Most multinationals in different countries of Latin America are now certified by these two norms.

NOTE

1. Bokashi in Japanese means fermented organic matter. It is a product made from rice or wheat bran, with incorporated effective micro-organisms (EM), and is widely used as an organic amendment on bananas in Latin America.

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9

NUTRITIONAL REQUIREMENTS

Bananas require large amounts of mineral nutrients to maintain high yields in commercial plantations. These can be supplied either by: (i) growing the crop in very fertile soils; (ii) supplementing moderate soil fertility with applied fertilizers; or (iii) improving plant ability to extract nutrients from the soil by the use of mycorrhizae (Jaizme-Vega and Azcon, 1995). Eventually, even the most fertile soils become depleted and require additional fertilization. However, of the total world hectarage of bananas and plantains, only a small portion (~15%) is intensively fertilized. The remainder is grown with minimal applied fertilizer, and/or some organic matter and household refuse. This undoubtedly contributes to the gradual depletion of soil fertility and the phenomenon of yield decline which is so prevalent in traditional plantain farming systems (see Fig. 11.9).

Bananas have a high demand for N and particularly for K. Early stages of vegetative growth are critical for later bunch development, thus minerals must be available to the plant at establishment and at the setting of ratoon suckers. N should be applied at regular short intervals during active growth, whereas K can be applied pre-planting and perhaps three or four times a year thereafter, as a top dressing. Phosphate may only be required at planting. Large quantities of nutrients are removed by a high-yielding banana crop and these must be effectively replaced to sustain high production. Many experiments have been conducted to show growth and yield responses of bananas to applied minerals in various combinations. These experiments are usually only valid for the specific soil, climate and cultivar of the experimental site. A more valuable approach is to analyse plant tissues and determine nutrient levels in relation to applied fertilizers. From there, nutrient level × yield response curves can be constructed to provide norms which are then more applicable over a wider range of localities.

NUTRIENT ELEMENTS – THEIR FUNCTIONS AND DEFICIENCY SYMPTOMS

Macroelements

Nitrogen (N)

N is a key element in banana nutrition and extra N must be frequently applied even on fertile soils. The banana plant cannot store N, so if current soil N is insufficient for growth, deficiency symptoms quickly develop. Leaves become pale green and chlorotic, especially in older leaves, and the midribs, petioles and leaf sheaths show a reddish-pink tinge. The leaf internode distance on the pseudostem becomes reduced, resulting in a choked appearance. N deficiency results in reduced bunch mass, delayed sucker emergence and longer cycles. Deficiency symptoms are enhanced when rooting is restricted or when weeds are abundant. Conversely, an oversupply of N will produce large plants with dark green leaves. Vegetatively, the plants look healthy but bunches are smaller than usual and do not fill out properly. They also have a reduced 'green life' after harvest. Sometimes the peduncle breaks off just inside the pseudostem causing premature bunch fall. Excessive N is thus not only wasteful but can also be damaging. Growth and development are promoted by N and the relationship between growth (total dry matter (DM) production) and N uptake is a close one. If water supply and temperature are not limiting then extra N will stimulate growth, but if the temperature is too low (daily mean <14°C – see Fig. 4.1) growth will not occur, thus extra N cannot stimulate growth and will be wasted. In the humid tropics, N is required the whole year round due to favourable temperatures, but excessive rainfall and leaching necessitate regular, small applications. In a free-draining soil of low fertility, low organic matter and poor root growth, coupled with high rainfall, it is possible to lose up to 150 kg N/ha annually through leaching, which must be compensated in the fertilizer programme. In the subtropics, N applications should allow for quantities supplied by mineralization of soil organic matter and also that coming from composts and banana leaf trash. N is not necessary when growth rate is inhibited by cold winters and in addition, less leaching occurs than in the tropics at most times of the year.

Phosphorus (P)

The P requirement of banana is not large compared with N and K, and deficiency symptoms are rarely seen in the field (Table 9.1). This is because: (i) banana plants accumulate the P they require over a long period; (ii) they lose relatively little through the fruit; and (iii) they redistribute it readily to the ratoon sucker. If deficiency symptoms do appear, they are shown as stunted plants with poor root development. Older leaves develop a serrated marginal chlorosis ('sawtooth' effect) and the petioles break easily. Younger leaves develop a bluish-green tinge. P deficiency may limit K absorption. Severe

Table 9.1. The average quantity of nutrients in banana and plantain plantations. Data based on a plant crop of 2400 plants/ha, bunch mass of 25 kg and 15 kg for banana and plantain, respectively, and yields of 50 and 30 t/ha, respectively (from Lahav and Turner, 1983; Lahav, 1995).

Nutrient	Quantity removed in fresh fruit (kg/ha)		Quantity remaining in plants (kg/ha)		Total quantity in plants (kg/ha)		Proportion removed in fruit (%)	
	Banana	Plantain	Banana	Plantain	Banana	Plantain	Banana	Plantain
N	189	76	199	189	388	265	49	29
P	29	11	23	16	52	27	56	41
K	778	243	660	945	1438	1188	54	20
Ca	101	9	126	149	227	158	45	6
Mg	49	11	76	53	125	64	39	17
Mn	0.5	0.2	12	6.8	12.5	7.0	4	3
Zn	0.5	0.1	4.2	0.7	4.7	0.8	12	12
B	0.7	N/A	0.57	N/A	1.27	N/A	55	N/A

N/A, Data not available.

P deficiency may result in yield reduction and longer ratoon cycles. However, the response to applied P is very slow to appear.

The banana plant absorbs most of its P requirement in the plant crop cycle, between 3 and 9 months after planting. During the reproductive phase uptake is decreased by 80%. Uptake is apparently enhanced by the association of roots with vesicular-arbuscular mycorrhizae (Fox, 1989). Conversely, it has been shown in the literature that low Mg supply reduces root uptake and distribution of P (Lahav and Turner, 1983).

Potassium (K)

K is the most important element in banana nutrition. A fully grown bearing banana plant contains more K than all the other minerals combined. Lahav and Turner (1983) calculated that a yield of 50 t/ha/year removes from the soil nearly 800 kg K in the fruit alone, while another 660 kg K remains behind in the plant residue for later recycling (Table 9.1). The most common deficiency symptom is an orange-yellow chlorosis on the oldest leaves and their subsequent rapid death. Other effects of K deficiency are reduced leaf size, delay in bunch initiation, reduced fruit number per bunch and reduced fruit size due to poor filling. Thus K deficiencies are closely correlated with yield reduction.

Uptake of K from the soil depends on soil K concentration and ontogenetic stage of the plant. There is a maximum soil level above which no more K is absorbed. This level is determined by climate, growth rate, root vigour, soil water status, disease, and the over or undersupply of other cations (see Chapter 6 section 'Cation balance'). Uptake is also greater during the first half of the vegetative growth phase than during bunch development, thus bunches attract K from other organs which must have sufficient reserves from their earlier uptake.

Growth is the assimilation of DM in the plant. A shortage of K reduces total DM production and also changes its distribution within the plant. The organ that suffers most from DM redistribution is the bunch. Thus, if total growth is reduced by 50%, bunch DM may be reduced by 80% and roots not affected at all. Bunch DM is restricted by low K because: (i) photosynthesis is reduced; (ii) transport of carbon assimilates from leaves to bunch is reduced; and (iii) conversion from sugars to starch within the bunch is inhibited. Thus, small, fragile bunches with thin fruit are produced.

Calcium (Ca)

Ca is very immobile within the banana plant and therefore deficiency symptoms are found mostly on the youngest leaves. Interveinal chlorosis occurs near the leaf margins and towards the leaf tip. When these patches die they create a serrated necrosis along the leaf edge. A temporary shortage of Ca causes the 'spike-leaf' symptom in the field, in which the lamina on new leaves is deformed or almost absent. Symptoms appear in early summer after a spring

flush of growth and in plantations receiving a large amount of K. Sometimes only one leaf may be affected and leaf Ca levels are very low in such plants. Ca is very important in cell wall strength, thus in Ca-deficient plants fruit quality is inferior and the peel splits easily when ripe. Ca uptake by the plant depends not only on Ca concentration in the soil but also on the concentration of other elements, especially K and Mg.

Magnesium (Mg)

After N and K, a deficiency of Mg is the most common in banana-growing countries. Deficiencies usually occur in old plantations in which Mg fertilizers have not been applied and/or where large quantities of K or Ca have been applied. Leaf symptoms include marginal yellowing on older leaves, changes in phyllotaxy, purple mottling of petioles and separation of leaf sheaths from the pseudostem. Since Mg is the central element in the chlorophyll molecule, a deficiency causes leaves to turn yellow in a broad marginal band, which consequently also reduces photosynthesis and yield potential. It is recommended to apply small amounts of Mg regularly to avoid reduced yields. Unlike Ca, Mg moves from old leaves to the youngest leaves and to the bunch.

Uptake of Mg is influenced more by Mg concentration around the roots than by rate of plant growth, so time of application is not critical. Uptake can be suppressed by high concentrations of Mn and K. The Mn level is increased in acid soils which should thus be avoided. The correct balance of K and Mg is required in the soil solution to allow adequate uptake of both (see Chapter 6 'Cation balance'). A reduced yield caused by low Mg supply is proportional to reduced growth in other plant parts, whereas with low K supply bunch size is reduced more than other plant parts (Turner and Barkus, 1980).

Sulfur (S)

Deficiencies of S have been reported in the field. S is actively distributed from old to young leaves and, with a shortage, symptoms appear in the young leaves which become yellowish-white. As the deficiency progresses, necrotic patches appear on leaf margins and vein thickening occurs. Growth is stunted and the bunch is small or choked. The most rapid uptake of S occurs between sucker selection and flowering. After this, uptake is reduced and S needed for fruit growth comes from leaves and pseudostem.

Microelements

Zinc (Zn)

Zn is the most important microelement for bananas, as with many other fruit types. A shortage of Zn causes leaves to become narrow, with yellow to white horizontal stripes between the secondary veins. This causes alternating yellow and green stripes. Oblong, brown necrotic patches may develop in the

yellow stripes. Leaves of young suckers can be very thin, comprising a midrib and serrated narrow lamina. Bunches developing on such plants have small twisted fingers with a characteristic prominent light green tip. Zn deficiencies are very prevalent in young *in vitro* plants, which have a rapid growth rate but no mother plant or rhizome to act as a nutrient reservoir. On such plants, Zn deficiency shows as a widespread purple tinge on the underside of the leaf. Zn deficiency is common on naturally high-pH soils or on highly-limed soils, because Zn ions become fixed in the cation exchange complex. At the very high pH of 8.7, yield can be severely diminished due to reduced Zn availability (Turner *et al.*, 1989). Sometimes Zn deficiency may result from high P concentration which antagonizes the Zn.

Manganese (Mn)

A deficiency of Mn is shown by a 'comb tooth' leaf chlorosis and the presence of the fungus *Deightoniella torulosa* in the chlorotic areas. Chlorosis starts on the leaf margins and spreads along the veins towards the midrib, with interveinal areas remaining green, hence the comb-tooth appearance. Leaves desiccate prematurely causing poor fruit development.

A greater problem than Mn deficiency, especially on acid soils, is Mn toxicity. Although very high levels of Mn can be found in leaves (up to 6000 mg/kg) it has been difficult to demonstrate reductions in yield directly due to excess Mn. More importantly, high soil Mn can reduce uptake of Ca by nearly 30%, Mg by up to 40% and Zn by up to 20%. High Mn in the leaf will reduce 'green life' of harvested fruit, thereby contributing to the disorder known as 'mixed ripe' (Chapter 4). Mn toxicity can be avoided by liming.

Boron (B)

B deficiency has been reported on some acid soils in tropical America, and is also prevalent in the subtropics on low pH soils. Symptoms include leaf tip curling and deformation, prominent raised leaf veins, bent cigar leaf and, short white stripes perpendicular to the veins on the underside of the lamina.

Iron (Fe)

Fe deficiency in bananas is usually associated with high pH calcareous soils or soils with a high water table or with excess Mn. The most common symptom on young leaves is a yellow/white chlorosis of the entire leaf. The chlorosis is more acute in spring and autumn than in summer, and is more evident under dry conditions. Photosynthesis is reduced in Fe-deficient leaves.

Copper (Cu)

Symptoms of serious Cu deficiency are leaf midrib and main veins that bend backwards giving the plant an umbrella shape. Leaves also have a yellow/bronze colour. Cu is actively absorbed and translocated within the plant but requirements are very small.

Toxicities

Chlorine (Cl)

Cl toxicity occurs due to the use of saline irrigation water (see Chapter 6 'Soil salinity'), excessive use of Cl-based fertilizers (e.g. KCl) or when sea breezes are present. Symptoms of excess Cl are leaf chlorosis and/or desiccation of leaf margins, physiologically-induced growth inhibition and bunch abnormalities.

Aluminium (Al)
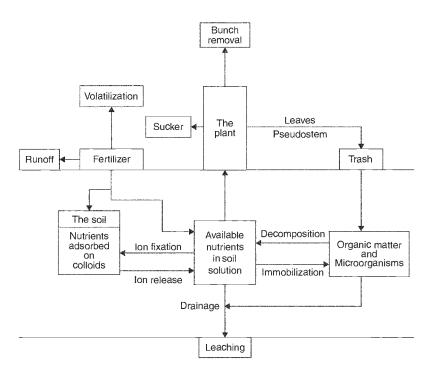
Al toxicities occur in acid soils (ferralitic soils at pH <5.2), although visible symptoms are not clear. Damage may be due more to induced shortage of Ca, Mg and K, than to direct toxicity of Al, although excess Al reduces root growth (Lassoudiere, 2007).

Nutrient interactions

Nutrient antagonisms and synergisms have been widely studied and reported for bananas. Several field problems have also been associated with nutrient imbalances. For example, finger drop of ripe banana bunches ('degrain') is due to a low K:high N imbalance; mottling of the petiole ('blue') has been associated with low K:high Mg imbalance; 'yellow pulp' in ripe fruit is associated with high K:low Mg. Yellow pulp is also associated with high Ca:low Mn and the problem can be avoided by applying S which reduces excess Ca and increases absorption of Mn. Turner and Barkus (1983) found that increased soil K increased uptake of K and P but decreased uptake of N, Ca, Mg and Cu. High Mn supply reduced uptake of Ca, Mg and Zn. It is important to understand these relationships so that fertilizer programmes can aim to balance the soil nutrients optimally.

NUTRIENT CYCLING

Nutrients within a banana plantation are distributed throughout the soil and in the roots, rhizome, suckers, pseudostem, leaves and bunch. Nutrients in each site and the rate at which they move around are important in the nutrition of bananas. For example, nutrients in the soil need to move readily into the roots, and nutrients in the trash need to be released into the soil. Nutrients have to be added to the cycle by fertilization because they are depleted from the cycle via bunch removal, leaching and runoff (Fig. 9.1).

Fig. 9.1. Diagrammatic representation of the nutrient cycle in a banana plantation. Some of the nutrients in the plant will pass directly to the sucker of the next plant without first going through the trash/microbial breakdown/soil solution/nutrient uptake phase.

Nutrient losses and gains

The approximate total quantity of each nutrient present in mature banana and plantain plants, and the quantity removed in bunches at harvest, is detailed in Table 9.1. From this it is clear that K is removed in far greater quantities than any other element, followed by N and then by Ca. From 45 to 55% of the N, P, K and Ca in the whole banana plant is removed in the fruit, whereas for plantains a much lower proportion is removed in the fruit, especially for K and Ca. Up to 80% of the K in plantain plants is available for recycling compared with only about 45% of the K in banana plants.

During heavy rains, nutrient losses can occur through leaching, which is greatest on light soil of low fertility and where root vigour is poor. In heavier soil, clay and organic matter particles hold more of the nutrients in the rootzone. The quantity of nutrients lost by leaching is difficult to measure but when all factors are in favour of leaching, losses can be as high as 80% of the

applied fertilizer. To counteract such losses, root vigour should be promoted by controlling nematodes, and fertilizers should be applied on a 'little and often' basis. Runoff is less serious than leaching but up to 10% of applied fertilizers can be lost this way. P is not leached but can certainly be lost in runoff. Mulching techniques should be improved to minimize runoff.

The main sources of nutrient gain are the soil itself, applied fertilizers or manures and banana trash (Fig. 9.1). A fertile loam soil will need less applied fertilizers, and infertile sandy soils will require more.

Movement of nutrients

A banana plantation always has plants of different size growing on one mat, and the parent–sucker relationship is important in nutrition (see also Chapter 5 section 'Physiological interaction between parent and sucker'). Nutrients left in the standing pseudostem after bunch harvest can move to the follower sucker to provide for its early needs (Fig. 9.1). A sucker thus has access to nutrients in the soil via the parent root system as well as its own roots. Unwanted suckers should therefore be removed early before they become competitive for nutrients, and the pseudostem should be cut as high as possible after bunch harvest to maximize direct translocation of nutrients.

Trash left on the soil surface after harvest and during deleafing and desuckering, contains nutrients which can be recycled. For each tonne of fresh fruit harvested, 1 t of DM is added to the soil as trash. Soluble nutrients like K are released rapidly from trash but the less soluble Ca and Mg are released more slowly. The rate of trash breakdown depends on ambient temperatures and water reaching the soil surface, which influence microbial activity. Nutrients from the trash are washed into the soil solution from where they are reabsorbed by roots (Fig. 9.1).

In Uganda, Wortman *et al.* (1994) studied the flow of nutrients from senescent banana pseudostems. They found that 61 and 55% of the initial N and P, respectively, in standing senescent pseudostems was translocated to attached growing pseudostems by 6 weeks after harvest. Lesser proportions of initial K, S, Fe, Zn and B were translocated and negligible proportions of Ca, Mg and Mn. From the mulch of cut and shredded pseudostems, however, over 50% of the initial N, K and Mg was released into the soil by 6 weeks after harvest and over 70% by 9 weeks.

Implications of nutrient cycling

Cycling of nutrients is important in planning fertilizer strategy. During the first year of a new plantation, nutrient supply from fertilizers must be enough to support not only the growth of the plant crop to harvest but also that of

the first ratoon sucker. In the second year, fertilizer requirement must also be high because the first ratoon produces a much larger plant and bunch, while small pseudostems from the plant crop have only limited reserves of recycled nutrients. From the second ratoon onwards, fertilizer needs should gradually decrease because recycled nutrients from large harvested pseudostems compensate for this. The amount of reserve nutrients in the trash is proportional to crop yield, thus a high-yielding plantation has large reserves of nutrients in the rhizome and pseudostem, and vice versa (Table 9.1).

For greatest efficiency of fertilizer use, the amount supplied should match the productivity of the site. Thus, an irrigated plantation yielding 50 t/ha annually will need twice as much fertilizer to replace fruit removal losses as a non-irrigated one producing only 25 t/ha. However, there is also a larger degree of nutrient compensation from the trash of a 50 t/ha crop.

PLANT ANALYSIS

Information on the concentration of nutrients in plant tissues is useful in diagnosing nutrient deficiencies, provided critical threshold values are known. Such data can identify specific nutrient deficiencies when symptoms are similar or where there are multiple deficiencies masking each other. Plant analysis can diagnose toxicity as well as deficiency.

Factors influencing nutrient concentration

Apart from nutrient supply, many other factors (internal and external) affect concentration of nutrients in banana plant tissue, which in turn affect sampling procedures:

- Different organs within the plant – For example, N concentration is about 3.5% in the DM of unemerged leaf tissue but may be only 0.5% in the rhizome. **Tissue chosen** for analysis should thus be standardized.
- Leaf age – In healthy plants, the concentrations of N, P, K, Cu and Na decrease with leaf age, while Ca, Mg, Fe, Mn and Zn increase. **Leaf age** should thus be standardized for analyses.
- Plant ontogeny – After bunch emergence, mobile nutrients are redistributed within the plant and nutrients move from leaves to fruit. Thus, a decrease in nutrient concentration usually occurs in the lamina between bunch emergence and harvest. **Ontogenetic stage** should thus be standardized.
- Seasonal effects – These are more pronounced in the subtropics than in the tropics. In an Australian study, N concentration was highest in spring and lowest in autumn/winter. Temperature is the main seasonal factor affecting nutrient concentration in banana tissues (Lahav and Turner, 1985). On a

whole plant basis, the concentration of all elements except Cu and Fe was reduced when temperatures dropped below 29/22°C (day/night). **Season** should thus be standardized for analysis.

- Cultivar/genome differences – Turner and Hunt (1984) compared lamina nutrient concentrations in 30 cultivars and found that those with *M. acuminata* genome had higher nutrient concentrations than those with *M. balbisiana* genome (*Musa* AAA > AAB > ABB).
- Heavy rainfall – This leads to leaching of nutrients from the banana leaf. Due to the high intensity and duration of rain, leaching losses in the humid tropics can be very high, especially with K. Irrigation is important in two ways: (i) frequent overhead irrigations reduce N, P and K levels in the leaves, probably due to soil and leaf leaching; (ii) water stress due to lack of irrigation, reduces absorption of K into the leaf.
- Diseases and nematodes – Fusarium wilt infection severely reduces K concentration in leaves due to destruction of roots and blockage of xylem vessels. It is presumed that nematodes act the same way, via root infestation damage. In traditional plantain systems, nematodes and banana weevil are major constraints, and the effect of these pests on plant nutrition is discussed by Obiefuna (1990).

Sampling methods

For a diagnostic service, there are three important prerequisites, namely: (i) the sampling method must allow an empirical relation to be established between concentration of the nutrient and yield response to the application of that nutrient; (ii) variation from plant to plant should be low for the particular tissue analysed; and (iii) concentration in the sample needs to reflect the nutrient status of the whole plant, although this may be difficult to achieve with normal healthy plants in the field.

Based on the above factors affecting banana nutrient concentration, the plant sampling technique in the subtropics of South Africa is as follows:

1. Samples are taken from small blocks with uniform growth. Large blocks with soil variations must be subdivided.
2. A minimum of ten plants but preferably 20 per block should be chosen, and these should be representative of and evenly dispersed throughout the block.
3. Plants should have just produced an inflorescence, but not have a developed bunch.
4. The season of sampling should be late summer (February/March).
5. The target organ is the third youngest fully open leaf. Two squares of lamina (150 mm × 150 mm) are cut out on either side of the midrib at the mid-point of the leaf. The marginal area of the leaf is discarded. Leaf samples from all sample plants are combined, and there should be no sign of sunburn, nutrient deficiency, insect damage or disease.

When all these sampling requirements are met, the analysis results of a plantation can be related to known optimum norms for leaf nutrient status. By knowing how much fertilizer was previously applied, the necessary adaptations can be made to this programme, with the aid of the analysis results. The process should be repeated annually so that any deficiencies, excesses or imbalances can be corrected gradually over a number of seasons.

Establishing concentration standards

Many banana experiments have been conducted to establish critical concentration standards of an element below which a response to added fertilizer may be expected. These concentration standards vary with cultivar, site, climate and sampling procedure. Standards for interpreting leaf analysis data have been established in many countries, based partly on experiments and partly on growing experience (Table 9.2). They certainly provide a useful guide to the nutrition of a crop when considered along with other evidence such as deficiency symptoms, soil analyses and previous fertilizer applications. In bananas, their use is widely recommended and fairly common in different countries.

Table 9.2. Tentative critical concentrations of nutrient elements in the DM of the lamina (third leaf) as summarized from a number of areas using AAA Cavendish cultivars (after Lahav and Turner, 1983). These are compared with the normal range of values derived from experimental work on Cavendish in South Africa and used by the ARC-ITSC,[a] and the standards used for United Fruit Plantations in Honduras and Costa Rica (Stover and Simmonds, 1987).

Element	Critical concentrations (Lahav and Turner, 1983)	Range of norms (ARC-ITSC, South Africa)	Commercial standards (Stover and Simmonds, 1987)
N (%)	2.6	2.5–3.0	2.40
P (%)	0.2	0.1–0.2	0.15
K (%)	3.0	3.0–4.0	3.0–3.5
Ca (%)	0.5	0.80–1.25	0.45
Mg (%)	0.3	0.25–1.0	0.20–0.22
Zn (ppm)	18	25–50	15–18
Cu (ppm)	9	5–20	5
Mn (ppm)	25	100–500	60–70
Fe (ppm)	80	50–200	60–70
B (ppm)	11	15–60	N/A

N/A, data not available.
[a] ARC-ITSC, Agricultural Research Council-Institute for Tropical and Subtropical Crops.

Optimum leaf concentrations for **plantains** do not differ very much from those for bananas (Table 9.2). Nutritional reference norms for Horn plantain leaves are as follows: N 2.7%; P 0.2%; K 4.3%; Ca 0.5%; Mg 0.3%; Zn 10 ppm; Cu 9 ppm; Mn 66 ppm; Fe 69 ppm; S 1 ppm (Rodríguez *et al.*, 2007).

FERTILIZATION

Fertilization practices vary widely according to climate, cultivar, yield level, soil fertility and management expertise of the grower.

Fertilization strategy

Some general considerations are as follows:

- Placement – Insoluble or partially soluble fertilizers, such as phosphate, lime or gypsum, should be incorporated deep into the soil before planting, either with ploughing operations or at the bottom of planting holes. After planting, effective placement of insoluble fertilizers is difficult since tillage is discouraged. Soluble fertilizers such as K and N can easily be applied to the roots after planting as a 'top dressing'. Roots quickly ramify away from the pseudostem therefore fertilizers should be applied in a wide band and not in a 'dollop' or narrow concentrated ring around the pseudostem. 'Fertigation' or fertilizer placement through irrigation water is the most efficient because nutrients are taken to the precise locality of the roots.
- Timing – Balanced nutrition during the early vegetative stages of banana growth is vitally important to the bunch development stage. The developing bunch takes much of its nutrient requirement, especially K, from that accumulated earlier in the vegetative phase. Thus, increased fertilizer applications early in the life of the plant crop would be justified. However, in ratoon plantations it is impossible to fertilize according to ontogenetic stage because plants are at all stages of development, and they carry attached suckers, also at different stages of development. Practically, therefore, timing of fertilizer increase should coincide with seasonal climatic conditions for optimal growth and development, and decrease when growing conditions become suboptimal (called 'phenological management').

   Timing of fertilizer application on plant crop plantains was studied by Obiefuna (1984) and here again it was shown that early applications were critical. When the first application was delayed by 3 months, recovery from nutritional stress was inhibited, and a delay of 6 months reduced yield by 42%, despite normal fertilization practices after the delay.
- Frequency – In general, fertilizers should be applied on a 'little and often' basis because nutrient uptake is slow but continuous, and the plant cannot

utilize large amounts quickly. Frequent applications are especially important where the soil is light and lacking in fertility, and/or when rainfall is heavy. Heavy soils in subtropical localities can be fertilized less frequently. For example, in the subtropics of South Africa, N application can be reduced to four times a year whereas in the humid tropics of Costa Rica, N must be applied manually eight times a year or more to counteract leaching losses. Since N does not accumulate in the plant it is always preferable to apply this element frequently. Fertigation facilitates very frequent applications of N (weekly or even daily). For K, which accumulates in the plant and which is not leached so readily, less frequent application is permissible, but with larger quantities each time. P is usually applied only once, prior to planting.

Types of fertilizer

N requirement is provided by a range of N fertilizers, of which the most common are ammonium nitrate, limestone ammonium nitrate, ammonium sulfate and urea (Table 9.3). The chemical used will depend on soil pH and whether application is by hand or by fertigation. Potassium nitrate is also a very suitable fertilizer for banana since it supplies both K and N in an appropriate ratio of 3:1. On a heavy soil in South Africa with minimum leaching, about 150 kg/ha N is applied annually. In Costa Rica, with high yields, heavy rainfall, surface runoff and highly leached soils, from 300 to 450 kg/ha N are applied annually, and up to 600 kg/ha N in Assam, India. The most commonly used P fertilizer is superphosphate applied at the annual rate of about 50 kg/ha P in the subtropics. This is usually incorporated into the soil before planting. Other sources of P are MAP and DAP (Table 9.3).

For a good crop of bananas in the subtropics of South Africa or New South Wales (~50t/ha), an application of 600–800 kg K/ha is recommended annually to replace that which is taken out in the fruit. This is applied as potassium chloride or potassium sulfate. The chloride form is the cheapest and most common source of K, but Cl toxicity can occur over time. Potassium nitrate can be used but is expensive. In K-starved soils, such as the coastal plain of Israel, up to 1200 kg K/ha/year are applied. Conversely, in some K-rich soils, no K is applied (some soils in the Sula Valley, Honduras, and in the Jordan Valley, Israel). Types of N, K and P fertilizers suitable for applying through an irrigation system are shown in Table 9.3.

N and K are the two most important nutrients for banana production and strategies to manage them have remained almost unchanged over the years. However, fertilizer recommendations for these two elements need to take into account potential yields under each environment/management scenario, as well as nutrient contribution from the soil and trash. Further field studies are needed to fine-tune common recommendations of N and K usually given for extensive production areas (Espinosa and Mite, 2008).

Table 9.3. The chemical formula, composition and solubility of fertilizers suitable for applying to bananas through an irrigation system.

Nutrient	Fertilizer	Chemical formula	Composition (%)				Solubility at 20°C (kg/100 l)
			N	P	K	S	
N	Urea	$CO(NH_2)_2$	46	–	–	–	90
	Ammonium sulfate	$(NH_4)_2SO_4$	21	–	–	24	70
	Ammonium sulfate nitrate (ASN)	–	27	–	–	13	70
	Urea ammonium nitrate (UAN)	Urea-N 16.5% (NH_4)-N 7.75% (NO_3)-N 7.75%	32	–	–	–	Liquid
	Calcium nitrate	$Ca(NO_3)_2$	14	–	–	–	102
K	Potassium chloride	KCl	–	–	50	–	35
	Potassium sulfate	K_2SO_4	–	–	40	16.4	12
	Potassium nitrate	KNO_3	13	–	38	–	13
P	Phosphoric acid	H_3PO_4	–	26.8	–	–	Liquid
	Monoammonium phosphate (MAP)	$NH_4H_2PO_4$	11	22	–	–	23
	Diammonium phosphate (DAP)	$(NH_4)_2HPO_4$	18	20	–	–	39

Ca is usually applied in the carbonate form as calcitic or dolomitic lime. These compounds have the dual purpose of increasing soil pH and supplying available Ca to the soil. Dolomitic lime is also the most commonly used Mg carrier but can only be used on acidic soils. Magnesium sulfate is used on acidic soils which have a relatively high Ca level. Gypsum (calcium sulfate) can be used on normal/high pH soils with high Mg status but low Ca:Mg ratio.

Zn, the most important trace element, can be applied as a foliar spray of zinc sulfate. Zinc oxide can also be used. B shortage can be rectified by foliar sprays of 'Solubor' or soil application of borax. Foliar sprays of trace elements should be applied to the underside of young *in vitro* plants in spring, in the morning, and with a wetter added.

SOIL DEGRADATION AND THE RISE OF ORGANIC NUTRITION

According to Magdoff (2007), a healthy soil is 'a soil that has the continued capacity to function as a vital living system to sustain plants, animals and humans'. For banana production, a good soil should fulfil at least five key functions: (i) support plant growth; (ii) store and recycle nutrients; (iii) store and supply water; (iv) suppress pests and diseases; and (v) filter toxins (Pattison *et al.*, 2008). Due to agronomic initiatives developed in the middle of the 20th century, banana production benefited from a technology involving intensive use of agrochemicals for higher productivity and profitability. However, in many countries, particularly in Latin America, a **decrease** in productivity has been registered, due to the progressive physical, chemical and biological degradation of soils following intensive use of fertilizers (Acuña *et al.*, 2006; Serrano *et al.*, 2006; Stella Riveros *et al.*, 2006). It is generally well-known that:

- Excessive application of P depresses arbuscular mycorrhizal activity (Hayman, 1987).
- Excess N from intensive use of ammonium fertilizers, increases soil acidity. Soil pH lower than 5.0 can induce Al toxicity, which significantly reduces Ca and Mg uptake as well as transpiration rate (Delvaux *et al.*, 2005).
- Excessive applications of K can also decrease pH and cause leaching of Ca and Mg from the soil (Vimpani *et al.*, 1991).

After many years of pesticide applications, increased residues of heavy metals have accumulated in soils and consequently, organisms which aerate the soils have been eliminated over time. The practice of 'clean cultivation', eliminating all weeds and ground cover, further accelerates soil erosion, compaction and soil degradation. Experience in the Canary Islands (Galán Saúco and Cabrera Cabrera, 2006) showed it was possible to

maintain very high productivity with appropriate integrated management, in the natural absence of serious biotic pressures (leaf disease, Panama disease and burrowing nematode). However, without doubt one of the most viable alternatives to reduce soil degradation is the frequent use of organic amendments. In addition to direct nutrient supply, organic amendments contribute to increased beneficial micro-organism activity, increased soil fertility, improved soil structure, reduced toxic mineral salts, increased organic carbon content, reduced erosion, leaching and runoff of nutrients, and improved water and nutrient absorption.

For different primary reasons, including environmental concerns and increased demand for organic products, many banana producers are changing to organic nutrition. The objective is to either: (i) improve soil health as described above; (ii) complement inorganic fertilizers (integrated production); or (iii) totally replace inorganics to become fully organic producers under a certified programme (see Chapter 8). Organic nutrition can restore the biological dynamics of a soil but it can take several years to re-establish in a sterile soil the natural nutrient cycle of a healthy soil. A common practice is to add well-rotted cow manure at around 20 t/ha or chicken manure at half that level, both at the pre-plant stage and annually thereafter. Other organic amendments such as compost or bokashi, produced with bunch residues from banana crops or other vegetative material, are also commonly used in Latin America. Composts have: (i) a higher capacity to retain nutrients than natural animal manures; (ii) a smaller volume than manure; and (iii) fewer pathogens and weed seeds due to the increase in temperature during the composting process. Composts derived from milled banana peduncles and reject fruit may have a K content as high as 4.5%, which means smaller quantities of compost are needed than with manures (Fig. 9.2). Compost may be specially prepared to include the four sources of nutrient supply to plants, namely:

- macroelements in chemical form;
- microelements in chemical form;
- various organic forms of nutrition (guano, animal manures, seaweed products) and different plant extracts such as humic and fulvic acids;
- living biological agents of nutrition (rhizobacteria, active fungi, *Trichoderma*, protozoa, arbuscular mycorrhizae and 'effective micro-organisms' (EM)-based products).

EM and 'compost tea' are concentrated preparations of beneficial bacteria increasingly being used to accelerate the microbiological breakdown of raw organic matter into compost and thereafter into humus (Robinson, 2007).

Fig. 9.2. Some of the ingredients collected to make 'banana-based' compost: banana peduncles (foreground left); reject banana fruit (foreground right); and sawdust (background). After milling and composting, the final product has high nutrient content.

10

WATER REQUIREMENTS AND IRRIGATION

GENERAL WATER REQUIREMENTS WORLDWIDE

A banana plantation requires large quantities of water for maximum productivity and this is well documented in the literature. Purseglove (1972) maintains that 25 mm/week is the minimum required for satisfactory growth in the tropics. Stover and Simmonds (1987) state that a tropical banana plantation can consume 900–1800 mm water in the 10 months from planting to harvest. This amounts to a consumption of 3–6 mm/day depending on the combination of leaf area index, temperature, humidity, radiation, cloud cover and wind.

The banana plant is sensitive to both a shortage and an excess of water. The first symptom of water shortage is a reduction in LER (Kallarackal *et al.*, 1990; Turner *et al.*, 2007) and a shortening of internodes, resulting in a longer cycle and stunting of growth. A shortage of water also results in small, underfilled bunches and/or maturity bronzing characterized by orange discolouration and fruit peel cracking (Broadley *et al.*, 2004; Nelson *et al.*, 2006). Conversely, prolonged waterlogging of soils results in oxygen starvation of roots, causing rapid 'shutdown' of the plant (Daniells and Evans, 2005).

The water requirements of banana and plantain are met by effective rainfall and supplementary irrigation. The proportion of seasonal water requirements derived from these two sources varies widely throughout the world. At one extreme there are the humid tropics of Costa Rica and Panama which receive between 2500 and 4500 mm rainfall, well distributed throughout the year. Water deficits are rare and there is no need for irrigation. On the contrary, efficient drainage systems are required to remove excess water that accumulates in the rootzone. Also in the tropics there are drier areas receiving only 1500 mm annual rainfall which is concentrated in about 8 months of the year (certain parts of Honduras, Colombia, Ecuador, French West Indies and the Windward Islands). In these areas, supplementary irrigation is required to avoid water deficits in the dry months.

Outside the tropics, water requirements of banana are derived increasingly from supplementary irrigation. Despite more than 3000 mm rain in the wet semi-tropics of North Queensland, a 15–20% yield increase is achieved by irrigating during the hot, dry season from September to December (Daniells, 1984). Thus, more than 90% of growers there make use of supplementary irrigation, while also making provision for drainage during heavy rains. In the subtropical banana areas of New South Wales in Australia and Mpumalanga in South Africa, annual rainfall is 1700 and 950 mm, respectively. Rainfall distribution is variable, being characterized by heavy summer thunderstorms and long dry periods. Supplementary irrigation is recommended for both areas in summer and is essential in South Africa where effective rainfall provides less than one-third of the annual water requirement of bananas.

In semi-arid or Mediterranean banana areas, virtually the entire annual water requirement is provided by irrigation. As a result of high temperatures, low humidities and cloudless days, water demand is high and irrigation scheduling critical. For example, in semi-arid Carnarvon, Western Australia, annual evaporation is a massive 2580 mm and rainfall is only 227 mm, mostly falling in the cold winter. The annual banana irrigation requirement at Carnarvon is around 2000 mm. Israeli and Canary Islands' banana production are almost totally dependent on irrigation (1050 mm/year in Western Galilee and 1500 mm/year in the Jordan Valley) since the annual rainfall of 400–600 mm in Israel and 250 mm in the Canaries falls entirely in winter when no growth occurs. This explains the critical importance of sufficient summer irrigation in the dry subtropics, and reduced applications of water during winter in response to cessation of growth caused by low temperatures.

Water demand of banana is lower in a young plant than in an adult plant and lower after bunch emergence than before (Meyer and Schoch, 1976). This is relevant to water management in single cycle plantings, recently used in the Canary Islands (Galán Saúco and Cabrera Cabrera, 2006).

IRRIGATION SYSTEMS

There are five main systems for applying water to bananas, namely: (i) flood or furrow; (ii) overcanopy sprinklers; (iii) undercanopy sprinklers; (iv) microjet or microspinners; and (v) drip irrigation.

Flood

Flood or furrow irrigation of bananas is still practised in a few countries but these methods are rapidly becoming obsolete in banana plantations because: (i) soil levelling is difficult and costly; (ii) water distribution is uneven in a

furrow and random with flood; (iii) saturated conditions can be created on heavier soils; (iv) fertilizer distribution is uneven and ineffective; and (v) nematodes and diseases are spread in the moving water.

Overcanopy and undercanopy sprinklers

Still a common irrigation system for bananas is the overcanopy sprinkler in its various forms. This system is widely used in tropical areas that require supplementary irrigation, also in North Queensland (as a permanent system or a large 'travelling irrigator'), and in the cool subtropics of South Africa (as a semi-permanent, permanent or centre-pivot type). These all have impact-type sprinkler heads. A new, efficient type of overhead sprinkler developed in South Africa is the 'floppy' sprinkler which has no moving parts and ejects water out of a vibrating silicone tube (Fig. 10.1). Advantages of overcanopy sprinklers are:

- The semi-permanent version is relatively inexpensive.
- Any malfunctioning can be clearly seen.
- They are robust and easy to handle.
- They do not impede plantation accessibility.
- They improve plantation microclimate.
- The filtration requirement is not critical.

However, overhead sprinklers also have several disadvantages related to:

- unsuitability for short irrigation cycles and for tall banana cultivars;
- susceptibility to wind distortion and evaporative losses;
- poor water distribution;
- intensive labour requirement for the portable type;
- unsuitability for 'fertigation';
- the enhancement of leaf diseases.

The use of permanent undercanopy sprinklers is a distinct improvement on the overcanopy type in respect of all the named disadvantages, while they still retain many advantages of overhead sprinklers. Portable low pressure 'dragline' systems are cheaper but have a higher labour requirement especially for the short-cycle irrigations needed in hot areas. Uniformity of water application can be improved with a system of flexible pipes connected from lateral lines to the sprinklers (Da Costa *et al.*, 2008).

Micro-irrigation

Many banana-growing countries are now using micro-irrigation systems instead of impact sprinklers. These include microspinner, microjet, and drip

Fig. 10.1. Permanent overhead 'floppy' irrigation system in a young tissue culture banana plantation, delivering a unique, uniform, 100% rainfall-like pattern (no misting). This is ideal for evaporative cooling in very hot, dry conditions. It has a simple water delivery method with no moving parts.

or trickle irrigation. Microspinners apply water in a uniform 360° pattern with a radius of about 2 m from the nozzle (Fig. 10.2). Drip irrigation (Fig. 10.3) is almost universally used for bananas in Israel and the Canary Islands, where water is in short supply. In North Queensland and South Africa, both drip and microspinners are used with success. The main advantage of all micro-irrigation systems compared with overhead sprinklers is that they are completely permanent and a large area can be irrigated simultaneously from a single control point. Labour requirement is therefore minimal, uniformity of application is high, a specific rootzone area can be continuously wetted and any desired cycle time can be chosen. In addition, pump pressure requirements are lower, water loss by evaporation is low (especially with drip), and soluble fertilizers can be applied easily and efficiently through the system directly to the rootzone (fertigation).

Specific advantages of **drip irrigation** relate to minimizing water loss (~95% application efficiency), avoiding evaporative cooling of leaves, pseudostem and soil (which is an advantage only in cool subtropical areas) and control of salinity in dry areas. However, compared with microspinners there are certain disadvantages of using drip:

Fig. 10.2. Undercanopy microspinner irrigation nozzle showing the characteristic 360° spray pattern of the water (nozzles deliver 40–80 l/h with approximately 2 m radius of spread).

Fig. 10.3. Drip irrigation line showing the minimal surface wetting pattern of drippers (low pressure). Drip nozzles deliver 1–4 l/h and are spaced 1.0–0.5 m apart, providing two to four drippers per plant. In light soils, double drip lines per banana row are preferable.

- Physical water quality is important and extra filtration is required due to the fine nozzle pores.
- Drippers wet a smaller volume of soil and the wetting pattern is in a ball shape which is not related to the natural rooting pattern of banana (Fig. 10.3).
- Roots become concentrated in the drip zones which must therefore be kept constantly wet to avoid water stress (daily irrigation).
- Dripper blockages induce localized water stress very rapidly and such blockages are difficult to detect in the field.
- Drippers cannot provide wetting and cooling to young *in vitro* transplants which become stressed and burnt under hot, dry conditions.
- Summer rains in the subtropics encourage widespread rooting in areas not wetted by drippers. These roots become inefficient in subsequent dry periods.

System comparisons

In Israel, drip irrigation was reported to be the most successful system for bananas, especially when water is applied very frequently (Lahav and Kalmar, 1981). In Hawaii, Young *et al.* (1985) stated that drip irrigation of bananas produced double the yield obtained from a well-managed, sprinkler-irrigated plantation. In India, Hegde and Srinivas (1989) demonstrated that drip irrigation was superior to basin irrigation in all aspects of growth and yield of banana and also in water use efficiency.

Two fundamental differences between drip and sprinkler irrigation are: (i) the soil wetting pattern; and (ii) the microclimatic influences. Drip wets only a portion of the total rootzone whereas sprinklers wet the entire profile. The shallow, spreading root system of a banana plant should, in theory, be more suited to sprinkler irrigation. However, there appears to be no detrimental effect of progressively restricting banana root spread to a smaller wetted soil volume, provided soil water potential (SWP) in the wetted portion remains optimal (Lahav and Kalmar, 1981; Daniells, 1988b).

In respect of microclimatic changes, it has been widely demonstrated that in times of heat stress, intermittent sprinkler irrigation induces evaporative cooling on the leaves of many crops, with beneficial effects on growth and yield. Robinson and Alberts (1987) observed this effect under cool subtropical conditions, whereby sprinkler irrigation cooled the leaves and pseudostems of banana plants. However, in this case the cooling was detrimental since it reduced LER and lengthened the cycle time, thereby reducing yield per annum, compared with drip, which had no microclimatic influences. The point here is that there is no such thing as the 'best' irrigation system for bananas. Each plantation has to be scientifically evaluated on merit. The main factors to be considered when deciding on the relative merits of a sprinkler, microspinner

or drip system, are: (i) available water quantity; (ii) water quality (salinity, organic matter); (iii) soil type and percentage clay; (iv) topography; and (v) locality and microclimatic preference (cooling or heating required).

IRRIGATION SCHEDULING

Irrigation scheduling for bananas involves accurate calculations of: (i) the amount of water to apply at each irrigation; and (ii) the interval between irrigations for each soil–plant–climate combination. The banana is a tropical, herbaceous evergreen plant which has no natural dormant phase and which has a high water demand throughout the year, especially at high temperatures. In this respect, the important characteristics of the banana plant are:

- A high transpiration potential due to the large broad leaves and high leaf area index.
- A shallow adventitious root system compared with most tree fruit crops.
- A poor ability to withdraw water from soil which is drying out.

These factors are generally believed to be responsible for the rapid physiological response of banana to soil water deficit (Van Vosselen *et al.*, 2005; also see Table 5.3). However, another theory proposed by Turner *et al.* (2007) is that these three factors alone do not account for the sensitivity of the crop to soil drying. They contend that the plant is able to send a 'signal' on soil drying to the leaves which then activate stomatal closure. Following this, root pressure is able to maintain the plant in a hydrated state, due to the internally-controlled stomatal closure. In addition they contend that the most sensitive response of the plant to soil drying is phenological (reduced LER) rather than physiological (reduced transpiration rate). Whichever of these banana characteristics are dominant, banana plants are nevertheless sensitive to even slight variations in soil water content, emphasizing the importance of correct irrigation scheduling. Results of numerous field and lysimeter studies with banana have proved that plants respond best to the 'little and often' approach to scheduling and also that a large quantity of water is consumed annually.

Conventional scheduling

For conventional scheduling, also known as evaporation pan or crop factor scheduling, knowledge of four criteria is required. These are: (i) water-holding capacity of the soil type; (ii) effective root depth of banana for irrigation purposes; (iii) percentage depletion of total available water allowed before irrigation; and (v) the crop water use coefficient or 'crop factor'. The first three criteria determine the **amount** of water to apply at each irrigation, and the crop factor, together with evaporation data, determine the irrigation **interval.**

Water-holding capacity of the soil
This is the volume of water held in a soil between field water capacity (FWC) and permanent wilting point (PWP). The former is the volume of water held in the profile which does not move under gravity but is retained by soil particles. Much of this water is held at very low tension (10–15 kPa). PWP is the water retained by the soil at a tension of 1500 kPa. The percentage of soil water held between FWC and PWP is the 'total available water' (TAW), which is usually expressed in millimetres of water per metre of soil depth. A PWP of 1500 kPa is an arbitrary threshold used in calculations of water requirement. Water held between FWC and a soil tension of 100 kPa is normally called 'readily available water' (RAW) and can also be used in calculation of water requirement. Banana plants are actually water-stressed at a soil tension much lower than 100 kPa.

TAW varies between soil types, and average values are known for each textural class (e.g. clay loam 190 mm/m; sandy clay loam 150 mm/m; loamy sand 90 mm/m; and coarse sand 40 mm/m). These values also vary on soils within each textural class and should be accurately determined from soil samples. However, a clay loam soil can hold nearly five times the water held by a coarse sand and this fact makes the loam soil more suitable for banana irrigation.

Effective root depth of banana
For irrigation purposes, it is preferable to wet the soil profile to the depth where 80–90% of the feeder roots are situated, which is regarded as the 'effective rooting depth'. Irrigating to the deepest level at which roots are found is likely to be wasteful of both water and nutrients.

The main spread of banana roots is horizontal rather than vertical. In South Africa it was determined that 88% of primary roots of AAA 'Williams' were contained in the 0–300 mm vertical zone. This correlates closely with water extraction patterns in that 87% of total water extracted by roots came from the same vertical zone (Robinson and Alberts, 1989). Similar results have been found with plantain roots (Abruna *et al.*, 1980), thus the 'effective' root depth could be regarded as 300–400 mm depending on soil texture and drainage.

Available water depletion for banana
The level of TAW in a particular banana soil can be depleted by a certain percentage after which irrigation must restore the soil to FWC. Many field studies have been made to determine the threshold percentage of TAW depletion above which yields are reduced. This ranges from 33% to as low as 10%. The normal TAW depletion allowed is 20–30%. If the soil tends towards waterlogging in the upper rootzone, a higher depletion percentage should be used as shown by Abruna *et al.* (1980) for plantains.

Using the principles described above, the amount of water to be applied at each irrigation can be calculated. Two hypothetical examples are shown for two widely different soil types in Table 10.1.

To determine the required interval for applying these quantities of water, the crop water use coefficient for bananas has to be known, together with prevailing daily evaporation rates.

Crop water use coefficient for bananas ('crop factor')

The 'crop factor' refers to the combined loss of water from a plantation by transpiration and soil evaporation (Et) relative to that lost by evaporation from a United States Department of Agriculture (USDA) class A pan (Eo) over the same period. Experimental estimates of Et/Eo with banana have been made gravimetrically with soil samples (Robinson and Alberts, 1989), volumetrically with drainage lysimeters (Israeli and Nameri, 1987; Turner, 1987) or physiologically by measurement of transpiration loss (Robinson and Bower, 1988).

In the tropics, maximal Et/Eo is high as shown by various researchers. Values range from 1.28 to 1.4. In the subtropics, maximal summer Et/Eo is somewhat lower at 0.8–1.0, decreasing to 0.6 in winter. Theoretically, the Et water loss from a uniform ratoon plantation should be similar per unit of evaporative energy, irrespective of season. In the tropics, studies have confirmed this to be correct. In the subtropics, however, there is a pronounced seasonal fluctuation in Et/Eo which is due to several factors. In Israel, seasonal fluctuations in Et/Eo are due to changes in leaf area index between spring (low, 0.8) and autumn (high, 4.4). In Western Australia and South Africa, Et/Eo in winter is low despite a high leaf area index and this is ascribed to increased latex viscosity after cold nights (Hoffman, 1990) and a depleted functional root system during winter (Robinson and Alberts, 1989), respectively. Conversely, during severe heat stress in summer, 'temporary wilt' can occur in which increased evaporative demand leads to loss of turgor, stomatal closure and reduced Et relative to the high Eo (Robinson and Bower, 1988).

Using a class A evaporation pan and assuming no rain, the irrigation interval for bananas can be calculated as per the hypothetical examples in

Table 10.1. Calculation of the amount of water to be applied at each irrigation for hypothetical examples of two soil types.

	Well-drained loamy sand	Heavy clay loam soil
TAW (mm/m)	90	190
Effective rootzone (mm)	400	300
TAW in the rootzone (mm)	36	57
Depletion of TAW allowed (%)	20	30
Irrigation water to apply (mm)	7	17

Table 10.2 in which the water required per irrigation is taken as 17 mm (see previous calculation for heavy clay loam soil in Table 10.1).

In winter the irrigation interval is considerably extended because the crop factor is lower and prevailing evaporation rates are also lower than during summer.

With drip irrigation, intervals are usually **daily** irrespective of *Eo*, or even in pulses several times per day (Lahav and Kalmar, 1981). Water is applied according to the formula *Eo* (previous day) × *Et/Eo* (seasonal value). The daily requirement in millimetres is converted to the equivalent volumetric quantity for the area under drip (1 mm = 10 m^3/ha).

It has become evident that the 'crop factor' scheduling method is inaccurate in the subtropics because there are too many assumptions in the calculation, and too many seasonal changes to leaf area, functional root volume or prevailing climate, which are not accounted for in the crop factor. A more accurate method is to measure SWP directly, and irrigate accordingly.

Soil water potential (SWP) scheduling

Banana irrigations are often scheduled by monitoring SWP with a tensiometer. The advantage of this instrument is that it records directly the potential at which a banana root has to extract water from the soil, on a scale from 0 to -100 kPa. Whereas conventional scheduling involves many theoretical estimates of crop factors, effective rootzones and TAW depletion levels, the tensiometer indicates when irrigation should occur, irrespective of soil type, season, evaporation rate, rainfall and leaf area index. When integrated, all these factors cause a certain rate of soil drying which can be measured on the tensiometer as a practical index of water stress. However, for tensiometers to be a reliable tool for scheduling irrigations, the installation, placement, maintenance, replication and reading of the instruments must be optimal. Then, of course, the SWP threshold at which to irrigate the crop must have

Table 10.2. Calculation of the irrigation interval for three climatic situations using the hypothetical example for heavy clay loam soil in Table 10.1.

		Subtropics	
	Tropics	Summer	Winter
Water required per irrigation (mm)	17	17	17
Crop factor (Et/Eo)	1.2	1.0	0.6
Evaporation deficit required (mm)	14	17	28
Average daily evaporation – Eo (mm)[a]	5	6	4
Approximate irrigation interval (days)	3	3	7

[a] Averages from long-term data. Actual daily evaporation figures would be used in practice.

been pre-determined. A similar method of scheduling irrigations, but more accurate than tensiometers, is the use of a neutron moisture meter which measures soil water content directly through access tubes in the soil.

There have been many attempts to correlate banana yields or physiological processes with levels of SWP. In general it appears that the optimum SWP range for banana growth is from FWC to −20 kPa at 200 mm depth. Stomatal conductance, transpiration and photosynthesis start to become adversely affected at SWP more negative than this (Robinson and Bower, 1987; Eckstein, 1994; see Table 5.3). At a SWP of −50 kPa and lower, photosynthesis becomes significantly depressed (Eckstein and Robinson, 1996), and yields are reduced in a similar manner (Robinson and Alberts, 1986; Hill, 1990). The soil takes from 1 to 4 days to dry out from FWC to −20 kPa, depending on canopy cover, season, soil type and evaporative demand. The relationship between SWP and yield of banana is illustrated in Fig. 10.4 for different environments.

Regarding water use efficiency (yield per unit of water used), yield responses to irrigation vary from year to year, but a water use efficiency of 40 kg (fresh fruit)/ha/mm (water applied) is common and even up to 80 kg/ha/ mm water can be achieved in the absence of soil water deficit (Carr, 2009).
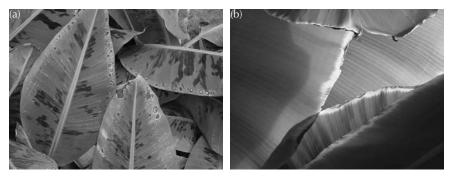
Fig. 10.4. Interaction between soil water potential (SWP), bunch yield (t/ha) and environment for AAA Cavendish subgroup bananas. Data from India are from a moist, tropical area in South India (Hegde, 1988), whereas data from Western Australia are from Carnarvon, a hot, dry area with no summer rain (Hill, 1990). Data from South Africa are from a cool, subtropical site with intermittent summer rain (Robinson and Alberts, 1986). Note that the yield response of banana to a reduced SWP is very severe in the hot, dry site, very mild in the moist, tropical site and intermediate in the cool, subtropical site.

Irrigation and salinity

Studies done in Israel (Israeli *et al.*, 1986) show that an average electrical conductivity higher than 3.6 dS/m in the irrigation water (3.0 in the soil) retards growth and yield. A sodium absorption ratio (SAR) higher than 13 was also detrimental for bananas, with some negative effects even if the SAR exceeded 6.6. (Fig. 10.5). The same authors indicated that water containing Cl values higher than 600 ppm are unsuitable for banana irrigation.

IRRIGATION OF PLANTAINS

For traditional, small-scale plantain production there should be at least 100 mm rain/month for reasonable production levels. This should be well distributed and the dry season should be as short as possible because irrigation may not be feasible or economically attainable for the smallholder. Where larger plantations are cultivated commercially, irrigation becomes necessary because quality is important and the crop is extremely sensitive to water stress. For example, plantain is an important commercial crop in Puerto Rico but is grown under semi-arid conditions there. Water requirements of drip-irrigated plantains were determined by Goenaga *et al.* (1993) in Puerto Rico. Using crop factors from 0.25 to 1.25, they found that all yield components were significantly improved with an increase in water applied. Only from plants irrigated with a crop factor more than 0.75 did average fruit mass exceed 270g, the minimum accepted for marketable plantains, whereas over 50% of the fruits harvested in crop factor treatments 0.25 and 0.50 were unmarketable. The highest marketable yield of 33.9 t/ha came from a crop factor treatment of 1.25. Even in Nigeria where plantains are grown

Fig. 10.5. Typical symptoms of salinity damage on banana leaves from saline irrigation water: (a) necrotic patches on leaf margins of young *in vitro* plants in a nursery; and (b) yellowing and marginal necrosis on mature field plants.

in the rainforest belt, Asoegwu and Obiefuna (1987) recorded almost double the ratoon yield with continuous irrigation compared with no irrigation. In traditional areas, organic mulching is therefore an essential practice to reduce the soil evaporation component of evapotranspiration in plantains.

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11

HORTICULTURAL MANAGEMENT

Commercial production of bananas for export or local market requires field management practices which are intensive, scientifically applied, costly, and demanding on equipment, chemicals, infrastructure, facilities and transport. Conversely, production of plantains or cooking bananas under traditional Central and West African conditions is done with an absence of financial or other resources and by using only family or village labour to manage the crop. Backyard soil is very rich in organic matter and nutrients from household refuse which is dumped there. Under these conditions, plantains grow and yield well. They grow in clusters, since each bearing plant produces many suckers which are not thinned out. Management activities are limited to manuring, mulching, propping the plants and harvesting.

The demand and price for plantains is increasing continuously, and many traditional farmers, particularly in certain countries of Latin America, are trying to increase production and change from subsistence to cash economy basis. This entails moving from the household cluster concept to field production away from the village. In this case, improved methods of cultivation, within the resources of the farmer, are required to boost the level of productivity and sustain it.

WEED CONTROL

Weeds are a universal constraint for banana farmers, and weed control should be strictly applied from planting onwards. Soon after planting, weeds usually proliferate due to: (i) a high population of weed seeds; (ii) water and nutrients applied to the soil; and (iii) abundance of light. Heavy mechanical cultivation is not recommended due to root damage, therefore regular light hand hoeing should be practised while plants are still small and definitely before the weeds produce seed. Gradually the weed problem will diminish as weed seeds become depleted and increased shade from the ratoon banana canopy suppresses weed growth.

Selected herbicides should only be used once the banana plants are taller (1–1.5 m) and the leaf canopy is raised. Herbicides generally registered for use on banana are ametryne, simazine, diuron, paraquat, glufosinate-ammonium and glyphosate. Registered herbicides are becoming fewer in many countries, thus alternative or complementary practices, like hand hoeing, mulching and ground covers should be used. Hand hoeing must be carefully done when close to irrigation lines, nozzles or young suckers, to avoid damage and deep-rooted weeds must be extracted completely.

Recommended chemicals should be used according to weed species present, age of the plantation, and strictly according to manufacturer's instructions. As a pre-emergence herbicide, ametryne can suppress general weed growth for 3–4 months. When the plantation is about 6 months old, the contact herbicide paraquat can be applied to the weed cover and is especially effective on broad-leaved annual weeds. In established plantations, perennial grass species build up and these are very competitive with banana (e.g. *Cyperus esculentus* – 'water grass'). When the grass has flowered it should be spot sprayed with a systemic herbicide like glyphosate. 'Chemical mowing' applies herbicides at low concentrations, not to kill the weeds, but to retard their development. This is practised to prevent erosion, particularly when planting on steep slopes. Glyphosate drift onto banana leaves must be avoided.

For subsistence plantain farmers in the tropics, weed growth is prolific and regarded as a key factor in the yield decline phenomenon. They do not have access to herbicides thus the best methods of reducing weed populations are: (i) hand hoeing; (ii) organic mulching; and (iii) intercropping with vegetables such as melons.

SUCKER MANAGEMENT

In order to obtain high yield, both in quantity and in quality, it is critical to maintain initial plant density and spatial distribution during the entire plantation life. This objective is only possible through appropriate management of suckers from the beginning. Since sucker production is closely dependent on a healthy and vigorous root system, any stress impacting on plant growth and development should be avoided.

Sucker management in banana plantations has two main components, namely desuckering and ratoon sucker selection. '**Desuckering**' describes the practice of destroying, by mechanical or chemical means, unwanted suckers which develop from the rhizome of a banana plant, thereby allowing the selected sucker to dominate and enhance plantation vigour. '**Sucker selection**', on the other hand, is choosing the **correct** follower sucker to perpetuate the ratoon plantation most effectively.

Desuckering

Removal of undesired suckers must be done frequently, not allowing them to become excessively large and unmanageable. Unwanted large suckers: (i) reduce transmission of radiation; (ii) cause a drain of assimilates from the parent plant; (iii) compete directly with the follower sucker, extending the cycle and reducing the yield of the latter; and (iv) push the parent rhizome above ground causing 'high mat'. With Cavendish subgroup bananas, Robinson and Nel (1990) determined experimentally that by allowing all excess suckers to reach 500 or 800 mm before removal, average yield per annum after three cycles was decreased by 7.6 and 15.6%, respectively, compared with the recommended 300 mm desuckering height.

Allowing several suckers to grow around the mother plant for later excavation as planting material, is common in subsistence farming, but not advisable in commercial plantings due to severe competition with the selected follower, leading to plantation yield loss (Robinson and Nel, 1990). Normally, the correct ratoon plantation density is established initially and thereafter maintained by selecting only one sucker per plant throughout the plantation life and removing the rest. Commercial variations on this norm are described in Table 7.3 and later in this chapter ('Sucker selection practices worldwide').

Methods of desuckering

Desuckering can be achieved by different procedures. **Temporary** desuckering is done in many countries, and especially on *in vitro* plants which produce a continuous flush of suckers until the mother plant is about 1 m high. Young suckers are simply cut off at ground level with a sharp curved knife or a machete, leaving their meristems intact. The disadvantages are: (i) high labour cost to cut the same suckers several times; and (ii) continuous growth of the undestroyed sucker rhizomes may push the parent rhizome out of the soil causing 'high mat'. Affected plants are then more susceptible to toppling.

Permanent desuckering removes the sucker meristem and may be done mechanically or chemically. Mechanical desuckering uses different spade gouges which extract the sucker completely by twisting it out (Fig. 11.1a). This system is labour intensive, may damage rhizome and roots of the mother plant, and helps to spread nematodes and soil-borne diseases. To avoid these disadvantages, a 'tube' gouge is used in South Africa which 'sucks out' the meristem of the cut sucker without damaging roots or making contact with the soil (Fig. 11.1b).

Another method of removing suckers is by chemical means. After cutting suckers at ground level as described, a small hole is made in the middle of the cut surface into which dieseline or kerosene (2 ml) is poured. By percolation the chemical kills the meristem, thus preventing sucker regrowth. Chemical desuckering can also be done by using a desuckering gun which injects the chemical at the base of the unwanted sucker just above the meristem position.
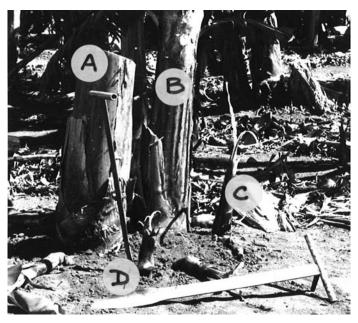
Fig. 11.1. Permanent desuckering methods. (a) A spade gouge in which the entire sucker is removed including most of its rhizome, by twisting it out. This method has hygiene disadvantages. (b) A tube gouge which extracts the sucker meristem without contact with the soil. The sucker is first cut as low as possible, then the gouge is inserted and withdrawn sucking the meristem with it. Note plug of extracted tissue inside the tube gouge.

Optimum sucker size for chemical desuckering is between 100 and 400 mm. The main advantages of chemical desuckering are less labour, lower disease risk and lower cost. These chemicals are no longer used in some countries, for example South Africa, due to perceived damage to the environment. Hormone desuckering has been used in Australia, using a solution 1:16 of 2, 4-D amine at 500 g/l, and two to 12 drops delivered at the apex of a 300–600 mm sucker (Gall, 1986).

Frequency of desuckering

Frequency of desuckering depends on season, intensity of sucker growth and labour costs. Under subtropical conditions suckers grow slowly during winter and they are not desuckered until spring. Conversely, suckers are removed every 3–4 weeks during summer (also under tropical conditions) and every 6–8 weeks during spring and autumn. In Australia, desuckering is only done twice a year due to prohibitive labour costs. The suckers to be removed should not become taller than 300 mm (Robinson and Nel, 1990) and leaves should still be in the thin, bract-like stage (Fig. 11.2). Taller suckers with broad leaves rapidly become competitive with the selected follower.

There are similar reports for plantains as for bananas. Martinez Garnica (1984) in Colombia showed that multiple sucker growth did not affect yield of the plant crop, but yield of the ratoon follower declined progressively when the number and vigour of competing suckers increased.

Fig. 11.2. Small, bract-leaved suckers being removed from a banana mat. (A) Recently-harvested mother pseudostem, (B) daughter pseudostem pre-flowering, (C) selected granddaughter follower, (D) unwanted suckers being removed by spade gouge. Note how (A), (B) and (C) are selected in a straight line as recommended for axial 'marching'.

Ratoon sucker selection

Under intensive banana cultivation systems, and particularly under subtropical conditions, sucker selection is critically important, not only for maintaining plant density and spatial integrity, but also to influence ratoon plant morphology, vigour, yield and harvest season. In all cases only vigorous 'sword' suckers are chosen in preference to the broad-leaf 'water' sucker type (see Fig. 3.4). Suckers of uniform size and morphology should be selected (Fig. 11.3) which facilitates management and reduces production cost since fewer labour passes are necessary for bunch management and harvesting. Uniform suckers also facilitate equal light interception between ratoon plants.

Selection of the correct follower is one of the most critical operations in a banana plantation, especially when changing from plant crop (PC) to first ratoon (R1). In general, an R1 sucker selection 5 months after planting could be termed 'early' and a 10 month selection 'late'. Under subtropical conditions R1 sucker selection is normally made between these two extremes depending on how winter intervenes. With very early selection, there is greater competition between parent and sucker whereby the latter grows more

Fig. 11.3. Ideal first ratoon sucker selection on plant crop banana plants. Note the high degree of uniformity in sucker shape, size and direction of selection. All unwanted suckers have been removed and only vigorous sword suckers are selected.

slowly, remains suppressed for longer and produces a smaller bunch. A banana plantation automatically compensates for the level of competition imposed on it, and it is generally not true that early R1 selection will shorten ratoon cycle time and increase yield per annum significantly using either *in vitro* or conventional planting material (see section below).

Stage of parent plant development
Some important general aspects of banana development must be considered for correct sucker selection. Sucker growth is strongly influenced by the parent plant, with a vigorous parent producing a vigorous sucker and vice versa, while the mother plant inhibits sucker development by apical dominance effects (Eckstein and Robinson, 1999). Thus, a good balance between plantation vigour and density should be established to facilitate optimal sucker development.

Vegetative activity of the sucker is correlated with development of the parent. The so-called F_{10} leaf (first leaf with a lamina width ≥ 10 cm) is used as a reference index for development. After a variable number of leaves have emerged (depending on cultivar and environmental conditions – see Chapter 3), the orthogonal leaf called F_0 (first leaf with the normal characteristic of the cultivar) is emitted, the dominance of the parent decreases and the sucker plant reaches the **vegetative independent phase** (Lassoudiere, 1978a, 1979; see Chapter 5). For production of a large ratoon bunch the time between F_{10} and F_0 should be long enough (eight to nine leaves) to ensure adequate carbohydrate

reserves accumulate in the sucker before dominance of the parent ceases at harvest (Lassoudiere, 1980). In other words, if the independence of the sucker occurs too early (as with a water sucker or by selecting too early) it will become weak and produce a small bunch. Conversely, if suckers are selected that are too young at the time of parent harvest (late selection), ratoon yield could also be reduced.

With conventional planting material of AAA 'Williams', several trials were conducted in South Africa to compare selection of the R1 sucker at 5 and 10 months after spring (September) planting. Results clearly showed that: (i) sucker development rate was suppressed with early selection and accelerated with late selection; and (ii) R1 bunch mass was much greater with late selection, so that cumulative yield per annum (PC + R1) was consistently superior for the late (10 month selection) treatment (Robinson *et al.*, 1985). Indications are that *in vitro* planting material responds exactly the same way regarding early versus late R1 sucker selection. With *in vitro* plants, selecting one of the first five suckers that emerge after planting ('first flush' or first pentagon) should be avoided because these are set too low down on the parent rhizome causing various problems (see Fig. 11.4). One of the suckers 6 to 12

Fig. 11.4. Excavated Cavendish banana plant from *in vitro* planting material showing 'first flush' suckers, (1), (2) and (3), originating from under the parent rhizome, and younger 'second flush' suckers originating higher up. The first flush suckers are physiologically too early for selection and they generally grow away at a wide angle and may push the parent rhizome above ground causing 'high mat'.

('second flush') should be selected, but making sure the direction of marching is correct (see also Fig. 3.5).

Direction of sucker selection
Many commercial plantations have become completely random, having lost their initial spatial arrangement due to poor sucker selection. It is essential that all R1 suckers are selected in exactly the same direction and that subsequent ratoon suckers follow this direction closely (Figs 11.2 and 11.3). Loss of symmetry and row structure makes accessibility and management more difficult and also weakens the plantation physiologically.

Several factors influence the direction of sucker selection, namely topography (select uphill), irrigation (along lines rather than across them), planting system (along tramline rows) and climate (select eastwards for sun exposure in the morning when photosynthesis is highest and for shade of the parent in the afternoon when heat stress is likely). A critical appraisal of every plantation situation is required before selecting the R1 sucker.

Selection of the R2 and subsequent ratoon suckers is much less critical than with the R1. Generally, the first 'peeper' (new sucker) that emerges from the rhizome of the R1 plant is selected, and so on. Invariably, this peeper will emerge along the axis of plantation marching as determined in the R1. If this first peeper deviates from the axis of marching by more than 30°, a subsequent peeper which is closer to the axis should be selected in preference to the one which is out of line. With good management, a well-developed, independent R1 sucker and an emerging R2 'peeper' should both be present before harvest of the parent plant, which is the ideal three generation/mat scenario of mother/daughter/granddaughter (Fig. 11.2).

Number of R1 suckers selected per mat
Normally, the correct ratoon plantation density is established initially (see Chapter 7 'Planting Densities and Spatial Arrangements') and thereafter it is maintained by selecting **one sucker per plant** for each generation. Commercial variations on this are described in the next section and listed in Table 7.3. To briefly summarize, there are three possible variations on the normal pattern:

1. Planting at half the recommended density then selecting two R1 suckers per plant to double up the ratoon density. This method was extensively used until recently in parts of Australia, Israel and Egypt. The disadvantages are that plant crop yield per hectare is too low, paired suckers are not as vigorous as single suckers in a mat, and the plantation marching pattern becomes disrupted in later ratoons. Consequently this option is used less and less in modern plantings, also because *in vitro* plant material allows greater uniformity with plantings at the chosen density.

2. Planting at one-third the recommended ratoon density, then selecting three R1 suckers from each plant to treble the ratoon density. In this case the disadvantages are even more severe and yield is seriously reduced. Thus in Brazil, Lichtemberg *et al.* (1986) recorded a cumulative 30-month plantain yield of 37.3 t/ha at 2 × 2 m spacing and one follower, compared with 15.7 t/ha at 4 × 4 m spacing and four followers per mat. Since it is not usual to prune out unwanted suckers in traditional plantain systems, this could be one of the main reasons for ratoon yield decline with this crop.

3. Planting at double the recommended density then selecting one sucker on alternate plants and no suckers on the other half, so that density is halved in the R1. This option has been adopted in some plantings under greenhouse in the Canary Islands (Galán Saúco and Cabrera Cabrera, 2006). Most new plantings in Israel, now planted under net (Galán Saúco and Damatto Junior, 2010) are established at 2500 plants/ha (4 × 3 m with three plants per station), then leaving only two suckers per mat for the R1 (1666 plants/ha). Although yield may be considerably boosted in the plant crop, disadvantages are that: (i) establishment costs are increased; and (ii) R1 suckers grow under a dense canopy thus delaying the ratoon cycle.

Sucker selection practices worldwide

In tropical countries, the axial sucker is initially selected as follower, but plantation symmetry is quickly lost in the ratoons, since they tend to select the most vigorous sucker rather than the axial sucker. When symmetry is lost a single sucker is selected on the most open side of the parent to keep the distance between mats as uniform as possible. Normally the axial sucker defines a permanent axis for grandmother to mother to daughter in a mat, thus preserving both density and spatial arrangement (Fig. 11.2). Following this principle, a mat will exhibit the ideal pattern of a bearing mother plant, a large daughter sucker and a small granddaughter 'peeper'. In the single row/double follower system (parts of North Queensland), two equal-sized suckers are selected on opposite sides of the plant for the R1, then one sucker on each of these for the R2. In the double row/single follower system ('tramline') a single sucker is selected on each plant along the row. Suckers must be the same size and in the same direction otherwise this planting system becomes unmanageable (Daniells, 1984).

Under subtropical conditions selection strategies are different. In the Canary Islands sucker number 9 from the 'second flush' is the preferred sucker for selection (Galán Saúco, 1992 – see also Fig. 3.5). Suckers produced on the parent plant are destroyed when they reach 300 mm high and final selection is made at the end of spring based on sucker leaf number (Galán Saúco, 1992). Sucker selection under greenhouse cultivation (see Chapter 8) is much easier than in open air plantations since there are more options to select the correct sucker. With single cycle plantings all suckers are destroyed as soon
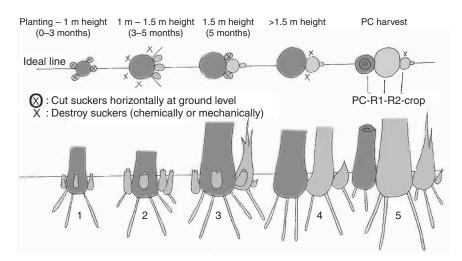
as they reach 300 mm, to avoid competition with the mother plant. In open air plantings in Israel, similar to the Canary Islands, the specific month of sucker selection and size of sucker is critical every year, in order to avoid flower initiation or flower emergence in winter. Their 5/6/6 system (5/8/8 in the first cycle) means that a sucker with five leaves is selected on the sixth day of the sixth month (June). With *in vitro* plants in the first cycle, the formula changes to 5/8/9.

In the subtropics of South Africa, single followers are selected between 5 and 10 months after planting depending on the interval from planting date to the onset of winter. Direction of selection is uniform (eastwards on flat land) in order to 'march' the plantation in the same direction and to maintain spatial arrangement for the life of the plantation (Figs 11.2 and 11.3).

Sucker management for tissue culture planting material
Tissue culture plants produce more suckers at a younger stage and have a more vigorous root system than conventional planting material (see Fig. 5.6) Suckers start developing from underneath the mother plant in a pentagonal spiral sequence upwards following normal banana phyllotaxy (see Fig. 3.5), and become visible above ground within a few weeks (Fig. 11.4). The first series of suckers (normally five), the so-called 'first flush', have a narrow and weak connection below the mid-point of the parent rhizome. They should be cut and destroyed as early as possible because: (i) their developing rhizomes push up the parent causing 'high mat'; (ii) they generally grow up leaning at an angle if left; and (iii) each of these suckers has apical dominance from its own meristem, which can suppress or delay emergence of newer suckers from higher up the parent rhizome, Their early destruction allows another group of five suckers to emerge above ground 4–8 weeks later. This new flush of suckers, referred to as the 'second flush', has a thicker and stronger connection with the parent allowing unimpeded vertical sucker growth. Due to these factors, R1 selection from the second flush of suckers is now the most frequent practice worldwide for newly-established tissue culture plantations. The only possible disadvantage of this 'second flush selection' is that there may not be an R1 sucker in exactly the right position to 'march' the plantation accurately. This necessitates selecting one which may be slightly out of line. To avoid this problem many farmers choose to do early selection from the first flush while others continue desuckering in the hope of getting a later one in line. This can lead to very late selection of the R1 sucker and a generation gap which may become too wide.

Following results obtained from physiological and field studies, Eckstein (1994) developed a practical sucker management system called 'sectorial sucker selection'(SSS) for tissue culture planting material in South Africa, which is summarized diagrammatically in Fig. 11.5.

| Planting – 1 m height | 1 m – 1.5 m height | 1.5 m height | >1.5 m height | PC harvest |
| (0–3 months) | (3–5 months) | (5 months) | | |

Fig. 11.5. Diagrammatic representation of the 'sectorial sucker selection' (SSS) system adopted in South Africa. Note there is a 'selection zone' which is 45° on either side of the ideal line to give flexibility, but the objective is to select exactly along the ideal line (Eckstein, 1994).

PLANTATION SOIL COVERS

Mulching

With plantains under subsistence cultivation systems, it has generally been reported that productivity is increased, surface moisture preserved, and root deterioration reduced by organic mulching. In West African plantain systems, Wilson (1987) emphasized the importance of organic mulching by quoting cumulative yields of 45 t/ha in mulched plots compared with less than 10 t/ha in non-mulched plots. Decomposition of organic matter is a problem in older plantations but mulching can help to replenish this important surface layer. In Nigeria, Salau *et al.* (1992) compared organic and plastic mulches with no mulch over two cycles of plantain production. In general, organic mulches (elephant grass and wood shavings) maintained better soil properties than plastic mulch. Combined first and second year bunch yield was 41% higher on mulched plots (organic plus plastic) than with no mulch.

It is worth emphasizing strongly that mulching is an extremely beneficial practice, likely to improve banana and plantain productivity especially where irrigation water is in short supply. The various benefits can be listed as follows:

- Retains soil water in the upper rootzone and there is a reduction of surface evaporation.
- Increases soil temperature in winter and decreases it in summer.
- Suppresses weed growth.
- Reduces soil erosion, surface water runoff and surface crusting.
- Reduces soil compaction.
- Adds organic matter.
- Increases nutritional value after breakdown (depending on type of mulch used).
- Encourages roots to migrate to the surface where they can avoid oxygen starvation in waterlogged soils and access the nutrients which are concentrated at the soil surface/mulch layer interface.

There are three main types of mulch used in banana plantations, namely dead organic mulch (banana leaf trash, sugarcane trash, coffee husks, wheat straw, pine leaves, etc.), polyethylene mulch and 'living mulch' (usually a legume cover crop). Even under normal irrigation supply, yields can be improved by mulching. With AAA 'Robusta' banana in India, Bhattacharyya and Madhava Rao (1985) found that irrigated yields were 113, 96, 86 and 77 t/ha, respectively, for black polyethylene, sugarcane trash, banana trash and no mulching, respectively. Although black polyethylene produced the highest yields, sugarcane trash gave the highest cost:benefit ratio.

Cover cropping

Sometimes a 'living mulch' or cover crop is used on hillside banana plantations primarily to control soil erosion. Legume cover crops can also improve soil fertility and reduce weed competition when mature. However, they should not be used where water is in short supply, otherwise banana yields will be further reduced. Cover crops use nutrients and water themselves and sometimes grow poorly in the shade of a banana canopy. Some species used successfully with bananas are *Arachis pintoii* in Australia, *Geophila repens* in Panama, *Flemingia congesta* in West Africa, and *Glycine tabasina*, *Aeschynomene falcate* or *Arachis glabrata* in South Africa.

Intercropping

Intercropping of plantains with other food crops is a common feature of the subsistence farming or cash economy sector in West Africa, East Africa and Central America. As agricultural land decreases in these areas, so the necessity for intercropping increases. The main purpose of these plantain-based systems is to produce a range of food crops off a limited area for home consumption,

and a surplus for sale if possible. However, management inputs are usually very limited in such systems.

In the bush fallow system practised in Nigeria, the land is cleared and a complex multistorey cropping mixture involving plantains, maize, cocoyams and beans is established (progressively reducing height). When the other crops have been harvested, plantains are ratooned for 1 year, after which the natural bush suppresses further plantain growth and a long bush fallow is allowed before replanting. Taller multistorey systems are also practised where soil is more fertile and rainfall higher. Species are arranged according to canopy level, starting with oil palm and followed by citrus or breadfruit, with plantain at the third level and finally cassava, cocoyam or beans. The different species are widely spaced and the management level is higher than with bush fallow. Cumulatively, yields and income are reasonable, but they are very low for each species separately. Plantain is less affected by the competition than the other crops. Plantain is also an important intercrop plant for coffee or cocoa in which the latter receive shade during their early development. Commercially, however, pure stands of plantain are increasing in response to the higher demand and increased prices, not only in West Africa, but also in Latin America (see Chapter 1, Tables 1.3 and 1.4). Intercropping requires different species to be planted at lower densities than normal in pure stands.

In Nigeria, Aiyelaagbe and Jolaoso (1994) determined productivity of 'False Horn' plantain/soybean intercrop scenarios. They concluded that when plantains at 1600 plants/ha were intercropped at flowering stage with soybeans at high density (208,000 plants/ha), neither the soybean seed yield nor the plantain growth and bunch yield was adversely affected, and weed growth was reduced by 45%. However, soybean yield was reduced by 47% when it was introduced at the plantain early vegetative stage.

With intensive commercial banana production, intercropping is rare, although banana and avocado have been intercropped successfully in Israel and the Canary Islands, where the banana density is progressively reduced until the fourth cycle, after which the banana plants are removed completely. Tramline bananas are sometimes intercropped with macadamia nut trees in South Africa, but this is no longer recommended. Although there is an early cash flow benefit from the bananas, the practice was shown to be damaging for both crops in the longer term.

CANOPY MANAGEMENT
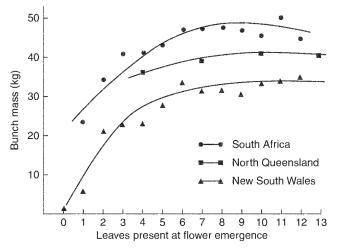
Removal of whole leaves from a banana plant is usually carried out for four main reasons:

- Leaves with more than 30% of the area showing Sigatoka leaf spot disease are excised to reduce disease spread. This practice has become compulsory in

plantations in Brazil grown for integrated production systems (Rodrigues *et al.*, 2008). Failure to do this regularly causes an upsurge of disease infection later in the season.

- Old leaves which are senescent with collapsed petioles and which hang down the pseudostem are no longer useful to the plant. They inhibit light penetration to suckers and the soil surface, and pseudostem temperatures are also reduced which is detrimental to plant development in cool areas. Such leaves serve a more useful purpose as mulch on the plantation floor.
- One or two young healthy leaves which are rubbing and scarring fingers on the developing bunch may be sacrificed to improve fruit quality, if bunch covers are not used.
- Healthy leaves are removed under protected cultivation when leaves become too large and light penetration is reduced (see Chapter 8).

Removal of healthy leaves at flowering of 'Williams' was tested by Turner (1970), Robinson *et al.* (1992) and Daniells *et al.* (1994), to try to accelerate ratoon sucker growth in the subtropics. Although the latter was achieved to a limited extent when only four leaves were retained at flowering, bunch mass was reduced to a greater extent due to poor filling (Fig. 11.6), and green storage life was also reduced. On the contrary, therefore, there should

Fig. 11.6. Influence of functional leaf removal at flowering stage on bunch mass in 'Williams' banana plants at three localities. Bunch mass potential becomes severely reduced when there are fewer than four healthy leaves present at flowering, due to a lack of fruit extension growth and filling. The period of 'green life' is adversely affected even with as many as six to eight leaves present, thus as many healthy leaves as possible should be present at flowering, especially in export localities. Data redrawn from Robinson *et al.* (1992) for South Africa, Daniells *et al.* (1994) for Queensland and Turner (1970) for New South Wales.

preferably be a minimum of 12 healthy leaves at flowering and nine at harvest, to obtain maximum bunch filling and green life extension, and optimum canopy management should be emphasized to achieve this.

The height at which to cut down the old pseudostem after bunch harvest was investigated by Daniells and O'Farrell (1987). They found that cutting high (2 m) increased bunch mass on the follower by 12% and decreased time to the next harvest by 5% compared with cutting low (0.1 m).

WINDBREAKS

Living windbreaks are often planted in subtropical banana areas, especially near the sea, to reduce prevailing wind damage. In New South Wales, closely planted 'Lady Finger' bananas are commonly used as windbreaks due to their height and pseudostem strength. In Western Australia, *Casuarina* windbreaks are used to reduce the high incidence of bunch stalk breakage induced by a combination of heat stress and strong winds. Tree species used as windbreaks in the coastal areas of South Africa are *Casuarina*, *Grevillea* and *Syncarpia* spp. Artificial windbreaks are used in parts of Israel (sheets of polypropylene net with 40–50% permeability) and in the Canary Islands (breezeblock bricks protecting terrace plantings). In the Canaries, protected greenhouse cultivation was introduced primarily to protect bananas from damaging sea breezes (see Chapter 8).

According to research on wind damage by Eckstein *et al.* (1996), it may be economical to establish a windbreak if the prevailing wind constantly tears new leaves into strips less than 50 mm wide. However, there are many disadvantages of windbreaks, namely, they: (i) induce shading (see Chapter 5 'Photosynthetically active radiation (PAR)'); (ii) delay cycle time by 11% in the protected area (Eckstein *et al.*, 1997); (iii) occupy plantation space; (iv) are expensive (artificial windbreaks); (v) compete for nutrients and water; and (vi) afford only limited wind protection to a distance of 10 × (windbreak height minus plantation height) on the leeward side.

BUNCH MANAGEMENT

Bunch propping
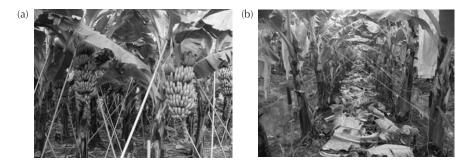
The toppling of banana pseudostems supporting immature or mature bunches can cause total bunch loss or partial damage, respectively. This phenomenon can be caused by: (i) poor anchorage; (ii) rhizomes above ground level; (iii) selecting deep, 'first flush' suckers on *in vitro* plants; (iv) exceptionally large bunches; (v) thin and flexible pseudostems; (vi) strong winds; (vii) damage due to *Erwinia* rhizome rot, banana weevil or the burrowing

nematode, *Radopholus similis*; or (viii) the use of tall cultivars. Damage is most serious when the rhizome is completely uprooted because no more suckers can develop on that mat. If the pseudostem snaps, the bunch may be lost, but ratoon suckers can at least grow normally from the rhizome which remains in the soil.

If bunch losses in an unpropped plantation are more than about 5% then it may be cost-effective to prop throughout. There are three main methods of bunch support:

1. Wooden poles are used where timber is inexpensive and readily available. Treated wooden props are more expensive, but are resistant to termites and may be more cost-effective in the long term. It is recommended to use two poles per plant, which are tied together at the top, leaving a gap which cradles the peduncle. Double props are more stable against wind from different directions and the bunch is not in contact with either prop. Single props should definitely not be used since they are directly under the bunch and cause severe damage to the latter. Commonly used wood species for poles are *Eucalyptus* spp. in South Africa, bamboo in Taiwan and indigenous hardwood offcuts in New South Wales. Metal props are used in high-yielding banana farms in the Canary Islands (Fig. 11.7a). They are more expensive than wooden poles but are long lasting and easy to store.

2. An alternative method of plant and bunch support is based on the 'mutual support' principle and entails tying adjacent plants together with polypropylene twine. Bunches need to be at the same stage of development and leaning in exactly opposite directions, therefore the systematic double row or 'tramline' system practised in North Queensland is most suited to the use of twine. For extra support, each plant may be tied to two other plants in the adjacent row. Twine is tied from throat to base for stronger support, and the operation is done soon after bunch emergence. Twine is normally much cheaper than using wooden poles. The principle is based on the assumption that adjacent plants lean away from each other and throw their bunches outwards as seen in Fig. 11.7(b). Thus, uniformity of sucker growth and bunch emergence must be maintained for equal and effective mutual support. Plants with bunches falling inwards have to be individually propped with a wooden stake.

3. The overhead cable system of supporting banana bunches is widely used nowadays, especially: (i) in large multinational plantations; (ii) where timber is in short supply; and (iii) in protected cultivation greenhouses (see Chapter 8). A 5-mm diameter wire is suspended above each banana row, supported by uprights, braced by crosswires and stabilized at the end by anchors embedded in concrete. Bunches are tied to the wire with polypropylene twine. Although initially expensive, the system is cost-effective in the long term since it is long lasting. Other advantages are that no bunches are lost, it is less labour intensive than normal propping, chafing of bunches is reduced and plantation access is greatly enhanced.

Fig. 11.7. Two common methods of propping banana plants carrying bunches. (a) Double metal poles per plant give rigid and stable support, and no bunch chafing. (b) Polypropylene twine supporting plants in a tramline plantation. Note all bunches hang outwards where the plants lean and leaning plants mutually support each other. Twine is tied from the neck of one plant to the base of one or two opposing plants.

Bunch trimming

On commercial Cavendish banana bunches, the white, fleshy styles and perianths persist at the distal end of fruits. These can easily be snapped off by hand when a brown abscission layer forms at their base, some 8–12 days after bunch emergence (except for 'Dwarf Cavendish' where they must be cut with a knife). This practice has been shown to reduce fruit scarring and the incidence of cigar-end rot, and is now widely practised in tropical export plantations. In subtropical plantations, the dried and black flower parts are usually rubbed off after harvest in the packshed.

The male flower bud or 'bell' is usually broken off by hand once the distance between the distal hand and the top of the bell is between 120 and 150 mm and hermaphrodite fruits have abscised. This operation removes unwanted mass from the hanging bunch. The bell is also a competing 'sink' for assimilates and if not removed it keeps extending, since it contains the apical meristem of the bunch. The bell also provides shelter for thrips and mites to proliferate, as well as being a reservoir for fungi (*Colletotrichum musae*) and bacteria (*Xanthomonas campestris* pv. *musacearum*). Bell removal is compulsory for integrated production of bananas in Brazil (Rodrigues *et al.*, 2008). In Israel and Mexico it has been reported that early removal of the apical meristem from the male bud can increase bunch mass, provided it is excised immediately after flower emergence, before the female bracts have lifted away from the peduncle. This operation requires expert judgement on precisely where to cut.

It has been claimed that early removal of smaller distal hands, leaving only one 'nurse finger' to stop peduncle rot, improves export quality of the

banana bunch. In fact, removing up to three distal hands is standard practice on Cavendish bananas in the tropics, in order to increase finger length on the remaining hands (Soto, 1995). Research on this topic in the tropics and semi-tropics, and also on plantains, has shown contradictory results. Irizarry *et al.* (1991) reported that hand removal on 'Superplatano' plantain caused a bunch weight decline which nullified the increase in length and grade of the remaining fruits. Also, Rodríguez *et al.* (2006) found with FHIA 21 in Venezuela, that while increases in finger length, caliper and weight did occur with hand removal, a corresponding reduction in bunch weight occurred. Similar results were obtained on AAA 'Williams' by Daniells *et al.* (1994), and on experiments with other banana and plantain cultivars by Quintero and Aristizábal (2002) and Aristizábal (2004), while Rodrigues *et al.* (2002) found almost no differences with AAB 'Prata Ana'. In summary, distal hand thinning is useful for tropical export plantations where finger length is more important than bunch mass, but otherwise should not be recommended.

Bunch covers

The use of polyethylene bunch covers is almost universal throughout the commercial banana-growing world. They were initially used to avoid cold damage to the fruit cuticle and also for pest protection (Soto, 1995). Now they are regarded as essential to improve yield and especially fruit quality, of commercially-grown bananas. In subtropical banana-growing countries, with cold winters and strong winds, the benefits of bunch covers are both physiological (improved microclimate) and physical (larger fruit and reduced chafing from dust and leaves). There are many reports describing increased finger length, higher yield and shorter flower to harvest interval in various subtropical countries (Galán Saúco, 1992 and Table 11.1) In tropical countries, no differences were observed in yield, finger length or flower to harvest interval between covered or uncovered bunches, and benefits are related more to blemish control and reduction of pest damage (Rodrigues *et al.*, 2008).

For bunches developing over cool winters in the subtropics, their development period can be as long as 7 months (see Chapter 5 'Phenological Responses'). Researchers in these areas have consistently shown that both yield and quality are significantly improved by using polyethylene covers. In South Africa, a 16.7% increase in 'Williams' bunch mass was recorded due to a 10% increase in finger length under blue covers (Table 11.1), compared with uncovered bunches (Robinson and Nel, 1984). In addition, the proportion of first-grade fruits increased by 10–15% under covers, due to reduced mechanical damage and fewer undersized fruit on the distal hands. Average temperature was increased by only 0.5°C under blue covers compared with white, but the increase was much greater when direct sunlight reached

Table 11.1. Influence of polyethylene bunch covers applied just after flower emergence, on some phenological and yield components of AAA Cavendish bananas, in different localities.

Reference	Locality	Bunch treatment	E–H (days)	Bunch mass (kg)	Finger length (mm)
Robinson and Nel (1984)	South Africa	Covered	196	57.9*[a]	223*
		Uncovered	199	49.6**	203**
Daniells *et al.* (1987b)	Australia	Covered	159*	21.4*	267
		Uncovered	164**	20.6**	262
Daniells *et al.* (1992)	Australia	Covered	99	33.4	265
		Uncovered	110	33.4	257
Irizarry *et al.* (1992)	Puerto Rico	Covered	N/A	20.1*	171*
		Uncovered	N/A	18.3**	163**
Galán Saúco *et al.* (1996)[b]	Canary Islands	Covered	221*	41.8**	172**
		Uncovered	229*	32.4*	169*

E–H, Flower emergence to harvest duration; N/A, data not available.

[a] For each locality, means identified with different numbers of asterisks (* or **) are significantly different at $P = 0.05$.
[b] Results vary with locations and types of bunch covers. Data are for the most favourable differences between covered and uncovered bunches.

the covers. Winter fruit fill faster under covers, thus bunch development is accelerated, benefiting overall cycle time (Daniells *et al.*, 1987b). Similar advantages were obtained in the Canary Islands (Galán Saúco *et al.*, 1996). Experimental results from different localities are summarized in Table 11.1. Increases in yield per annum are due to either faster bunch development, larger bunches, or both.

In the tropics, or over summer in the subtropics, microclimatic changes associated with covers (increased temperature and humidity) are not required. On the contrary, the covers can damage the bunch physiologically due to overheating, rotting and premature ripening. In addition, bunch pests proliferate rapidly under the covers. However, mechanical protection of the fruit from leaf scarring, dust, light hail and handling damage during harvest and transport is very important. Thus, in tropical exporting countries, these requirements are met by using: (i) white covers for heat reflection; (ii) perforated bunch covers for aeration and cooling; and (iii) pesticide-impregnated covers for pest control (Fig. 11.8a). Interesting results were recently obtained in Colombia (Cayón Salinas and Daza Sanabria, 2006), where red and green covers produced larger fruit, better quality fruit and longer shelf life than blue or transparent covers. Differences are related to PAR transmission which is increased with green or red covers.

Fig. 11.8. Applying bunch covers in the tropics. (a) White perforated covers which give aeration and better heat protection. Note that the cover hangs well below the bottom hand. (b) Thin, translucent blue cover applied very early for better insect control. Note that the hand bracts are still present and fingers still point downwards.

For practical field use, covers in the tropics are applied early for better pest protection and before the bracts covering the hands have fallen, or the fingers start curling upwards or the floral remnants have hardened (Fig. 11.8b). Polyethylene tubing with flat width of about 700 mm is cut into lengths of 1–1.5 m depending on bunch length. The cover should hang at least 150 mm below the distal hand and be securely attached to the bunch stalk above the proximal hand. Thickness of the cover varies from 5 to 50 μm. Very thin covers are sometimes used in the tropics (Fig. 11.8b) because there is very little wind, the bunch development time is only about 3 months and the covers are only used once. The most common covers in the tropics are made with translucent polyethylene of 20–50 μm perforated with holes (diameter 5–12 mm) which are 75–100 mm apart in both directions (Soto, 1995; Moreira, 1999). Protective paper sheets can be placed inside or outside but covering the top hand to reduce direct sunburn. In the subtropics, blue covers with a thickness of 35–50 μm are used to protect against hail and wind, and may be used for two or three bunch cycles. They are usually impregnated with UV protection to prolong their useful life. Translucent blue is the most popular, which allows heat transmission but reduces sunburn damage.

The use of bunch covers on plantains has not been widely reported,

although they should be evaluated when high-grade commercial plantains are needed. Bunch covers are not used in the subsistence or cash economy sectors of plantain production.
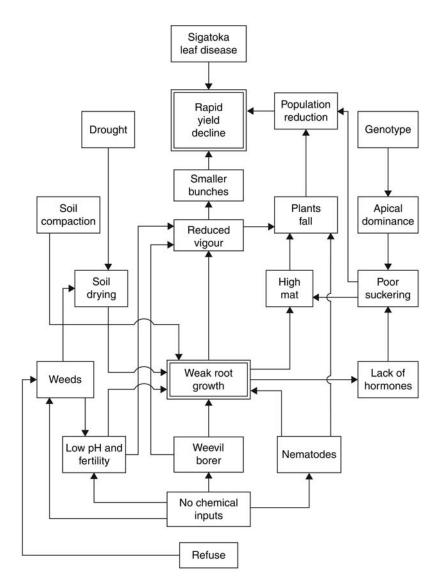
RATOONING AND PLANTATION LIFE

Practices in different countries

The life of a banana plantation is extremely variable worldwide, ranging from one crop cycle (10–18 months) to permanent plantations where replanting is never considered. Single-cycle plantations are not usually established out of choice but out of necessity. Where Fusarium wilt disease (*Fusarium oxysporum* f. sp. *cubense*) is a severe problem, this sometimes restricts the plantation to only one cycle before infection becomes limiting. Also, single-cycle banana plantations at high densities are now a viable alternative for some areas in the Canary Islands to channel production into the high price season (Galán Saúco and Cabrera Cabrera, 2006). While bunch yields per hectare are high at 3333 plants/ha and prices good, the establishment costs are very high, marketable fruit percentage drops, and the plantation never benefits from ratoon vigour (see Chapter 7 'Planting Densities and Spatial Arrangements').

Banana plantations with an intermediate life span (six to eight crop cycles) are found in most modern commercial plantings and with spatial arrangements which facilitate mechanization. After a few years, spatial arrangement tends to become more random. In South Africa, bananas must be replanted every 7–10 years due to yield decline resulting from nematodes, low pH, soil compaction, population reduction and/or loss of spatial arrangement (see Fig. 11.9). Annual yield levels are monitored and when yield decline starts, the problem is evaluated. If it can be rectified such as with soil pH and nematodes, this is chosen in preference to costly replanting. Severe nematode infestation or irreversible problems like soil compaction, reduced density and/or random plant spacing, will normally justify replanting.

Very long-term plantations used to be the normal practice in the humid tropics of Central America and in the subtropical conditions of the Canary Islands, where many plantations reached 30–40 years old. In the tropics, random spatial arrangements and soil compaction were tolerated since replanting was complicated by plantation infrastructures. Nematode levels build up rapidly but they are monitored regularly and soils are treated several times a year. Although low pH and low organic matter levels are inherent problems of these highly leached soils, fertilizer quantities and timing are adjusted accordingly to sustain high yields over the long term. More recently, replanting has become frequent in the tropics, using *in vitro* planting material as a starting point.

Fig. 11.9. Diagrammatic representation of factors involved in **progressive yield** decline in bananas and plantains. The key to delaying yield decline is to promote vigorous root growth or to eliminate factors causing weak root growth and development. Note how weak root growth is the central problem. The two pest factors weevil and nematodes play a vital role in enhancing yield decline. There is a strong association between nematode and banana weevil infestation in smallholder plantations. Suckers infested with nematodes are four times more likely to be infested with weevil than suckers without nematodes (Speijer *et al.,* 1993). The processes involved in yield decline are normally activated much quicker with smallholder plantains than with commercially-managed bananas. Diagram modified from Swennen *et al.* (1988).

Plantains grown in a subsistence or cash economy have a very short life cycle. The phenomenon of 'rapid yield decline' is common in such systems due to the absence of commercial management inputs (inorganic fertilizers, irrigation, weed and pest control – Fig. 11.9). Soil fertility and organic matter are rapidly depleted, necessitating replanting on new land. Traditional management practices such as organic wastes and mulching may slow the process of decline, but only marginally and the results are inconsistent. Plantains in bush fallow systems last only two cycles before bush encroachment, pests and lack of soil fertility cause yield decline. In commercial plantain farms, replanting every 3–4 years is the norm, when 'high mat' or 'double rhizome' problems start to occur. Although these problems are less for well-irrigated plants in deep soils, replanting is still necessary after four to five cycles due to other factors (Tazán, 2006).

Rotation cropping

In virgin soil, it is possible to replant directly to bananas after the initial plantation is removed. For subsequent replantings, fallowing for 1–2 years or establishing a rotation crop becomes necessary. The accepted benefits of crop rotation are: (i) reduction of soil diseases, root pests and nematodes; (ii) improved soil fertility and cation balance; and (iii) increased organic matter. In addition, this is an opportunity to change to a more productive cultivar, adopt a more appropriate density/spacing, change the irrigation system, improve soil conditions and even to re-orientate the harvesting season to a period of higher prices. The lack of rotation cropping is regarded as one of the major constraints to banana production in the Caribbean (Dorel and Perrier, 1990) and plantain production in the tropics (N'Guessan and Ganry, 1990). In a study by Ternisien (1989), the productivity of plant crop bananas was greatest following a crop of green manure legumes, due to enrichment of soil fertility and control of burrowing nematode. For long-term banana rotations, sugarcane or pineapples are used, whereas for short-term rotations, green beans, brassica and other vegetables, and legumes (velvet beans, sunhemp) have been recommended. Even a ploughed fallow standing for a year between successive banana crops is superior to immediate replanting, since nematode populations are reduced by starvation. An important consideration before fallowing or rotation is to ensure that all banana rhizome residues are eliminated from the soil to prevent nematodes and banana weevil from feeding and surviving.

Plantation productivity

Yield levels achieved in banana plantations vary greatly according to soil type, prevailing climate, management level and whether dessert bananas or plantains are being grown. In areas where commercial banana yields are near to their biological maximum, such as the multinational company plantations in the humid tropics or under greenhouse in the Canary Islands, the only possibility to increase yield is to breed new cultivars with increased biological efficiency or improved horticultural characteristics. Alternatively, and perhaps more feasible, is to breed for resistance to crippling pests and diseases such as *R. similis*, *Cosmopolites sordidus*, *F. oxysporum* f. sp *cubense* or *Mycosphaerella fijiensis*, thereby greatly increasing gross margins by reducing production costs. In areas where banana yields are well below their biological potential, such as in traditional smallholder situations, field research is required to attain the appropriate management technology, coupled with efficient transfer systems for this technology.

In the humid tropics, Stover and Simmonds (1987) refer to the increase in average annual marketable yields of bananas from between 10 and 15 t/ha before 1960, to levels of between 50 and 60 t/ha by 1987. They ascribe this increase to the application of research technology in respect of cultivar choice, horticultural management and plant protection. Under exceptional growing conditions they say it is possible to approach 70 t/ha marketable fruit annually in the tropics. In the semi-tropics of North Queensland, average annual ratoon yields of the best growers are also high at around 60 t/ha, while in subtropical areas like the Canary Islands, South Africa or Israel, peak yields may also reach 70 t/ha. Although climatic conditions in these localities are severe in both winter and summer, high yields are achieved through: (i) long, cloudless summer days; and (ii) the development of appropriate management systems to counteract the climate (efficient irrigation and the avoidance of winter flower initiation or emergence). However, in recent years, problems related to soil degradation (Chapter 9), and also due to many other interacting factors as shown in Fig. 11.9, have impacted more severely on the ability to sustain high yields.

Plantain yields are very much lower than those of banana. Plantains in West Africa yield from 10 to 30 t/ha from traditional and intensive production systems, respectively (Wilson, 1987). Higher yielding clones of 'Maricongo' plantain in Puerto Rico can produce up to 45 t/ha (Irizarry, 1985). While yield increases are urgently needed for plantains in traditional farming systems, this staple food crop is instead subjected to progressive yield decline in ratoon cycles due to depletion of fertility and organic matter, and build-up of weeds, pests and leaf disease (Fig. 11.9).

12

DISEASES

Although bananas and plantains can adapt efficiently to produce high yields under a wide range of climatic extremes (Chapter 4), they are susceptible to a range of serious and debilitating diseases. The most serious of these is black leaf streak (*Mycosphaerella fijiensis*), commonly called 'black Sigatoka' which is a fungal disease closely related to but more virulent than the common yellow Sigatoka (*Mycosphaerella musicola*). Black leaf streak has caused devastation to commercial bananas grown in tropical localities, and has also spread to plantains grown in smallholder situations in West Africa. The danger to staple food supplies caused by this disease led to the creation of INIBAP (now part of Bioversity International) in 1984, whose task it was to coordinate international research into the management and control of black leaf streak disease.

Another important banana disease is Panama wilt disease (*Fusarium oxysporum* f. sp. *cubense*), which destroyed over 40,000 ha of AAA 'Gros Michel' export bananas in tropical America, until this cultivar was replaced by the resistant AAA Cavendish subgroup bananas in the late 1950s and early 1960s. Currently, another race of Panama disease, namely 'subtropical race 4' is destroying Cavendish banana plantations in subtropical countries like South Africa, Taiwan and parts of Australia. New strains of this fungus known colloquially as 'tropical race 4' (TR4) started attacking Cavendish and other cultivars planted in the 1990s in Malaysia and Indonesia, and there is a serious risk that this can also affect Cavendish banana plantings in tropical America, Africa or the Caribbean (Jones, 2009). Thus, the continuing dependence of world trade on cultivars of the Cavendish subgroup is a potentially dangerous situation.

In addition to black leaf streak and Panama disease, other banana diseases like Moko disease, banana bunchy top disease and banana streak disease, continue to be serious threats to world banana production, and the situation has not changed much in the last 20 years. Meanwhile new disease problems, such as Xanthomonas wilt, have recently arisen in Central and East Africa. Chemical sprays for black leaf streak in tropical banana export

plantations have become extremely expensive and are increasingly restricted by the concerns of governments and consumers regarding environmental and health issues. In any case, chemical treatments are not effective for diseases like Moko, Xanthomonas or Panama. Although resistance breeding continues to be a critical research priority to overcome the threat of all these diseases, a more integrated approach is now a priority. Best results will be obtained by combining: (i) high-yielding resistant hybrids; (ii) forecasting systems for reducing chemical sprays; (iii) genetically-modified new cultivars with disease resistance; (iv) better understanding of host–pathogen interactions; and (v) healthy approaches like in organic cultivation systems (Markham, 2009).
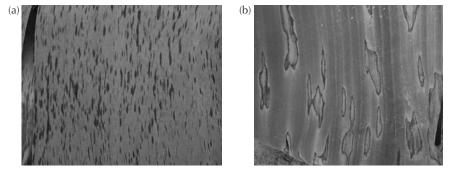
Small-scale, traditional growers of plantain or cooking bananas may be even worse off since they do not have the option of using chemicals, which are both expensive and dangerous if used incorrectly. In the absence of cultivars which are resistant to the debilitating leaf and rhizome diseases of *Musa* spp., the traditional farmer has minimal control over the infection rate and yield decline associated with these diseases. Extensive systems of cultivation usually preclude sanitary practices like removal of infected plants or plant parts, or the use of clean tissue culture plants, thus making resistant cultivars available is even more critical than with bananas. The interrelationship of all factors (biotic and agronomic) normally causing rapid yield decline in plantain, is shown in Fig. 11.9.

This chapter covers the main fungal, bacterial and viral diseases that affect bananas but the reader is referred to the literature for more detailed information.[1]

FUNGAL DISEASES

Black leaf streak (BLS)

BLS, also called **black Sigatoka**, is caused by the airborne fungus *M. fijiensis*. Initial disease symptoms on the leaves are small, translucent, pale yellow streaks which develop into black, oblong flecks (Fig. 12.1a) which, in turn, eventually become dark, necrotic lesions. When the lesions coalesce, patches of leaf are destroyed, which ultimately leads to reduced yields and premature ripening of bunches (up to 50% yield loss). The morphology of and symptoms caused by the BLS pathogen are somewhat different to those of **yellow Sigatoka** (YS), also called simply 'Sigatoka disease', caused by *M. musicola* (Fig. 12.1b). BLS is much more destructive since its increased virulence enables it to damage the younger banana leaves 2 to 5 which are photosynthetically more efficient (see Chapter 5 'Physiological Responses'). Thus, BLS affects many cultivars that have tolerance to the milder YS, such as many plantain cultivars (Jones, 1993).

Fig. 12.1. Two different types of Sigatoka disease infection on banana leaves. (a) Symptoms of 'black leaf streak' (black Sigatoka) on banana leaves in the tropics. Note the concentration of black oval lesions without borders or yellow halos. (b) Symptoms of 'Sigatoka disease' (yellow Sigatoka) on a banana leaf in the subtropics. Note the large grey lesions with black borders and yellow halos.

First recognized in Fiji in 1964, BLS was later widely reported in the Pacific and Asia. It was identified in Latin America (Honduras) in 1972 and rapidly spread to other countries in the region. In the early1980s BLS arrived in Mexico and Panama, followed by Colombia (1981), Ecuador (1986), Venezuela (1991) and Brazil (1998). In the Caribbean it was reported in Cuba in 1992, Jamaica (1995), Dominican Republic (1996), Florida (1998), Trinidad (2003), Bahamas (2004), Puerto Rico (2006) and most recently it reached Grenada, and St Vincent in 2009. In Africa, BLS was reported in Gabon in 1978 from where it spread to other West African countries, reaching Nigeria and Ghana in 1986, Rwanda (1987), Uganda (1990), Malawi (1992) and Tanzania and coastal Kenya in 1998, arriving also in Madagascar and other islands in the Indian Ocean. The rapid spread through West, Central and East Africa seriously endangers the production of plantains which are the staple food of around 70 million people in the region (BLS now also seriously affects the East African Highland cooking cultivars). The same critical situation applies to plantain production in Tropical America, and smallholdings of 'Pisang Berangan' in Malaysia and 'Pisang Mas' (syn. 'Kluai Khai') in Thailand (Jones, 2009). Although BLS is normally a wind- or water-borne pathogen, long-distance spread is probably through movement of infected leaves and suckers.

General recommendations for BLS control are similar to those used for YS. Systemic fungicides mixed with oil are still the only successful way to control BLS in the humid tropics. The application frequency (10–60 sprays/year) depends on prevailing climatic conditions (Abadie *et al.*, 2009). However, widespread use of these fungicides is expensive, may be damaging to the environment, and can lead to rapid development of resistance. In fact, the range of chemical fungicides is being increasingly restricted by certification

requirements of EU markets (see Annex 1 of directive 94/414/EEC; Europa, 2010).

Forecasting programmes to adjust (diminish) spray applications during climatic conditions not favouring pathogen sporulation, have been used successfully in several African countries (Markham, 2009). Organic fungicides (biofungicides) have also been used recently in Cameroon, but without satisfactory control of BLS under high inoculum pressure. However, aerial sprays of a combination of two *Bacillus* spp. with contact fungicides seem to have reduced overall fungicide requirement. Despite forecasting progress made to reduce fungicide applications per year, some countries increased the number of field sprays, with a consequent increase in BLS resistance problems. To overcome these problems, contact fungicides, like chlorothalonil, have replaced systemic fungicides in Cameroon (De Lapeyre de Bellaire *et al.*, 2009).

Among recent strategies used in BLS control is the enhancement of pathogen antagonists living in the phyllosphere (through application of foliar substrates like chitin, barley and urea) that may reduce the need for systemic fungicides (Patiño *et al.*, 2006). Organic formulations, like derivatives of *Melaleuca fijiensis* (Monreri, 2008) or new approaches based on the inhibition of extracellular enzymes of the pathogen (Boels, 2009), are now being tried. However, despite all these strategies, sustainable control of BLS may only be achieved through the breeding of resistant/tolerant cultivars, which must conform to legislative requirements and allow BLS control at reasonable cost. But this solution is not yet available.

Some commercial cultivars are highly tolerant to BLS, such as ABB 'Pisang Awak', ABB 'Pelipeta' and BBB 'Saba', but breeding has to produce tolerant/resistant cultivars which are **also** horticulturally acceptable to the consumer. Recently, the FHIA breeding programme in Honduras produced some resistant tetraploids with potential to replace susceptible Cavendish cultivars (Rowe and Rosales, 1996; Rowe, 1999). Similarly, at IITA (Nigeria), some 14 plantain hybrids were bred with BLS resistance, and these were distributed to other African countries to test for field resistance and consumer acceptability (Vuylsteke *et al.*, 1993). However, these bred cultivars are not always acceptable to growers and consumers in countries with the disease. Recent work done by CIRAD FHLOR in the French West Indies gave rise to three promising hybrids, namely 'FhlorBan 916', 'FhlorBan 918' and 'FhlorBan 920'. These hybrids combine sustainable tolerance based on slow lesion development, with good commercial characteristics, and may show promise for the fight against BLS. However, a BLS-resistant Cavendish cultivar has still to be developed.

The optimum mean temperature for growth of ascospore germination tubes of the BLS fungus is 27°C (11°C/38°C minimum/maximum) and this is reduced by 50% at temperatures below 20°C (Pérez-Vicente *et al.*, 2006). This may explain why BLS has not yet been recorded in subtropical banana-growing countries, but a risk exists that it could spread south from Cape York

Peninsula to the semi-tropical North Queensland banana belt. Thus strict quarantine and eradication measures have been applied in North Queensland, to prevent southerly spread of BLS. Despite this, in 2001 there was an outbreak of BLS recorded in the Tully banana area which was subsequently contained and eradicated in 2 years by a remarkable hygiene-based control programme of Queensland Department of Primary Industries in cooperation with the Tully growers.

Both North Queensland and South Africa have YS and, in North Queensland, the high rainfall, humidity and temperature favour the epidemiology and disease spread of YS, which necessitates regular spraying to avoid yield loss and field ripening (Ramsey *et al.*, 1990). In South Africa, the low rainfall and humidity, and long dry spells, are not conducive to the epidemiology and spread of YS and chemical control is hardly ever necessary. The disease is controlled effectively by horticultural methods, such as reducing overhead irrigations and regular removal of infected leaves and their placement as mulch (to deactivate spores and decrease pathogen load). For YS, a protocol has been recently formulated for a stepwise biological forecasting system to control the disease in bananas and plantains, with minimal chemical application. This includes field data collection, estimating stage of disease development and appropriate timing of fungicidal applications, as necessary (Ganry *et al.*, 2008).

Other leaf diseases

Apart from the two types of Sigatoka leaf spot, there are several other leaf spot pathogens which are normally of minor importance but can become locally serious in some countries.

Freckle disease or 'blackspot' caused by *Guignardia musae* (anamorph *Phyllosticta musarum*), attacks the foliage of Cavendish cultivars in Asia and is a serious problem in Taiwan and the Philippines. Different forms of this fungus also affect ABB cultivars such as 'Bluggoe' in the South Pacific, leaving Cavendish clones unaffected. Both AAA and ABB types are damaged in South-east Asia and also 'Lakatan' (AAA) in Malaysia. This wide range of hosts suggests that more than one fungus may be involved in freckle disease (Jones, 2009). The pathogen can attack young tissue cultured plants within 3 months after planting. Small, black lesions are produced on leaves and midrib, usually on older, senescing leaves. Spots on the fruit skin can cause economic losses. It is usually controlled by the same chemicals used to control BLS.

Cordana leaf spot caused by *Cordana musae* occurs widely in all major banana-growing areas, with a higher incidence on B genome cultivars (Cordeiro *et al.*, 2005). Individual brown lesions are up to several centimetres in length with a dark margin and surrounded by a chlorotic halo. This disease is not usually important itself but can occur together with other leaf spots,

enhancing overall leaf damage. Sigatoka sprays will also control *Cordana* spot.
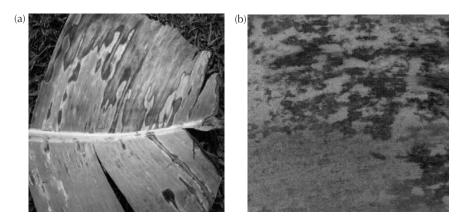
Cladosporium speckle (causal agent *Metucladosporiella musae* (Crous *et al.*, 2006), previously *Cladosporium musae* (Jones, 2000)) is also widespread, particularly in Africa, affecting Cavendish types as well as East African Highland cultivars previously infected by BLS. It can also be serious on AA genome cultivars like 'Pisang Mas' or 'Pisang Berengan' in South-east Asia. Symptoms of this disease are orange to dark coalescing lesions (Jones, 2009). The lesions are blotchy, very similar to those caused by *M. musae* (Fig. 12.2a).

Mycosphaerella speckle caused by *Mycosphaerella musae* is a minor disease found worldwide. However, in Australia and South Africa it is a serious problem that causes leaf death. In South Africa, *M. musae* is even more serious than YS (*M. musicola*), and is characterized by round, smokey black blotches in a yellow background, that coalesce causing leaf death (Fig. 12.2b). Control is by regular removal of infected leaves, similar to *M. musicola*.

Deightoniella torulosa is a weak pathogen causing small brown spots on stressed leaves, winter leaves, older leaves and also on fruit. Economic damage has been caused on Cavendish fruits in South Africa, where the typical symptom is a mass of fine pinprick-sized black spots on pre-harvest fruit. Control is not usually necessary.

Panama disease

Panama disease or Fusarium wilt is caused by many different strains or genotypes of the soil-borne pathogen *F. oxysporum* f. sp. *cubense* (FOC). The
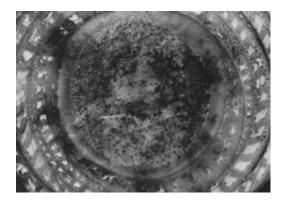
Fig. 12.2. Other common leaf diseases on Cavendish banana. (a) Cladosporium speckle showing orange to brown coalescing lesions. (b) Mycosphaerella speckle showing irregular smokey black blotches which coalesce into necrotic patches.

first report of FOC was from Australia in 1874 but it became epidemic in Central America in 1890 (Panama). The disease is currently widespread in banana-growing regions of Asia, Africa, Australia, the South Pacific and Latin America.

Although symptoms are first seen on leaves, the site of infection is actually the root system, where the fungus penetrates through wound tissue, and spreads through the xylem system into the rhizome and pseudostem. When the pseudostem or rhizome of an infected plant is cut, vascular tissues show red-to-brown dots and streaks due to host gels and tyloses blocking the xylem vessels (Fig. 12.3). Externally, the older leaves begin to turn yellow prematurely. Yellowing begins along leaf margins and advances towards the midrib. Necrotic patches appear along the margins and petioles turn brown and buckle. Buckled leaves eventually hang around the pseudostem like a skirt, and the plant dies, usually after flowering. Symptoms are similar to drought since water-conducting vessels are effectively blocked by the defence mechanisms of the plant. In the case of a severe soil infection, young plants can wilt and die when only a few months old. Surface water runoff and infected planting material are the two major methods of pathogen dispersal over long distances. Short-distance spread is enhanced by infected soil attached to implements and shoes, and by root-to-root contact. Infected patches should be fenced off and no access allowed.

According to the traditional classification proposed by Stover (1962) there are three races of FOC (races 1, 2 and 4) which attack edible banana cultivars, and one (race 3) which only attacks *Heliconia* spp. Race 1 attacks AAA 'Gros Michel' and AAB 'Silk' and is the race responsible for destroying over 40,000 ha in Latin America before race 1-resistant Cavendish cultivars were planted there. Subsequently, race 4 was discovered in Taiwan in 1965 where it destroyed over 6000 ha of Cavendish cultivars. Race 4 also spread in South

Fig. 12.3. A banana pseudostem with transverse cut to show typical internal symptoms of Panama disease infection (red-to-brown spots and streaks). This indicates host reactions to fungal spread, which block the vascular tissues of the plant, causing external wilt symptoms.

Africa, the Canary Islands and South Queensland during the 1970s, attacking Cavendish cultivars there. Race 2 of FOC has destroyed mainly ABB 'Bluggoe' in parts of Central America.

Currently, many isolates of the FOC pathogen have been collected worldwide, and these have been used in vegetative compatibility tests, where their ability to fuse with other isolates has facilitated classifying them into 'vegetative compatibility groups' (VCGs). The genetic diversity indicated by these VCGs has been confirmed by DNA fingerprint patterns using RAPD primers. Thus, race 4 has four separate VCGs which attack Cavendish bananas in different parts of the world. Pathogen diversity studies are essential in banana breeding programmes so the exact pathotype against which resistance is required, can be identified (Ploetz, 1993). Tropical race 4 (TR4), the most destructive race of Panama disease, is fortunately restricted mainly to Southeast Asia. All Cavendish cultivars, many ABB cultivars, the whole plantain subgroup, and various AA, AAA, AB and AAB dessert types are all susceptible to TR4 (Ploetz, 2008). Some recent studies (Buddenhagen, 2009) recommend dropping the concept of races and substitute with strains, identified by VCG analysis and given numbers. According to this modern classification, TR4 is the VCG 01213 strain.

There are no economically viable chemical or cultural methods of controlling Panama disease in an infected field. Measures such as quarantine (critically important to keep 'TR4' out of the western hemisphere), fumigation and the use of *in vitro* plantlets which are disease free, can be applied, but re-infection can easily take place from infected soil or irrigation water. Once again, breeding for tolerance or resistance is the only long-term solution. In the 1990s two promising bred cultivars, namely the conventionally-bred FHIA 01 'Goldfinger' from Honduras and the somaclonal variant GCTCV 215-1 'Tai Chiao' from Taiwan (see Chapter 2 'Somaclonal variation') offered good prospects for cultivation in fields infected with Panama disease. FHIA 01 has been mostly discarded as a dessert banana due to its taste being different to Cavendish types. GCTCV 215-1 with moderate resistance to VCG 01213, is used in Taiwan for one or two cycles before production is stopped to allow flooding and rotation with rice, prior to replanting.

Other rhizome diseases

Apart from Panama disease, the only rhizome fungal disease of economic importance is *Armillaria.* This occurs in Australia and South Africa, usually on new plantations from recently cleared bushland. External symptoms are similar to those caused by FOC, but internal symptoms are quite different. When the rhizome is cut open, white, finger-like shoots of fungal mycelium are seen ramifying throughout. The disease usually occurs within the first 2 years

of planting on new ground. The fungus is associated with forest and bush trees and if the land is not properly stumped, the fungus will attack bananas after planting.

Fruit diseases

Apart from pre-harvest fruit damage caused by the foliar pathogens *P. musarum* and *D. torulosa*, several specific fruit diseases can cause economic damage on bananas. 'Cigar-end rot', associated with two fungi, *Verticillium theobromae* and *Trachysphaera fructigena*, has been recorded in several banana-growing countries including West Africa, South Africa, the Canary Islands, Morocco, Israel, Trinidad and Queensland. The fungal pathogen attacks flowers, infecting the perianth. During fruit development, the initial perianth infection spreads slowly along the fruit, causing the skin to blacken. The infected tip area later becomes covered in a powdery mass of spores, at which time it resembles the ash on a cigar. Removal of the pistil and perianth from 8 to 11 days after bunch emergence provides a means of control. Polyethylene bunch covers also help to prevent infection.

Crown rot is a major postharvest disease of banana fruit throughout the world but particularly in packsheds which do not practise strict sanitation. Several fungi are associated with the disease in Central America and the West Indies, namely *Colletotrichum musae*, *Fusarium moniliforme*, *Fusarium pallidoroseum* and, to a lesser extent *V. theobromae* and *Botryodiplodia theobromae.* Other fungi play a role in different countries. Fungal spores colonize the wound where hands of banana are excised from the bunch. Rotting may spread from the cut surface into the crown of the hand during transport, and in more severe cases the pedicel may also rot. Infection occurs from banana trash in the field or from inoculum build-up in the packshed and dehanding tanks.

Anthracnose peel blemish is another important disease, caused by *C. musae.* Infection originates on immature fruit in the field but lesions do not develop until the fruit ripens and the fungus can penetrate the peel. Large oval lesions develop with salmon-coloured fruiting spore bodies. Lesions may also develop on green fruit but usually only when the peel is mechanically damaged.

Fungicide dips have been extensively used in the past to prevent anthracnose and crown rot during extended transport, and the most commonly used chemicals were thiabendazole, imazalil, benomyl and prochloraz. Recent concerns about fungicide treatments and strict legislation in the markets (only thiabendazole is now allowed in the EU) necessitated alternative control methods both in the field and in the packshed. Natural fungicides, for example BC1000, a mixture of grapefruit seed and pulp plus bioflavonoids, has been shown to control fruit diseases (Llontop-Llaque and Rojas-Campos, 2008). Field sanitation practices (including early removal of flowers, sanitary deleafing, early bunch bagging and practices designed to

reduce wounding and bruising) facilitate fruit export from highland areas with low susceptibility to anthracnose, without the need for chemical treatments (Côte *et al.*, 2009).

BACTERIAL DISEASES

Moko disease

This disease, caused by the bacterium *Ralstonia solanacearum* is one of the most serious diseases of bananas and plantains. It has caused severe crop losses in smallholder plantations in Central and South America and the Caribbean. Outside the western hemisphere the disease has been reported only in the Philippines and Indonesia. AAA Cavendish cultivars are susceptible as are some ABB cultivars like 'Bluggoe' (syn. 'Moko'), whereas AAB Horn plantain and ABB 'Pelipeta' are resistant. On commercial banana plantations in Central America, damage from Moko is slight due to rigorous and expensive prevention systems. There are three races of *R. solanacearum* of which only race 2 attacks banana and plantain.

Moko disease causes wilt symptoms in older leaves, while the youngest leaves turn pale green or yellow and collapse at the petiole. Young suckers have yellow or black leaves and they are twisted and stunted. Internally there is vascular blackening in the leaf sheaths near the centre of the pseudostem and in the rhizome. Yellow fingers on a green bunch are indicative of bunch infection and these fingers show a brown rot of the pulp when cut.

The bacterium can be transmitted from plant to plant by pruning knives. On healthy plants the cut surfaces of harvested or desuckered plants provide a ready source of entry to the pathogen. Fruit infection is common and occurs through fresh scars of male flower bracts which have abscised from the peduncle. Insects visiting the sap oozing from bract scars transmit the pathogen from bunch to bunch. Spread can also occur by root-to-root contact similar to Fusarium wilt. After infection, the bacteria multiply rapidly resulting in vascular system blockage also similar to Fusarium wilt.

Effective control in commercial blocks is carried out by teams of inspectors who survey infected plantations at 2–4 week intervals and detect and destroy diseased plants together with surrounding adjacent, healthy plants. In all such plantations, cutting tools are disinfected between each healthy mat. Infected plants and suckers are not cut but are injected with a systemic herbicide such as glyphosate. Since the extending male bud can be visited by insects carrying the pathogen, the peduncle is broken off at an early stage to reduce insect transmission. Replanting an infected site should occur only after a 12-month fallow. If adequately implemented, these measures can eradicate Moko from banana plantings. A good example of this success was in Australia where Moko was introduced on imported *Heliconia* plants from Hawaii but was

quickly eliminated (Jones, 2009). These measures are usually not enforceable in patches of smallholder bananas/plantains.

Among the bred FHIA cultivars, FHIA 03 cooking banana can replace the highly susceptible AAB 'Bluggoe' and a programme to effectively substitute it was carried out in Grenada in the Caribbean (Rowe, 1999). Presently, however, FHIA 03 is only cultivated successfully in Cuba where it is used as a dessert banana (see Chapter 2 'FHIA hybrids').

Xanthomonas wilt (X wilt)

The first description of this bacterial disease was made in Ethiopia in the late 1960s affecting *Ensete*. Curently X wilt seriously affects banana plantings in a larger area of Central and East Africa including Ethiopia, Uganda, Democratic republic of Congo, Rwanda, Uganda, Kenya and Burundi (Tripathi *et al.*, 2009). This disease is one of the main constraints of banana production in Uganda, with yield losses of US$35 million by 2005 (Tushemereirwe *et al.*, 2006a). The pathogen causing this disease was classified by Young *et al.* (1978) as *Xanthomonas campestris* pv. *musacearum*, but according to recent taxonomic studies (Aritua *et al.*, 2008) which are still pending official nomenclature approval (Jones, 2009) it is a pathovar of *Xanthomonas vasicola*.

Symptoms of X wilt are present throughout the plant including leaves (progressive yellowing and subsequent wilting), fruits (uneven and premature ripening with typical yellowish blotches in the pulp and dark placental scars), flowers (wilting of bracts, shrivelling and decay of male buds, yellow-brown flower). After cutting the pseudostem and peduncle of affected plants, yellowish bacterial ooze appears. Brown or yellow streaks can be observed in the vascular tissues and affected plants may finally wilt and rot.

Management practices like early male bud excision and removal and burying of infected plants are very effective ways of controlling this disease, as insect vector transmission occurs only via the male bud (Tinzaara *et al.*, 2006; Blomme *et al.*, 2009). Disinfecting tools and replanting with tissue culture plants will also help, but these practices are not easy to implement under the extensive systems of banana cultivation in East and Central Africa. Since spread of the disease was overtaking these eradication measures, all role players in Uganda formed a taskforce called the Banana Bacterial Wilt Control Initiative (BBWCI). The purpose was to try and 'contain and manage' the disease by encouraging farmer participation at community level (Tushemereirwe *et al.*, 2006a).

X wilt affects almost all cultivars commercially planted in East and West Africa, but the ABB beer banana cultivar 'Kayinja' (syn. 'Pisang Awak') is the most seriously affected, probably due to its dehiscent bracts and its extensive

system of cultivation. Although no resistant cultivars have been reported, those with persistant bracts, like 'Dwarf Cavendish', which impede insect vector transmission, are the least affected (Jones, 2009).

VIRAL DISEASES

Virus pathogens are assuming greater potential importance in banana production due to the current widespread movement of *Musa* germplasm, as *in vitro* plantlets, throughout the world. While *in vitro* plantlets are guaranteed free from fungal and bacterial pathogens, as well as nematodes, viruses can be readily disseminated via the *in vitro* process. This poses the threat of international virus spread which in turn necessitated the introduction of a reliable international virus indexing scheme for safe *Musa* germplasm exchange, coordinated by Bioversity International (see Chapter 2).

Banana bunchy top virus (BBTV)

Banana bunchy top disease is the most important and widespread viral disease of bananas. It is caused by BBTV in the genus *Bavuvirus*. It has a multicomponent, circular, single-stranded DNA genome with a minimum of six integral components (BBTV DNA-1 to -6), which are consistently linked to bunchy top infection worldwide. There are at least three other non-integral components (BBTV S1, S2 and Y), which have been isolated in Taiwan (Horser *et al.*, 2001).
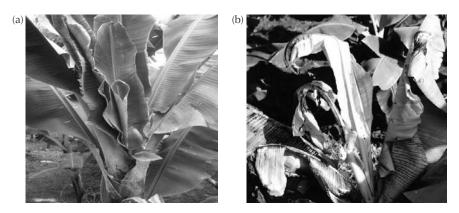
First recorded in Fiji in 1889, BBTV was progressively reported after the turn of the century in Taiwan, Egypt, Sri Lanka and Australia. It is currently endemic to South-east Asia and occurs in many countries of the eastern hemisphere, including the Philippines and India. It also affects plants in parts of northern, central and eastern Africa, but the strain there is not as destructive as that in Asia and the Pacific. BBTV does not occur in Central or South America, the Canary Islands, Israel or South Africa. The vector of BBTV is the banana aphid *Pentalonia nigronervosa*, which is widespread, and causes new infections within and between neighbouring plantations. Long-distance transmission is via infected plant material (suckers or non-indexed tissue culture). There is no mechanical transmission of BBTV.

The initial symptom of BBTV is the development of dark green flecks along the leaf veins, producing a 'dot-dash' pattern, with 'hooks' at the junction with the midrib. This symptom is also clearly seen behind the petiole. A later symptom is that affected leaves become more upright than usual and become pale yellow around the margin, with leaf margins more wavy than usual. At an advanced stage of infection, plant development is curtailed, emerging leaves become progressively smaller, and leaves become choked

in the throat of the plant, creating the 'bunchy top' effect with pronounced stunting (Fig. 12.4a). Plants affected at an early stage rarely produce a bunch whereas those affected later may produce unmarketable bunches which are stunted and point upwards.

Where BBTV is prevalent in commercial banana areas, a strict inspection and eradication programme is essential. Control depends on early detection and destruction of diseased mats with herbicide. Such a programme has been rigorously enforced in Australia, since the 1920s. It is expensive, but as a result, BBTV has been kept out of Western Australia, the northern Territory, North Queensland and the Coffs Harbour region of New South Wales (Biosecurity Australia, 2007). The status of BBTV has now been reduced to that of a minor disease in these affected areas. It will only remain so if the detection and eradication programme continues, coupled with strict quarantine and indexing procedures to prevent spread of infected plant material. In areas where effective eradication could not be applied, such as The Philippines, India, Fiji and Pakistan, BBTV remains a major production constraint. Eradication of infected plants is difficult to enforce, especially in smallholder plantations.

Cucumber mosaic virus (CMV)

Despite its worldwide distribution, CMV is usually a minor problem in bananas. It can be serious in young plantations established close to weeds of the genus *Commelina*, *Stellaria*, *Bryonia* and *Solanum*, which are important host reservoirs of the virus, and particularly if the aphid vectors of this virus, *Aphis gossypii* and *Myzus persicae* are present (Jones, 2009).

Fig. 12.4. Leaf symptoms of two important viruses in banana. (a) Severe infection of banana bunchy top virus (BBTV) in which leaves become progressively smaller and plants assume a stunted, rosette appearance. (b) Advanced symptoms of cucumber mosaic virus (CMV) showing leaf streaking and dieback, and central leaf rotting.

CMV infects Cavendish cultivars and Horn plantain, and is likely to occur sporadically wherever *Musa* is grown. The disease is characterized by conspicuous, sharply defined interveinal chlorosis of the leaves, which, if serious, can lead to necrosis and rotting of the heart leaf and central tissues (Fig. 12.4b). However, serious infection is seldom encountered. CMV is usually transmitted from weed and vegetable host plants to banana by several different aphid species.

Infection of banana plants by CMV is most likely to occur during warm weather and in the proximity of cucurbit vegetables. Very hot weather can suppress infection and/or symptom development but the virus is systemic and, although plants may appear to recover, suckers from an infected plantation should never be used for planting material. Banana plantations should be kept free of weeds and not intercropped with vegetables. Early removal of infected plants, elimination of weed hosts of CMV, and control of the virus vector, are effective ways to combat CMV. In addition, all mother plants for tissue culture multiplication should first be indexed for the presence of CMV.

Banana bract mosaic virus (BBrMV)

BBrMV in the genus *Potyvirus*, was initially confused with CMV, but was recognized as a new disease in the Philippines in 1988 (Frison and Putter, 1989). It affects banana plants in India, Sri Lanka and the Philippines. BBrMV symptoms include mosaics on bunch bracts and pseudostem, stripes and spindle-shaped streaks on pseudostem bases, misshapen fruits and distorted suckers. It affects many cultivars, and no resistance has yet been identified. The virus is transmitted by the same aphids that spread CMV (Jones, 2009) and control measures are similar to those for CMV.

Banana streak virus (BSV)

This virus was first identified in Morocco in 1986 where the infection rate exceeded 50% in a 'Dwarf Cavendish' plantation. Since then BSV has been shown to occur worldwide and to infect a wide range of *Musa* genotypes. AAB 'Mysore' is particularly sensitive. BSV is a member of the genus *Badnavirus* containing bacilliform particles with double-stranded DNA. Three different species of BSV have already been recognized, namely *Banana streak Gf virus*, *Banana streak Mysore virus* and *Banana streak OL virus* (Fauquet *et al.*, 2005), but the future discovery of other species of this highly variable virus is anticipated (Jones, 2009). These viruses are readily transmitted by mealybugs (*Planococcus* spp.), but can also be moved from plant to plant by ants. The

principal means of spread, however, would be in planting material, which emphasizes the importance of a reliable indexing technique for BSV in tissue culture mother plants.

Symptoms of BSV infection are yellow streaks, either continuous or broken, running across the leaf blade. These blacken with time. Distribution is erratic over the plant and symptoms are more pronounced on leaves produced in summer. Growth and yield are depressed, but data on economic losses are scanty. Infected plants should be eradicated and clean planting material used.

BSV has the potential to become a serious virus problem of bananas worldwide, affecting breeding programmes, *Musa* germplasm exchange systems and commercial plantations. However, the main problem in developing a reliable indexing method for BSV is the wide serological and genomic variability among isolates of the virus. Therefore no single antiserum or DNA probe is capable of identifying the wide range of virus isolates. In addition, a unique problem concerning BSV is the integration of genomic sequences of the virus into the DNA of B genome bananas, which then become episomal and active under stress conditions, such as passing the material through tissue culture. This is a serious problem for safe international movement of shoot-tip tissue cultures of banana cultivars, containing the B genome (Jones, 2009). Research to develop sensitive and reliable diagnostic tests for BSV has been done at the University of Minnesota, USA since the end of 1980s (INIBAP, 1994) and also at the Bioversity International Transit Centre in Leuven, Belgium, where strategies have been devised to eliminate episomal BSV and other viruses from *in vitro* plants (Panis *et al.*, 2005).

Other banana viruses

Two new bananas viruses, banana virus X (BVX) and banana mild mosaic virus (BanMMV) have been recently discovered, but their etiology, transmission vectors and control treatments are still not well known (Geering, 2009).

ROLE OF FUNGAL AND BACTERIAL ENDOPHYTES IN CONTROLLING BANANA DISEASES

The reader is referred to the last section of Chapter 13 (Pests) for a detailed analysis of current research regarding the use of endophytes for controlling both pests and diseases in *Musa.*

NOTE

1. The textbook *Diseases of Banana, Abacá and Ensete* (Jones, 2000), published by CABI, gives a comprehensive updated review of banana diseases. The recently published *Acta Horticulturae* 828 which covers the Proceedings of an International Symposium on Recent Advances in Banana Crop Protection for Sustainable Production and Improved Livelihood (Jones and Van den Bergh, 2009) covers the most recent research papers in this field, some of them already referred to in this chapter. Specifically on the relatively new problem of X wilt, the reader is referred to the special issue of the *African Crop Science Journal* – 'Banana bacterial wilt in Uganda: a disease that threatens livelihoods' Vol. 14, No. 2, June 2006 (Tushemereirwe *et al.*, 2006b).

13

PESTS
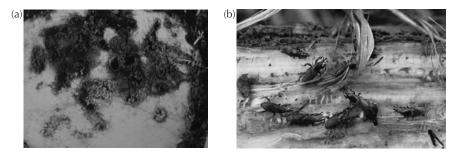
RHIZOME AND ROOT PESTS

Banana weevil

The banana weevil, *Cosmopolites sordidus*, is distributed widely in Central and South America, East, West, Central and South Africa, the Canary Islands, the Caribbean, Australia and on many Indian and Pacific Ocean islands and also in Asia. It is the main pest of banana rhizomes and is specific to all *Musa* species and cultivars. No cultivar is resistant to the pest. Eggs are laid at the base of the pseudostem and the larva of the weevil enters, feeds and tunnels in the rhizome of the plant. Tunnels are circular and up to 8 mm in diameter (Fig. 13.1a). With severe infestation the rhizome can be riddled with tunnels which may also extend 300 mm or more up the pseudostem. Such injury to the rhizome interferes with root initiation and vascular transport into the plant, thus the youngest leaves wilt and die prematurely, and small bunches with undersized fruit are produced. Plants may break and topple over due to the weakened rhizome.

The adult weevil is about 12 mm long with a hard black shell and pronounced snout (Fig. 13.1b). Adults emerge from the rhizome mostly during spring and late summer. They are nocturnal and during the day they shelter in leaf sheaths or in trash on the ground. They may live for several months to over a year, during which egg laying continues throughout the year but at a reduced rate during winter in the subtropics. During summer, eggs hatch in 6–8 days and the young larvae immediately tunnel into the rhizome. In the subtropics, the average life cycle from egg to adult ranges from 30 days in summer to 180 days in winter.

Weevils are spread from farm to farm via infested sucker planting material. Within a plantation, they are spread by adults crawling from mat to mat. Several strategies can be used to control the pest. Cultivation practices relate to the elimination of hiding places and breeding sites, such as efficient weed control and chopping old pseudostems into small pieces that rot quickly.

Fig. 13.1. (a) Tunnels and damage caused by the banana weevil in a banana rhizome. Tunnels are up to 8 mm in diameter and a severe infestation depletes reserves and interferes with root initiation and vascular transport in the plant. (b) Adult banana weevils, which are about 12 mm long, crawling on the underside of a pseudostem trap.

In vitro planting material should always be used, failing which suckers should be thoroughly pared and inspected for tunnels (Fig. 13.1a). For evaluating infestation potential, pieces of freshly cut pseudostems are used as traps from which adults are collected, counted and destroyed. Pesticides previously used for weevil control included highly toxic organochlorides (chlordecone), organophosphate insecticides and phenylpyrazole (Chabrier *et al.*, 2005), but these compounds can be toxic for humans and other organisms. They are severely restricted for use in places like the French West Indies where only Nemathorin®, a nematicide product with secondary insecticide action, is allowed for weevil control (Côte *et al.*, 2009). Concern about chemicals is growing worldwide and efforts are instead being directed to the use of pheromone traps and other biological control methods.

Quarantine precautions are vital to prevent the spread of the weevil into areas which are free of the pest. Undetected movement of infested sucker planting material allowed the weevil to be brought into the isolated area of Kununurra, Western Australia, where the pest proliferated in the hot, wet conditions and heavily trashed plantations, to become a major economic constraint.

Alternative control methods include the use of fungal pathogens (*Beauveria bassiana*; Akello *et al.*, 2009), entomopathogenic nematodes (*Steinernema* and *Heterorhabditis* spp.; Treverrow *et al.*, 1991) and bacteria (*Bacillus thuringiensis*; Quilici, 1993). The use of such biological control agents in pseudostem traps together with pheromone attractants are now common practice for weevil control. The protocol for pseudostem trapping is as follows: during spring/summer, 100 mm thick pseudostem discs are cut from harvested pseudostems and placed on clean ground next to banana mats (about 20 traps/ha). After a week they are inspected and the weevils counted and destroyed (repeated weekly). If counts are high (more than one weevil/trap/week), then chemical treatments are scheduled such as pseudostem injections in winter when adults

are hibernating, or 'butt' sprays in summer when adults are actively looking for egg-laying sites around stem bases. Not all *Musa* cultivars are attacked equally. Work in Cameroon by Fogain and Price (1994) on 52 cultivars of *Musaceae* indicated that AAB plantains were the group most susceptible to *C. sordidus* damage. Recent studies in India (Padmanaban *et al.*, 2006) on 155 cultivars of different genomes also revealed that ABB and BB cultivars are more sensitive than the other groups. Rhizome gallery assessments (number of weevil tunnels/unit volume of rhizome) showed that AAA bananas were much less susceptible to damage than plantains and other B genome bananas.

Burrowing nematode

The burrowing nematode, *Radopholus similis*, is the most widespread and damaging nematode attacking bananas and plantains. It is present throughout the tropics and in the subtropics of New South Wales and parts of South Africa, but does not occur in Israel, Taiwan or the Canary Islands. *R. similis* is commonly associated with Cavendish cultivars and can cause severe damage in the export plantations of Central America unless regular nematicide treatments are applied. In Cameroon, AAB plantains were found to be more susceptible to *R. similis* damage than either AAA dessert bananas or ABB cooking bananas (Price, 1994a,b; Table 13.1). Further detailed studies on this topic were conducted in Ivory Coast by Mateille (1993). In general, plantains are highly susceptible, but some good resistance is found in the dessert bananas 'Silk' and 'Mysore' (Sarah, 2000).
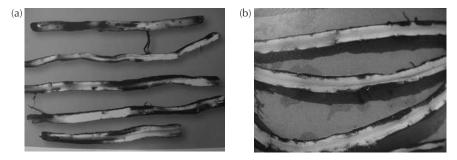
R. similis is easily spread within a plantation by water runoff, adhering soil particles or desuckering gouges. As with banana weevil, the most important means of spread is via infested planting material and this is how the pest has been introduced to most areas which were previously clean. The nematode is semi-endoparasitic and adults range in length from 0.4 to 0.9 mm. The female can lay an average of four eggs/day over a period of 7–14 days. Eggs hatch after 8–10 days and larvae mature in 10–13 days (Loos, 1962).

Burrowing nematodes usually penetrate at the tip of the banana root and the earliest visible symptoms of damage are elongated dark lesions, covering the epidermis. When roots are cut longitudinally, elongated reddish lesions can be seen parallel to the xylem (Fig. 13.2a). Inside the root, the nematode feeds by puncturing individual cells with its stylet and sucking out the cell contents. As these cells are destroyed, the root tissue colour changes from white to red to black. Infestation spreads along the roots into the rhizome causing similar red-coloured lesions. Damage can be enhanced by other destructive organisms which enter through the lesions. The roots of a heavily infested plant rot away to short stubs that are unable to anchor the plant securely, so the pseudostem topples over easily, especially when carrying a bunch.

Table 13.1. The susceptibility of different *Musa* genomes and cultivars to root infestation by two banana-parasitic nematodes, *Radopholus similis* and *Pratylenchus goodeyi,* in two plantations in Cameroon (from Price, 1994a, b). Data show wide differences in *Musa* susceptibility.

R. similis				P. goodeyi			
Cultivar	Genome	Genetic group	Numbers[a]	Cultivar	Genome	Genetic group	Numbers
Laknao	AAB	Laknao	32,859	Pelipeta	ABB	Pelipeta	41,356
Ebanga	AAB	Plantain	24,342	Corne type	AAB	Plantain	34,890
Corne No. 5	AAB	Plantain	10,937	Christine	ABB	Bluggoe	33,859
Grand Nain	AAA	Cavendish	4,446	French Clair	AAB	Plantain	18,214
Bluggoe	ABB	Bluggoe	2,440	Kedongkekang	AAB	Plantain	12,581
Pisang Mas	AA	–	1,211	Grand Nain	AAA	Cavendish	4,865
Poyo	AAA	Cavendish	1,096	Poyo	AAA	Cavendish	4,674
Americani	AAA	Cavendish	446	Obel	AAB	Plantain	3,778
Pelipeta	ABB	Pelipeta	163	Batard	AAB	Plantain	583
Gros Michel	AAA	Gros Michel	80	Gros Michel	AAA	Gros Michel	54
Yangambi	AAA	Ibota	4	French Sombre	AAB	Plantain	–

[a] Numbers refer to nematodes counted/100 g fresh mass of roots.

Fig. 13.2. Parasitic nematode species on banana roots. (a) Internal lesions of burrowing nematode which are elongated and deep-seated in the cortex. (b) Internal lesions of spiral nematode which are smaller, shallower and less extensive than with burrowing nematode.

The impaired growth and function of infested roots render them unable to absorb water and nutrients. Before toppling, the plant will show symptoms of leaf yellowing, small bunches, choke throat, and typical drought and nutrient deficiency symptoms. Apart from cultivar susceptibility (Table 13.1), factors enhancing damage are poor soil fertility (especially with plantains), high pathogenicity of the particular nematode strain, weak root vigour and lack of suckers (Gowen, 1995).

Control of *R. similis* can be ensured, at least temporarily, by planting nematode-free *in vitro* plantlets on virgin soil or fumigated replant soil. This will keep the problem away for many years. If using conventional planting material, the pieces must be thoroughly pared, inspected and treated with nematicide or hot water, before planting. In export plantations of Central America, nematicides (fenamiphos, fosthiazate, oxamyl, cadusaphos, carbuforan) are applied routinely, but they are progressively being restricted, with the last two being specifically forbidden in the EU. If used, nematicides should be rotated to prevent their rapid degradation by soil microflora, or resistance build-up by the nematode. Organic mulching is recommended in traditional, low-input plantations and these have been shown to promote vigour and delay yield decline. It is not known if this effect is directly or indirectly related to nematodes.

Crop rotation experiments in Cameroon (Price, 1994c) showed that the traditional rotation crop, groundnuts, did not reduce levels of *R. similis*, whereas cassava and sweet potato rotations sharply decreased nematode levels. In South Africa, long-term rotation with sugarcane is efficient in suppression of burrowing nematodes from an infested field, and for short-term rotations, various bean species, or sunhemp are normally used (Robinson, 2007). Intercropping with antagonistic plants like *Crotalaria*, *Tagetes*, lucerne or coriander has been recommended in Brazil (Ribeiro *et al.*, 2008). Large amounts of organic matter have also been shown to suppress burrowing

nematode in banana soil, although not all types have the same effect. In Australia, Pattison *et al.* (2006) showed that high organic carbon, particularly the labile fraction, and reduced nitrate-N in the soil (for example by applying legume hay, grass hay or banana trash) are the most important factors in achieving a sustainable reduction of plant parasitic nematodes.

Studies by Sarah *et al.* (1993) showed wide variation in the pathogenicity of different populations of *R. similis.* The Ivory Coast population showed the highest pathogenicity, rapidly causing serious damage, whereas Martinique and Sri Lankan populations were much slower to cause damage after inoculation. Such mild strains could be used in resistance breeding programmes. Breeding nematode-resistant bananas has not progressed as much as breeding for disease resistance, but the scope is there (Sarah, 1993), and the AAAB hybrid, FHIA 01 ('Goldfinger') has shown considerable tolerance to *R. similis* and other nematodes in different countries. Partial resistance has been found in FHIA 18 (AAAB), 'Maravilha' (AAAB), 'Pacovan Ken' (AAAB) and 'Thap Maeo' (AAB) (Ribeiro *et al.*, 2008), and also good resistance was found in 'Silk' and 'Mysore', both AAB dessert bananas (Sarah, 2000).

Microbial-based strategies are the most promising alternative for biological control. These include the use of: (i) fungal endophytes; (ii) nematode antagonists with different modes of action; (iii) the induction of systemic resistance; and (iv) the use of molecular tools for detecting suitable antagonists (zum Felde *et al.*, 2009). This is discussed in more detail at the end of the chapter ('Role of Fungal and Bacterial Endophytes in Controlling Banana Pests and Diseases').

Other parasitic nematodes
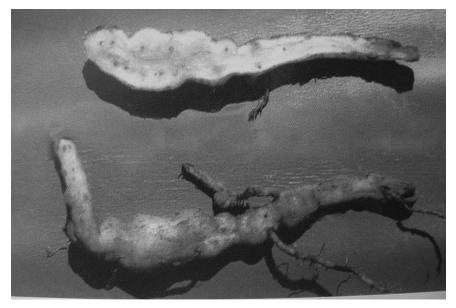
The lesion nematodes *Pratylenchus coffeae* and *P. goodeyi* are endoparasites that cause damage to banana and plantain roots similar to that caused by *R. similis*, although less extensive. *P. goodeyi* is a serious nematode pest on bananas in cooler areas such as the African highlands and the Canary Islands. Nematicides (fenamiphos, oxamyl and etaprophos) are currently used in the Canaries on commercial Cavendish cultivars. *P. coffeae* is particularly important in the Pacific and South-east Asia causing damage to 'Kluai Namwa' (ABB). Plantains are particularly sensitive to both lesion nematode species, but Cavendish cultivars are also affected (Jones, 2009). The wide range of susceptibility of *Musa* cultivars to *P. goodeyi* was studied by Price (1994b) and this is shown in Table 13.1. Control measures are similar to those used for burrowing nematode.

The spiral nematode, *Helicotylenchus multicinctus*, is a widely distributed and abundant banana nematode especially on sandy soils. It occurs on all cultivars of banana in the tropics and subtropics, and is often present with

R. similis. Important losses from *H. multicinctus* have been reported from Israel and Cyprus. Reddish lesions appear in the cortex of primary roots, similar to *R. similis*, but these lesions are less extensive and shallower than those of *R. similis* (Fig. 13.2b).

Root-knot nematodes (*Meloidogyne* spp.) occur wherever bananas are grown. Although they can cause severe gall formation and stunting of the root system (Fig. 13.3), especially on sandy soils, there is little evidence that they cause serious economic damage to banana on the scale shown by *R. similis*. There may be some reduced growth and evidence of wilting at high populations, but plants do not topple over. They are regarded as an important pest in Taiwan because other, more serious nematode species do not occur there.

BUNCH PESTS

The majority of banana bunch pests cause superficial peel damage which does not affect the eating quality of the fruit. In this respect, the subsistence or cash cropping sector of banana production is not severely disadvantaged by bunch pests. Localized commercial markets may also allow a degree of tolerance in their quality standards, tolerating superficial damage caused by thrips, mites,

Fig. 13.3. External (bottom) and internal (top) symptoms of root-knot nematode in banana roots. External symptoms are characterized by swollen lumps (galls) protruding from the root surface. Internal symptoms show dark spots which are the egg sacs of the nematode situated inside the galls.

caterpillars, moths or beetles. However, for the discerning export markets of the world, quality standards are strict, and external blemishes caused by bunch pests are totally unacceptable.

Thrips

Thrips are small insects, about 1–2 mm long, that occur on the fruit as the bunch is emerging and the bracts lift. They feed on the soft skin of immature fruit, usually on hidden surfaces between closely packed fingers.

Red rust thrips species (*Chaetanaphothrips* spp.) cause rust-coloured blemishes to form on the fruit due to feeding of nymphs and adults. When the fruit develops, rust blemishes become roughened and cracked. There are three species of red rust thrips which are widely distributed throughout Central and South America, Asia and Australia. Most species can be controlled by polyethylene bunch covers applied early, just after bunch emergence. Control is enhanced by using chlorpyrifos-impregnated covers, dichlorvos-impregnated plastic strips inside the cover, recommended chemical sprays, and by early removal of the male bud.

The 'corky scab' thrips, which occurs in India, Queensland and the Philippines, is caused by one of the *Thrips florum* complex. These thrips feed on flower tips and fruit even before the bunch emerges from the plant and up to 2 weeks after emergence. They cause a grey-brown roughening of the fruit surface which becomes corky and cracked as the fruit approaches maturity.

Flower thrips (*Frankliniella* spp., *T. florum* and *Thrips exilicornis*) are widespread throughout the Caribbean and Latin America, and also in South Africa. The adult lays eggs individually in the skin of soft immature fruit, even before hands are visible, and this causes a small raised pimple capped by a black spot, to develop on the surface. The insect is difficult to control but damage is usually not conspicuous enough for fruit to be rejected. Unlike silvering thrips, damage is not caused by feeding of the adult insect but by: (i) lesions from old egg sites; and (ii) blemishes from larval emergence sites. Control is the same as for red rust thrips.

The banana silvering thrips, *Hercinothrips bicinctus*, has become a problem in subtropical areas like Australia, the Canary Islands and South Africa. Mottled, silvery patches appear on the fruit skin covered by black dots which are dried faecal drops. Damage is caused by the feeding of adults and nymphs. Control is the same as for red rust thrips.

Moths

The banana scab moth, *Nacoleia octasema*, is a serious bunch pest in Australia and the Pacific Islands. Eggs are laid on the flag leaf of the plant

just before bunch emergence. Larvae then feed in groups under the bracts of young developing fruit, and cause unsightly scabby brown scars to form. Their excrement forms dark loose deposits between the fingers and hands. Infestation in a plantation may not be widespread but attacked bunches are severely damaged. The usual control method in Queensland consists of injecting insecticide directly into the tip of the emerging bunch while it still points upwards.

The banana moth, *Opogona sacchari*, is an important bunch pest in the Canary Islands and Brazil. Another one is *Lobesia stericta* in South Africa. Larvae feed on young fruit immediately after bunch emergence and, like the banana scab moth, they are difficult to control before damage occurs. Larvae complete their life cycle in harvested pseudostems which should therefore be chopped up after harvest. Other cultural practices like early removal of flower parts or the male bud, help to control these pests.

Miscellaneous bunch pests

Banana fruit scarring beetles (*Colaspis* spp.) have been recorded causing sporadic damage in Central and South America, and the common fruit chafer beetle (*Pachnoda* spp.) in South Africa. Adult beetles feed on the fruit and the larvae on roots and weeds. Insecticide-impregnated bunch covers will prevent damage. The banana slug (*Urocyclus flavescens*) causes rasping marks on banana fruit peel by feeding at night. During the day slugs hide under weeds and trash to keep themselves moist. Damage is more serious during rainy periods, and control is by metaldehyde pellets and by maintaining a weed-free plantation. They are periodically a serious pest in South Africa. Scale insects are a sporadic pest but their occurrence does not justify specific control measures. Spraying such sporadic pests is not recommended due to the greater damage caused to beneficial predators and parasites.

Various mites can cause occasional seasonal damage on banana fruit such as crimson spider mite (*Tetranychus lombardinii*), ornamental flat mite (*Brevipalpus obovatus*) and grey mite (*Calacarus citrifolii*). The crimson spider mite is characterized by a silvery-white speckling of the peel and a fine, dense web between fingers. Unlike thrips, mite damage usually occurs at a later stage of bunch development, and damage is greatly enhanced on overmature bunches. Control is the same as for thrips.

LEAF PESTS

The leaf-eating caterpillar, *Antichloris viridis*, causes highly visible damage to banana leaves in Central and South America. A series of feeding holes between leaf veins gives a pronounced 'shot hole' effect, but this mechanical

damage does not seem to reduce photosynthesis or yield, therefore specific control measures are not recommended. Similarly, 'slug caterpillars' (different species of *Antichloris*, *Calligo*, *Osiphanes and Sibine*) defoliate banana leaves, and the spines on their backs can sting plantation labourers in Central and South America. A serious leaf pest in South Africa is the tomato semi-looper (*Chrysodeixis acuta*), which walks with a looping gait and feeds on the emerging cigar leaf, causing lines of holes after leaf opening. Control must be early, since serious economic damage is caused if the pest reaches emerged bunches.

In the Canary Islands, the mealybug (*Dysmicoccus grasii*) can be a problem, particularly by attacking young leaves in the field, causing them to turn yellow and then necrotic. Controlling ants and the release of predators like *Cryptolaemus monstruozieri* effectively reduce the incidence of mealybugs. Various mealybugs are also the vector of BSV. Two species of white flies, *Lecanoideus floccissimus* and *Aleurodicus dispersus* also affect banana leaves in the Canary Islands. These sap-sucking insects produce a white cottony and sticky substance which covers the leaves and fruits. Release of *Encarsia* spp. and sprays with *Beauveria* and other biological products, are the usual way of controlling white flies (Perera González and Molina León, 2002).

The banana aphid (*Pentalonia nigronervosa*) is widely distributed in all banana-growing areas but its significance as a pest is due to the transmission of BBTV from plant to plant. Similarly, various insects that visit banana flowers, bract abscission surfaces and cut suckers and pseudostems, can mechanically transmit Moko disease and Xanthomonas wilt from plant to plant.

ROLE OF FUNGAL AND BACTERIAL ENDOPHYTES IN CONTROLLING BANANA PESTS AND DISEASES

An **endophyte** is an endosymbiont, often a bacterium or fungus, that lives within a plant for at least part of its life without causing apparent disease. On the contrary, endophytes may be effective antagonists of plant pathogens by stimulating production of chemicals by the host, which inhibit growth of pathogenic organisms and which may even enhance plant growth. Although endophytes are ubiquitous and found in all plant species studied to date, most of these endophyte–plant relationships are not well understood. However, an increase in phenolic activity in plants treated with plant growth-promoting rhizobacteria (PGPR) has already been correlated with increased virus resistance in other crops (Kandan *et al.*, 2002), and could also be involved in systemic-induced resistance in bananas. Researchers have indicated that production of antibiotics or toxic secondary metabolites may facilitate control of nematodes, not only by paralysing nematode action, but also by inhibiting the infection process (Sikora *et al.*, 2003).

Much work has been devoted to finding and characterizing useful endophytes for pest and disease control in bananas, but we are still far from commercializing these techniques.[1] Both fungal and bacterial micro-organisms have proven useful in specific trials on banana pests. PGPR were recently shown to induce systemic resistance against fungi, bacteria and viruses as well as enhancing plant growth. As indicated by Sikora and Reiman (2004), pest/disease suppression is a function of rhizosphere-specific microbial communities interacting with each other.

Synergystic endophytes from roots have been of special interest in controlling banana nematodes, because nematicides used in commercial banana plantings usually suppress beneficial micro-organisms as well. Initial studies on the use of endophytes to control banana nematodes were those on the interaction between *R. similis* and vesicular-arbuscular mycorrhizae (VAM) on banana root vigour and yield (Umesh *et al.*, 1989; Declerck *et al.*, 1993). These studies showed better growth and nutrient absorption on bananas inoculated with VAM (now called arbuscular mycorrhiza fungi or AMF), compared with the control. Besides an induced nematode bioprotective effect, AMF are also efficient in suppressing pathogenic soil bacteria and fungi. The selection of suitable intercrops favouring AMF build-up in banana soil is highly beneficial against both (Elsen *et al.*, 2009). Successful *in vitro* culture systems adapted to banana mycorrhization have been developed (Koffi *et al.*, 2009) which seek to explain how AMF control major banana pests and diseases.

In recent laboratory and fields trials in Central America, several other effective synergistic endophyte antagonists of nematodes have been found, the most effective being non-pathogenic isolates of *Trichoderma atroviride* and *Fusarium oxysporum*, but their potential must still be evaluated (zum Felde *et al.*, 2009). The method preferred for controlling *R. similis* is the inoculation of vitroplants with endophytes before planting in trays for transfer to the weaning greenhouse (Jaizme-Vega and Azcon, 1995; zum Felde *et al.*, 2006). Some isolates of *T. atroviride* showed promise for reducing nematicide treatments prior to replanting banana fields (Pocasangre *et al.*, 2006). Combinations of endophytes with different modes of action are probably the way forward for sustainable control of plant parasitic nematodes. For example, certain combinations of bacteria (*Bacillus* spp. and *Pseudomonas* isolates) with fungi (non-pathogenic *F. oxysporum* isolates) have shown promise for reducing nematode damage in banana (Chaves *et al.*, 2009). Also, combinations of endophytes like AMF and non-pathogenic *Fusarium*, both independantly proven effective for banana nematode control, is an obvious line of research for the future.

The beneficial protection effect of AMF in bananas has been demonstrated for different soil-borne pathogens like *F. oxysporum* f. sp. *cubense* (FOC) and *Cilindrocladium* spp. (Jaizme-Vega *et al.*, 1998; Declerck *et al.*, 2002). Inoculation of vitroplants with non-pathogenic *F. oxysporum* isolates at 2–4 weeks after transfer from laboratory to weaning stage, has also suppressed wilt

incidence although only in the initial stages (Ting *et al.*, 2009). Incorporating these isolates with other endophytes like *Trichoderma harzianum* UPM40 or with soil amendments like calcium nitrate (Ting *et al.*, 2003) or even with AMF, may considerably enhance the effectiveness of field control of FOC.

Application of *Beauvaria bassiana* as an endophyte may be a promising way to control *C. sordidus*, although research is still pending in relation to the extent and longevity of this protection. Research has already shown that *B. bassiana* can colonize internal banana tissues for at least 4 months after dipping tissue culture plants into a suspension of spores thus initially reducing potential for banana weevil infection (Akello *et al.*, 2009).

Finally, PGPR were able to reduce banana bunchy top incidence in field experiments, and also increased leaf nutrient status, enhancing growth, bunch yield and fruit quality (more suckers and higher sugar:acid ratio; Kavino *et al.*, 2009). Vitroplants (15 cm tall) were inoculated with a 1% soil drench of a mixture of endophytic and rhizobacterial microorganisms (*Bacillus subtilis* EPB22 and *Pseudomonas fluorescens* strains PF1 and CHA0), and challenged by adding ten individuals of the insect vector *Pentalonia nigronervosa* per plant for 2 days. This induced systemic resistance against BBTV, showing 20–80% reduction of infection compared with control plants (Harish *et al.*, 2009).

NOTE

1. The recently published *Acta Horticulturae* 828 which covers the Proceedings of an International Symposium on Recent Advances in Banana Crop Protection for Sustainable Production and Improved Livelihood (Jones and Van den Bergh, 2009) covers the most recent publications on banana pests and endophyte research, some of them already referred to in this chapter.

14

HARVESTING AND FRUIT HANDLING

The determination and maintenance of optimum harvesting stage for banana bunches, and the correct handling of fruit during transport and packing, are vitally important prerequisites for obtaining high quality and premium prices at the marketplace. Incorrect harvesting, transport, packing and storage techniques can lead to either physical or physiological damage to the fruit, the extent of which will determine by how much the fruit becomes downgraded in quality and price. It is important to mention here that pre-harvest factors also play a major role in the postharvest performance of banana fruit and, at harvest, the intention is always to produce a large, blemish-free bunch, with premium-grade finger length and with a long 'green life' potential. **Green life** is defined as the period between harvesting and the visible stage of the climacteric phase (yellowing of the fruit and softening of the pulp). In the case of 'Grand Nain' for export, green life is measured at 14°C, which is close to the transport temperature. The higher the storage temperature the shorter the green life. For each 10°C increase, green life is halved (Lassoudiere, 2007). Pre-harvest factors affecting postharvest potential of a banana bunch are primarily: (i) cultivar; (ii) climatic conditions; (iii) soil conditions; (iv) management expertise; (v) harvest maturity; and (vi) functional leaf area on the plant during bunch development. With the exception of harvest maturity, these factors have been adequately dealt with in earlier chapters.

HARVESTING

Fruit maturity standards

These vary from country to country depending on anticipated green life required by fruit before ripening takes place. For example, fruit could be harvested fully mature for immediate ripening and local marketing. For on-site marketing or short-distance transport of green fruit, 90% of full maturity could be used, and for medium-distance transport by truck, 75% maturity is

normally used. Another term for referring to 75% maturity is when fingers are 'three-quarters round' – still having pronounced ridges but with convex planes between them. For long-distance transport by ship, less than 75% maturity is required. These maturity standards are critical because allowing fruit to become overmature during hot weather can lead to premature ripening during transport. Conversely, harvesting too immature in cool weather can lead to several kilograms loss of bunch mass and extended ripening requirements.

Various methods have been used to determine the correct stage of harvest but these are either destructive, impractical or subjective. Examples are the ratio of pulp to peel, and a firmness index of fruit skin. In many subtropical countries, the 'three-quarters round' index is used which is satisfactory for the local markets, but it is difficult to maintain accuracy and consistency with this subjective method.

The best practical and objective method of standardizing harvest maturity is with a combination of phenology (expected flower emergence to harvest duration (E–H)), coloured ribbons and caliper measurement of finger diameter. This method, initially practised in multinational company plantations of Central America, is now common in most regions where fruit go to high-quality export markets. Two weeks after flowering, when bunch covers are applied, a coloured polyethylene strip or woollen string is tied to the peduncle. Each week another colour is used on new flowers, then, after 8 weeks, the colour sequence is repeated. The first advantage of this technique is that weekly flower counts can be made based on the number of tags used, and these counts form the basis of crop forecasting. Second, harvest control and planning are made easier. In the tropics, average E–H varies seasonally from 98 to 115 days (Stover, 1979; see Fig. 5.3). Thus, at a stage 91 days after flowering during the hottest season, bunches with the appropriate colour code are checked with a caliper for harvest maturity (finger diameter) and a few bunches may be cut. As top hands mature quicker than bottom hands, caliper measurement is always made on the middle finger of the outer whorl of the second hand to have a standardized measurement. At 98 days most of the bunches with that colour will be cut, and at 105 days all remaining bunches are cut. For any week therefore, bunches with three colour codes are checked with the caliper. This measurement has to be between 31 and 41 mm. During the cooler fruit development period, the first caliper measurement will only be done after 105 days due to a longer E–H. In terms of market preference, the USA market prefers slightly fuller fruit than the European market, within the 31–41 mm caliper range.

Theoretically, the increase in fruit diameter for Cavendish bananas, in the absence of limiting edaphic and phytopathological constraints, is a function of 'total daily temperature' (TDT) (Ganry, 1978). TDT is calculated from a 14°C threshold which is the lowest mean daily temperature growth limit for Cavendish cultivars. TDT is calculated according to the equation:

TDT = Σ [(daily Tmax + daily Tmin /2)–14]

where Tmax and Tmin are maximum and minimum temperatures, respectively, for that day (see also the equation in Chapter 5 under 'Flower emergence to harvest duration (E–H)', in which TDT is referred to as 'cumulated heat units' or alternatively 'degree days'). When TDT reaches a value of 900°C (counted from first female hand open – the E stage, see Chapter 5) the bunch is considered ready for harvesting (three-quarters round stage with a 34 mm caliper measurement). The full round stage thus corresponds with a cumulative TDT of 1200°C.

The use of TDT combined with fruit caliper measurement is practised in the French West Indies, where new bunches are rigorously labelled with coloured strips twice a week (Lassoudiere, 2007). To apply this method it is necessary to use a digital thermometer or temperature sensor and a weather instrument shelter (Ganry and Chillet, 2009). Weekly harvesting is determined by: (i) 20–30% of bunches which will reach 900°C the following week and with a minimum caliper measurement of 32 mm (central finger of last hand, in contrast with the second hand measured in Central America – see above); (ii) around 50% of bunches which reached 900°C that week; and (iii) 20–30% of bunches left from the preceding week. No bunches are harvested with a caliper measurement of less than 32 mm. Bunches from Sigatoka-infected blocks are harvested as close as possible to the departure of boats to compensate for their shorter green life.

Maturity standards and harvesting procedures for **plantains** are considerably less organized than they are for dessert bananas. In smallholder units, harvesting is usually done when the bunch is fully mature, because this is the consumer preference and it is important to maximize fruit mass for subsistence purposes. For commercial plantains destined for the export market, it is necessary to follow similar procedures to bananas. Studies on 'French Sombre' plantain (N'da Adopo, 1992) indicate that this cultivar reaches three-quarters round between 900 and 1000°C TDT, very similar to Cavendish cultivars. In Brazil, the maturity time for plantain 'Dominique hartón' is also similar to Cavendish (Lichtemberg *et al.*, 2008). In practice, harvesting criteria are based on bunch age, length of the E–H interval, finger caliper and/or colour of skin and flesh. The degree of fruit filling is the most commonly-used criterion although Marchal (1993) indicates that harvest maturity is more accurate when combining degree of filling and flesh colour. Accordingly, three criteria have been defined for harvesting plantains, namely: (i) Stage 1 – non-angular fruits with pale and whitish pulp; (ii) Stage 2 – intermediate between Stage 1 and 3; and (iii) Stage 3 – rounded fruits with well-coloured (yellow) pulp (Tchango Tchango *et al.*, 2003).

Method of harvesting

For **commercial dessert bananas** throughout the world, harvest method follows a similar pattern, with minor variations. When the bunch is commercially mature (fruit three-quarters round or 31–41 mm diameter for Cavendish) a 'carrier' moves into position to catch the bunch. The 'cutter' cuts leaves in proximity to the bunch and also the twine supporting the plant. He then cuts a notch into the pseudostem so that it falls slowly towards the carrier who guides the bunch on to a shoulder pad or harvesting tray. The cutter severs the peduncle 300 mm above the proximal hand and then cuts the top piece of pseudostem and leaf canopy into pieces before moving to the next plant. The carrier meanwhile carries the bunch to the trailer, dehanding rack or nearest cableway point, depending on the transport method used.

With most **plantain** types, as with taller banana cultivars, the pseudostem cut should be at the correct height for a slow and smooth bedding of the bunch on the carrier's shoulder tray. The cut is normally in the upper third, around 2 m from the ground. The peduncle should only then be cut ensuring the point of cut is outside the tray to avoid sap stain on the fruits.

TRANSPORT FROM FIELD TO PACKSHED

This is a critical operation which largely determines how much mechanical damage is ultimately visible in packed fruit. For export quality, bunches should not come into contact with each other, neither should any external pressure be exerted on bunches or hands. This necessitates transporting bunches from field to packshed individually on a cableway, or dehanding in the field and transporting loose hands on padded trailers.

The use of rigid trays for transporting cut bunches inside the plantation to the cableway is imperative for commercial plantings destined for export. They should be kept clean, free of latex, sand or any other substances which can stain or scratch fruits, and should be replaced whenever necessary. Movement of workers inside the blocks should be slow and careful to avoid unnecessary damage to both harvested and hanging bunches.

Cableway transport systems are common in Latin America. They comprise a series of mainlines and secondary lines, the latter being 100 m apart throughout the plantation. Any bunch must therefore be carried 50 m or less to the nearest attachment point. Bunches are suspended by their peduncle, spaced 1.5 m apart on the cable, and a small motor pulls 75–100 bunches from field to packshed across flat terrain. A minimum of bunch handling and chafing occurs with this method, because bunches do not touch each other (Fig. 14.1). Cableway systems are not appropriate for smaller plantations due to the high capital cost of installation. Also, cableways are not well suited to variable terrain for logistical reasons. However, smaller cableway units of

Fig. 14.1. Transporting banana bunches individually on a cableway system from field to packshed. Minimal mechanical damage occurs with this system. Note bunches are kept apart with spacer bars, and individual hands are protected from each other within the bunch.

reasonable cost are being integrated into the high technology but sloping plantations of the Canary Islands, to reduce mechanical damage.

Dehanding of bunches in the field is an alternative method of transport appropriate for high-quality export fruit because mechanical damage is kept as low as 3% on some plantations. However, labour costs of fruit handling are greatly increased with this method. One man cuts off the hands as the bunch is supported by the carrier who brings the bunch to the field edge. Hands are placed individually, finger tips downwards, on foam-padded trailers which are drawn as a train slowly to the packshed.

In the subtropics, banana bunches are carried by trailer to the packshed horizontally layered on a banana leaf or foam base (Fig. 14.2), or vertically propped against a central divide. Also, trailers or cages designed for vertical suspension of bunches, which can then be automatically discharged at the packshed, are being used to minimize mechanical damage (Fig. 14.3). This concept of hanging bunches is similar to the cableway system but the cages are logistically more practical on smaller subtropical farms. Such vertical pendulous systems with automatic unloading ensure minimal damage to the fruit.

In many commercial plantations of banana and plantain which produce fruit for the local market, harvested bunches are laid alongside the road, sometimes overheating during the day. They are then picked up and stacked either vertically or horizontally on trailers for transport, with only a bed of banana leaves for protection (sometimes a foam mattress). Bunches are then offloaded manually and hung in the packshed. With these systems, there is

Fig. 14.2. Transporting bananas by trailer in which bunches lie flat in their bunch covers on top of a soft padded cushion. Sometimes the 'cushion' comprises only a thick layer of banana leaves, in which case some bruising and pressure damage occurs.

Fig. 14.3. Transporting banana bunches in a specially-constructed tractor-drawn cage on which 20–40 bunches hang independently. This is a similar concept to the cableway system, but some rubbing may still occur with this method. In this example harvesting bags are used to cushion any sideways bumping during transport.

inevitably some lateral pressure on bunches and chafing of hands during transport. They are also handled more frequently than export fruit, and the damage is clearly evident after ripening (Fig. 14.5a). Although local markets may be more tolerant towards mechanical damage on the peel, premium prices are still paid for fruit which is blemish-free. Better systems must strive to reduce: (i) lateral pressure on the bunch; and (ii) the total number of handling operations involved from harvesting to packing.

Bananas or **plantains** to be sold commercially in smallholder situations are normally packed as whole bunches or as detached hands, into lorries or other vehicles, and are transported unprotected over long distances to the market and sold loose (Fig. 14.4). Considerable mechanical damage is incurred this way. Cutting of bunches into hands and packing in re-usable cardboard boxes is an alternative to reduce damage during transport to market. It also extends storage life since boxes can be moved easily to ventilated shelters at any stage. Packing plantain fruit in semipermeable, sealed plastic bags was shown to extend green life fourfold at ambient temperatures, due to the modified atmosphere effect. Such a technique could be used to preserve quality of plantains transported over long distances (Collin, 1991).

Fig. 14.4. Transporting loose banana hands which were detached from bunches in the field, and stacked high in a lorry for transport to a ripening room or direct to a market. This leads to a very poor quality ripened product with many bruises as seen in Fig. 14.5(a).

COOLING OF FRUIT FROM THE FIELD

Not only must **physical** damage to the fruit during harvest, transport and packing, be minimized, but the **physiological** condition of the fruit must also be protected during these operations. It is well known that banana fruit which are harvested, transported, packed and stored at high temperatures, have a much shorter green life and poorer quality after ripening. Overheating of banana bunches can lead to the phenomenon of 'mixed ripe' (see Chapter 4) and this is a potential problem in all tropical areas and especially in subtropical areas during summer.

Several guidelines can be recommended to banana producers to help control the overheating problem in very hot conditions:

- Do not allow bunches on the plant to exceed the chosen commercial criterion for harvest maturity.
- Cut fruit during cooler periods. This means from early to mid-morning or during overcast weather.
- Do not expose harvested fruit to direct sunlight as this quickly causes serious overheating and even burning. Bunches should be transported to the packshed without delay and should be shaded during transport.
- Packsheds in hot areas should be insulated against heat, especially on the roof, west wall and east wall. Insulation can be achieved with reflective foil, polyurethane foam or polystyrene sheeting.
- Packsheds should be shaded and protected. This can be achieved using awnings over doors and windows, shade trees on the western side or using white paint.
- Offloading of bunches from trailer or cable to bunch-carrying rails, should be on the south side of the packshed in the southern hemisphere, and on the north side in the northern hemisphere.
- Bunches arriving at the packshed should be immediately cooled in cold water dips or moved through a lateral spray race to remove field heat.
- Packed fruit should be pre-cooled before transport to ripening facilities. In very hot production areas, packed fruit are usually pre-cooled in the packshed to 13°C prior to loading into refrigerated transport for a long road journey.

PACKSHED OPERATIONS

Assuming that whole bunches are transported to the packshed, the successive operations involved for commercial bananas are basically the same, irrespective of packshed design or type of market. They are dehanding, washing and delatexing, clustering, fungicide treatment, quality control operations and packing.

Dehanding

Bunches arriving at the packshed are offloaded into a shaded holding area and in turn are conveyed on rollers into the dehanding area. There is no handling necessary if a cableway system is used. Field bunch covers and hand dividers are removed at this stage. Removal of dry flower parts, if not done earlier in the field, should also be performed at this stage. Hands are cut smoothly from the peduncle using a special sharp, curved blade or a curved chisel. A large chunk of the crown (pedicel pad) should be left attached to the hand to safeguard against crown rot infection (Fig. 14.5b). The cut hand is placed in a dehanding tank of water.

Washing, delatexing and disease control

The dehanding tank consists of clean, flowing water which is used to remove: (i) dirt from the fruit surface; (ii) latex which exudes from the cut surface of the crown; and (iii) fungal spores which are present on the fruit and which can cause crown rot (see Chapter 12 'Fruit diseases'). It is usual for a common dishwashing detergent to be diluted in the water, at an approximate dosage of 200 ml/100 l water for small tanks without water renewal or 20–40 ml/100 l water for bigger tanks (>9 m^2) with frequent water renewal. It is also common to add aluminium sulfate to facilitate healing of cut surfaces and precipitation of latex and other organic residues. Dosage varies from 100 to 400 g/100 l

Fig. 14.5. (a) Mechanical bruising and scarring damage showing up on the skin of banana fruit that have been ripened. Such severe mechanical damage would be rejected on most commercial markets. Mechanical scarring is the single most important fruit defect and can be caused either by poor bunch management and harvesting procedures, or during transport to the packshed. (b) Excellent quality banana clusters in a tropical export packshed that are totally free from any mechanical blemish. Such fruit will also be blemish-free after ripening.

water (500 g/100 l in small tanks). These quantities are increased in hot weather when latex exudation increases. In tanks with circulating water the concentration of aluminium sulfate can be reduced. A tank surface area of 9 m^2 is considered the smallest to minimize fruit damage. Tanks should not be filled to more than 75% of their volume. Tap water, usually chlorinated by addition of liquid chlorine, should be used for minimizing organic residues and fungal microorganisms (Lichtemberg *et al.*, 2008).

   In addition to removing dirt, latex and fungal spores, the water flow also transports hands from the dehanding side of the tank to the opposite side. Hands may remain in the washing tank for 15–20 min to ensure complete removal of latex. Then they are removed and broken into clusters of four to eight (a range of two to nine is allowed in Brazil; CEAGESP, 2006) (see 'Quality control and classification standards' later in this chapter.) Small, defective, double and triple fingers are discarded at this stage. Clusters are dried and then disinfected in one of three ways, namely: (i) transferred into cluster tanks containing thiabendazole or similar authorized fungicide at the appropriate dosage (for organic cultivation, citric-based products like Biomergex® or Ecolife® in the cluster tank at concentrations of 150 ml/100 l water, are recommended; Lichtemberg *et al.*, 2008); (b) treated with a fungicide spray applied over flat trays (plateaux) on a conveyor system; or (c) the fungicide can simply be applied by painting the top of the crown. The use of plateaux is very convenient for the packing of clusters. Each plateau is filled on a balance with the exact quantity needed for a cardboard carton. Clusters are placed side by side with crown facing up. After fungicide treatment, brand stickers are placed on the concave face of the banana in the centre of the cluster. In turn, the cleaned, treated and branded clusters are transported on a conveyor system to the packing area.

Packing

First-grade bananas are packed into cardboard cartons as whole hands, clusters or singles and the packed carton mass can vary from 12 to 18 kg, depending on countries and markets. Cartons must be strong enough to withstand the forces of palletization and be well ventilated to maintain an even temperature during refrigerated shipment. Hands or clusters should be packed in a neat, regular pattern to reduce movement and chafing, thus cartons must be full but not overfull. Pads (usually kraft paper or plastic) are inserted to insure protection between fruit rows. Polyethylene film liners are commonly used in export fruit cartons to reduce water loss during transport and to provide some protection from chafing damage. Air may also be vacuumed out of the liner to remove oxygen. A typical packshed in Central America, which may serve a plantation of 250 ha, can pack 500 × 18 kg cartons/h or 5000 cartons/day, and packing may continue for 3 days/week.

In Israel and Egypt, 70% of the bananas are transported, ripened, distributed and offered for sale as whole bunches, from which the customers choose the hands they want. Thus, no packaging is involved.

Quality control and classification standards

Export markets for bananas in the EU are very strict regarding fresh fruit consumption. A summary of the EU Directive 2257/94 (EUR.lex, 2010b), regarding fruit quality, presentation and marking, for Cavendish bananas imported to EU markets, is presented below:

1. QUALITY
   a. Minimum requirements in all classes are that, subject to special provisions and tolerances for each class, the bananas must be:
   – green and unripened, intact, firm and sound;
   – clean and practically free from visible foreign matter, and from pest or disease damages;
   – pedicel intact, without bending, fungal damage or desiccation, and pistils removed;
   – free from malformation or abnormal curvature of fingers; and
   – practically free from bruises and damages due to low temperatures, and also free of any foreign smell and/or taste, and from abnormal external moisture.
   There are also minimum requirements for hands and clusters.
   b. Classification – Bananas are classified into three classes: (i) Extra; (ii) Class 1; and (iii) Class 2. These differ in tolerance levels for defects, both in number and in size. Under no circumstances may defects affect the flesh of the fruit.

4. PRESENTATION
   a. Uniformity – Contents of each package must be uniform and consist exclusively of bananas of the same origin, variety and/or commercial type, and quality. The visible part of the contents must be representative of the entire package.
   b. Packaging – Bananas must be packed so as to protect the produce properly. Materials used inside the package must be new, clean and must not cause any external or internal deterioration of the produce. Use of materials such as wrapping papers or adhesive labels bearing commercial markings is allowed provided the printing and labelling is done with non-toxic ink or glue. Packages must be free from any foreign matter.
   c. Presentation – Bananas must be presented in hands or clusters (parts of a hand) of at least four fingers. Some tolerances regarding number of fingers per cluster are allowed. In the producing regions, bananas may be marketed by whole bunch.

5. MARKING

Each package must bear the following particulars in writing, all on the same side, legibly and indelibly marked, and visible from the outside:

a. Identification

b. Nature of produce – The word 'Bananas' where the contents are not visible from the outside, plus name of the variety or commercial type.

c. Origin of the product – Country of origin and, in the case of EU produce: production area and (optionally) national, regional or local name.

d. Commercial specifications – Class, net weight and size expressed as minimum length and, optionally, as maximum length.

e. Official control mark (optional).

Banana fruits destined for US markets must be longer than for the EU market. The minimum acceptable length for US export market is 203 mm measured on the middle finger of the outer whorl of each hand, before putting fruit through the packshed processes. If this finger makes the grade, the hand passes through the washing and disinfecting processes and the fruit are packed. If the middle finger does not make the 203 mm minimum, the entire hand is unmarketable and is discarded. In addition to minimum finger length, the fruit must be totally blemish-free (Fig. 14.5b). These are very stringent standards and, in some packsheds, the proportion of discarded fruit (shrinkage) can reach 30%. There may be periods in which a fruit shortage on the export market will permit a relaxation of standards to allow fruit shorter than 203 mm to be marketed.

Shorter fruits are commercially acceptable in local subtropical markets of Australia and South Africa but a premium is still paid there for clean fruit longer than 200 mm. Conversely, in the Canary Islands, Madeira and even in mainland Spain, smaller fruits are more popular and higher prices are paid for smaller fruits but with a minimum of skin imperfections (see Chapter 1 section 'Markets for subtropical local production').

TRANSPORT TO MARKET

After packing, **banana** cartons are palletized in order to reduce handling damage. For local markets, pallets of cartons are loaded on to lorries for transport to ripening rooms. Eight layers of cartons with a base of six standard cartons form a regular pallet. For export, refrigerated trucks take fruit to ships where the pallets are transferred to refrigerated holds. Refrigerated transport is essential to prevent green fruit from initiating the ripening process before arrival at the destination. Placement of fruits into the cold chain should not be delayed more than 24 h after harvesting (commonly called the 'cut to cool' period), but the most efficient systems can reduce this time to 8 h. A temperature of 13–14°C is required for Cavendish bananas to prevent ripening without causing chilling damage, and 10–12°C may be better for bananas

of the 'Prata' subgroup. Apparently the B genome confers more resistance to cold both in the field and during transport (Lichtemberg, 2001). Renewal of air to avoid ethylene accumulation is necessary during transport. The recommended rate of air renewal is 30 times the volume of the container/h (Lassoudiere, 2007). Ventilation and refrigeration should be started before loading the refrigerated container (reefer). Reefers should also be loaded in the boats as quickly as possible. While loading the boat, as well as during sea transport, temperature and ventilation levels must be maintained correctly. On arrival at their destination, palletized cartons are rapidly transferred by road to ripening rooms and then to the wholesale distributing agents in Europe, the USA or elsewhere.

Several constraints affect market quality of **plantains**. Freshly cut bunches are often left unprotected at the harvest site for long periods. In addition, production areas may be remote from the market, and transport may take several days over rough roads. Finally, there are very few precautions relating to fruit handling from harvest to market, thus many postharvest losses occur during this period. It is usual that entire bunches or sections of them are carried combined with other commodities in baskets on people's heads or in baskets hung on their backs. Sometimes even individual fingers are placed in bags together with other commodities. In African local markets it is common for bunches or hands to be loaded in bulk, without special care, into vans, trucks or even in ships from one country to another, where they travel long distances before being sold (Fig. 14.4).

To reduce damage, the use of plastic protection, refrigeration and air ventilation, should also be provided for plantains. A temperature of 12–14°C and relative humidity of 85–95% are considered optimal transport conditions for plantains. 'False Horn' plantains from Cameroon, in great demand in Europe, are exported either by air or by boat. By air, they are harvested at full maturity stage, covered with perforated plastic film and packed in well-ventilated cartons. By ship, they are transported in reefers at 12–14°C, but should be harvested at an earlier stage of maturity since the trip to market takes about 15 days. 'False Horn' and 'Dominico hartón' are the cultivars planted in Latin America for export to both the USA and the EU. In this case, single fruits are packed in cartons after thiabendazole treatment, palletized and transported in reefers at 8–9°C. Market reports suggest, however, that Latin American plantains ripen poorly and have inferior quality compared with those transported by plane or ship at the optimum transport condition for plantains (Tchango Tchango *et al.*, 2003).

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Ripening, Biochemistry and Uses
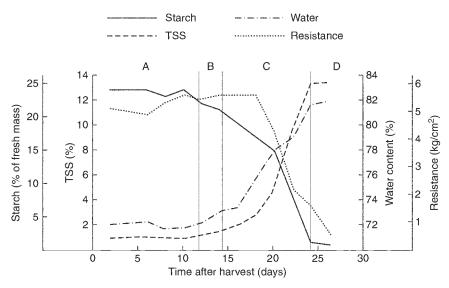
While banana fruit remain attached to the plant they continue to develop and accumulate starch in the pulp. Increase in finger length continues until about 80–90 days after flowering (in the tropics) when fruit maturation begins. At this stage, fingers stop elongating, but they continue to increase in width until the fruit is harvested (see Fig. 3.9). If left beyond the 'commercially mature' stage of three-quarters round, fingers become fully round and bloated, eventually splitting longitudinally while still green. **Harvesting** is required to terminate physical maturity at the required stage.

A harvested banana fruit passes through four physiological development stages, namely the pre-climacteric or 'green life' stage, the climacteric stage, the ripening stage, and finally the eat-ripe and senescence stage (Fig. 15.1).

THE PRE-CLIMACTERIC

The green life stage of a harvested banana, as indicated in Chapter 14, represents the period from harvest until the visible stage of the respiratory climacteric. It is a period of low metabolic activity and the commercial objective is to prolong this period for as long as possible This is achieved in three main ways, namely: (i) by inducing in the harvested bunch an inherently long green life with good pre-harvest management; (ii) by harvesting at an early stage of fruit maturity (Chapter 14); and (iii) by low temperature control (13°C) during transport of bunches and packed fruit. It is also possible to extend the pre-climacteric by hormonal treatment (gibberellin) or by modified/controlled atmosphere (CA) storage and/or ethylene scrubbing.

Sealed polyethylene bags, widely used to delay banana ripening, can reduce water loss, reduce O_2 concentration and increase CO_2 concentration, all of which extend the pre-climacteric. The reduction of O_2 and increase in CO_2 reduce the respiration rate, and the increased CO_2 also inhibits the synthesis of ethylene. High humidity delays the internal synthesis of ethylene by preventing water loss. Wax coatings around the fruit, such as Semperfresh®,

Fig. 15.1. Changes in starch, total soluble solids (TSS) and water content in pulp of 'Giant Cavendish' bananas, and in mechanical resistance of fruit, during pre-climacteric, climacteric and ripening stages. The time course in this study refers to fruits ripened at 20°C without addition of ethylene. A = pre-climacteric (fruits green and hard); B = climacteric; C = ripening (fruits change from green to yellow and start softening); D = eat-ripe and senescent stage (fruits yellow and soft). Note: the approximate position of the pre-climacteric, climacteric, ripening and eat-ripe stages have been superimposed on the graph but the occurrence of these stages relative to days after harvest will vary considerably, depending on temperature and stage of ethylene introduction. Redrawn from John and Marchal (1995).

achieve the same beneficial effects on green life as polyethylene bags. CA has been successfully used in transporting bananas from Latin America to the USA and Europe (Lichtemberg *et al.*, 2008). The CA requirements for bananas have been defined by Kader (2001) as 12–16°C, 2–5% O_2 and 2–5% CO_2. This combination also increased green life of mature-green bananas stored at 14°C to 4–6 weeks compared with 2–4 weeks under normal conditions (Kader, 2002).

Ethylene scrubbers, such as $KMnO_4$, are also used to prevent ripening, particularly in association with CA and low temperature storage. Many trials have been conducted recently to evaluate the anti-ethylene compound 1-methylcyclopropene (1-MCP) alone or combined with polyethylene bags, wax or edible coatings (Jiang *et al.*, 1999; Harris *et al.*, 2000; Moradinezhad *et al.*, 2006, 2008; Dos Santos *et al.*, 2006; Báez Sañudo *et al.*, 2009). However, the effectiveness of this chemical varies with fruit maturity, cultivar and harvesting season, making 1-MCP of limited commercial value for delaying ripening of bananas. Growth regulators such as auxins, gibberellins,

cytokinins, jasmonates and poly-amines are known to retard ripening of fruits and may have some potential application in bananas. In Ecuador, the painting of export banana crowns (collars) with products containing GA_3 is a common practice. The action of GA_3 is to delay amide degradation, sugar accumulation and the peaking of amylase activity in fruit (Rossetto *et al.*, 2004).

Pre-harvest factors inducing a short green life are: (i) depleted leaf canopy; (ii) leaf disease; (iii) fruit mechanical injury (stimulates water loss and ethylene production); (iv) anthracnose lesions on the fruit; and (v) delayed harvesting. Postharvest factors are high temperatures, low humidity and traces of ethylene from individual fingers which have started to ripen. In a study of factors affecting postharvest life of **plantains**, Ferris *et al.* (1993) found that out of genotype, level of maturity and mechanical damage, it was damage that reduced fruit green life the most. Abrasions increased fruit moisture loss and reduced green life by 39%, compared with undamaged fruit at 70–90% humidity. At 100% humidity, abrasion had no effect on the rate of ripening due to the prevention of water loss.

THE CLIMACTERIC

All fruits produce ethylene but in climacteric fruits like banana there is a rapid and massive increase in ethylene production which precedes the respiratory climacteric. After triggering the initial rise in respiration, ethylene production decreases again. Ethylene is produced internally via the following pathway:

methionine → S-adenosylmethionine (SAM) → 1-aminocyclopropane-l-carboxylic acid (ACC) → ethylene

The two enzymes that regulate ethylene synthesis in fruits are ACC synthase which generates ACC, and ethylene-forming enzyme (EFE) which generates ethylene from ACC. The more mature the fruit becomes the more efficient are the enzyme systems required to complete this pathway and to produce sufficient ethylene to initiate rapid respiration and the ripening process.

The respiratory climax (climacteric) is identified by rapid O_2 uptake and CO_2 evolution to a maximum rate of 250 mg CO_2 kg/h from a pre-climacteric low of around 30 mg CO_2. The time taken to reach this maximum from the pre-climacteric state depends on temperature, humidity and ethylene concentration, and the ripening process is accelerated when the respiratory maximum is attained. Subsequently, the respiration rate decreases progressively to reach zero at the physiological death of the fruit. Once initiated, the climacteric is irreversible.

RIPENING

The physiology of ripening

Several noticeable changes take place simultaneously during the ripening process. Tissue softening commences, during which starch is degraded to sugars in both pulp and peel, and rupture strength of cell walls slowly deteriorates (Fig. 15.1). The concentration of soluble pectic polysaccharides and uronic acid, and their related enzyme activity, increases. The peel of the fruit turns to light green and then to yellow as chlorophyll is broken down. During the colour change, the pulp becomes softer and sweeter as the ratio of sugars to starch increases, and a characteristic aroma is produced. Various enzyme systems are involved in all the changes. Eventually the peel becomes spotted brown and then completely brown and the pulp loses its firm, white texture to become brown and gelatinous.

In the retail trade there is a colour chart for ripening bananas which has seven stages (Stage 1 = hard green fruit with high starch content; Stage 7 = soft yellow fruit with brown flecks and high sugar content). The duration of 'green life' corresponds to the colour Stages 1 to the end of Stage 3, whereas the duration of 'shelf life' corresponds to the colour Stages 4 (fruit more yellow than green) to the end of Stage 7. This, in turn, depends on storage temperature and disease control.

Artificial ripening

Mature banana fruits left to ripen naturally will eventually soften, but the peel may sometimes become dull, pale yellow and unattractive. To be assured of a firm pulp texture, good flavour, bright yellow peel colour and uniform ripening, green fruit must be ripened artificially by treatment with exogenous ethylene. Bananas are commercially ripened in closed chambers with air renewal, controlled temperature and humidity, ethylene injectors, and equipped with sophisticated instruments for monitoring CO_2, temperature and relative humidity. There are three stages in the ripening process: (i) temperature increase; (ii) ethylene injection; and (iii) ventilation during decreasing temperature. Ethylene gas is applied to Stage 1 fruit at a concentration of 1000 ppm and at the desired starting temperature. After this, the rooms remain sealed for 24 h, then the doors are opened, air is renewed and the rooms are ventilated daily to remove CO_2 that has accumulated during the ripening process, while temperatures are reduced gradually. Once fruits reach colour Stage 4, pulp temperature should be about 13–14°C and fruits are then removed from the chamber. Relative humidity should be kept at 95% during the whole ripening process.

Depending on initial temperatures chosen, ripening time to colour Stage 4 can take from 4 days (18°C) to 8 days (14°C). For ripening in 4 days, bananas are placed for 2 days at 18°C, followed by 1 day at 16°C and the last day at 14°C. For ripening in 6 days, bananas are placed for 4 days at 16°C, 1 day at 15°C and the last day at 14°C, and for 8 days ripening, the temperature should be kept at 14°C during the 8 days (Lassoudiere, 2007). According to Lichtemberg *et al.* (2008), the ideal starting temperature for Cavendish bananas is 18°C compared with 16°C for the 'Prata' subgroup. If initial ripening temperatures are too high (>25°C), the fruit develops a soft, ripe pulp while the skin colour is only greenish yellow (called 'green ripe'). Conversely, temperatures below 13°C cause chilling in which the peel develops a greyish-yellow colour due to discolouration of latex vessels (see Chapter 4 section 'Underpeel discolouration (UPD)'). Uneven ripening can be caused by low temperatures and/or insufficient ethylene.

BIOCHEMICAL CHARACTERISTICS

Water

Water is the most abundant constituent in the pulp and peel of a banana, and the pulp of banana has a higher water content than that of plantain. Water percentage increases in the pulp during ripening due to respiratory breakdown of starch and osmotic movement of water from peel to pulp (Fig. 15.1). Water is also lost from the peel externally due to transpiration, until the ripening processes degrade the peel tissue preventing further water loss. In a fully ripe banana, water occupies about 75% of the pulp mass and for a plantain it is about 66% (Table 15.1).

Carbohydrates

The main change in fruit pulp during ripening is the conversion of starch to sugars, and peel colour is closely correlated with the starch:sugar ratio. Starch declines from about 20–23% at harvest to 1–2% in ripe fruit (Fig. 15.1). Sugars increase in about the same proportions. During the early stage of ripening, the ratio of sugars is about 65:20:15 (sucrose:glucose:fructose), indicating that sucrose appears first, and hexose sugars later. This conversion of starch to sucrose is at a maximum 2 days after the ethylene peak. Loss of carbohydrate via respiration is small and total carbohydrate remains fairly constant during ripening. Many enzymes are apparently involved in the total conversion process, and the initiation of enzymatic starch hydrolysis during the ethylene peak appears to be regulated by fructose 2, 6-bisphosphate.

Table 15.1. Summary of nutritional constituents, mineral composition and vitamin contents of mature banana and plantain fruit pulp (after Stover and Simmonds, 1987; John and Marchal, 1995).

(a) Nutritional constituents (% pulp fresh mass).

	Water	Carbohydrate	Protein	Fat	Ash
Banana (ripe)	75.7	22.2	1.1	0.2	0.8
Plantain (ripe)	66.4	31.2	1.1	0.4	0.9

(b) Mineral composition (mg/100 g pulp fresh mass).

	P	K	Ca	Mg	S
Banana (unripe)	27	460	7	36	34
Plantain (unripe)	32	440	14	32	24

(c) Vitamin content (mg/100 g pulp fresh mass).

	A	Thiamine (B_1)	Riboflavin (B_2)	Pantothenic acid (B_5)	Pyridoxine (B_6)	Ascorbic acid (C)
Banana (ripe)	Medium	0.04	0.07	0.26	0.51	10
Plantain (unripe)	High	0.05	0.05	0.37	N/A[a]	20

[a] N/A, data not available.

Plantains are richer in starch than dessert bananas. At full ripeness starch virtually disappears from dessert bananas, while in plantains, the breakdown of starch and synthesis of sugars continues in fully ripe and even senescent fruits.

Pigments

During ripening, peel colour changes from dark green to bright yellow and this is due to chlorophyll breakdown which gradually unmasks the carotenoid pigments also present in the unripe peel. These processes occur readily at controlled ripening temperatures of 16–18°C but when ripening occurs naturally at ambient temperatures above 25°C, the degradation of chlorophyll is suppressed while the pulp ripens rapidly (producing 'green ripe' fruit).

Aromatic compounds

The characteristic aroma of a ripening banana is due to a combination of many volatile compounds, knowledge of which is still incomplete. These compounds are derived during the ripening period from metabolic pathways

involving the formation of esters, acetates, alcohols and carbonyl compounds. As ripening proceeds, aroma emission increases until the peel turns brown after which the aroma subsides. Altogether more than 300 compounds have been observed which could have a role in the aroma component of ripening banana fruit.

Phenolics

Phenolics are responsible for the astringency of bananas before ripening, and also for certain browning reactions. They are localized mainly in the latex vessels of the pulp and peel. Loss of astringency during ripening is due to polymerization of the phenolics. For example, dopamine represents about 80% of the tannin in the pulp at harvest but it gradually decreases during the ripening process. Browning is linked to enzymatic oxidation of phenolics (of which dopamine is the main one) and polyphenoloxidase is the enzyme. The peel contains double the total polyphenol content of the pulp, at harvest. Excessive browning of phenolics in the latex vessels of the peel, induced by temperatures below 13°C, is commercially important, causing the disorder called 'underpeel discolouration' (see Chapter 4).

Pectins

Ripe pulp contains 0.5–0.7% pectin. As ripening progresses, the water-soluble pectins increase and the insoluble pectins decrease, which is associated with pulp softening. These changes are catalysed by pectin methylesterase whose activity remains constant during ripening.

Lipids

Lipid concentration remains fairly constant during the ripening process. Lipids comprise about 1% of the fresh mass of peel and between 0.2 and 0.5% of the pulp of bananas and plantains. What few lipid constituents are present comprise mostly polyunsaturated fatty acids, particularly linolenic acid. Cholesterol content is zero.

Proteins

Although the protein content of a ripe banana amounts to only about 1.1% of its total composition, this comprises some important essential amino acids, such as lysine. In the pulp of Cavendish bananas, total free amino acids

increase from 330–750 mg/100 g fresh mass when green to 2700–3500 mg/100g at the overripe stage. Histidine, asparagine and glutamine are the predominant amino acids at the fully ripe stage.

Other constituents

The main organic acids are malic, citric and oxalic. During ripening, pH decreases and free acidity increases in the pulp (pH 4.0 at fully ripe stage).

Bananas contain about 0.8% fibre in the pulp and somewhat more in the peel. Non-cellulosic insoluble polysaccharides are the most abundant fibre component.

Banana is a good source of vitamin C (ascorbic acid). Vitamins A and B are also present and vitamin B_6 (pantothenic acid and pyridoxine) is particularly significant in the pulp of banana compared with other fruits.

NUTRITIONAL VALUE AND USES

Dessert bananas have become very popular in modern westernized diets. They are popular for their flavour, texture and convenience value, being easy to peel and eat. Bananas make a useful contribution to the vitamin A, C and B_6 content of the diet, and are an important and immediate source of energy, often being eaten by sportspeople during competition. They are also cholesterol-free and high in fibre.

A medium-sized banana contains 280 kJ which is more than deciduous or citrus fruits. The energy and nutritional status of banana and plantains relative to other common tropical and subtropical fruits is shown in Table 15.2. From this, it is evident that both banana and plantain are high-energy fruits which are richer than most other fruits in carbohydrate, P, Fe and, in the case of plantains, vitamin A. In Cameroon, Ngoh Newilah *et al.* (2009) showed that some plantain cultivars are especially rich in provitamin A carotenoids and are important in enhancing nutritional status, while preventing cancer and other human diseases. Bananas and plantains are particularly high in K, having more than double the concentration in ripe pulp than most other tropical fruits (Morton, 1987). However, important differences exist between banana genotypes regarding Ca and Mg, with plantains having significantly lower levels than dessert bananas and cooking bananas (Dufour, 2008). Differences in mineral concentrations (P, Mg and Ca) as well as carbohydrate concentration in fruit pulp are also influenced by location and duration of bunch growth (Bugaud *et al.*, 2009). These differences may justify special labels to differentiate bananas from different places, which may provide an excellent market strategy to add value to bananas from a given origin.

Table 15.2. Energy and nutritional value of bananas and plantain in relation to other common tropical and subtropical fruits. For each fruit type, values vary widely according to different laboratories and the particular stage of fruit development. Values in the table represent a mean of the range of data available (information obtained from Samson, 1980; Morton, 1987).

	Energy (kJ/100 g)	Nutritional value (g/100 g edible portion)			Nutritional value (mg/100 g edible portion)					
		Protein	Fat	Carbohydrate	Calcium	Phosphorus	Iron	Vitamin A	Vitamin B (thiamine)	Vitamin C
Banana	368	1.1	0.2	22	7	27	0.9	0.03	0.04	10
Plantain	556	1.1	0.4	31	14	32	0.9	0.20	0.05	20
Orange	210	1.0	0.2	12	42	20	0.5	0.06	0.07	53
Mango	260	0.4	0.4	16	9	12	0.5	0.30	0.03	30
Avocado	690	1.5	15	5	10	40	0.8	0.09	0.07	15
Papaya	100	0.2	0.5	6	25	14	0.5	0.30	0.03	50
Guava	210	1.0	0.3	10	15	24	0.5	0.10	0.05	300
Pineapple	250	0.4	0.2	15	20	9	0.6	0.03	0.09	50
Date (fresh)	580	1.8	1.0	36	35	350	6.0	0.01	0.07	30

Dessert bananas have therapeutic values in many special diets:

- Ripe mashed banana is an excellent food for babies due to easy digestibility and the mineral and vitamin content. It is also very good for sports people.
- For elderly people, the fruit can be consumed in large quantities without being fattening or causing digestive disturbances.
- Banana is low in sodium, contains very little fat and no cholesterol, therefore it is useful in managing patients with high blood pressure and heart disease.
- Bananas are free from substances that give rise to uric acid. Therefore they are ideal for patients with gout or arthritis.
- Due to low sodium and protein content, banana is used in special diets for kidney disease sufferers.
- Banana can neutralize free hydrochloric acid, suggesting its use in peptic ulcer therapy. A fully ripe banana mixed with milk powder is especially recommended for ulcer patients.
- For patients with gastritis and gastro-enteritis, banana is one of the first foods to be introduced after nausea and vomiting are brought under control.
- The low lipid/high palatability combination is ideal for the diet of obese people.
- Fe'I bananas of the Australlimusa series, some of which are eaten fresh and others cooked, are rich in carotenoids as well as vitamin C, K and fibre. They are used in the Federated States of Micronesia (FSM) as the first solid food for babies after weaning, and may have good potential for helping to treat diabetes, heart disease and cancer in the FSM (Englberger, 2003).

The dessert banana in normal western diets is basically a supplementary snack food. It is not a whole meal or even a major part of a meal; therefore it differs from plantains and cooking bananas which often fit into the latter category. However, dessert banana is a good source of energy, due to its high carbohydrate content (twice the value of apples and three times that of citrus). The plantain has a lower sugar content but a higher nutritive value than the potato (Lassoudiere, 2007). Bananas and plantains together represent more than 25% of the food energy requirements of Africa (Frison and Sharrock, 1999). However, when constituting a whole meal, for example as a staple food in many developing countries, both the energy and the protein value of plantains are insufficient for daily dietary needs. Thus, assuming an adult needs 10,500 kJ of energy/day, a large quantity of peeled plantain (2 kg) must be eaten to provide this requirement (Table 15.2). Even with such a large amount, only half the daily protein requirement is satisfied. Thus, a plantain diet must be supplemented by a high energy/high protein food such as beans or meat. Even in Uganda, which has the highest per-capita plantain consumption of any country, only 18% of the daily energy requirement is derived from this crop.

Ripe bananas are usually consumed fresh, either directly after peeling or in salads mixed with other fruits. They can also be mixed with cereals or

yogurts during breakfast and for ice cream, milk shakes or pie fillings. They may also form part of more elaborate cooking dishes. One of the simplest and most popular in Latin America is 'Huevos a la cubana' (eggs Cuban style) where fried bananas are served with eggs, rice and bacon, a dish that can be prepared with bananas or plantains. In Uganda, the country with the highest per-capita consumption of bananas and plantains (243 kg/annum versus 7–15 kg in the EU), the main dish of the daily diet, called 'matoke', is prepared with unripe plantains that are first peeled, then steamed while wrapped in their own leaves, and finally mashed to a starchy paste (Frison and Sharrock, 1999). Green and commercially rejected bananas are also used as animal feed. It is beyond the scope of this book to give recipes for banana consumption as these can be found in cooking literature. Plantains can be eaten ripe or unripe, but many countries have developed commercial processes to provide a wide variety of products (see 'Processing' section in this chapter) from both plantain fruits and green bananas.

Besides the fruit itself, many parts of the banana plant are used as food, fodder or for industrial or ornamental purposes, as follows:

- Male buds, young flowers or even pseudostems of some cultivars are cooked and eaten as vegetables.
- Leaves are used as wrapping material for cooking other food.
- Ashes from burned green leaves and pseudostems are used to prepare curries in South-east Asia.
- Several cultivars, mainly AAB or ABB plantain types, are cultivated in southern India exclusively for the production of leaves which are used as environmentally-friendly 'disposable plates' (Singh, 1996).
- Leaves, pseudostems, peduncles and peel are common as fodder. In the Canary Islands, fresh and chopped leaves of Cavendish bananas constitute around 80% of the diet of 'Pelibuey', a race of sheep well adapted to tropical and subtropical conditions.
- Juice extracted from the male bud is thought to be good for stomach problems.
- Banana pseudostems are also cooked in India as a dish named 'khich khach', consumed monthly to prevent constipation.
- Many other preparations made from banana parts are used as remedies against different human diseases, but most of them are not well documented and require further research prior to their generalized use (Galán Saúco, 2003).

Bananas also form part of many cultures. Banana plants are commonly found in numerous paintings by 'masters' like Braque, Gaugain or Renoir who had a fondness for the tropics. They are also present in sculpture and ceramics such as church carvings in the Orotava Valley of the Canary Islands, where bananas are the main horticultural product. Banana is cited in many African

or Latin American proverbs and in poetry. Plantain consumption is regarded as compulsory during weddings or funerals in countries like Cameroon (Tchango Tchango *et al.*, 2003).

PROCESSING

In order for a banana processing industry to be successful, several preconditions must be satisfied. First, there must be sufficient surplus fruit available as rejects from the fresh fruit market to keep a factory going, and a steady supply of such fruit at a low price must be maintained through the year. Second, the processed product must have a viable alternative market because fresh fruit are available the whole year round. Finally, the processed product must receive a value-added return compared with fresh fruit, since factory infrastructure and labour costs have to be covered. There are many different products which can be processed from banana and plantain, and the different procedures involve canning, drying, freezing, extraction, frying or fermentation. However, compared with the volume of fresh fruit exports, processed banana products represent a very minor proportion. Different processed products can be made from postharvest rejects of green or ripe bananas. The most common products derived from **ripe** banana pulp include purée, nectar, sweets, concentrated and clarified juice, 'figs', alcoholic drinks, ethanol and vinegar. Chips and banana flour are mostly prepared from **green** bananas (Poiani *et al.*, 2008).

From a study made by INIBAP (2006) in nine important banana-producing countries, it is calculated that approximately 5% of bananas and 24% of plantains are processed. The most important processed **banana** product is banana purée which is canned ripe pulp with no sugar or preservatives added. A large volume of rejected Cavendish bananas is converted into banana purée in Costa Rica and India. The purée can, in turn, be used in dairy products, baking, beverages and baby food. Sliced ripe bananas in cans with syrup is another important product. These are used for desserts and fruit salads. The important dried banana products are figs, made from drying ripe whole fingers, and flour, ground from dried whole green fruit. Banana flour, both from green and ripe fruit, enriched with sugar, powdered milk, minerals and vitamins, is widely used in baby foods. Banana essence, extracted from ripe fruit, is a clear, colourless liquid which has an agreeable, concentrated aroma and is used in desserts, juices and drinks. Other processed products of banana, which are not so important commercially, are: (i) powder (cf. flour) made from grinding dried ripe fruit; (ii) juice extracted from ripe pulp with enzymes; (iii) jams made from cooked ripe pulp; (iv) flakes, which are dried, thin ripe slices; and (v) alcoholic beverages (liqueur).

Unripe bananas, or preferably **plantains**, can be sliced thinly and fried in vegetable oil to produce savoury chips which are packed in sealed,

moisture-proof bags. In fact, the most important processed products made from plantains are chips, sweets and roasted plantains sold on the street. In the case of **cooking bananas** other than plantains, around 30–40% of the production is processed and sold as beer, alcohol, chips, ketchup and street food). Not all cultivars are equally suited for each type of product. In the case of chips, AAB plantain types, AAB cooking bananas or the bred FHIA 21 (AAAB) are preferred (INIBAP, 2006).

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References

Abadie, C., Chilin Charles, Y., Huat, J., Salmon, F., Pignolet, L., Carlier, L., Lescot, T., Côte, F. and Jenny, C. (2009) New approaches to select cultivars of banana with durable resistance to *Mycosphaerella* leaf spot diseases. *Acta Horticulturae* 828, 171–178.

Abruña, F., Vicente-Chandler, J., Irizarry, H. and Silva, S. (1980) Evapotranspiration with plantains and the effect of frequency of irrigation on yields. *Journal of Agriculture of the University of Puerto Rico* 64, 204–210.

Acuña, O., Peña, W., Serrano, E., Pocasangre, L.E., Rosales, F.E, Delgado, E., Trejos, J. and Segura, A. (2006) La importancia de los microorganismos en la calidad y salud de los Suelos. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 222–233.

Aguilar Morán, J.F. (2006) Banana hybrids developed by FHIA. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 173–177.

Aiyelaagbe, O. and Jolaoso, M. (1994) Productivity of intercropped plantain-soybean in southwestern Nigeria. *Fruits* 49, 191–195.

Akello, J., Dubois, T., Coyne, D. and Hillnutter, C. (2009) *Beauveria bassiana* as an endophyte in tissue-cultured banana plants: a novel way to combat the banana weevil *Cosmopolites sordidus*. *Acta Horticulturae* 828, 129–137.

Anon. (2008a) Australian Scientists Announce GM Banana resistant to Fusarium. Crop Biotechnology Update. Available at: http://www.promusa.org/index (accessed 31 October 2008).

Anon. (2008b) The Biology of *Musa* L. (banana). Version 1: January 2008. Department of Health and Ageing Office of the Gene Technology Regulation. Australian Government. Available at: http://www.ogtr.gov.au/ (accessed 1 February 2009).

Anon. (2009a) Bananas. Worldwide banana roundup. *Fruit World International* 1/2009, 28–33.

Anon. (2009b) Building market linkage for a more lucrative banana farming. Available at: www.agribusiness.com (accessed 1 February 2009).

Anon. (2010) Agricultura. Medianías. Brasil Cuatriplicará sus Envíos de Banana a la Unión Europea. Available at: http:www.copepalma.com (accessed 14 May 2010).

Antignus, Y., Nestel, D., Cohen, S. and Lapidot, M. (2001) Ultraviolet-deficient greenhouse environment affects white fly attraction and flight behavior. *Environmental Entomology* 30, 394–399.

Araya, M. (2005) Stratification and spatial distribution of the banana (*Musa* AAA, Cavendish subgroup, cvs Valery and Grande Naine) root system. In: Turner, D.W. and Rosales, F.E. (eds) *Banana Root System*: *Towards a Better Understanding for its Productive Management.* Proceedings of an International Network for the Improvement of Banana and Plantain (INIBAP) symposium in Costa Rica, 3–5 November 2003. INIBAP, Montpellier, France, pp. 83–103.

Arias, O. and Valverde, M. (1987) Producción y variación somaclonal de plantas de banano variedad Grande Nain producidas por cultivo de tejidos. *Revista de la Asociación Bananera Nacional* (Costa Rica) 28, 6–11.

Arias, P., Dankers, C., Liu, P. and Pilkauskas, P. (2004) *La Economía Mundial del Banano* 1985–2002. Estudios Food and Agricultural Organization (FAO) Productos Básicos 1. FAO, Rome.

Aristizábal, J.M. (2004) Efectos del desmane y la distancia de siembra sobre las características productivas del plátano 'FHIA-20'. *InfoMusa* 13(1), 9–12.

Aritua, V., Parkinson, N., Thwaites, R., Heeney, J.V., Crozier, J., Jones, D.R., Tushemereirwe, W., Reeder, R., Stead, J.V. and Smith, J. (2008) Characterisation of the bacterium causing Xanthomonas wilt of banana and *Ensete* reveals it is a strain of *Xanthomonas vasicola*. *Plant Pathology* 57, 170–177.

Asoegwu, S.N. and Obiefuna, J.C. (1987) Effect of irrigation on late season plantains. *Tropical Agriculture* (Trinidad) 64, 139–143.

Avilán, R.L., Meneses, L., Sucre, R., Orta, C. and Sangle, O. (1979) Distribution of the root system of banana cv. Pigneo Gigante under four soil management systems. *Agronomia Tropical* 29, 299–312.

Avilán, R.L., Meneses, R.L. and Sucre, R.E. (1982) Distribución radical del banano bajo diferentes sistemas de manejo de suelos. *Fruits* 37, 103–110.

Báez-Sañudo, M., Siller-Cepeda, J., Muy-Rangel, D. and Basilio Heredia, J. (2009) Extending the shelf-life of bananas with 1-methylcyclopropene and a chitosan-based edible coating. *Journal of the Science of Food and Agriculture* 89(14), 2343–2349.

Banana Link (2008) Costa Rica: Productores nacionales exigen un aumento del precio por caja. *Boletín Bananero* 40, 7.

Belalcazar, S., Arcila, M.I., Valencia, J.A., Cayon, D.G. and Franco, G. (1994) Growing plantain at high densities. *Infomusa* 3(1), 12–15.

Belalcazar, S.C., Rosales, F.E. and Pocasangre, L.E. (2005) Development and formation of plantain roots (*Musa* AAB Simmonds). In: Turner, D.W. and Rosales, F.E. (eds) *Banana Root System*: *Towards a Better Understanding for its Productive Management.* Proceedings of an International Network for the Improvement of Banana and Plantain (INIBAP) symposium in Costa Rica, 3–5 November 2003. INIBAP, Montpellier, France, pp. 75–82.

Bhattacharyya, R.K. and Madhava Rao, V.N. (1985) Water requirement, crop coefficient and water-use efficiency of Robusta bananas under different soil covers and soil moisture regimes. *Scientia Horticulturae* 25, 263–269.

Biosecurity Australia (2007) Revised Draft: Import Risk Analysis Report for the Importation of Cavendish Bananas from The Philippines, Parts B and C. Commonwealth of Australia, Canberra. Available at: http://www.daff.gov.au/_ data/assets/pdf_file/0006/157965/2007-06b.pdf (Part B) and http://www.daff.

gov.au/_data/assets/pdf_file/0007/157966/2007-06c.pdf (Part C) (accessed 1 February 2009).

Blomme, G. (2000) The interdependence of root and shoot development and the influence of different biophysical factors of this relationship. *Infomusa* 9(1), 14–17.

Blomme, G., Draye, X., Gervais, R., Declerk, S., De Waele, D., Tenkouano, A. and Swennen, R. (2004) Progress in understanding the roots of *Musa* spp. *Annual Report INIBAP* 203, 1–8.

Blomme, G., Turyagenda, L.F., Musaka, H., Deekiwoko, F., Mpiira, S. and Eden-Green, S. (2009) The effect of the prompt removal of the inflorescence-infected plants and early debudding of inflorescences on the control of Xanthomonas wilt of bananas. *Acta Horticulturae* 828, 51–56.

Boels, G. (2009) Single leaf test to confirm the potential of enzyme inhibition as an alternative means for the control of black Sigatoka on banana. In: *Abstracts Workbook. XVIII ACORBAT International Meeting. Guayaquil, Ecuador. 10–14/ XI/ 2008*, p.60.

Borges, A.J. da S., Trinidade, A.V., de Matos, A.P. and Peixoto, M. de F. da S. (2007) Reduçao do mal do panama em bananeira Maça por inoculaçao de fungo micorrícico arbuscular. *Pesquisa Agropecuaria Brasileira* 42, 35–41.

Bozalek, S.J. (1980) Advantages of banana and pineapple cultivation on northerly aspects. *Subtropica* (South Africa) 1(8), 7–9.

Bright, R. (2008) Africa, banana and multinationals. Chiquita makes giant leap into Africa. *FRuiTrop* 154, 5.

Broadley, R., Rigden, P., Chay-Prove, P. and Daniells, J. (2004) *Subtropical Banana Grower's Handbook.* Queensland Department of Primary Industries, Brisbane, Queensland, Australia, 206 pp.

Buddenhagen, I, (2009) Understanding strain diversity in *Fusarium oxysporum* f. sp.*cubense* and history of introduction of 'tropical race 4' to better manage banana production. *Acta Horticulturae* 828, 193–204.

Bugaud, C., Daribo, M-O., Beauté, M.-P., Telle, N. and Dubois, C. (2009) Relative importance of location and period of banana bunch growth in carbohydrate content and mineral composition of the fruit. *Fruits* 64(2), 63–74.

Burgess, L. (2003) Biosecurity, trade and plant pathology. *Australasian Plant Pathology* 32, 129–131.

Cabrera Cabrera, J. and Galán Saúco, V. (2003) Crecimiento y desarrollo de la platanera. (*Musa acuminata* Colla AAA) bajo distintos tipos de cubierta. Avance de resultados. *Actas de Horticultura* 39, 257–259.

Cabrera Cabrera, J. and Galán Saúco, V. (2005) Evaluation of the banana cultivars Zelig, Grande Naine and Gruesa under different environmental conditions in the Canary Islands. *Fruits* 60(6), 1–13.

Cabrera Cabrera, J. and Galán Saúco, V. (2006) Evaluación de selecciones locales de 'Pequeña Enana' (*Musa acuminata* Colla AAA, subgrupo Cavendish) en las Islas Canarias. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 468–471.

Carlier, J., Fouré, E., Gauhl, F., Jones, D.R., Lepoivre, P., Mourichon, X., Pasberg-Gauhl, C. and Romero, R.A. (2000) Black leaf streak. In: Jones, D.R. (ed.) *Diseases of Banana, Abacá and Ensete*. CABI Publishing, Wallingford, Oxon, UK, pp. 56–62.

Carr, M.K.V. (2009) The water relations and irrigation requirements of banana (*Musa* spp.). *Experimental Agriculture* 45, 333–371.

Cayón Salinas, G.M. and Daza Sanabria, M.A. (2006) Efecto del color de las bolsas de polietileno sobre características fisíco químicas de frutos de banano. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, p. 319.

CEAGESP (Companhia de Entrepostos e Armazéns Gerais de São Paulo) (2006) Bananas (*Musa* spp: normas de classificaçao). *Documentos CEAGESP* 29. CEAGESP, São Paulo.

Chabrier, C., Hubervic, J. and Quénéhervé, P. (2005) Evaluation de l'efficacité de deux formulations d'oxamyl contre les nèmatodes et charançons des bananiers à la Martinique. *Nematropica* 35, 11–22.

Chaves, N.P., Pocasangre, L.E., Elango, F., Rosales, E. and Sikora, R. (2009) Combining endophytic fungi and bacteria for the biocontrol of *Radopholus similis* (Cobb) Thorne and for effects on plant growth. *Scientia Horticulturae* 122(3), 472–478.

CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement) (2007a) Banana. Close-up. *FRuiTrop* 145, 5–34.

CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement) (2007b) FLO (Fair Trade Labelling Organizations International) started to revise its fair trade standards in January 2007. *FRuiTrop* 144, 3.

Cobley, L.S. (1963) *An Introduction to the Botany of Tropical Crops.* Longmans, London, pp. 258–262.

Collin, M.N. (1991) Conservation du plantain sous film plastique. *Final report ofMRTcontract no. 8660454.* Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD)-FLHOR, Montpellier, France, pp. 21–35.

Colqhoun, L. (2007) The Great Barrier Debate. ASB Magazine. 06.09.07. Issue I. Available at: www.Business.unsw.edu.au/magazine/asb-magazine.nsf (accessed 1 February 2009).

Cordeiro, Z.J., Matos, A.P. and Kimati, H. (2005) Doenças de bananeira. In: Kimati, H., Amorim, I., Rezende, J.A. and Camargo, L.E.A. (eds) *Manual de Fitopatologia: Doenças de Plantas Cultivadas*. Agronomica Ceres, São Paulo, pp. 99–117.

Côte, F.X., Abadie, C., Achard, R., Cattan, P., Chabrier, C., Dorel, M., de Lapeyre de Bellaire, L., Risède, J.M., Salmon, F. and Tixier, P. (2009) Integrated management approaches developed in the French West Indies to reduce pesticide use in banana production systems. *Acta Horticulturae* 828, 375–382.

Crous, P.W., Schroers, H.J., Groenewald, J.Z., Braun, U. and Schubert, K. (2006) *Metulocladosporiella* gen. nov. for the causal organism of *Cladosporium* speckle disease of banana. *Mycological Research* 110(3), 264–275.

Da Costa, E.L., Celho, E.F., Simao, F.R., Filho, M.A.C. and De Oliveira, P.M. (2008) Irrigaçao da bananeira. *Informe Agropecuario* 29(245), 38–46.

Dale, J., Dugdale, B., Webb, M., Becker, D., Khanna, H., Peraza-Echeverria, S., Taylor, K., Kleidon, J., Dickman, M. and Harding, R. (2004) Strategies for Transgenic Disease Resistance in Banana. Available at: www.africancrops.net/abstracts2/banana/dale.htm (accessed 1 March 2009).

Daniells, J.W. (1984) The banana industry in North Queensland. *Queensland Agricultural Journal* Sept./Oct., 282–290.

Daniells, J.W. (1988a) Comparison of growth and yield of bananas derived from tissue culture and conventional planting material. *Newsletter of the International Group on Horticultural Physiology of Banana, University of Western Australia* 11, 2.

Daniells, J.W. (1988b) The effect of volume of root zone irrigated on yield and fruit quality of plant crop bananas. In: Guzman, J.A. (ed.) *Proceedings of the 4th Meeting of the International Group on Horticultural Physiology of Banana*, Asociación Bananera Nacional de Costa Rica (ASBANA), Costa Rica, August 1986. ASBANA, San José, Costa Rica, pp. 37–43.

Daniells, J. (2006) New banana cultivars with market potential. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 284–288.

Daniells, J. and Evans, D. (2005) Better drainage for banana plantations. Department of Primary Industries and Fisheries Note, Queensland Department of Primary Industries and Fisheries. Available at: http://www2.dpi.qld.gov.au/horticulture/5047.html (accessed 1 June 2009).

Daniells, J.W. and O'Farrell, P.J. (1987) Effect of cutting height of the parent pseudostem on yield and time of production of the following sucker in banana. *Scientia Horticulturae* 31, 89–94.

Daniells, J.W. and O'Farrell, P.J. (1988) Yield and plant characteristics of 21 banana cultivars in north Queensland. *Queensland Journal of Agricultural and Animal Sciences* 45, 139–143.

Daniells, J.W., O'Farrell, P.J. and Campbell, S.J. (1985) The response of bananas to plant spacing in double rows in north Queensland. *Queensland Journal of Agricultural and Animal Sciences* 42, 45–51.

Daniells, J.W., O'Farrell, P.J., Mulder, J.C. and Campbell, S.J. (1987a) Effects of plant spacing on yield and plant characteristics of banana in north Queensland. *Australian Journal of Experimental Agriculture* 27, 727–731.

Daniells, J.W., O'Farrell, P.J., Mulder, J.C. and Campbell, S.J. (1987b) Effects of bunch covering and bunch trimming on bananas in north Queensland. *Queensland Journal of Agricultural and Animal Sciences* 44, 101–105.

Daniells, J.W., Lisle, A.T. and O'Farrell, P.J. (1992) Effect of bunch covering methods on maturity bronzing, yield and fruit quality of bananas in North Queensland. *Australian Journal of Experimental Agriculture* 32, 121–125.

Daniells, J.W., Lisle, A.T. and Bryde, A. (1994) Effect of bunch trimming and leaf removal at flowering on maturity bronzing, yield and other aspects of fruit quality of bananas in north Queensland. *Australian Journal of Experimental Agriculture* 34, 259–265.

Daniells, J., Jenny, C., Karamura, D. and Tomepke, K. (2001) *Musa*logue: a catalogue of *Musa* germplasm. Diversity in the genus *Musa.* Compiled by Arnaud, E. and Sharrock, S. International Network for the Improvement of Banana and Plantain (INIBAP), Montpellier, France.

Ddungu, J.C.M. (1987) Regional needs for banana and plantain improvement in eastern Africa. In: Persley, G.J. and De Langhe, E.A. (eds) *Banana and Plantain Breeding Strategies*. Proceedings of an international workshop, Cairns, Australia, October 1986. ACIAR Proceedings no. 21. Australian Centre for International Agriculture Research (ACIAR), Canberra, pp. 36–38.

De Langhe, E. (1961) La phyllotaxie du bananier et ses conséquences pour la comprehension du sistéme rejetonnant. *Fruits* 16, 429–441.

De Lapeyre de Bellaire, L., Essoh Ngando, J., Abadie, C., Chabrier, C., Lescot, T., Carlier, J. and Côte, F. (2009) Is chemical control of *Mycosphaerella* foliar diseases of banana sustainable? *Acta Horticulturae* 828, 161–170.

Declerck, S., Devos, B., Delvaux, B., Planchette, C. and Strullu, D.G. (1993) Prospects for the use of mycorrhized banana plants. *Fruits* 48, 34.

Declerk, S., Risède, J.M., Rufykiri, G. and Delvaux, B. (2002) Effects of arbuscular mycorrhizal fungi on severity of root rot of bananas caused by *Cylindrocladium spathiphylli*. *Plant Pathology* 5, 109–115.

Delvaux, B. (1995) Soils. In: Gowen, S.R. (ed.) *Bananas and Plantains.* Chapman & Hall, London, pp. 230–257.

Delvaux, B., Rufykiri, G. and Dufey, J. (2005) Ion absorption and proton extrusion by banana roots. In: Turner, D.W. and Rosales, F.E. (eds) *Banana Root System*: *Towards a Better Understanding for its Productive Management.* Proceedings of an International Network for the Improvement of Banana and Plantain (INIBAP) symposium in Costa Rica, 3–5 November 2003. INIBAP, Montpellier, France, pp. 114–121.

Dorel, M. and Perrier, X. (1990) The influence of the environment and cultural techniques on the productivity of banana plantations in Guadeloupe. *Fruits* 45, 237–244.

Dos Santos, S.B., Pereira, M.E.C., Silva, S. de O., Bispo, A.S. da R. and Soares, T.L. (2006) Influenciado 1 – metilciclopropeno na longevidade póscolheita de frutos de genóptipos de bananeira resistentes á Sigatoka negra. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 849–854.

Draye, X., Lecompte, F. and Pages, L. (2005) Distribution of banana roots in time and space: new tools for an old science. In: Turner, D.W. and Rosales, F.E. (eds) *Banana Root System*: *Towards a Better Understanding for its Productive Management.* Proceedings of an International Network for the Improvement of Banana and Plantain (INIBAP) symposium in Costa Rica, 3–5 November 2003. INIBAP, Montpellier, France, pp. 58–74.

Drew, R.A. and Smith, M.K. (1990) Field evaluation of tissue cultured bananas in south-eastern Queensland. *Australian Journal of Experimental Agriculture* 30, 569–574.

Dufour, D. (2008) Physicochemical and functional properties of dessert bananas, cooking plantains and FHIA hybrids: varietal preference of the consumers in Colombia. In: *Abstracts Workbook. XVIII ACORBAT International Meeting. Guayaquil. Ecuador. 10–14/XI/2008*, 76. (Whole paper on unpublished CD).

Dumas, J. (1958) Determination d'une feuille-origine pour l'etude des bananiers cultivés. *Fruits* 13, 211–214.

Eckstein, K. (1994) Physiological responses of banana (*Musa* AAA; Cavendish subgroup) in the subtropics. PhD thesis, Institut für Obstbau und Gemüsebau, Universität Bonn, Germany, 203 pp.

Eckstein, K. and Robinson, J.C. (1995a) Physiological responses of banana (*Musa* AAA; Cavendish subgroup) in the subtropics. (I) Influence of internal plant factors on gas exchange of banana leaves. *Journal of Horticultural Science* 70, 147–156.

Eckstein, K. and Robinson. J.C. (1995b) Physiological responses of banana (*Musa* AAA; Cavendish subgroup) in the subtropics. (II) Influence of climatic conditions

on seasonal and diurnal variations in gas exchange of banana leaves. *Journal of Horticultural Science* 70, 157–167.

Eckstein, K. and Robinson, J.C. (1995c) Physiological responses of banana (*Musa* AAA; Cavendish subgroup) in the subtropics. (IV) Comparison between tissue culture and conventional planting material during the first months of development. *Journal of Horticultural Science* 70, 549–559.

Eckstein, K. and Robinson, J.C. (1996) Physiological responses of banana (*Musa* AAA, Cavendish subgroup) in the subtropics. (VI) Seasonal responses of leaf gas exchange to short-term water stress. *Journal of Horticultural Science* 71(5), 679–692.

Eckstein, K. and Robinson, J.C. (1999) The influence of the mother plant on sucker growth, development and photosynthesis in banana (*Musa* AAA; Dwarf Cavendish). *Journal of Horticultural Science Biotechnology* 74(3), 347–350.

Eckstein, K., Robinson, J.C. and Davie, S.J. (1995) Physiological responses of banana (*Musa* AAA; Cavendish subgroup) in the subtropics. (III) Gas exchange, growth analysis and source-sink interaction over a complete crop cycle. *Journal of Horticultural Science* 70, 169–180.

Eckstein, K., Robinson, J.C. and Fraser, C. (1996) Physiological responses of banana (*Musa* AAA; Cavendish subgroup) in the subtropics. (V) Influence of leaf tearing on assimilation potential and yield. *Journal of Horticultural Science* 71(3), 503–514.

Eckstein, K., Robinson, J.C. and Fraser, C. (1997) Physiological responses of banana (*Musa* AAA; Cavendish subgroup) in the subtropics. (VII) Effects of windbreak shading on phenology, physiology and yield. *Journal of Horticultural Science* 72(3), 389–396.

Elsen, A., Van der Veken, L. and De Waele, D. (2009) AMF-induced bioprotection against migratory plant parasitic nematodes in banana. *Acta Horticulturae* 828, 91–100.

Engelborghs, I., Sagi, L. and Swennen, R. (2004) Early detection of Dwarf off-types in banana (*Musa* spp.) using AFLP, Te-AFLP and MSAP analysis. In: Jain, S.M. and Swennen, R. (eds) *Banana Improvement Cellular, Molecular Biology, and Induced Mutations*. Science Publishers Inc., Enfield, New Hampshire, USA, pp. 331–340.

Englberger, L. (2003) Bananos ricos en carotenoides en Micronesia. *Infomusa* 12(2), 2–5.

Escalant, J.V. and Jain, S.M. (2004) Banana improvement with cellular and molecular biology and induced mutations. In: Jain, S.M. and Swennen, R. (eds) *Banana Improvement Cellular, Molecular Biology, and Induced Mutations*. Science Publishers Inc., Enfield, New Hampshire, USA, pp. 359–368.

Espino, R.R.C. and Pimental, R.B. (1990) Electrophoretic analysis of selected isozymes in BB cultivars of Philippine bananas. In: Jarret, R.L. (ed.) *Proceedings for Identification of Genetic Diversity in the Genus Musa.* International Network for the Improvement of Banana and Plantain (INIBAP), Montpellier, France, pp. 36–40.

Espinosa, J. and Mite, F. (2008) Búsqueda de eficiencia en el uso de nutrients en banano. In: *Abstracts Workbook. XVIII ACORBAT International Meeting. Guayaquil. Ecuador. 10–14/XI/2008*, p.60.

EUR.lex (2010a) Available at: eur-lex.europa.eu (accessed 14 May 2010).

EUR.lex (2010b) EU Directive 2257/94. Available at: eur-lex.europa.eu/es/legis/latest/chap036054.htm (accessed 14 May 2010).

Europa (2010) Directive 94/414/EEC. Available at: http://europa.eu/scadplus/leg/en/lvb/128178.htm (accessed 14 May 2010).

FAO (Food and Agriculture Organization) (2001a) *Review of Banana Trade Policy Developments*. Intergovernmental Group on Bananas and on Tropical Fruits. Committee on Commodity Problems. Second Session. San José, Costa Rica, 4–8 December 2001. FAO, San José, Costa Rica.

FAO (Food and Agriculture Organization) (2001b) *Guidelines for Production, Processing, Labelling and Marketing of Organically Produced Foods*. GL 32-1999. Rev.1-2001. FAO, Rome. Available at: http://www.fao.org/organicag/doc/glorganicfinal.pdf (accessed 1 October 2009).

FAOSTAT (2010) FAO Database. Food and Agriculture Organization of the United Nations. Available at: http://faostat.fao.org (accessed 28 April 2010).

Fauquet, C.M., Mayo, M.A., Maniloff, J., Desselberger, U. and Ball, L.A. (eds) (2005) *Virus Taxonomy*. Elsevier Academic Press, London, UK.

Ferris, R.S.B., Hotsonyame, G.K., Wainwright, H. and Thompson, A.K. (1993) The effects of genotype, damage, maturity and environmental conditions on the postharvest life of plantains. *Tropical Agriculture* (Trinidad) 70, 45–50.

Fogain, R. and Price, N.S. (1994) Varietal screening of some *Musa* cultivars for susceptibility to the banana borer weevil. *Fruits* 49, 247–251.

Fox, R.L. (1989) Detecting mineral deficiencies in tropical and temperate crops. In: Plucknett, D.L. and Sprague, H.B. (eds) *Westview Tropical Series 7*. Westview Press, Boulder, Colorado, USA.

Frison, E.A. and Putter, C.A.J. (eds) (1989) *FAO/IBPGR Technical Guidelines for the Safe Movement of* Musa *germplasm.* Food and Agriculture Organization (FAO)/ International Board for Plant Genetic Resources (IBPGR), Rome, Italy.

Frison, E.A. and Sharrock, S.L. (1999) Introduction: the economic, social and nutritional importance of banana in the world. In: Picq, C., Fouré, E. and Frison, E.A. (eds) *Bananas and Food Security International Symposium*. Douala, Cameroon, 10–14 November 1998. International Network for the Improvement of Banana and Plantain (INIBAP), Montpellier, France, pp. 21–25.

Galán Saúco, V. (1992) *Los Frutales Tropicales en los Subtrópicos. I. Plátano Banano*. Mundi-Prensa, Madrid, 173 pp.

Galán Saúco, V. (2002) Greenhouse cultivation of tropical fruits. *Acta Horticulturae* 575(2), 727–735.

Galán Saúco, V. (2003) Banana and plantain. In: Katz, S.H. and Weaver, W.W. (eds) *The Encyclopedia of Food and Culture*, Vol. 1. Charles Scribner and Sons, New York, pp. 159–164.

Galán Saúco, V. (2005) Tropicales y subtropicales. In: Mateo Box, J.M. (coordinator) *Prontuario de Agricultura*. Mundi-Prensa, Madrid, pp. 824–903.

Galán Saúco, V. and Cabrera Cabrera, J. (2002) Cultivo bajo invernadero. In: Fernández Galván, D. and Hernández Delgado, P.M. (eds) *Actividades del ICIA en Platanera*. Instituto Canario de Investigaciones Agrarias, Valle de Guerra, La Laguna, Tenerife, pp. 11–20.

Galán Saúco, V. and Cabrera Cabrera, J. (2006) El cultivo del plátano (banano, *Musa acuminata* Colla AAA, subgrupo Cavendish) en las Islas Canarias. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 289–301.

Galán Saúco, V. and Damatto Junior, E.R. (2010) Banana. In: Chavarria, G. and Pessoas dos Santos, H. (eds) *Fruticultura em Ambiente Protegido.* Universidade do Passo Fundo, Passo Fundo, Brazil. In press.

Galán Saúco, V. and Robinson, J.C. (2010) Field establishment of *in vitro*-derived banana plants. *Fruits* 65(1), 43–51.

Galán Saúco, V., García Samarín, J. and Carbonell, E. (1984) Estudio de la práctica del deshijado y la fenología de la platanera (*Musa acuminata* Colla AAA, cv. 'Pequeña Enana') en la isla de Tenerife. *Fruits* 39, 595–605.

Galán Saúco, V., Cabrera Cabrera, J. and Hernandez Delgado, P.M. (1992) Phenological and production differences between greenhouse and open-air bananas (*Musa* AAA, cv. Dwarf Cavendish) in the Canary Islands. *Acta Horticulturae* 296, 97–112.

Galán Saúco, V., Cabrera Cabrera, J. and Gómez Leal, P. (1996) The evaluation of different bunch covers for bananas (*Musa acuminata*) in the Canary Islands. *Fruits* 51(1), 13–24.

Galán Saúco, V., Cabrera Cabrera, J., Hernández Delgado, P.M. and Rodríguez Pastor, M.C. (1998) Comparison of protected and open-air cultivation of Grande Naine and Dwarf Cavendish bananas. *Acta Horticulturae* 490, 247–259.

Galán Saúco, V., Ait-Oubahou, A. and Abdelhaq, H. (2004) Greenhouse cultivation of bananas. *Chronica Horticulturae* 44(2), 35–37.

Gall, E.N. (1986) Bananas – South Queensland. Sucker and plant management. Farm Note. AGDEX 231/20. F56/Jun86. Queensland Department of Primary Industry, Brisbane, Queensland, Australia.

Ganry, J. (1978) Recherche d'une methode d'estimation de la date de récolte du bananier dans les conditions des Antilles. *Fruits* 33, 669–680.

Ganry, J. and Chillet, M. (2009) Methodology to forecast the harvest date of banana bunches. *Fruits* 63(6), 371–373.

Ganry, J., De Lapeyre de Bellaire, L. and Mourichon, X. (2008) A biological forecasting system to control Sigatoka disease of bananas and plantains. *Fruits* 63(6), 381–387.

Geering, A.D.W. (2009) Viral pathogens of banana: outstanding questions and options for control. *Acta Horticulturae* 828, 39–45.

Goenaga, R., Irizarry, H. and Gonzalez, E. (1993) Water requirement of plantains (*Musa* AAB) grown under semi-arid conditions. *Tropical Agriculture* (Trinidad) 70, 3–7.

Gómez, C., Rumbos, R., Vera, J., Rosales, H., Magaña-Lemus, S. and Surga, J.G. (2006) Efecto de cuatro densidades de siembra sobre la producción de plátano (*Musa* AAB Simmonds) en el sur del Lago Maracaibo. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, p. 344.

González, M. (2008) Exportaciones del banano ecuatoriano hacia Argentina y Uruguay: situación actual y tendencias. In: *Abstracts Workbook. XVIII ACORBAT International Meeting. Guayaquil. Ecuador. 10–14/XI/2008* (unpublished CD).

Gowen, S.R. (1988) Exploited plants – bananas. *Biologist* 35, 187–192.

Gowen, S.R. (1995) Pests. In: Gowen, S.R. (ed.) *Bananas and Plantains.* Chapman & Hall, London, pp. 382–402.

Haarer, A.E. (1964) *Modern Banana Production.* Leonard Hill, London, 136 pp.

Harish, S., Kavino, M., Kumar, N. and Samypayan, R. (2009) Biopriming banana with plant growth-promoting endophytic bacteria induces systemic resistance against banana bunchy top virus. *Acta Horticulturae* 828, 295–302.

Harris, D.R., Seberry, J.A., Wills, L.J. and Spohr, L.J. (2000) Effect of fruit maturity on efficiency of 1-methylcyclopropene to delay the ripening of bananas. *Postharvest Biology and Technology* 20(3), 303–308.

Hayman, D.S. (1987) VA micorrhizas in field crop systems. In: Safir, G.R. (ed.) *Ecophysiology of VA Micorrhizal Plants*. CRC Press, Boca Raton, Florida, pp. 171–192.

Hegde, D.M. (1988) Growth and yield analysis of Robusta banana in relation to soil water potential and nitrogen fertilization. *Scientia Horticulturae* 37,145–155.

Hegde, D.M. and Srinivas, K. (1989) Growth, yield, nutrient uptake and water use of banana crops under drip and basin irrigation with N and K fertilization. *Tropical Agriculture* (Trinidad) 68, 331–334.

Hernández, G., Villa Nemesi, Y., Foùrtul, R., Grace, K. and de la Cruz, J. (2008) Endogenous level of gibberellins, calcium and the other mineral elements during the floral transition in plantain (*Musa* AAB) cv False Horn. In: *Abstracts Workbook. XVIII ACORBAT International Meeting. Guayaquil. Ecuador. 10–14/XI/2008*, p.16. (Whole paper on unpublished CD).

Hernández, Y., Giménez, C.A., Rodríguez, P., Gómez Lima, M., Paredes, C. and Labarca, J. (2006) La transición floral en plátano *MUSA* (AAB) cv. Hartón enano: genética y ontogenia. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006*. ACORBAT/ACAFRUTA, Joinville, Brazil, p. 307.

Hill, T.R. (1990) Banana water use – scheduling irrigation for bananas with tensiometers. In: *Proceedings of the First National Banana Symposium*, Kununurra, Western Australia (WA), June 1990. WA Department of Agriculture, Kununurra, WA, pp. 51–55.

Hoffman, H.P. (1990) Transpiration from banana leaves (cv. Williams) as affected by seasons – soil moisture potential and vapour pressure deficit in a subtropical climate. In: *Proceedings of the First National Banana Symposium*, Kununurra, Western Australia (WA), June 1990. WA Department of Agriculture, Kununurra, WA, pp. 60–72.

Hord, H.H.V. and Spell, D.P. (1962) Temperature as a basis for forecasting banana production. *Tropical Agriculture* (Trinidad) 39, 219–223.

Horser, C.L., Harding, R.M. and Dale, J.L. (2001) Banana bunchy top nanovirus DNA-1 encodes the master replication initiation protein. *Journal of General Virology* 82, 459–464.

Hwang, S.C. and Ko, W.H. (1987) Somaclonal variation of bananas and screening for resistance to Fusarium wilt. In: Persley, G.J. and De Langhe, E.A. (eds) *Banana and Plantain Breeding Strategies.* Proceedings of an international workshop, Cairns, Australia, October 1986. ACIAR Proceedings no. 21. Australian Centre for International Agriculture Research (ACIAR), Canberra, pp. 151–156.

Hwang, S.C., Chen, C.L., Lin, J.C. and Lin, H.L. (1984) Cultivation of bananas using plantlets from meristem culture. *HortScience* 19, 231–233.

IFOAM (International Federation of Organic Agriculture Movements) (2009) Available at: www.ifoam.org (accessed 1 October 2009).

INIBAP (International Network for the Improvement of Banana and Plantain) (1994) *Bananas, Plantains and INIBAP.* Annual report for 1993. INIBAP, Montpellier, France, 73 pp.

INIBAP (International Network for the Improvement of Banana and Plantain) (2002) *Strategy for the Global* Musa *Genomics Consortium*. INIBAP, Montpellier, France, 44 pp.

INIBAP (International Network for the Improvement of Banana and Plantain) (2006) *Adding Value to Bananas: the Results of a Study and Workshop on the Contribution of* Musa *Processing Businesses to Rural Development*. Progress report to the Rockefeller Foundation. INIBAP, Montpellier, France.

Infomusa@ (2009) Three-way Approach to Tackle Drought Stress. Available at: www.promusa.org (accessed 29 April 2009).

Irizarry, H. (1985) Intensive plantain production in the humid mountains of Puerto Rico. In: *Proceedings of the 3rd Meeting of the International Association for Research on Plantain and Banana (IARPB)*, Abidjan, Ivory Coast, May 1985, pp. 55–60.

Irizarry, H. and Rodriguez, J.A. (1981) Tillage and yields of Horn-type Maricongo plantain on an ultisol. *Journal of Agriculture of the University of Puerto Rico* 65, 118–122.

Irizarry, H., Silva, S. and Vicente-Chandler, J. (1980) Effect of water table level on yield and root system of plantains. *Journal of Agriculture of the University of Puerto Rico* 64, 33–36.

Irizarry, H., Rodriguez-Garcia, J. and Diaz, N. (1981) Effect of three population densities and fertilizer levels on yields of high-yielding clones of plantains at two localities. *Journal of Agriculture of the University of Puerto Rico* 65, 395–400.

Irizarry, H., Rivera, E., Krikorian, A.D. and Rodriguez, J.A. (1991) Proper bunch management of the French-type superplantain (*Musa* AAB) in Puerto Rico. *Journal of Agriculture of the University of Puerto Rico* 75, 163–171.

Irizarry, H., Rivera, E. and Rodriguez, J.A. (1992) Bunch and ratoon management for profitable production of high quality bananas (*Musa acuminata*, AAA). *Journal of Agriculture of the University of Puerto Rico* 76, 119–129.

Israeli, Y. and Blumenfeld, A. (1985) *Musa*. In: Halevy, A.H. (ed.) *Handbook of Flowering*, Volume 3. CRC Press, Boca Raton, Florida, pp. 390–409.

Israeli, Y. and Lahav, E. (1986) Banana. In: Monselise, S. (ed.) *Handbook of Fruit Development.* CRC Press, Boca Raton, Florida, pp. 45–73.

Israeli, Y. and Nameri, N. (1987) Seasonal changes in banana plant water use. *Water and Irrigation Review* (Tel Aviv, Israel), January, 10–14.

Israeli, Y., Lahav, E. and Nameri, N. (1986) The effect of salinity and sodium adsorption ratio in the irrigation work on growth and productivity of bananas under drip irrigation conditions. *Fruits* 41, 297–302.

Israeli, Y., Nameri, N., Gat, Z. and Burd, P. (1988a) Relating banana flowering distribution in the Jordan Valley (Israel) to climate and phenology. *Agricultural and Forest Meteorology* 43,109–119.

Israeli, Y., Reuveni, O. and Nameri, N. (1988b) Genetic variability and performance of *in vitro* propagated banana plants. In: Guzman, J.A. (ed.) *Proceedings of the 4th Meeting of the International Group on Horticultural Physiology of Banana*, Asociación Bananera Nacional de Costa Rica (ASBANA), Costa Rica, August 1986. ASBANA, San José, Costa Rica, pp. 97–104.

Israeli, Y., Lahav, E. and Reuveni, O. (1995a) *In vitro* culture of bananas. In: Gowen, S.R. (ed.) *Bananas and Plantains.* Chapman & Hall, London, pp. 147–178.

Israeli, Y., Plant, Z. and Schwartz, A. (1995b) Effect of shade on banana morphology, growth and production. *Scientia Horticulturae* 62, 45–56.

Jaizme-Vega, M.C. and Azcon, R. (1995) Responses of some tropical and subtropical cultures to endomycorrhizal fungi. *Mycorrhiza* 5, 213–217.

Jaizme-Vega, M.C., Sosa Hernández, B. and Hernández Hernández, J. (1998) Interaction of arbuscular mycorrhyzal fungi and the soil pathogen *Fusarium oxysporum* f. sp. *cubense* on the first stages of micropropagated Grande Naine bananas. *Acta Horticulturae* 490, 285–295.

Jaramillo, R. (1987) Banana and plantain production in Latin America and the Caribbean. In: Persley, G.J. and De Langhe, E.A. (eds) *Banana and Plantain Breeding Strategies*. Proceedings of an international workshop, Cairns, Australia, October 1986. ACIAR Proceedings no. 21. Australian Centre for International Agriculture Research (ACIAR), Canberra, pp. 39–43.

Jiang, Y.M., Joyce, D.C. and Macnish, A.J. (1999) Extension of the shelf life of banana fruit by 1-methylcyclopropene in combination with polyethylene bags. *Postharvest Biology and Technology* 16(2), 187–193.

John, P. and Marchal, J. (1995) Ripening and biochemistry of the fruit. In: Gowen, S.R. (ed.) *Bananas and Plantains.* Chapman & Hall, London, pp. 434–467.

Jones, D.R. (1993) Evaluating banana and plantain for reaction to black leaf streak disease in the South Pacific. *Tropical Agriculture* (Trinidad) 70, 39–44.

Jones, D.R. (2000) *Diseases of Banana, Abacá and Ensete.* CABI Publishing, Wallingford, Oxon, UK, 544 pp.

Jones, D.R. (2009) Diseases and pests: constraints to banana production. *Acta Horticulturae* 828, 21–36.

Jones, D.R. and Tezenas du Montcel, H. (1993) Safe movement of *Musa* germplasm. *Infomusa* 2(2), 3–4.

Jones, D.R. and Van den Bergh, I. (eds) (2009) *Acta Horticulturae* 828, 427 pp.

Kader, A.A. (2001) *A Summary of CA Requirements and Recommendations for Fruits Other Than Apples and Pears.* Postharvest Horticultural Series No. 22A. University of California, Davis, California.

Kader, A.A. (2002) *Postharvest Technology of Horticultural Crops*, 3rd edn. University of California, Davis, California.

Kaemmer, D., Afza, R., Weising, K., Kahl, G. and Novak, F.J. (1992) Oligonucleotide and amplification fingerprinting of wild species and cultivars of banana (*Musa* spp.). *Bio/Technology* 10, 1030–1035.

Kahl, G. (2004) The banana genome in focus: a technical perspective. In: Jain, S.M. and Swennen, R. (eds) *Banana Improvement Cellular, Molecular Biology, and Induced Mutations*. Science Publishers Inc., Enfield, New Hampshire, USA, pp. 263–270.

Kallarackal, J., Milburn, J.A. and Baker, D.A. (1990) Water relations of the banana. III. Effects of controlled water stress on water potential, transpiration, photosynthesis and leaf growth. *Australian Journal of Plant Physiology* 17, 79–90.

Kandan, A., Radjacommare, R., Nandakumar, R., Raguchander, T., Ramiah, M. and Samypayan, R. (2002) Induction of phenyl propanoid metabolism by *Pseudomonas fluorescens* against tomato spotted wilt virus in tomato. *Folia Microbiologica* 47(2), 121–129.

Kavino, M., Harish, S., Kumar, N. and Samiyappan, R. (2009) Rhizobacteria-mediated growth promotion of banana leads to protection against banana bunchy top virus under field conditions. *Acta Horticulturae* 828, 69–76.

Ke, L.S. (1980) Studies on the physiological characteristics of banana in Taiwan. III. Study of daily variation in photosynthesis, stomatal movement and leaf water potential of banana plant. *Journal of the Chinese Society of Horticultural Science* 26, 18–26.

Khayat, E. (2008) Application of genetic engineering for solving problems related to Musaceae crop production. In: *Abstracts Workbook. XVIII ACORBAT International Meeting. Guayaquil. Ecuador. 10–14/XI/2008*. (unpublished CD).

Khayat, E., Duvdevani, A., Lahav, E. and Ballesteros, B.A. (2004) Somaclonal variation in banana (*Musa acuminata* cv. Grande Naine). Genetic mechanism, frequency, and application as a tool for clonal selection. In: Jain, S.M. and Swennen, R. (eds) *Banana Improvement Cellular, Molecular Biology, and Induced Mutations*. Science Publishers Inc., Enfield, New Hampshire, USA, pp. 97–110.

Koffi, M.C., de la Providencia, I.E., Else, A. and Declerck, S. (2009) Development of an *in vitro* culture system adapted to banana mycorrhization. *African Journal of Biotechnology* 8(12), 2750–2756.

Kuhne, F.A., Kruger, J.J. and Green, G.C. (1973) Phenological studies of the banana plant. *Citrus and Subtropical Fruit Research Institute Information Bulletin* 8, 11–16.

Lahav, E. (1995) Banana nutrition. In: Gowen, S.R. (ed.) *Bananas and Plantains*. Chapman & Hall, London, pp. 258–316.

Lahav, E. and Kalmar, D. (1981) Shortening the irrigation interval as a means of saving water in a banana plantation. *Australian Journal of Agricultural Research* 32, 465–477.

Lahav, E. and Turner, D.W. (1983) Fertilizing for high yield-banana. *International Potash Institute, Bulletin* no. 7, Berne, Switzerland, 62 pp.

Lahav, E. and Turner, D.W. (1985) Temperature influences the composition of diagnostic samples used to assess the nutrient status of banana plants. *Scientia Horticulturae* 27, 275–283.

Lassoudiere, A. (1978a) Quelques aspects de la croissance et du développement du bananier 'Poyo' en Côte d'Ivoire, 4° en 5° partie. *Fruits* 33(5), 294–338; *Fruits* 33(6), 373–412; *Fruits* 33(7–8), 457–503.

Lassoudiere, A. (1978b) Quelques aspects de la croissance et du développement du bananier 'Poyo' en Côte d'lvoire 2. Le système radical. *Fruits* 33, 314–338.

Lassoudiere, A. (1979) Comportement du bananier 'Poyo' au seconde cycle. (I). *Fruits* 34(11), 645–658; *Fruits* 34(12), 713–728.

Lassoudiere, A. (1980) Comportement du bananier 'Poyo' au seconde cycle. (IV). *Fruits* 35(1), 3–17; *Fruits* 35(2), 69–93.

Lassoudiere, A. (2007) *Le Bananier et sa Culture*. Quae, Versailles CEDEX, France, 383 pp.

Lescott, T. (2008) Estado actual de la producción de Musáceas en Africa, Asia Pacífico y el Caribe. In: *Abstracts Workbook. XVIII ACORBAT International Meeting. Guayaquil. Ecuador. 10–14/XI/2008*, p.99.

Lescott, T. and Loeillet, D. (2008) Banana and environment. Towards cleaner production in 10 years time. *FRuiTrop* 153, 3–4.

Lichtemberg, L.A. (2001) Pós-colheita de banana. In: *Anais do Simpósio Norte Mineiro Sobre a Cultura da Banana*. Nova Porteirinha, Empresa de Pesquisa Agropecuária de Minas Gerais (EPAMIG) Centro Tecnológico do Norte de Minas (CTNM), Minas Gerais, Brazil, pp. 105–130.

Lichtemberg, L.A., Hinz, R.H. and Malburg, J.L. (1986) Effect of spacing and desuckering on the performance of 'ENXERTO' banana (*Musa* AAB) in Southern Santa Catarina, Brazil. *Proceedings of the Interamerican Society for Tropical Horticulture* 30, 25–33.

Lichtemberg, L.A., Vilas Boas, E.V.d.V. and Carvalho Dias, M.S. (2008) Colheita e pós-colheita da banana. *Informe Agropecuario* 29(245), 92–110.

Llontop-Llaque, J. and Rojas-Campos, E. (2008) Effectiveness of the natural fungicide-bactericide BC 1000 for the control of crown rot of organic bananas (*Musa* sp.) in the post harvest. In: *Abstracts Workbook. XVIII ACORBAT International Meeting. Guayaquil. Ecuador. 10–14/XI/2008*, p.50.

Loeillet, D. (2007a) Banana market. Banana, ACP and EPA, which way is up?... *FRuiTRop* 151, 7–9.

Loeillet, D. (2007b) The US legal authorities have decided.... *FRuiTRop* 148, 1.

Loeillet, D. (2008a) Close-up. Producer country sheet: banana in Martinique. *FRuiTrop* 155, 23–25.

Loeillet, D. (2008b) Doha non-agreement and the banana dispute. Deus ex machina? *FRuiTRop* 159, 2–3.

Loeillet, D. (2008c) Banana in Europe: report on 2007 prices – strong pressure on import margins. *FRuiTrop* 152, 2–9.

Loeillet, D. (2009) European banana market: prices in 2008. Banana unaffected by the crisis. *FRuiTRop* 163, 7–11.

Loos, C.A. (1962) Studies on the life-history and habits of the burrowing nematode, *Radopholus similis*, the cause of black-head disease of banana. *Proceedings of the Helminthological Society of Washington* 29, 43–52.

López, J., Gómez, R., Montano, N., Reinaldo, D., Trujillo, R., Rayas, A., Cantero, A., Cabrera, M., Santos, A., Ventura, J., Toledo, H., Medero, V., Basail, M., García, M., Roman, M.I. and Pérez, L. (2006) Methodology for somatic embryogenesis in plantain (Group AAB) interphase with plant breeding. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006*. ACORBAT/ACAFRUTA, Joinville, Brazil, p. 341.

Lorch, J. (1958) Analysis of windbreak effects. *Bulletin of the Research Council of Israel* 6D, 211–220.

Magdoff, F. (2007) Ecological agriculture: principles, practices and constraints. *Renewable Agriculture and Food System* 22(2), 109–117.

Mak, C., Mohamed, A.A., Liew, K.W. and Ho, Y.W. (2004) Early screening techniques for Fusarium wilt resistance in banana micropropagated plants. In: Jain, S.M. and Swennen, R. (eds) *Banana Improvement Cellular, Molecular Biology, and Induced Mutations*. Science Publishers Inc., Enfield, New Hampshire, USA, pp. 219–228.

Marchal, J. (1993) The quality of dessert bananas and plantains. *Fruits* 48, 40–44.

Markham, R. (2009) Managing diseases and pests of banana: the way ahead? *Acta Horticulturae* 828, 417–427.

Martinez Garnica, A. (1984) Effect of sucker removal on plantain yields in the humid tropics of Colombia. *Revista del Instituto Colombiano Agripecuario* 19, 357–359.

Mateille, T. (1993) Effects of banana-parasitic nematodes on *Musa acuminata* (AAA group) cvs. Poyo and Gros Michel vitroplants. *Tropical Agriculture* (Trinidad) 70, 325–331.

Meyer, J.P. and Schoch, P.G. (1976) Besoin en eau du bananier aux Antilles. Mesure de l'évapo-transpiration maximale. *Fruits*, 31, 3–19.

Monreri, S.A. (2008) Biological effectiveness of three dosages of an organic formulation of *Melaleuca alternifolia* in the fight against black Sigatoka in banana crop production. In: *Abstracts Workbook. XVIII ACORBAT International Meeting. Guayaquil. Ecuador. 10–14/XI/2008*, p.51.

Moradinezhad, F., Able, A.J., Sedgley, M. and Klieber, A. (2006) Concentration and duration of ethylene treatment influences the response of banana to 1-methylcyclopropene. *Acta Horticulturae* 712, 747–751.

Moradinezhad, F., Sedgley, M., Klieber, A. and Able, A.J. (2008) Variability of responses to 1-methylcyclopropene by banana: influence of time of year at harvest and fruit position in the bunch. *Annals of Applied Biology* 152(2), 223–234.

Moreira, R.S. (1999) *Banana: Teoría e Prática de Cultivo*, 2nd edn. Fundação Cargill, São Paulo, Brazil.

Morton, J.F. (1987) *Fruits of Warm Climates*. Morton, Miami, Florida, 505 pp.

Musagenomics (2010) Available at: www.musagenomics.org (accessed 14 May 2010).

Nava, C. and Sosa, L. (2006) The plantain (*Musa* AAB) and its relation between the cycle and production. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, p. 306.

N'da Adopo, A. (1992) *Reducing Postharvest Losses of Bananas and Plantains in Cameroon*. André Mayer Fellowship report. Food and Agriculture Organization (FAO), Rome, 119 pp.

Nelson, S.C., Ploetz, R.C. and Kepler, A.K. (2006) *Musa* species (bananas and plantains). In: Eletvitch, C.R. (ed.) *Species Profiles for Pacific Islands Agroforestry*. Permanent Agricultural Resources, Holualoa, Hawaii. Available at: http://www.agroforestry. net/tti/Musa-banana-plantain.pdf (accessed 1 February 2009).

Ngoh Newilah, G., Dhuique-Mayer, C., Rojas-Gonzalez, J., Tomekpe, K., Fokou, Ë. and Etoa, F.X. (2009) Carotenoid contents during ripening of banana hybrids and cultivars grown in Cameroon. *Fruits* 64(4), 197–206.

N'Guessan, A.E.B. and Ganry, J. (1990) Systèmes de culture et techniques culturales pour la production de plantain. *Fruits* (special issue), 103–106.

Norgrove, L. and Hauser, S. (1998) Effect of tree density and crop management upon growth of plantain in a low input agrisilvicultural system. *Acta Horticulturae* 490, 187–194.

Novak, F.J. (1992) *Musa* (bananas and plantains). In: Hammerschlag, F.A. and Litz, R.E. (eds) *Biotechnology of Perennial Fruit Crops.* CAB International, Wallingford, Oxon, UK, pp. 449–488.

Novak, F.J., Afsa, R., Van Duren, M. and Omar, M.S. (1990) Mutation induction by gamma irradiation of *in vitro* cultured shoot tips of banana and plantain (*Musa* cvs). *Tropical Agriculture* (Trinidad) 67, 21–28.

Obiefuna, J.C. (1984) Effect of delayed fertilizer application on the growth and yield of plantains in South Western Nigeria. *Fertilizer Research* 5, 309–313.

Obiefuna, J.C. (1986) The effect of monthly planting on yield, yield patterns and yield decline of plantains (*Musa* AAB). *Scientia Horticulturae* 29, 47–54.

Obiefuna, J.C. (1990) Effect of manures and composts on nematodes, borer weevils and yield of plantain. *Biological Agriculture and Horticulture* 6, 227–283.

Obiefuna, J.C., Majumder, P.K. and Ucheagwu, A.C. (1982) Spacing and sucker management in the commercial plantain production in the rainforest belt of Nigeria. *Annals of Applied Biology* 101, 391–396.

Padmanaban, B., Uma, S. and Sathiamoorthy, S. (2006) Relative susceptibility of *Musa* germplasm against banana corm weevil, *Cosmopolites sordidus* Germ. (Coleoptera: Curculioniddae). In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 805–807.

Panis, B. (1995) Cryopreservation of banana (*Musa* spp.) germplasm. PhD thesis, Catholic University of Leuven, Leuven, Belgium, 201 pp.

Panis, B. and Thinh, N.T. (2001) INIBAP Technical Guideline 5. In: *Cryopreservation of* Musa *Germplasm*. International Network for the Improvement of Banana and Plantain (INIBAP), Montpellier, France, 44 pp.

Panis, B., Dhed'a, D. and Swennen, R. (1992) Freeze-preservation of embryogenic *Musa* suspension cultures. In: Adams, R.P. and Adams, J.E. (eds) *Conservation of Plant Genes.* Academic Press, New York, pp. 183–195.

Panis, B., Strosse, H., Remy, L., Sagi, L. and Swennen, R. (2004) Cryopreservation of banana tissues: support for germplasm conservation and banana improvement. In: Jain, S.M. and Swennen, R. (eds) *Banana Improvement Cellular, Molecular Biology, and Induced Mutations*. Science Publishers Inc., Enfield, New Hampshire, USA, pp. 13–22.

Panis, B., Helliot, B., Srosse, H., Remy, S., Lepoivre, P. and Swennen, R. (2005) Germplasm conservation, virus eradication and safe storage of transformation-competent cultures in banana: the importance of cryopreservation. *Acta Horticulturae* 692, 51–59.

Patel, N.L. and Chundawat, B.S. (1988) Effect of size and resting period of suckers on growth and yield of banana. *Indian Journal of Horticulture* 45, 189–196.

Patiño, L.F., Salazar, L.M., Collazos, J.C., Piedrahita, R.A. and Bustamante, E. (2006) Bacterias líticas y sustratos en la filosfera de banano y plátano para el control de la Sigatoka negra. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 133–140.

Pattison, T., Cobon, J. and Sikora, R. (2006) Soil quality improvement and nematode management on banana farms in Australia. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 268–283.

Patisson, A.B., Lindsay, S., Cobon, J.A., Rosales, F.E., Pocasangre, L.E., Araya, M.A. and Sikora, R.A. (2008) Understanding soil functions for better banana soil health. In: *Abstracts Workbook. XVIII ACORBAT International Meeting. Guayaquil, Ecuador. 10–14/XI/2008*, p.61.

Perera González, S. and Molina León, M.J. (2002) *Plagas y enfermedades de la Platanera en Canarias*. COPLACA, Canary Islands, Spain.

Pérez-Vicente, L., Porras, A., Mauri-Mollera, F., Hernández-Mancilla, A. (2006) Relaciones entre los factores climáticos y la velocidad de la evolución de la Sigatoka negra en bananos y plátanos. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 702–709.

Pillay, M. and Tripathi, L. (2007) Banana. In: Kole, C. (ed.) *Genome Mapping and Molecular Breeding in Plants*, Vol. 4. *Fruits and Nuts*. Springer-Verlag, Berlin, pp. 281–301.

Ploetz, R.C. (1993) A brief introduction to studies on variability in *Fusarium oxysporum* f. sp. *cubense.* In: Valmayor, R.V., Hwang, S.C., Ploetz, R., Lee, S.W. and Roa, N.V.(eds) *Proceedings of the International Symposium on Recent Developments in Banana Cultivation Technology*, Taiwan, December 1992. International Network for the Improvement of Banana and Plantain (INIBAP), Los Baños, The Philippines, pp. 214–219.

Ploetz, R. (2008) Tropical race 4 of Panama disease: risk assessment and an action plan to address the problem. In: *Abstracts Workbook. XVIII ACORBAT International Meeting. Guayaquil, Ecuador. 10–14/XI/2008*, 38.

Pocasangre, L.E., Donaldo Menjivar, R., zum Felde, A., Stella Riveros, A., Rosales, F.E. and Sikora, R.A. (2006) Hongos endofíticos como agentes biológicos de control de fitonematodos de banano. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006*. ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 249–254.

Poiani, L.M., Borges, M.T.M.R., Vilas Boas, E.V. de B., Lichtemberg, L.A. and de Godoy, R.C.B. (2008) Aproveitamento industrial dos descartes de pós-colheita. *Informe Agropecuario* 29(245), 111–119.

Price, N.S. (1994a) Field trial evaluation of nematode susceptibility within *Musa. Fundamental Applied Nematology* 17, 391–396.

Price, N.S. (1994b) Field trial evaluation of *Musa* varieties and of other crops as hosts of *Pratylenchus goodeyi* in Cameroon. *Afro-Asian Journal of Nematology* 4, 11–16.

Price, N.S. (1994c) Alternate cropping in the management of *Radopholus similis* and *Cosmopolites sordidus*, two important pests of banana and plantain. *International Journal of Pest Management* 40, 237–244.

Purseglove, J.W. (1972) *Tropical Crops – Monocotyledons.* Longman, London, pp. 343–384.

Quilici, S. (1993) Insect pests of banana. *Fruits* 48, 29–31.

Quintero, S.J. and Aristizábal, J.M. (2002) Efectos del desmane sobre las características productivas de 'Dominico Hartón' y 'Africa' en Colombia. *InfoMusa* 12(1), 44–45.

Ram, H.Y.M., Ram, M. and Steward, F.C. (1962) Growth and development of the banana plant. 3B. The structure and development of the fruit. *Annals of Botany* NS 26, 665–673.

Ramsey, M.D., Daniells, J.W. and Anderson, V.J. (1990) Effects of Sigatoka leaf spot (*Mycosphaerella musicola* Leach) on fruit yields, field ripening and greenlife of bananas in North Queensland. *Scientia Horticulturae* 41, 305–313.

Reefer Trends (2008) Dom Rep organic bananas face Sigatoka threat. *Reefer Trends Online Daily News* 1 December 2008.

Reefer Trends (2009a) AQIS bar 'too high' for Philippine banana exports. *Reefer Trends Online Daily News* 10 June 2009.

Reefer Trends (2009b) FWI extends sustainable banana project. *Reefer Trends Online Daily News* 25 June 2009.

Reefer Trends (2009c) Russian banana market 'collapses'. *Reefer Trends Online Daily News* 4 August 2009.

Reefer Trends (2010) EU banana imports fall 6%. Drop in USA banana imports. *Reefer Trends Online Daily News* 19 February 2010.

Ribeiro, R.C.F., Xavier, A.A. and Dias-Arieira, C.R. (2008) Nematoides na bananicultura. *Informe Agropecuario* 29(245), 59–65.

Robinson, J.C. (1982) The problem of November dump fruit with 'Williams' banana in the subtropics. *Subtropica* 3(9), 11–16.

Robinson, J.C. (1987) Root growth characteristics in banana. *1TSC Information Bulletin* no. 183, 7–9.

Robinson, J.C. (1992) Phenology of the banana plant in the subtropics. *Subtropica* 13(11), 26–32.

Robinson, J.C. (1994) General recommendations for managing tissue culture banana plants in the field. *ITSC Information Bulletin* no. 257, 1–5.

Robinson, J.C. (2006) Present and future situation of banana production in the subtropics In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 255–267.

Robinson, J.C. (2007) Nutritional requirements. In Robinson, J.C. and De Villiers, E.A. (compilers) *The Cultivation of Banana.* Agricultural Research Council (ARC) Institute For Subtropical Crops (ARC/Landbou Navorsingsraad) and Du Roi Laboratory, Nelspruit, Mpumalanga, South Africa, pp. 94–111.

Robinson, J.C. and Alberts, A.J. (1986) Growth and yield responses of banana (cultivar 'Williams') to drip irrigation under drought and normal rainfall conditions in the subtropics. *Scientia Horticulturae* 30, 187–202.

Robinson, J.C. and Alberts, A.J. (1987) The influence of undercanopy sprinkler and drip irrigation systems on growth and yield of bananas (cultivar 'Williams') in the subtropics. *Scientia Horticulturae* 32, 49–66.

Robinson, J.C. and Alberts, A.J. (1989) Seasonal variations in the crop water use coefficient of banana (cultivar 'Williams') in the subtropics. *Scientia Horticulturae* 40, 215–225.

Robinson, J.C. and Anderson, T. (1991) The influence of temperature on dry matter assimilation and distribution in young banana plants. *Newsletter of the International Group on Horticultural Physiology of Banana* 14, 37.

Robinson, J.C. and Bower, J.P. (1987) Transpiration characteristics of banana leaves (cv. 'Williams') in response to progressive depletion of available soil moisture. *Scientia Horticulturae* 30, 289–300.

Robinson, J.C. and Bower, J.P. (1988) Transpiration from banana leaves in the subtropics in response to diurnal and seasonal factors and high evaporative demand. *Scientia Horticulturae* 37, 129–143.

Robinson, J.C. and Galán Saúco, V. (2009a) Weaning (acclimatization) of *in vitro*-produced banana plants. *Fruits* 64, 325–332.

Robinson, J.C. and Galán Saúco, V. (2009b) Nursery hardening of *in vitro*-produced banana plants. *Fruits* 64, 383–392.

Robinson, J.C. and Human, N.B. (1988) Forecasting of banana harvest ('Williams') in the subtropics using seasonal variations in bunch development rate and bunch mass. *Scientia Horticulturae* 34, 249–263.

Robinson, J.C. and Nel, D.J. (1984) Influence of polyethylene bunch covers on yield and fruit quality of winter-developing banana bunches. *Horticultural Science* (South Africa) 1, 26–28.

Robinson, J.C. and Nel, D.J. (1985) Comparative morphology, phenology and production potential of banana cultivars 'Dwarf Cavendish' and 'Williams' in the Eastern Transvaal Lowveld. *Scientia Horticulturae* 25, 149–161.

Robinson, J.C. and Nel, D.J. (1988) Plant density studies with banana (cv 'Williams') in a subtropical climate. I. Vegetative morphology, phenology and plantation microclimate. *Journal of Horticultural Science* 63, 303–313.

Robinson, J.C. and Nel, D.J. (1989a) Plant density studies with banana (cv. 'Williams') in a subtropical climate. II. Components of yield and seasonal distribution of yield. *Journal of Horticultural Science* 64, 211–222.

Robinson, J.C. and Nel, D.J. (1989b) Banana density comparison between high and medium vigour plantations. *1TSC Information Bulletin* no. 207, 3–4.

Robinson, J.C. and Nel, D.J. (1990) Competitive inhibition of yield potential in a 'Williams' banana plantation due to excessive sucker growth. *Scientia Horticulturae* 43, 225–236.

Robinson, J.C., Nel, D.J. and Alberts, A.J. (1985) Parent to sucker competition within a banana mat. *ITSC Information Bulletin* no. 157, 11–13.

Robinson, J.C., Nel, D.J. and Bower, J.P. (1989) Plant density studies with banana (cv. 'Williams') in a subtropical climate. III. The influence of spatial arrangement. *Journal of Horticultural Science* 64, 513–519.

Robinson, J.C., Anderson, T. and Eckstein, K. (1992) The influence of functional leaf removal at flower emergence on components of yield and photosynthetic compensation in banana. *Journal of Horticultural Science* 67, 403–410.

Robinson, J.C., Fraser, C. and Eckstein, K. (1993a) A field comparison of conventional suckers with tissue culture banana planting material over three crop cycles. *Journal of Horticultural Science* 68, 831–836.

Robinson, J.C., Nel, D.J. and Eckstein, K. (1993b) A field comparison of ten Cavendish subgroup cultivars and selections (*Musa* AAA) over four crop cycles in the subtropics. *Journal of Horticultural Science* 68, 511–521.

Robinson, J.C., Fraser, C. and Van Eeden, V.J. (1994) Determining the optimum density of Chinese Cavendish bananas at Burgershall after two crop cycles. *ITSC Information Bulletin* no. 267, 4–5.

Rodrigo López, J. (1973) Defensa de la platanera contra el viento en las Islas Canarias. *Mag* VII, 3–9.

Rodrigues, M.G. and Leite, M.A.V. (2008) Aspectos socioeconómicos da bananicultura. *Informe Agropecuário* 29(245), 7–12.

Rodrigues, M.G.V., Souto, R.F. and Menegucci, J.L.P. (2002) Efeito da poda da ùltima penca do cacho da bananeira Prata Aná (AAB) irrigada na produçao de frutos no norte de Minas Gerais. *Revista Brasileira de Fruticultura* 24(1), 108–110.

Rodrigues, M.G.V., Dias, M.S.C., Ruggiero, X.C. and Lichtemberg, L.A. (2008) Planejamento, implantaçao e manejo do bananal. *Informe Agropecuario* 29(245), 14–24.

Rodríguez, G., Muñoz, N. and Márquez, J. (2006) Poda de manos en el clon FHIA-21 (*Musa* AAB) y su efecto sobre las dimensiones del fruto y aspectos de calidad. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 536–544.

Rodríguez, V.J., Malavolta, E., Sánchez, A., Rodríguez, O., Lavoranti, O. and Guerra, E. (2007) Soil and plant reference norms for evaluating Horn plantain nutritional status. *Communications in Soil Science and Plant Analysis* 38, 1371–1383.

Rodríguez, Y.G. and Lobo, L.D. (2008) Limitantes en el desarrollo y distribución de raíces en diez clones de *Musa* en un suelo del Estado Carabobo. In: *Abstracts Workbook. XVIII ACORBAT International Meeting. Guayaquil, Ecuador. 10–14/XI/2008*. (unpublished CD).

Roque Vaquero, M. (2005) Soil physical properties and banana root growth. In: Turner, D.W. and Rosales, F.E. (eds) *Banana Root System*: *Towards a Better Understanding for its Productive Management.* Proceedings of an International Network for the Improvement of Banana and Plantain (INIBAP) symposium in Costa Rica, 3–5 November 2003. INIBAP, Montpellier, France, pp. 125–131.

Rose, R. (2008) Las Islas de Barlovento: productores de comercio justo subiendo en la cadena bananera. *Boletín Bananero* 40, 12–13.

Rossetto, M.R.M., Lajolo, F.M. and Cordenunci, B.R. (2004) Influència do ácido giberélico na degradação do amido durante o amadurecimento da banana. *Ciencia Tecnologia de Alimentos Campinas* 24(1), 76–84.

Roux, N.S. (2004) Mutation induction in *Musa*, a review. In: Jain, S.M. and Swennen, R. (eds) *Banana Improvement Cellular, Molecular Biology, and Induced Mutations*. Science Publishers Inc., Enfield, New Hampshire, USA, pp. 23–32.

Roux, N.S., Toloza, A., Dolezel, J. and Panis, B. (2004) Usefulness of embryogenesis cultures for the induction and selection of mutants in *Musa* spp. In: Jain, S.M. and Swennen, R. (eds) *Banana Improvement Cellular, Molecular Biology, and Induced Mutations*. Science Publishers Inc., Enfield, New Hampshire, USA, pp. 33–44.

Rowe, P.R. (1999) *Breeding Disease-resistant Bananas and Plantains – Crucial Developments and their Implications*. Third Australian Banana Industry Congress, Queensland, Australia, May, 1999. Australian Banana Growers Council (ABGC), Brisbane, Queensland, Australia.

Rowe, P. and Rosales, F. (1993) Diploid breeding at FHIA and the development of 'Goldfinger' (FHIA-01). *Infomusa* 2(2), 9–11.

Rowe, P.R. and Rosales, F.E. (1996) Bananas and plantains. In: Janick, J. and Moore, J.N. (eds) *Fruit Breeding*, Volume 1. *Tree and Tropical Fruits*. John Wiley and Sons, New York, pp. 167–211.

Salau, O.A., Oparanadi, O.A. and Swennen, R. (1992) Effects of mulching on soil properties, growth and yield of plantain on a tropical ultisol in southeastern Nigeria. *Soil and Tillage Research* (Netherlands) 23, 73–93.

Samson, J.A. (1980) *Tropical Fruits.* Longman, London, pp. 119–161.

Sarah, J.L. (1993) Early varietal screening of banana for resistance to nematodes. *Infomusa* 2(2), 7.

Sarah, J.L. (2000) Burrowing nematode. In: Jones, D.R. (ed.) *Diseases of Banana, Abacá and Ensete*. CABI Publishing, Wallingford, Oxon, UK, pp. 295–303.

Sarah, J.L., Sabatini, C. and Boisseau, M. (1993) Differences in pathogenicity to banana (*Musa* sp. cv. Poyo) among isolates of *Radopholus similis* from different production areas of the world. *Nematropica* 23, 75–79.

Serrano, E., Sandoval, J., Pocasangre, L., Rosales, F.E. and Delgado, E. (2006) Importancia de los indicadores físico-químicos en la calidad del suelo para la producción sustentable del banano en Costa Rica. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business*. *Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006*. ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 207–215.

Sikora, R.A. and Reiman, S. (2004) Suppressive soils, the edge of chaos and multitrophic strategies for biocontrol of pests and diseases in soil ecosystems. *IOBC WPRS Bulletin* 27, 251–258.

Sikora, R.A., Niere, B. and Kimenju, J. (2003) Endophytic microbial biodiversity and plant nematode management in African agriculture. In: Neuenschwand, P., Bergameister, C. and Langewald, J. (eds) *Biological Control in IPM Systems in Africa*, 2nd edn. CABI Publishing, Wallingford, Oxon, UK, pp.179–192.

Silayoi, B. and Chomchalow, N. (1987) Cytotaxonomic and morphological studies of Thai banana cultivars. In: Persley, G.J. and De Langhe, E.A. (eds) *Banana and Plantain Breeding Strategies*. Proceedings of an international workshop, Cairns, Australia, October 1986. ACIAR Proceedings no. 21. Australian Centre for International Agriculture Research (ACIAR), Canberra, pp. 157–160.

Silva, S. de O., Pereira, L.V. and Rodrigues, M.G.V. (2008) Variedades. *Informe Agropecuario* 29(245), 78–83.

Simmonds, N.W. (1962) *The Evolution of the Bananas*. Longman, London.

Simmonds, N.W. and Shepherd, K. (1955) The taxonomy and origins of the cultivated bananas. *Journal of the Linnaean Society London, Botany* 55, 302–312.

Singh, H.P. (1996) Growing banana for leaf. *Infomusa* 5(1), 27–28.

Smith, M.K., Hamill, S.D., Langdon, P.W. and Pegg, K.G. (1990) *In vitro* mutation breeding for the development of bananas with resistance to race 4, Fusarium wilt (*Fusarium oxysporum* f. sp. *cubense*). In: *In Vitro Mutation Breeding of Bananas and Plantains I.* Food and Agriculture Organization (FAO)/International Atomic Energy Agency (IAEA) coordination meeting held in Vienna, Austria, 1989. FAO/IAEA, Vienna, Austria, pp. 66–78.

Smith, M.K., Hamill, S.D., Becker, D.K. and Dale, J.L. (2005) *Musa* spp. – banana and plantain. In: Litz, R.E. (ed.) *Biotechnology of Fruit and Nut Crops*. CAB International, Wallingford, Oxon, UK, pp. 366–391.

Smith, M.K., Hamill, S.D., Langdon, P.W., Giles, J.E., Doogan, V.J. and Pegg, K.G. (2006) Towards the development of a Cavendish banana resistant to race 4 of Fusarium wilt: gamma irradiation of micropropagated Dwarf Parfitt (*Musa* spp., AAA group, Cavendish subgroup). *Australian Journal of Experimental Agriculture* 46(1), 197–113.

Soto, B.M. (1995) *Bananos. Cultivo y Comercialización.* Litografía e Imprenta LIL, San José, Costa Rica, 674 pp.

Speijer, P.R., Budenberg, W.J. and Sikora, R.A. (1993) Relationships between nematodes, weevils, banana and plantain cultivars and damage. *Annals of Applied Biology* 123, 517–525.

Stella Riveros, A., Rosales, F.E., Romero, J., Jiménez, M.I., Jiménez, R., Acuña, O., Tabora, P., Segura, R., Pocasangre, L.E. and Villalobos, M. (2006) Estandarización de enmiendas orgánicas para banano en América latina y El Caribe In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 234–240.

Stover, R.H. (1962) *Fusarial Wilt (Panama Disease) of Bananas and Other* Musa *Species.* Commonwealth Mycological Institute Phytoph. Papers 4. Commonwealth Mycological Institute, Kew, London, UK.

Stover, R.H. (1979) Pseudostem growth, leaf production and flower initiation in the Grand Nain banana. *SIATSA Bulletin* no. 8, La Lima, Honduras, pp. 3–37.

Stover, R.H. (1984) Canopy management in Valery and Grand Nain using leaf area index and photosynthetically active radiation. *Fruits* 39, 89–93.

Stover, R.H. (1987) Somaclonal variation in Grand Nain and Saba bananas in the nursery and field. In: Persley, G.J. and De Lange, E.A. (eds) *Banana and Plantain Breeding Strategies*. Proceedings of an international workshop, Cairns, Australia, October 1986. ACIAR Proceedings no. 21. Australian Centre for International Agriculture Research (ACIAR), Canberra, pp. 136–139.

Stover, R.H. (1988) Variation and cultivar nomenclature in *Musa*, AAA group, Cavendish subgroup. *Fruits* 43, 353–356.

Stover, R.H. and Simmonds, N.W. (1987) *Bananas*, 3rd edn. Longman, London. 468 pp.

Strosse, H., Van den Houwe, I. and Panis, B. (2004) Banana cell and tissue culture – review. In: Jain, S.M. and Swennen, R. (eds) *Banana Improvement Cellular, Molecular Biology, and Induced Mutations*. Science Publishers Inc., Enfield, New Hampshire, USA, pp. 1–12.

Subra, P. and Guillemot, J. (1961) Contribution a l'étude du rhizome et des rejets du bananier. *Fruits* 16, 19–23.

Swennen, R. and De Langhe, E. (1985) Growth parameters of yield of plantain (*Musa* cv. AAB). *Annals of Botany* 56, 197–204.

Swennen, R., De Langhe, E., Janssen, J. and Decoene, D. (1986) Study of the root development of some *Musa* cultivars in hydroponics. *Fruits* 41, 515–524.

Swennen, R., Wilson, G.F. and Decoene, D. (1988) Priorities for future research on the root system and corm in plantains and bananas in relation with nematodes and the banana weevil. In: *Proceedings of Workshop on Nematodes and the Borer Weevil in Bananas*, Bujumbura, Burundi, December 1987. International Network for the Improvement of Banana and Plantain (INIBAP), Montpellier, France, pp. 91–96.

Taylor, S.E. and Sexton, O.J. (1972) Some implications of leaf tearing in Musaceae. *Ecology* 53, 143–149.

Tazán, C.L. (2006) El cultivo de plátanos en Ecuador. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006*. ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 155–163.

Tchango Tchango, J., Bikoï, A., Achard, R., Escalant, J.V. and Ngalani, J.A. (2003) Banana plantain: post harvest operation. In: Mejia, D., Lewis, B. and Bothe, C. (eds) *Postharvest Compendium*. Postharvest Management Group of Agro-Industries and Post-Harvest Management Service (AGSI)/Food and Agriculture Organization (FAO), Rome. Available at: http://www.fao.org/info/content/compend/text/ch14-01.htm (accessed 1 November 2009).

Ternisien, E. (1989) Study of crop rotations in banana plantations. II. Impact of rotated crops on banana production and the health of the soil. *Fruits* 44, 445–454.

Thomas, D.S. and Turner, D.W. (2001) Banana (*Musa* spp.) leaf gas exchange and chlorophyll flourescence in response to soil drought, shading and lamina folding. *Scientia Horticulturae* 90, 93–108.

Ting, A.S.Y., Sariah, M., Jugah, K. and Amar, A.R. (2003) Potential use of suppressive soil in managing Fusarium wilt of banana seedlings. *InfoMusa* 12, 33–34.

Ting, A.S.Y., Sariah, M., Kadir, J. and Gurmit, S. (2009) Field evaluation of non-pathogenic *Fusarium oxysporum* isolates UPM31P1 and UPM39B3 for the control of Fusarium wilt in 'Pisang Berengan' (*Musa*, AAA). *Acta Horticulturae* 828, 139–143.

Tinzaara, W., Gold, C.S., Ssekiwoko, F., Tushemereirwe, W., Bandyopadhyay, R., Abera, A. and Eden-Green, S.J. (2006) Role of insects in the transmission of banana bacterial wilt. *African Crop Science Journal* 14(2), 105–110.

Treverrow, R., Bedding, R.A., Dettman, E.B. and Maddox, C. (1991) Evaluation of entomopathogenic nematodes for control of *Cosmopolites sordidus* Germar (Coleoptera, Curculionidae), a pest of bananas in Australia. *Annals of Applied Biology* 119, 139–145.

Tripathi, L., Mwangi, M., Abele, S., Airtua, V., Tushemereirwe, W.K. and Bandyopadhyay, R. (2009) Xanthomonas wilt. A threat to banana production in East and Central Africa. *Plant Disease* 93(59), 440–451.

Turner, D.W. (1970) Bunch covers, leaf number and yield of bananas. *Australian Journal of Experimental Agriculture and Animal Husbandry* 10, 802–805.

Turner, D.W. (1987) Nutrient supply and water use of bananas in a subtropical environment. *Fruits* 42, 89–93.

Turner, D.W. (1995) The response of the plant to the environment. In: Gowen, S.R. (ed.) *Bananas and Plantains.* Chapman & Hall, London, pp. 206–229.

Turner, D.W. and Barkus, B. (1980) Plant growth and dry matter production of the 'Williams' banana in relation to supply of potassium, magnesium and manganese in sand culture. *Scientia Horticulturae* 12, 27–45.

Turner, D.W. and Barkus, B. (1983) Long-term nutrient absorption rates and competition between ions in banana in relation to supply of K, Mg and Mn. *Fertilizer Research* 4, 127–134.

Turner, D.W. and Hunt, N. (1983) The relationship between temperature and the rate of appearance of new leaves on thirty banana varieties grown in the subtropics. *Garcia de Orto, Estudos Agronomicos* (Lisboa), 10, 91–94.

Turner, D.W. and Hunt, N. (1984) Growth, yield and leaf nutrient composition of 30 banana varieties in subtropical New South Wales. *Technical Bulletin* no. 31. Department of Agriculture, Sydney, New South Wales, 36 pp.

Turner, D.W. and Lahav, E. (1983) The growth of banana plants in relation to temperature. *Australian Journal of Plant Physiology* 10, 43–53.

Turner, D.W., Korawis, C. and Robson, A.D. (1989) Soil analysis and its relationship with leaf analysis and banana yield with special reference to a study at Carnarvon, Western Australia. *Fruits* 44, 193–203.

Turner, D.W., Fortescue, J.A. and Thomas, D.S. (2007) Environmental physiology of the banana (*Musa* spp.). *Brazilian Journal of Plant Physiology* 19(4), 463–484.

Tushemereirwe, W.K., Okaasai, O., Kubiriba, J., Nankinga, C., Muhangi, J., Odoi, N. and Opio, F. (2006a) Status of banana bacterial wilt in Uganda. *African Crop Science Journal* 14(2), 73–82.

Tushemereirwe, W.K., Kangire, A. and Tinzaara, W. (eds) (2006b) Banana bacterial wilt in Uganda: a disease that threatens livelihoods. *African Crop Science Journal* 14(2), 73–183.

Umesh, K.C., Krishnappa, K. and Bagyaraj, D.J. (1989) Interaction of burrowing nematode, *Radopholus similis*, and vesicular arbuscular mycorrhiza, *Glomus fasciculatum*, in banana (*Musa acuminata* Colla). *Indian Journal of Hematology* 18, 6–11.

Valmayor, R.V., Silayoi, B., Jamaluddin, S.H., Kusumo, S., Espino, R.R.C. and Pascua, O.C. (1991) Banana classification and commercial cultivars in Southeast Asia. *PCARRD Information Bulletin* no. 24. Philippine Council for Agriculture, Forestry

and Natural Resources Research and Development (PCARRD), Los Baños, The Philippines, 20 pp.

Valmayor, R.V., Espino, R.R.C. and Pascua, O.C. (2002) *The Wild and Cultivated Bananas of the Philippines*. Philippine Agriculture and Resources Research Foundation (PARFI) and BAR, Los Baños, Laguna, The Philippines, 242 pp.

Van Vosselen, A., Verplancke, H. and Van Ranst, E. (2005) Assessing water consumption of banana: traditional versus modelling approach. *Agricultural Water Management* 74, 201–208.

Veerannah, L. (1988) Studies on the source: sink relationship in certain banana cultivars. In: Guzman, J.A. (ed.) *Proceedings of the 4th Meeting of the International Group on Horticultural Physiology of Banana*, Asociación Bananera Nacional de Costa Rica (ASBANA), Costa Rica, August 1986. ASBANA, San José, Costa Rica, pp. 85–90.

Veldkamp, E., Huising, E.J., Stein, A. and Bouma, J. (1990) Variation of measured banana yields in a Costa Rican plantation as explained by soil survey and thematic mapper data. *Geoderma* 47, 337–348.

Vimpani, I., Johns, G. and Atkinson, I. (1991) *Fertilising Bananas in New South Wales*. Wollongbar Agricultural Institute, Wollongbar, Australia.

Vuylsteke, D., Swennen, R. and De Langhe, E. (1991) Somaclonal variation in plantains (*Musa* spp., AAB group) derived from shoot tip culture. *Fruits* 46, 429–439.

Vuylsteke, D., Swennen, R. and Ortiz, R. (1993) Registration of 14 improved tropical *Musa* plantain hybrids with black Sigatoka resistance. *HortScience* 28, 957–959.

Whiley, A.W., Pegg, K.G., Searle, C., Smith, M.K., Langdon, P.W. and Saranah, J.B. (1993) Living with Fusarium wilt in bananas – seeking a viable option. In: *Profit through Knowledge – Bananas.* Proceedings of seminar held at Maroochy Horticultural Research Station, Queensland, Australia. Queensland Department of Primary Industries, Brisbane, Queensland, Australia, pp. 25–27.

Wilson, G.F. (1987) Status of bananas and plantains in West Africa. In: Persley, G.J. and De Langhe, E.A. (eds) *Banana and Plantain Breeding Strategies*. Proceedings of an international workshop, Cairns, Australia, October 1986. ACIAR Proceedings no. 21. Australian Centre for International Agriculture Research (ACIAR), Canberra, pp. 29–35.

Wilson, G.F., Vuylsteke, D. and Swennen, R. (1985) Rapid multiplication of plantain: an improved field technique. In: *Proceedings of the 3rd Meeting of the International Association for Research on Plantain and Banana* (IARPB), Abidjan, Ivory Coast, May 1985. IARPB, Abidjan, Côte d'Ivoire, pp. 24–26.

Wortman, C.S., Karamura, E.B. and Gold, C.S. (1994) Nutrient flows from harvested banana pseudostems. *African Crop Science Journal* (Uganda) 2, 179–182.

Young, J.M., Dye, D.W., Bragbury, J.F., Panagopoulos, C.G. and Robbs, C.F. (1978) A proposed nomenclature and classification for plant pathogenic bacteria. *New Zealand Journal of Agricultural Research* 21, 153–177.

Young, S.C.H., Sammis, T.W. and Wu, I.-P. (1985) Banana yield as affected by deficit irrigation and patterns of lateral layouts. *Transactions of ASAE* 28, 507–510.

Zaffary, G.R. and Kerbauy, G.B. (2006) Detecçao de variaçao somaclonal em microplants de *Musa acuminata* cv. Grande Naine. In: Soprano, E., Tcacenco, F.A., Lichtemberg, L.A. and Silva, M.C. (eds) *Banana: a Sustainable Business. Proceedings XVII ACORBAT International Meeting. Joinville, Brasil, 15–20 October 2006.* ACORBAT/ACAFRUTA, Joinville, Brazil, pp. 335.

zum Felde, A., Pocasangre, I.F., Cañizares Monteros, C.A., Sikora, R.A., Rosales, F.E. and Riveros, A.S. (2006) Effects of combined inoculations of endophytic fungus on biocontrol of the burrowing nematode (*Radopholus similis*) in banana. *InfoMusa* 15(1–2), 12–18.

zum Felde, A., Mendoza, A., Cabrera, J.A., Kurtz, A., Schouten, A., Pocasangre, L. and Sikora, R.A. (2009) The burrowing nematode of banana: strategies for controlling the uncontrollable. *Acta Horticulturae* 828, 101–107.

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