7 Tropical environments

7.1 Tropical climates

The tropical environment is the area between 23.5 °N and 23.5 °S (Figure 7.1). This area covers about 50 million km^2 of land, almost half of it in Africa. According to the climatologist Köppen, there are three types of tropical climate (A). These include rainforest climates (Af), monsoon climates (Am) and savanna climates (Aw). These are shown on Figure 7.1.

Section 7.1 Activities

1. Describe the distribution of areas with a rainforest climate (Af), as shown on Figure 7.1.
2. Comment on the distribution of areas with a monsoon climate, as shown on Figure 7.1.
3. Describe the main features of a savanna climate, as shown by the climate graph for Banjul in Figure 7.1.
   You should refer to maximum and minimum temperatures, seasonal variations in temperatures, total rainfall, seasonal variations in rainfall and any links between temperatures and rainfall.

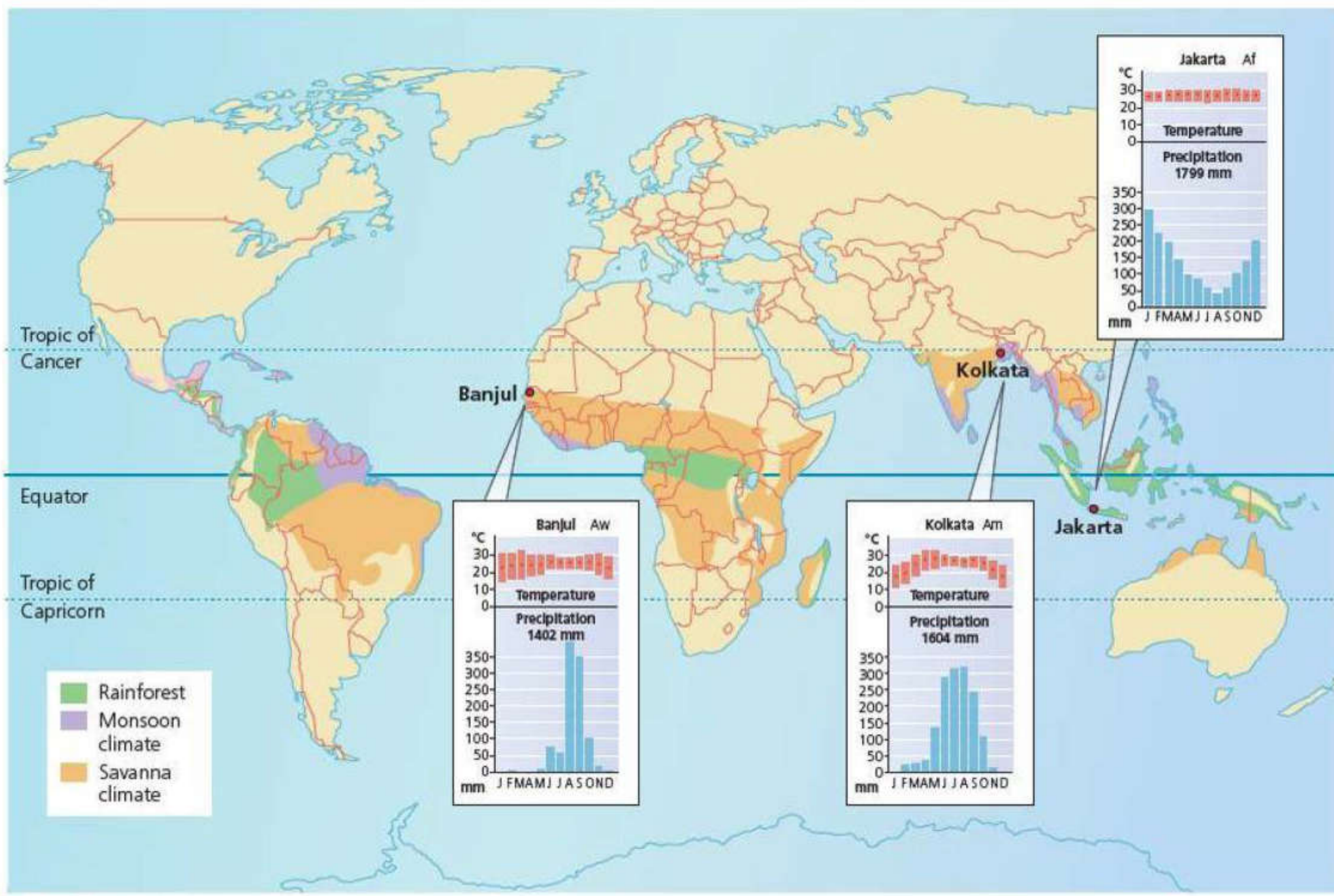


Figure 7.1 Tropical climates

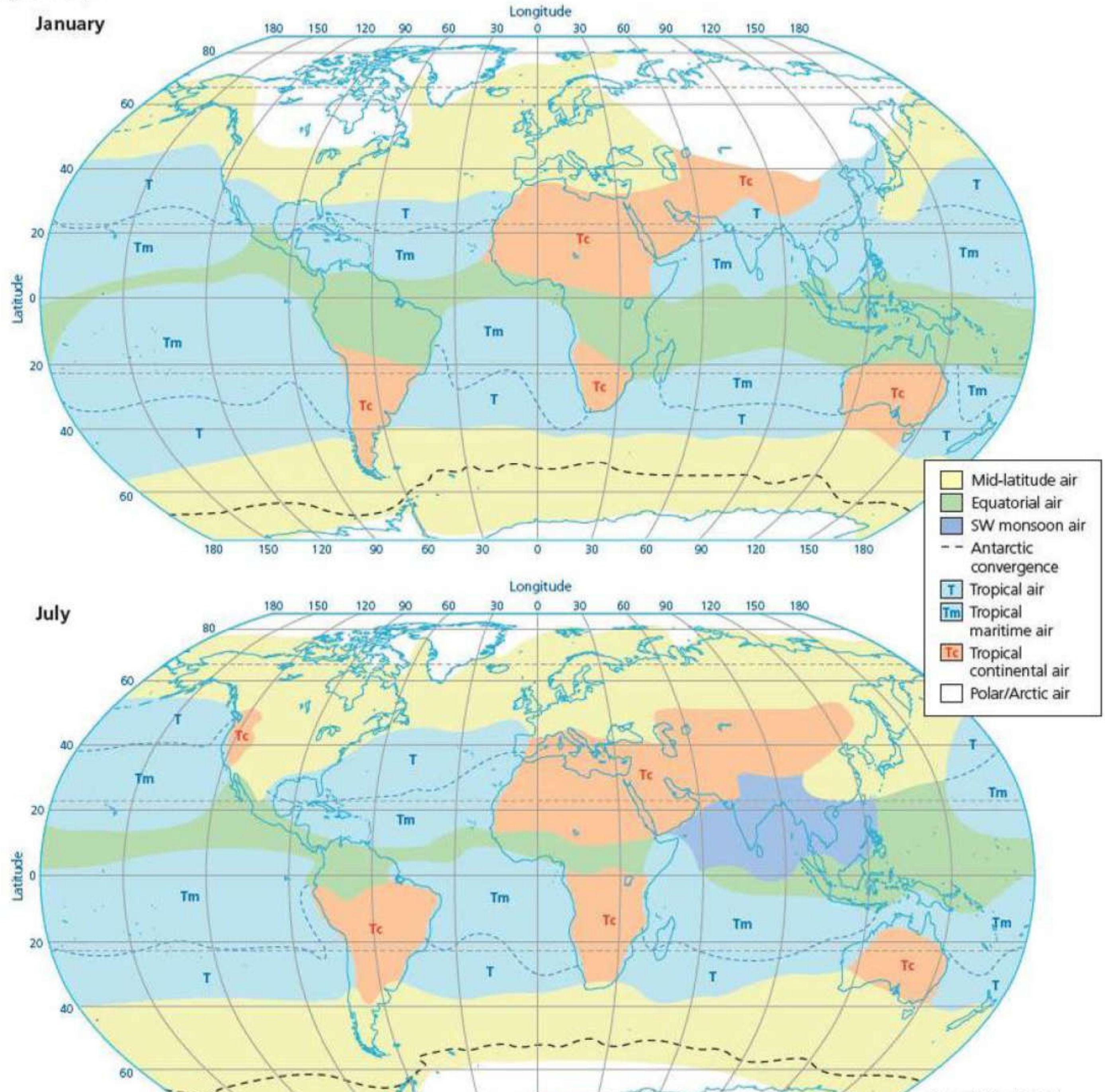
Air masses

The original concept of an air mass was that it was a body of air whose physical properties, especially temperature and humidity, were uniform over a large area. By contrast, it is now redefined as a large body of air in which the horizontal gradients (variation) of the main physical properties are fairly slack. It is generally applied only to the lower layers of the atmosphere, although air masses can cover areas of tens of thousands of km^2 (Figure 7.2).

Air masses derive their temperature and humidity from the regions over which they lie. These regions are known as source regions. The principal ones are:

- areas of relative calm, such as semi-permanent high-pressure areas
- where the surface is relatively uniform, including deserts, oceans and ice-fields.

Air masses can be modified when they leave their sources, as Figure 7.3 illustrates.



Source: Briggs, D. et al., *Fundamentals of the physical environment*, Routledge, 1997

Figure 7.2 Air masses

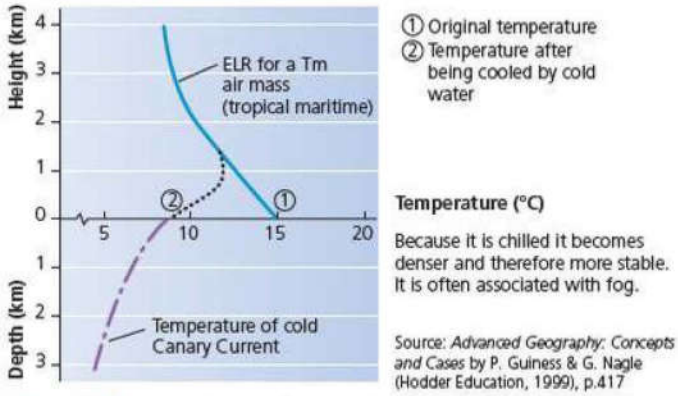


Figure 7.3 Temperature profiles showing the modification of air masses

The initial classification of air masses was made by Tor Bergeron in 1928. Primarily, they are classified first by the latitude of the source area (which largely controls its temperature) and secondly by whether the source area is continental (dry) or maritime (moist) (Table 7.1). A maritime tropical (mT) air mass is one that is warm and moist. A third subdivision refers to the stability of the air mass – that is, whether it has cooled and become more stable, or whether it has become warmer and less stable (Figure 7.3).

Table 7.1 Dominant air masses in tropical environments

Approx. latitude of source	Label	Temp. (°C) winter/summer	Stability winter/summer
Equatorial (0–10°)	cE (continental equatorial) mE (maritime equatorial)	25/25 25/25	Moist/neutral Moist/neutral
Subtropical (30°)	cT (continental tropical) mT (maritime tropical)	15/25 18/22	Stable, dry/neutral Stable/stable

As air masses move from their source regions, they may be changed due to:

- internal changes and
- the effects of the surface over which they move.

These changes create **secondary air masses** (Table 7.1). For example, a warm air mass that travels over a cold surface is cooled and becomes more stable. Hence it may form low cloud or fog but is unlikely to produce much rain. By contrast, a cold air mass that passes over a warm surface is warmed and becomes less stable. The rising air is likely to produce more rain. Air masses that have been warmed are given the suffix 'w' and those that have been cooled are given the suffix 'k' (*kalt*).

Section 7.1 Activities

1 Define the term *air mass*.
2 Outline the main characteristics of mE and cT air masses.
3 Compare the seasonal distribution of tropical air masses as shown in Figure 7.2.

Intertropical convergence zone (ITCZ)

Winds between the tropics converge on a line known as the **ITCZ** or 'equatorial trough'. It is actually a band a few hundred kilometres wide, enclosing places where wind flows are inwards and subsequently rise convectively (Figure 7.4).

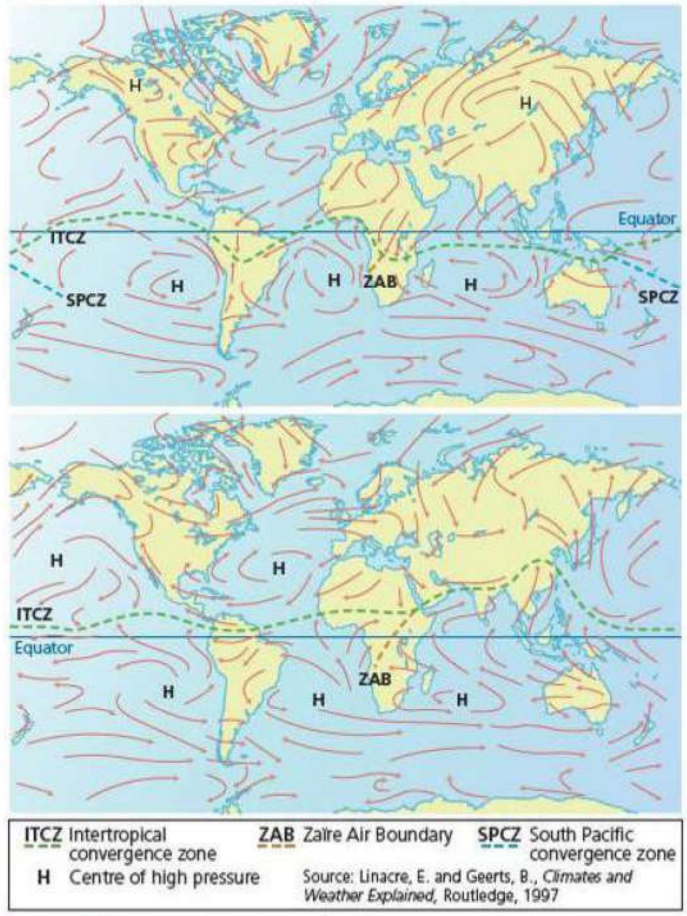


Figure 7.4 ITCZ and surface winds

The ITCZ lies at about 5°N on average. This is known as the 'meteorological equator'. It wanders seasonally, lagging about two months behind the change in the overhead Sun. The latitudinal variation is most pronounced over the Indian Ocean because of the large Asian continental land mass to the north. Over the eastern Atlantic and eastern Pacific Oceans, the ITCZ moves seasonally due to the cold Benguela and Peru **ocean currents**.

The movement of the ITCZ over South Africa, for example, is complicated by the land's shape, elevation and location. There is a southerly spur of the ITCZ known as the 'Zaire Air Boundary' (ZAB) (Figure 7.4). The largest and most prominent spur in the South Pacific is the South Pacific Convergence Zone (SPCZ), which is related to the 'warm pool' near Papua New Guinea, and is most pronounced in summer. It lies mostly over water. There is a convergence of:

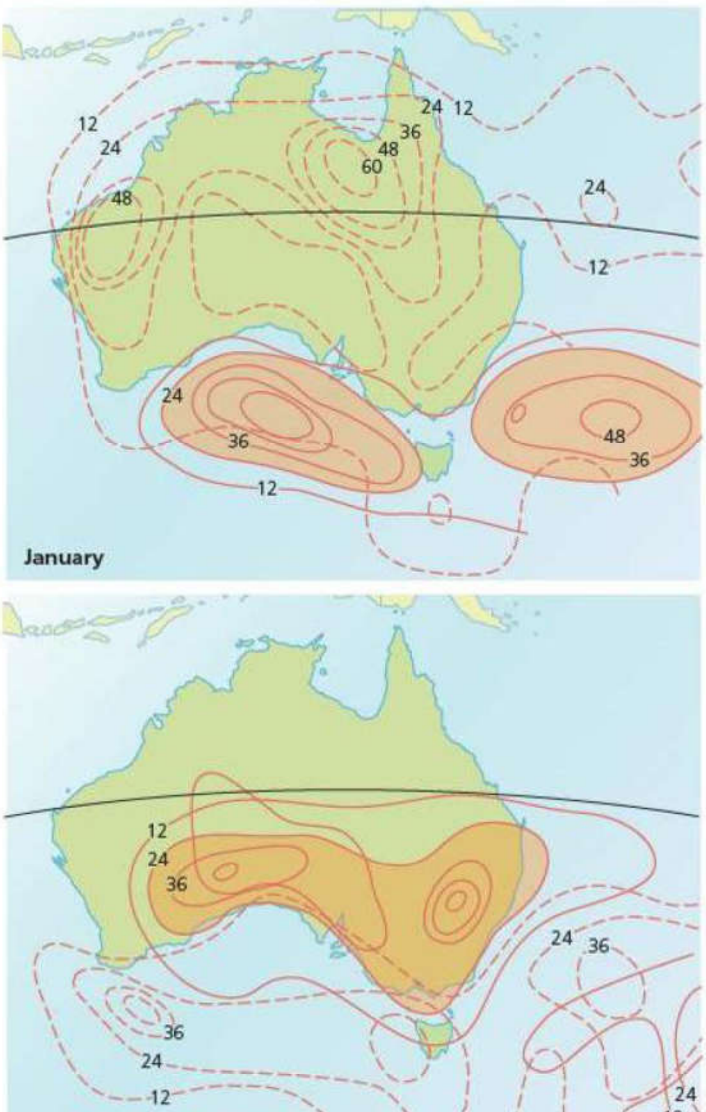
- moist northerlies from the semi-permanent high pressure in the south-east Pacific, and

- south-easterlies from mobile highs moving across the south-west Pacific in summer.

Winds at the ITCZ are commonly light or non-existent, creating calm conditions called the doldrums. There are, though, occasional bursts of strong westerlies, known as a 'westerly wind burst'.

Subtropical anticyclones

Centres or ridges of high pressure imply subsiding air and a relatively cold atmosphere. They tend to be found over continents, especially in winter. There is a high-pressure belt over south-east Australia in winter, whereas high pressure is located south of the continent in summer, when the sea is colder (Figure 7.5).



The continuous lines and shaded areas show the number of hours in a month when high pressure is centred over an area. The dotted lines show the number of hours that a centre of low pressure is positioned over a location. The shaded areas have high pressure centred there for at least 24 hours per month.

Figure 7.5 Seasonal high pressure over Australia

The subtropical high or warm anticyclone is caused by cold air descending at the tropopause. Two rings of high pressure lie around 30–35° north and south. The position of the high pressure coincides with the subsiding part of the Hadley cell, so it alters in response to the seasonal drift of the ITCZ, but only over 5–10°. On average, highs cross the east coast of Australia south of Sydney in summer, whereas in winter they pass further north.

The subtropical high-pressure belt tends to lie over the ocean, especially in summer, when there are low pressures over the continents caused by heating. One subtropical high is anchored over the eastern Pacific by an anticyclonic swirl induced by the Andes. The high there shifts from 32° in January to 23° in July. The high is particularly strong due to the cold ocean surface, except during El Niño events. Another semi-permanent high lies over the Indian Ocean, moving nearer to Australia in summer and Africa in winter.

Highs tend to be larger than low-pressure systems, reaching up to 4000 kilometres in width and 2000 kilometres north–south. Therefore smaller pressure gradients are involved and so winds are lighter.

The subtropical high-pressure belt is intersected by cold fronts. The subtropical high-pressure areas generally move eastwards at speeds of 30–50 kilometres/hour – hence a 4000 kilometre system moving at an average of 40 kilometres/hour would take about four days to pass over – if it keeps moving.

An anticyclone's movement may sometimes stall, and it may travel a distance equivalent to less than 20° latitude in a week. This is known as a 'blocking anticyclone', or 'blocking high'. It is not so common in the southern hemisphere because there are fewer land masses and mountain ranges to disturb the airflow.

Effects

Highs at the surface are associated with subsidence. A temperature inversion may occur, especially where there is a cold high in winter over a continent. Where there is moisture at low level and air pollution, low-level stratus clouds may form, causing an anticyclonic gloom, as found in Santiago and Melbourne in winter, for example.

Arid climates result from a prevalence of high pressure. North-east Brazil is arid, even at a latitude of 8°S, because it protrudes far enough into the South Atlantic to be dominated by high pressure. The same is true for the Galapagos Islands, dominated by the South Pacific High, even though they are located at the equator.

Section 7.1 Activities

1. Outline the main cause of the subtropical high-pressure belt.
2. Explain why it varies seasonally.
3. Describe the seasonal changes that occur to the ITCZ and wind patterns, as shown in Figure 7.4.

Ocean currents

The oceanic gyre (swirl of currents) explains why east coasts in the southern hemisphere and west coasts in the northern hemisphere are usually warm and wet, because warm currents carry water polewards and raise the air temperature of maritime areas. In contrast, cold currents carry water towards the equator and so lower the temperatures of coastal areas. West coasts tend to be cool and dry due to:

- the advection of cold water from the poles and
- cold upwelling currents.

For instance, in South Africa the east coast is 3–8 °C warmer than the west coast. An exception is Australia where the southward Leeuwin Current brings warmth to Perth. Continental east coasts in the subtropics are humid and west coasts arid – this is mainly due to the easterly winds around the tropics.

Table 7.2 shows the mean monthly temperatures and rainfall of some coastal cities on the west and east sides of three continents.

Table 7.2 A comparison of mean monthly temperatures (°C) and rainfall of some coastal cities

Continent	Coast	Place	Temperature (°C) January	Temperature (°C) July	Rainfall (mm) January	Rainfall (mm) July
Around 23 °S						
South America	West	Antofagasta	21	14	0	5
	East	Rio de Janeiro	26	21	125	41
South Africa	West	Walvis Bay	19	15	0	0
	East	Maputo	25	18	130	13
Australia	West	Carnarvon	27	17	20	46
	East	Brisbane	25	15	163	56
Around 34 °S						
South America	West	Santiago	21	9	3	76
	East	Buenos Aires	23	10	79	56
South Africa	West	Cape Town	21	12	79	56
	East	Durban	24	17	127	85
Australia	West	Perth	23	13	8	170
	East	Sydney	22	12	89	117

Section 7.1 Activities

1 Using examples, compare the temperatures of west-coast locations with those of east-coast locations for the same latitude.
2 How do you explain this pattern?

Wind

The temperature of the wind is determined by the area where the wind originates and by the characteristics of the surface over which it subsequently blows. A wind blowing from the sea tends to be warmer in winter but cooler in summer than the corresponding wind blowing from the land.

Monsoon

The word 'monsoon' is used to describe wind patterns that experience a pronounced seasonal reversal. The best-known monsoon is that experienced in India, but there are also monsoons in East Africa, Arabia, Australia and China. The basic cause is the difference in heating of land and sea on a continental scale.

In India, two main seasons can be observed:

- the north-east monsoon (Figure 7.6a), consisting of **a** the winter season (January and February) and **b** a hot, dry season between March and May
- the south-west monsoon (Figure 7.6b), consisting of **a** the rainy season of June–September and **b** the post-monsoon season of October–December; most of India's rain falls during the south-west monsoon.

During the winter season, winds generally blow outwards since high pressure is centred over the land. Nevertheless, parts of southern India and Sri Lanka receive some rain, while parts of north-west India receive rainfall as a result of depressions. These winter rains are important as they allow the growth of cereals during the winter. Mean temperatures in winter range from 26 °C in Sri Lanka to about 10 °C in the Punjab (these differences are largely the result of latitude). Northern regions and interior areas have a much larger temperature range than in coastal areas. In the north, daytime temperatures may reach over 26 °C, while frosts at night are common.

The hot, dry season occurs between March and May. It gradually spreads northwards throughout India. Daytime temperatures in the north may exceed 49 °C, while coastal areas remain hot and humid. Vegetation growth is prevented by these conditions and many rivers dry up.

In spring, the high-pressure system over India is gradually replaced by a low-pressure system. As there is low pressure over the equator, there is little regional air circulation. However, there are many storms and dust storms. Increased humidity near the coast leads to rain. Parts of Sri Lanka, the southern part of India and the Bay of Bengal receive rain and this allows the growth of rice and tea. For most of India, however, there is continued drought.

The rainy season occurs as the low-pressure system intensifies. Once pressure is low enough, it allows for air from the equatorial low and the southern hemisphere to be sucked in, bringing moist air. As it passes over the ocean, it picks up more moisture and causes heavy rain when it passes over India.

The south-west monsoon in southern India generally occurs in early June, and by the end of the month it affects most of the country, reaching its peak in July or early August (Figure 7.7). Rainfall is varied, especially between windward and leeward sites. Ironically, the low-pressure system over north-west India is one of the driest parts of India, as the monsoon has shed its moisture en route. The monsoon weakens after mid-September but its retreat is slow and may take up to three months. Temperature and rainfall fall gradually, although the Bay of Bengal and Sri Lanka still receive some rainfall.

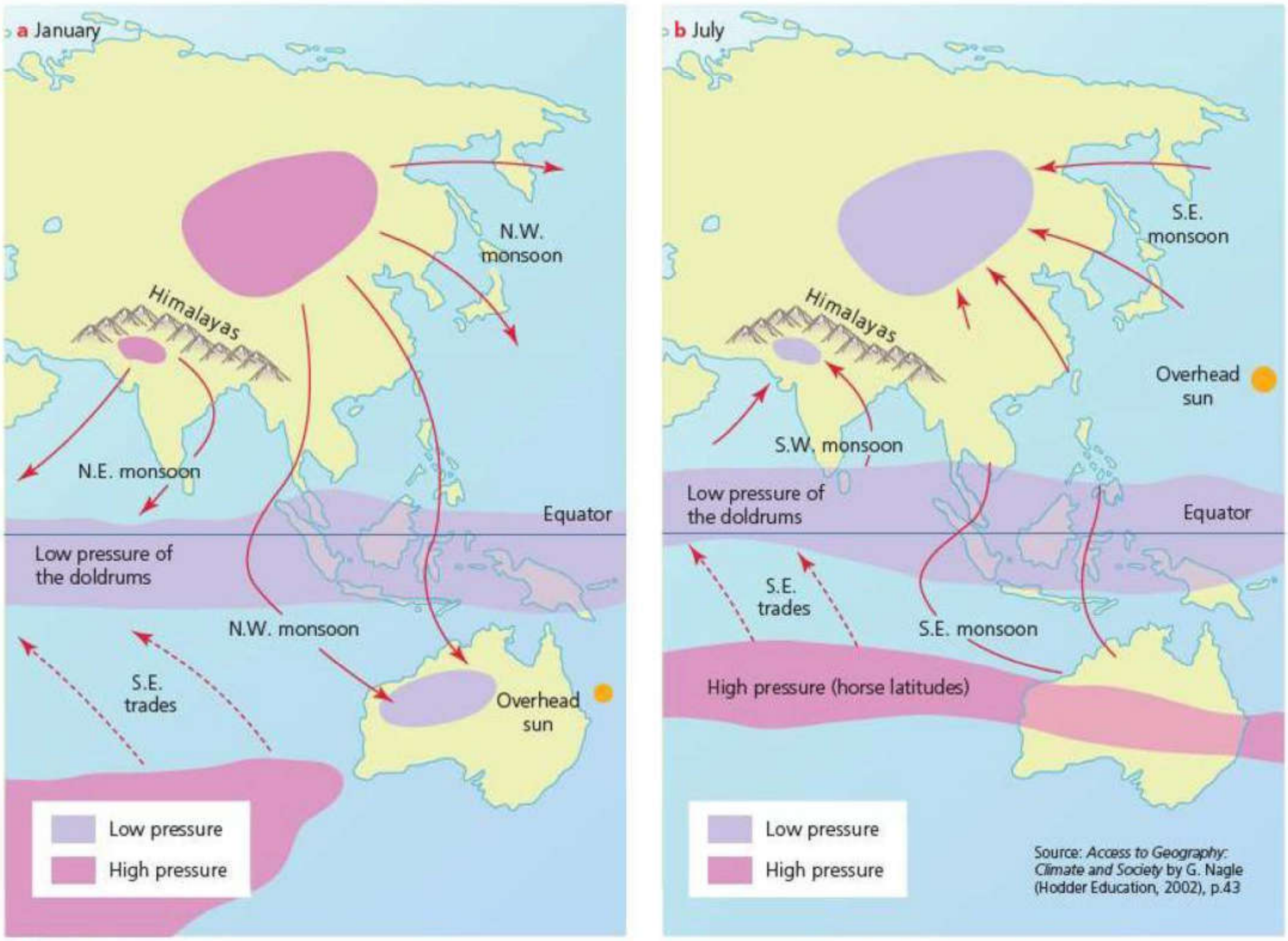


Figure 7.6 The Asian monsoon

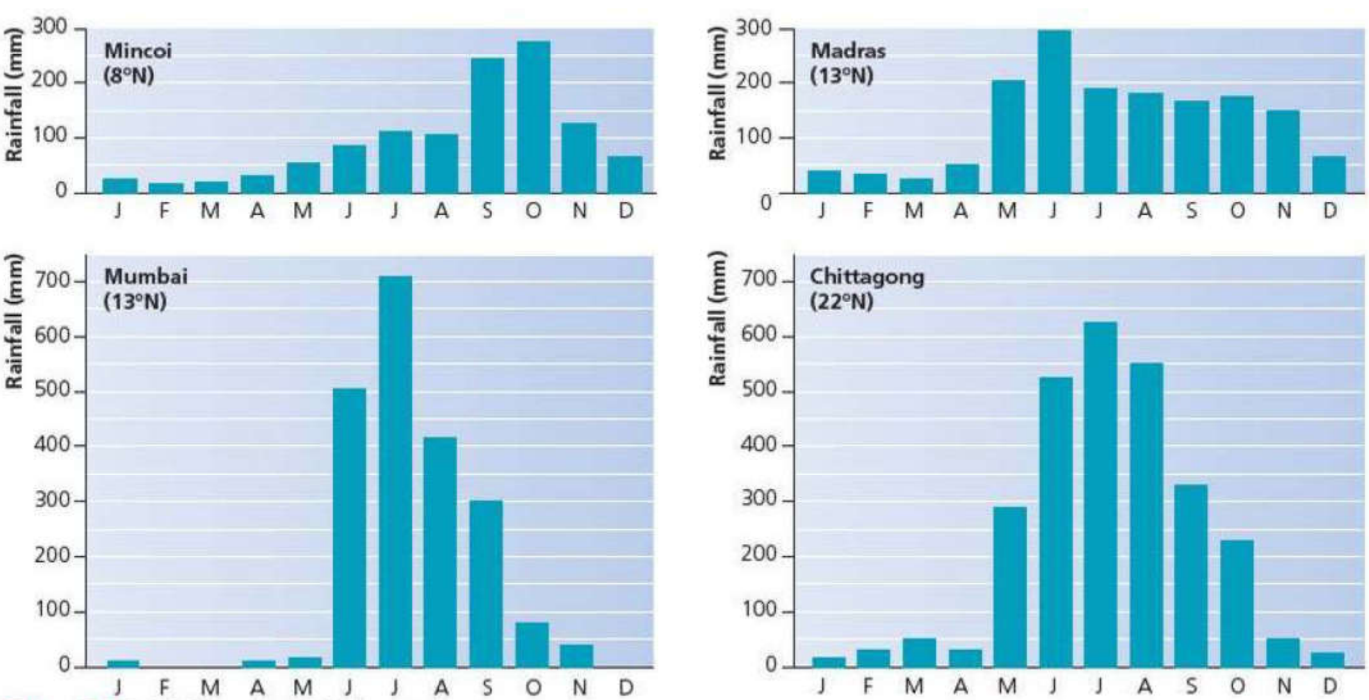


Figure 7.7 Rainfall in selected Indian stations

The simplest explanation for the monsoon is that it is a giant land–sea breeze. The great heating of the Asian continent and the high mountain barrier of the Himalayas, barring winds from the north, allow the equatorial rain systems to move as far north as 30°N in summer. At this time, central Asia becomes very hot, warm air rises and a centre of low pressure develops. The air over the Indian Ocean and Australia is colder, and therefore denser, and sets up an area of high pressure. As air moves from high pressure to low pressure, air is drawn into Asia from over the oceans. This moist air is responsible for the large amount of rainfall that occurs in the summer months. In the winter months, the Sun is overhead in the southern hemisphere. Australia is heated (forming an area of low pressure), whereas the intense cold over central Asia and Tibet causes high pressure. Thus in winter, air flows outwards from Asia, bringing moist conditions to Australia. The mechanism described here, a giant land–sea breeze, is, however, only part of the explanation.

Between December and February, the north-east monsoon blows air outwards from Asia. The upper airflow is westerly, and this flow splits into two branches north and south of the Tibetan plateau. The Tibetan plateau – over 4000 metres in height – is a major source of cold air in winter, especially when it is covered in snow. Air sinking down from the plateau, or sinking beneath the upper westerly winds, generally produces cold, dry winds. During March and April, the upper airflows change and begin to push further north (in association with changes in the position of the overhead Sun). The more northerly jet stream (upper wind) intensifies and extends across India and China to Japan, while the southern branch of the jet stream remains south of Tibet and loses strength.

There are corresponding changes in the weather. Northern India is hot and dry with squally winds, while southern India may receive some rain from warm, humid air coming in over the ocean. The southern branch of the jet stream generally breaks down around the end of May, and then shifts north over the Tibetan plateau. It is only when the southern jet stream has reached its summer position, over the Tibetan plateau, that the south-west monsoon arrives. By mid-July, the monsoon accounts for over three-quarters of India's rainfall. The temporal and spatial pattern is varied: parts of the north-west attract little rainfall, whereas the Bay of Bengal and the Ganges receive large amounts of summer rainfall. The monsoon rains are highly variable each year, and droughts are not uncommon in India. In autumn, the overhead Sun migrates southwards, as too does the zone of maximum insolation and convection. This leads to a withdrawal of the monsoon winds and rain from the region.

Section 7.1 Activities

1 Describe the seasonal variations in the monsoon, as shown in Figure 7.6.
2 Account for the variations in rainfall as shown in Figure 7.7.
3 Briefly explain the formation of the Asian monsoon.

Case Study: Pakistan's floods, August 2010

The heaviest monsoon rain to affect Pakistan for 80 years destroyed the homes of over 140 000 people, killing an estimated 1600, leaving 2 million homeless and affecting over 20 million people (Figure 7.8). Cases of the deadly disease cholera were reported following the flood.

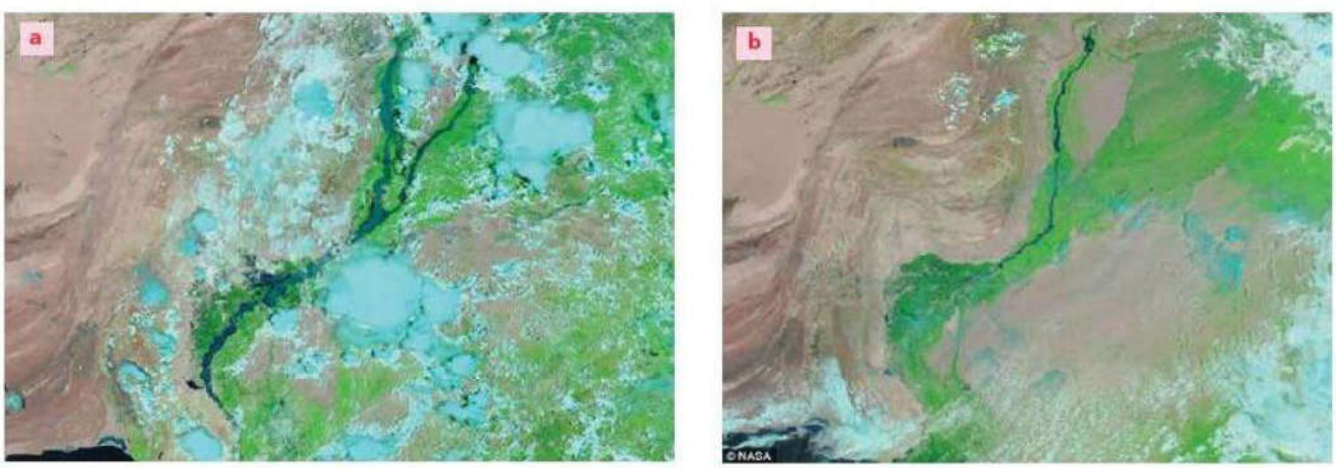


Figure 7.8 Flooding in Pakistan, 2010 – image **a** was taken on 15 August 2010, while image **b** shows the same area a year previously; the blue patches show the extent of the flooding, which left 20 million people homeless

The heavy rainfall, which was many times the usual expected during the monsoon and fell further north and west than usual, exposed the lack of investment in water infrastructure, including big dams, much of which was built in the 1960s. Over 270 millimetres of rain fell in Peshawar in one 24-hour period. The removal of forest cover may also have allowed rainwater to drain faster into the rivers. Further flooding in mid-August prevented vital repairs of embankments, allowing water to reach previously unaffected areas. The floods were the worst since at least 1929. Water levels in the River Indus, which flows through the middle of Pakistan and has most of the population huddled around it, were said to be the highest in 110 years. For example, between 27 and 30 July, 373 millimetres of rain fell at Murree, 394 millimetres at Islamabad and 415 millimetres at Risalpur. Discharge at Guddu peaked at 1.18 million cusecs, compared with a normal discharge of 327 000 cusecs.

One of the hardest-hit areas was the scenic Swat valley, further north, where the population was only just recovering from the Taliban takeover and a military operation in the previous year to drive out insurgents. One factor that may have contributed to the extreme flooding in Swat is the deforestation that accompanied the Taliban takeover. When the landowners fled after being targeted by the Taliban, the timber smugglers joined up with the insurgents to chop down as many trees as possible.

Agriculture was badly affected, causing spiralling food prices and shortages. Floods submerged 69 000 km² of Pakistan's most fertile crop area. The World Bank estimated that crops worth $1 billion (£640 million) were ruined and that the disaster would cut the country's growth in half. More than 200 000 animals also died.

Many roads, bridges and irrigation canals were destroyed, along with the electricity supply infrastructure. Also affected was Mohenjo-Daro, one of the largest settlements of the ancient Indus valley, built around 2500 BCE.

The Asian Development Bank estimated the cost of reconstruction at US$6.8–9.7 billion. This would force the Pakistani government to divert funds from other badly needed development programmes.

UN aid agencies and their partners requested almost $460 million (£295 million) to help Pakistan. Ten days after the start of the floods, just $157 million had been pledged. Based on the estimate of 14 million people affected, the UN said this meant only $4.11 had been committed for each affected person. After the Kashmir earthquake in 2005, which left 2.8 million people needing shelter, $247 million was committed in the first ten days – $70 per person. Ten days after the Haiti earthquake, $495 had been committed for each person affected. Following criticism from the UN, Saudi Arabia pledged $100 million to the Pakistan flood appeal.

Section 7.1 Activities

Study Figure 7.8, which shows the Indus valley before and during the 2010 floods. Compare the river during flood with that of normal flow.

World climates: a classification

The most widely used classification of climate is that of W. Köppen (Figure 7.9). His classification first appeared in 1900, and he made many modifications to it before his death in 1936. Although it has been refined since, the current version bears many resemblances to its early patterns.

Köppen classified climate with respect to two main criteria: temperature and seasonality of rainfall. Indeed, five of the six main climatic types are based on mean monthly temperature:

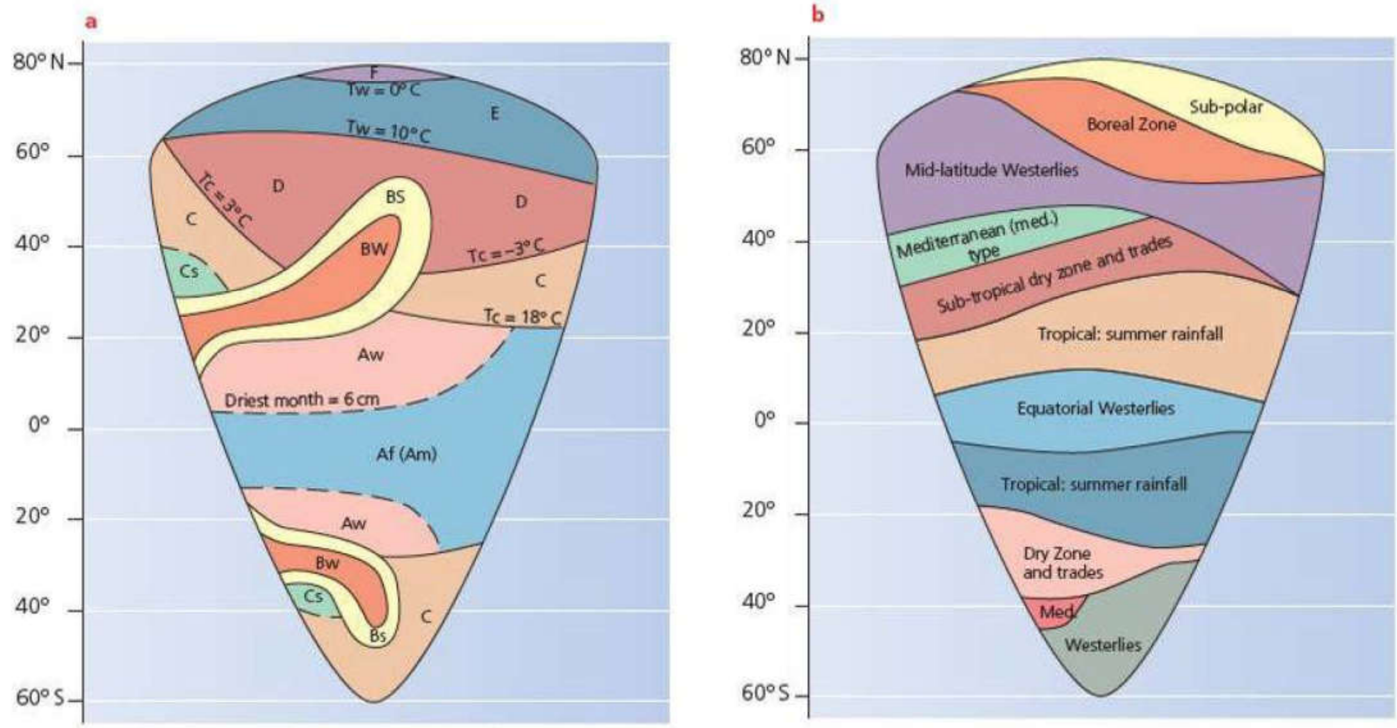
A **Tropical rainy climate** – coldest month >18 °C
B **Dry** (desert)
C **Warm temperate rainy climate** – coldest month −3 °C–18 °C; warmest month >10°C
D **Cold boreal forest climate** – coldest month ≤−3 °C; warmest month ≥10°C
E **Tundra** – warmest month 0–10 °C
F **Perpetual frost climate** – warmest month <0 °C.

The choice of the specific figures is as follows: 18 °C is the critical winter temperature for tropical forests; 10 °C is the poleward limit of forest growth; −3 °C is generally associated with two to three weeks of snow annually.

There are subdivisions that relate to rainfall:

- **f** – no dry season
- **m** – monsoonal (short dry season and heavy rains in the rest of the year)
- **s** – summer dry season
- **w** – winter dry season

Tropical humid climates and seasonally humid climates have a maximum temperature of >20 °C and a minimum monthly temperature of >13 °C. Tropical humid climates have a mean monthly rainfall of over 50 millimetres for between eight and twelve months. In contrast, seasonally humid climates have a mean monthly rainfall of over 50 millimetres for between one and seven months.



The distribution of the major Köppen climatic types on a hypothetical continent of low and uniform elevation.

Tw = mean temperature of warmest month	Tc = mean temperature of coldest month

The distribution of Fohn's climatic types on a hypothetical continent of low and uniform elevation.

Source: Barry, R. and Chorley, R., *Atmosphere, Weather and Climate*, Routledge, 1998

Figure 7.9 Köppen's climate classification

Tropical humid climates (Af) are generally located within 5–10° of the equator. Some higher latitudes may receive high levels of rainfall from unstable tropical easterlies. In Af climates, the midday Sun is always high in the sky – but high humidity and cloud cover keep temperatures from soaring. Some months, such as April and October, may be wetter due to movements of the ITCZ.

In contrast, seasonally humid climates (Aw) have a dry season, which generally increases with latitude. Rainfall varies from the moist low latitudes to semi-desert margins. As the midday Sun reaches its highest point (zenith), temperatures increase, air pressure falls, and strong convection causes thundery storms. However, as the angle of the noon Sun decreases, the rains gradually cease and drier air is re-established.

A variation of the Aw is the tropical wet monsoon (Am) climate. Winters are dry with high temperatures. They reach a maximum just before the monsoon, and then fall during the cloudy wet period when inflows of tropical maritime air bring high rainfall to windward slopes

Section 7.1 Activities

1 Describe the main climate characteristics of Jakarta (Af) and Kolkata (Am), as shown on Figure 7.1.
2 How do you account for the differences between them?

Case Study: The climate of Brunei Darussalam

Figure 7.10 Location of Brunei Darussalam

The climate of Brunei is influenced by its location on the north-west coast of Borneo within the equatorial tropics (Figure 7.10), and by the wind systems of South East Asia.

Brunei is located in an area of low pressure at the equator, sandwiched between two areas of high pressure over the subtropics. The low-pressure 'trough' at the equator (the ITCZ) is the area where air masses from the northern and southern hemispheres converge. The annual movements of the ITCZ and the associated trade winds produce two main seasons in Brunei, separated by two transitional periods.

Between December and March, the north-east monsoon winds affect the South China Sea and Borneo. The average position of the ITCZ is between the latitudes of 5°S and 10°S, having moved southwards across Borneo and Brunei during late December. From June to September, the ITCZ is situated at a latitude of around 15°N to the east of the Philippines, but to the west the ITCZ becomes a monsoon trough. The first transitional period occurs in April and May and the second one in October and November.

On a longer time scale (three to seven years), the climate of Brunei is influenced by the El Niño Southern Oscillation (ENSO). The warm episode or El Niño is normally associated with prolonged dry conditions in Brunei Darussalam. In contrast, La Niña episodes are cold and wetter than normal.

The annual rainfall total exceeds 2300 millimetres. There are clear seasonal patterns, with two maxima and two minima. The first maximum is from late October to early January, with December being the wettest month (Figure 7.11). The second minor maximum is from May to July, with May being relatively wetter. This seasonality is a reflection of the two monsoon seasons in conjunction with the related movements of the ITCZ and the influence of the localised land–sea circulations. The lowest minimum occurs from late January to March, and the next minor minimum is from June to August. The concept of a dry month or dry season in Brunei is relative!

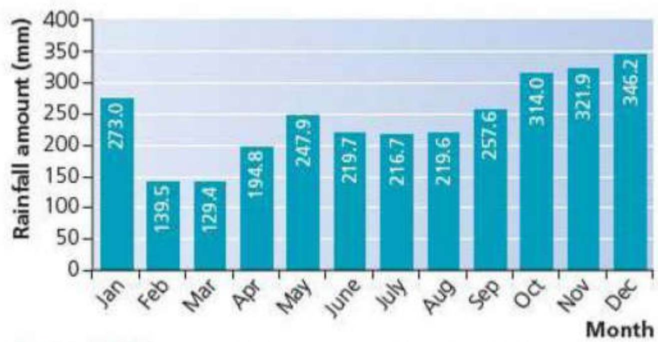


Figure 7.11 Mean monthly rainfall in Brunei, 1966–2006

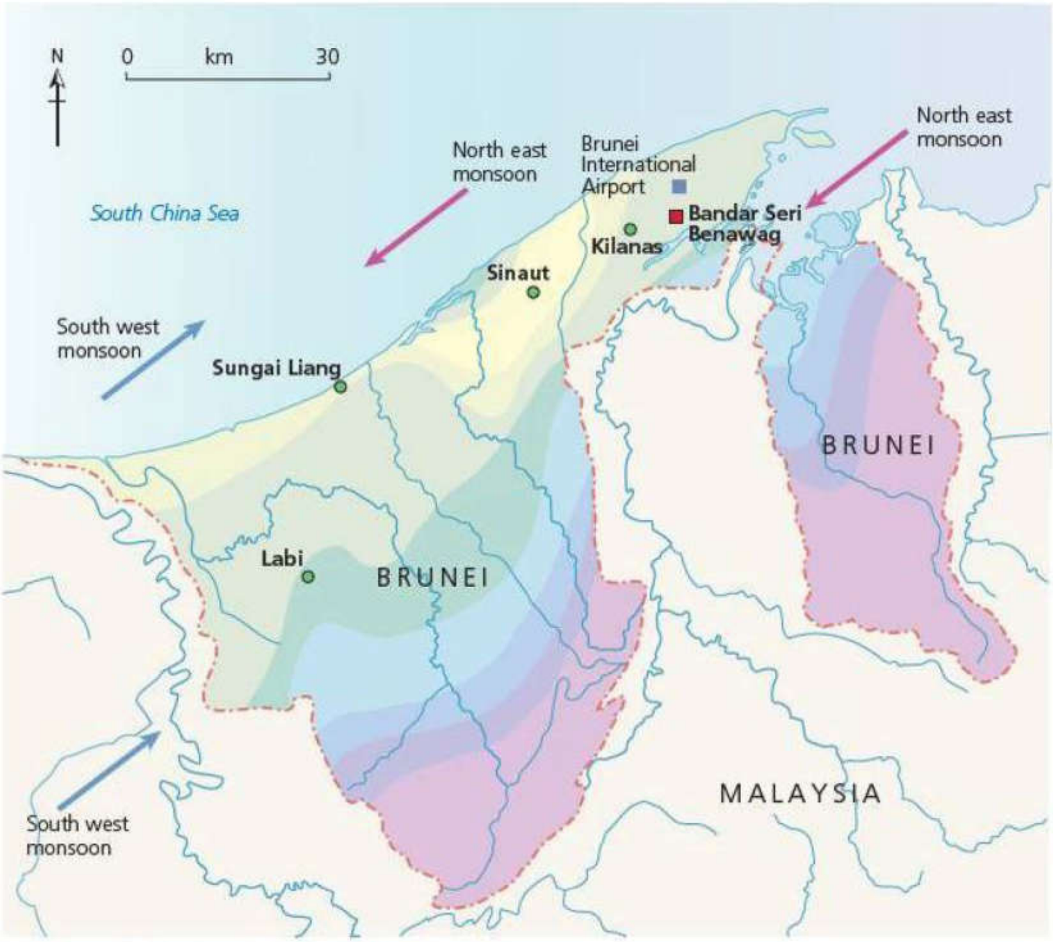
The orographic effect on rainfall in Brunei is notable, particularly in Temburong District. The stations of Semabat and Selangan in Temburong have mean annual rainfall totals of over 4000 millimetres, compared with stations nearer the coast such as Puni and Bangar with annual means of around 3600 millimetres. Rainfall in Brunei is characterised by high intensities (measured in millimetres per hour), with very large amounts falling over sharply delimited areas at short time intervals, in contrast to prolonged rainfalls associated with large-scale systems such as **tropical cyclones** (Figure 7.12).

The probability of thunderstorms shows that two peaks are evident: the higher peak in April and May from late afternoon to the early hours of the morning, and a secondary peak from September to November, mostly from late afternoon to just around midnight.

The temperature regime is notable for its uniformity, with only small variations both seasonally and in different parts of the country. Higher temperatures are generally recorded during the months of March to September, with higher solar heating and less cloudiness and rainfall than in other months. Cold air surges originating from the Siberia/China area during the north-east monsoon season affect Brunei, resulting in lower minimum temperatures.

Section 7.1 Activities

1 Describe and explain the main climate characteristics for Brunei.
2 Describe and suggest reasons for spatial variations in Brunei's climate.



Climate

Brunei Darussalam has a humid equatorial climate with warm temperatures, high humidity and high rainfall. Rainfall varies between 2200 mm on the coast to more than 4000 mm over the Temburong Highlands. The main wet season is from November to January when the north east monsoon wind blows.

Average annual rainfall (mm)

- Over 4000
- 3750–4000
- 3500–3750
- 3250–3500
- 3000–3250
- 2750–3000
- 2500–2750
- Under 2500

Winds (March to October)

Winds (November to January)

Climate station

Figure 7.12 Variations of rainfall in Brunei

Case Study: The El Niño Southern Oscillation

This case study shows that there are major interruptions to the normal functioning of tropical climates. One such interruption is the El Niño Southern Oscillation (ENSO). El Niño, which means 'the Christ Child', is an irregular occurrence of warm surface water in the Pacific off the coast of South America that affects global wind and rainfall patterns (Figure 7.13). In July 1997, the sea surface temperature in the eastern tropical Pacific was 2.0–2.5 °C above normal, breaking all previous climate records. El Niño's peak continued into early 1998 before weather conditions returned to normal.

During the 1920s, Sir Gilbert Walker identified a characteristic of the Southern Oscillation that consisted of a sequence of surface pressure changes within a regular time period of three to seven years, and was most easily observed in the Pacific Ocean and around Indonesia. When eastern Pacific pressures are high and Indonesian pressures are low relative to the long-term average, the situation is described as having a high Southern Oscillation Index (SOI). By contrast, when Pacific pressures are low and Indonesian pressures are high, the SOI is described as low. In 1972, J.N. Walker identified a cell-like circulation in the tropics that operates from an east to west (interzonal) direction, rather than a north–south (meridional) direction. The cell works by convection of air to high altitudes caused by intense heating followed by movement within the subtropical easterly jet stream and its subsequent descent.

El Niño is a phase of the Southern Oscillation when the trade winds are weak and the sea surface temperatures in the equatorial Pacific increase by between 1 and 4 °C. The impacts of the ENSO, which occurs every three to seven years and is the most prominent signal in year-to-year natural climate variability, are felt worldwide. During the 1982–83 ENSO, the most destructive event of the last century, damages amounted to about $13 billion. The event has been blamed for droughts (India, Australia), floods (Ecuador, New Zealand) and fires (West Africa, Brazil). Scientists are capable of forecasting the onset of El Niño up to one year in advance through sea-surface temperature signals.

El Niño has been studied since the early 1900s. In 1904, Sir Gilbert Walker investigated annual variability of the monsoon.

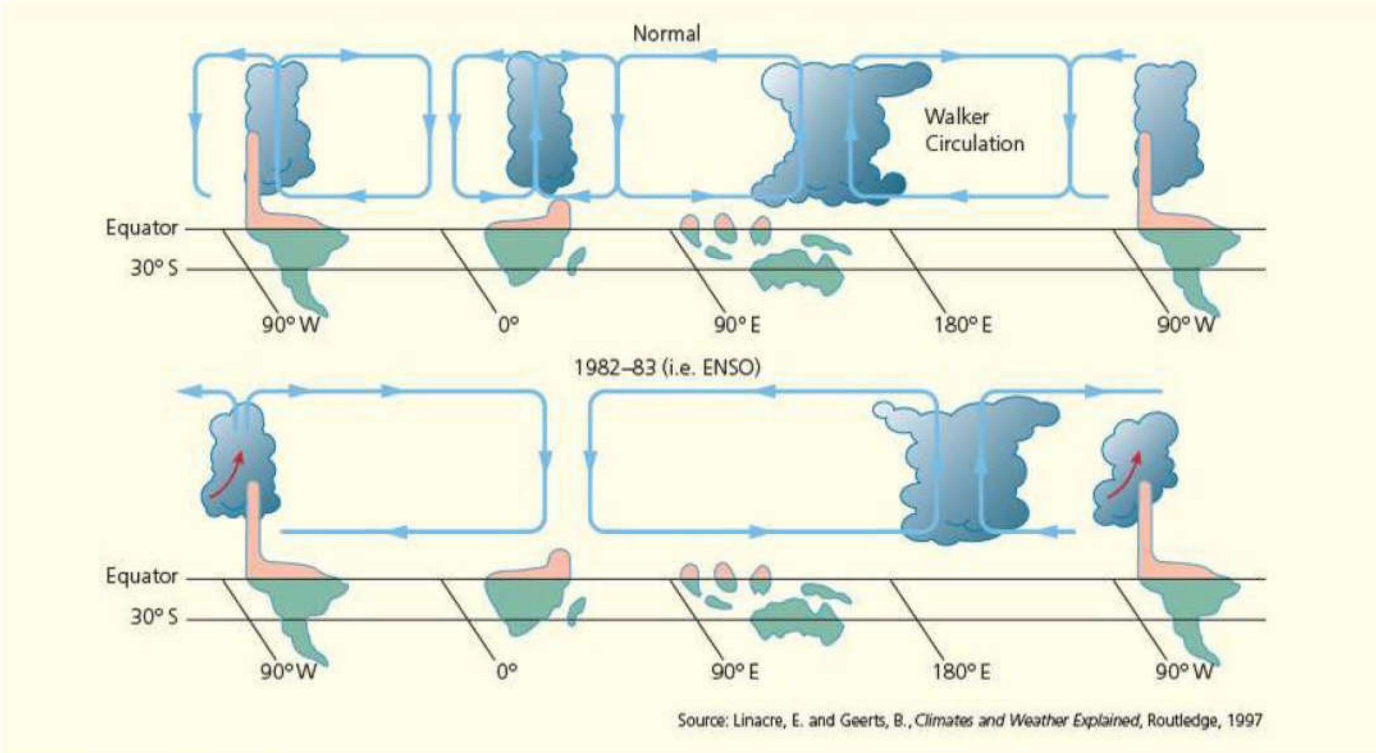


Figure 7.13 El Niño events

He discovered a correlation in the patterns of atmospheric pressure at sea level in the tropics, the ocean temperature and rainfall fluctuations across the Pacific Ocean, which he named the Southern Oscillation. He showed that the primary characteristic of the Southern Oscillation is a seesaw in the atmospheric pressure at sea level between the south-eastern subtropical Pacific and the Indian Ocean. During normal conditions, dry air sinks over the cold waters of the eastern tropical Pacific and flows westwards along the equator as part of the trade winds. The air is moistened as it moves towards the warm waters of the western tropical Pacific. The sea surface temperature gradients between the cold waters along the Peruvian coast and the warm waters in the western tropical Pacific are necessary for the atmospheric gradients that drive circulation.

Climatic anomalies induced by El Niño have been responsible for severe damage worldwide. Among the effects of the 1997–98 El Niño were:

- a stormy winter in California (and the 1982–83 event took 160 lives and caused $2 billion of damage in floods and **mudslides**)
- worsening drought in Australia, Indonesia, the Philippines, southern Africa and north-east Brazil
- drought and floods in China
- increased risk of malaria in South America
- lower rainfall in northern Europe
- higher rainfall in southern Europe.

Perception of the El Niño hazard has developed in a series of stages. Until the 1972–73 event, it was perceived as affecting local communities and industries along the eastern Pacific coast near Peru; then between 1972/73 and 1982/83, El Niño was recognised as a cause of natural disasters worldwide. However, since 1982–83, countries have begun to realise that there is a need for national programmes that will use scientific information in policy planning and that an integrated approach from a number of countries is required to reduce the effects of El Niño.

Section 7.1 Activities

1. Describe the climatic processes that occur during El Niño events.
2. What were the possible effects of the 1997–98 El Niño season?

7.2 Landforms of tropical environments

Tropical landforms are diverse and complex. They are the result of many interrelated factors, including climate, rock type, tectonics, scale, time, vegetation and, increasingly, human impact. In the early part of the twentieth century, the development of tropical landforms was thought to be largely the result of climate. Climatic geomorphology suggested that in a certain climate, a distinct set of processes and landforms would be produced. Critics of this idea showed that as the scale of the investigation became increasingly small and local, site-specific conditions, such as drainage and topography, become more important and the role of climate less important. In addition, many of the early studies of tropical landforms were in parts of tropical Africa, India and South America – regions that are tectonically stable.

Weathering

Mechanical and chemical weathering occur widely in the tropics. Much attention has been given to the processes of hydrolysis and exfoliation. **Hydrolysis** is a form of chemical weathering. Hydrolysis occurs on rocks with orthoclase feldspar, notably granite. Feldspar reacts with an acid water to produce kaolin (or kaolinite/china clay), silicic acid and potassium hydroxyl. The acid and hydroxyl are removed in solution, leaving kaolin as the end product. In the **humid tropics**, the availability of water and the consistently high temperatures maximise the efficiency of chemical reactions, and in the oldest part of the tropics these have been operating for a very long period. In contrast, in many savanna areas where there is less moisture, **exfoliation** or disintegration occurs. This is a form of mechanical weathering. Owing to large-scale diurnal (daytime/night-time) differences in the heating and cooling of rocks, rocks expand by day and contract by night. As rock is a poor conductor of heat, these stresses only occur in the outer layers of the rock, causing peeling or exfoliation.

In many regions, the depth of the weathering profile is very deep. As the depth increases, slopes may become less stable. Rapid mass movements are likely to take place in a cyclical pattern, once a certain amount of weathering has occurred (Figure 7.14).

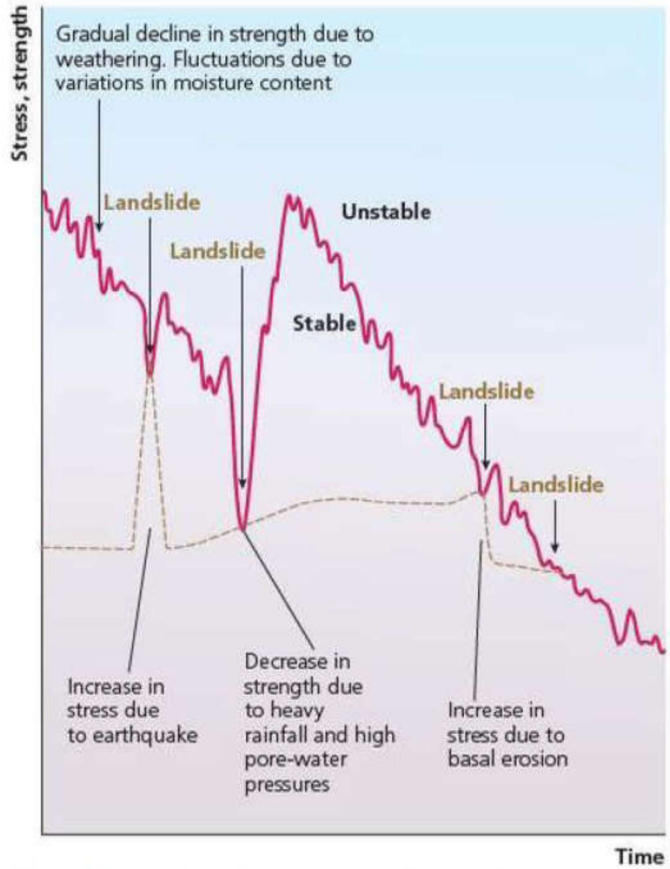


Figure 7.14 Cycles of weathering and landslides

Weathering profiles vary widely. The idealised weathering profile has three zones: residual soil, weathered rock and relatively unweathered bedrock. The residual soil is a zone of eluviation caused by the infiltration of water. Weathering alters the structure and texture of the parent rock. Soluble components may be removed, leaving behind clay-sized materials, especially those containing iron, aluminium and silica. In the lower part of the residual horizon (the C horizon), features of the original rock such as structure, joints and faults may be recognisable. Weathered rock is also known as **saprolite**.

In the weathered zone, at least 10 per cent of the rock is unweathered corestones. This zone is typically highly permeable, especially in the upper sections, and contains minerals in a wide range of weathering stages. In contrast, in the zone of unweathered bedrock, there is little alteration of feldspars and micas. The greatest depth at which unweathered rocks is reached occurs in areas where humid tropical conditions have existed for a prolonged time.

The weathering front or basal surface of weathering between solid rock and saprolite (weathered rock) may be very irregular. Typically, deep weathering occurs down to 30–60 metres, but because of variations in jointing density and rock composition, the depth varies widely over short distances. Depth of weathering has been recorded at 90 metres in Nigeria and Uganda, while in Australia a depth of 275 metres has been measured in New South Wales, as well as 80 metres in Victoria and 35 metres in Western Australia.

Section 7.2 Activities

1 Describe the main types of weathering that occur in tropical environments.
2 Explain why 'deep weathering' may occur in some tropical environments.

Features associated with granite

The word 'inselberg' describes any isolated hill or hills that stand prominently over a level surface. Inselbergs include:

- laterite-capped masses of saprolite
- hills of sedimentary rocks
- castle kopjes
- tors of residual core stones
- massive rock domes with near-vertical sides, called 'bornhardts' or 'domed inselbergs'.

Tors

Most tors and castle kopjes are found in strongly jointed rock. Tors are ridges or piles of spheroidally (rounded) weathered boulders (Figure 7.15) that have their bases in the bedrock and are surrounded by weathered debris. They vary in height from 20 to 35 metres and have core stones up to 8 metres in diameter.

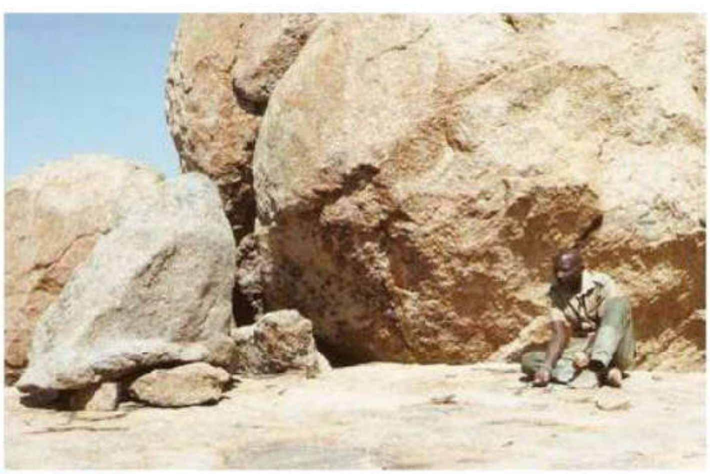


Figure 7.15 Spheroidal weathering

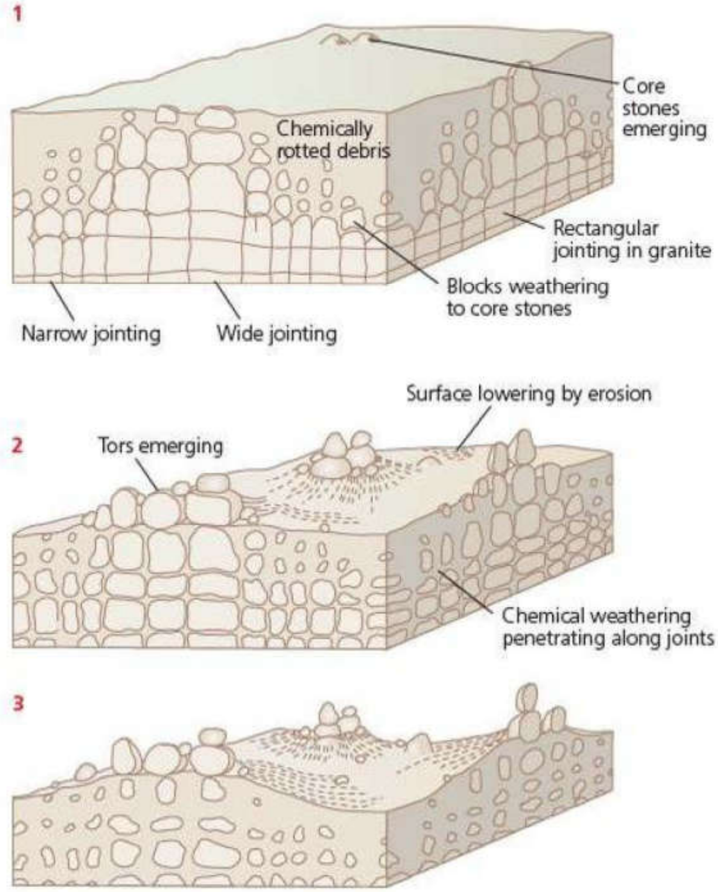


Figure 7.16 Tor formation

Tors are formed by chemical weathering of the rock along joints and bedding planes beneath the surface (Figure 7.16). If the joints are widely spaced the core stones are large, whereas if the joints are close together the amount of weathering increases and the core stones are much smaller. If denudation of the surface exceeds the rate of chemical weathering at the weathering front, the blocks will eventually be exposed at ground level. Gradually, the rocks below the surface will be chemically weathered and cause the collapse of the tor.

Good examples of tors are found on the Jos Plateau of Nigeria and in the Matopas region of Zimbabwe and around Harare.

Inselbergs

A striking feature of tropical plains is the rock hills known as 'inselbergs' (Figure 7.17). Conditions especially favourable for residual hills occur in the seasonal tropics. Residual hills are best developed on volcanic materials, especially granite and gneiss, with widely spaced joints and a high potassium content. However,

Figure 7.17 Inselberg and low plains

they can also be found on sedimentary rocks, such as sandstone.

Residual hills occur in a variety of sizes. The term 'inselberg' usually describes an almost abrupt rise from the plains. Duricrust-topped hills are the major exception. The terms 'tor' or 'boulder inselberg' are used to describe spheroidally weathered boulders rooted in bedrock.

Residual hills are the result of stripping weathered regolith from a differentially weathered surface. The major debate is whether deep weathering is needed for hill formation. The two-stage model requires the development of a mass of weathered material beneath the ground and its subsequent removal. Alternatively, weathering and erosion could occur simultaneously. The diversity of residual hills suggests that both mechanisms operate simultaneously.

Bornhardts

The monolithic domed inselberg or 'bornhardt' is a characteristic landform of granite plateaux of the African savanna, but can also be found in tropical humid regions. They are characterised by steep slopes and a convex upper slope (Figure 7.18). Bornhardts are eventually broken down into residual castle kopjes.

Bornhardts occur in igneous and metamorphic rocks. Granite, an igneous rock, develops joints up to 35 metres below the surface during the process of pressure release. Vertical jointing in granite is responsible for the formation of castle kopjes.

The two main theories for the formation of bornhardts are:

- the stripping or exhumation theory – increased removal of regolith occurs so that unweathered rocks beneath the surface are revealed
- Lester King's parallel retreat theory, which states that the valley sides retreat until only remnant inselbergs are left.

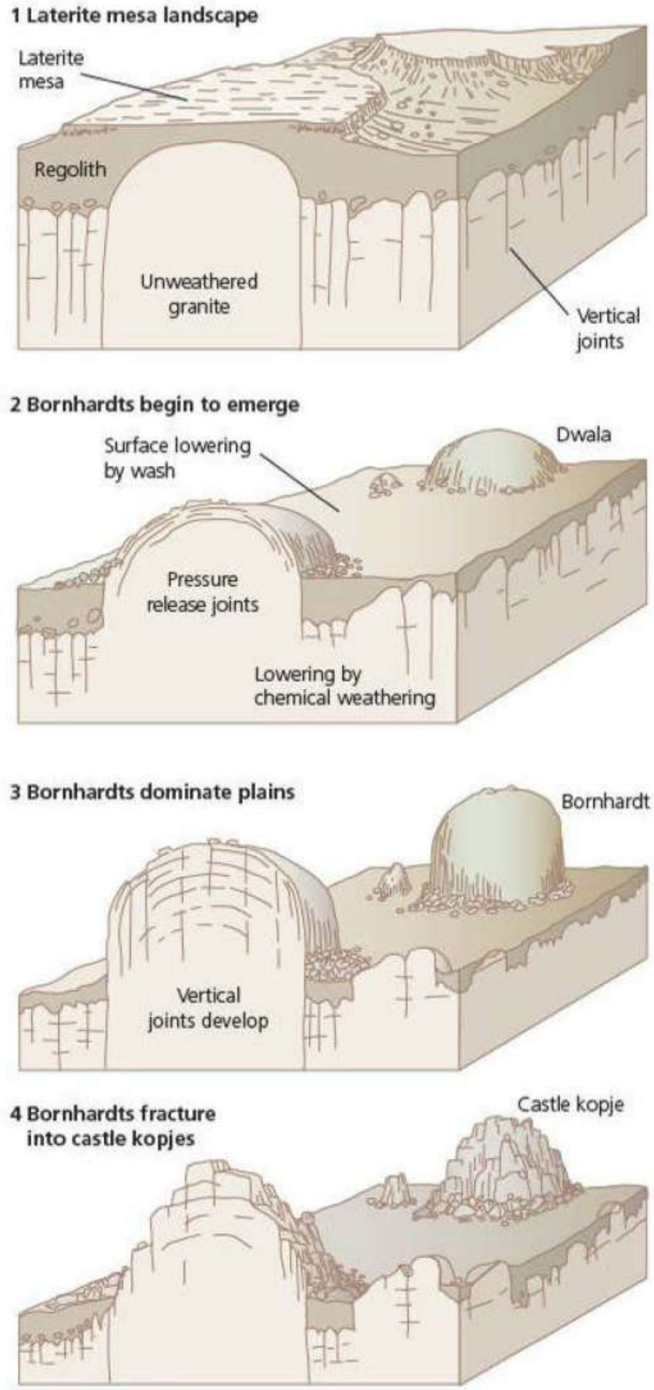


Figure 7.18 Formation of bornhardts

In the case of bornhardts, it seems that the major theory is that of etchplanation. There is a gradual evolution of the domed rock (ruware) through the bornhardt to an inselberg and then the residual castle kopje. As the theory invokes evolution through a series of periods of deep weathering, changing climatic conditions and uplift, this evolutionary approach might be the most appropriate.

Classic examples of bornhardts include Mount Hora in the Mzimba District of Malawi, and Zuma Rock near Abuja in Nigeria. Bornhardts are an example of equifinality; that is, different processes leading to the same end product.

Section 7.2 Activities

1 Explain why tors may be considered 'joint-controlled'.
2 To what extent are inselbergs 'relict' features?
3 Describe the development of bornhardts and castle kopjes as shown in Figure 7.18.

Features associated with limestone

Tropical karst

There are two major landform features associated with tropical karst. Polygonal or cockpit karst (Figure 7.19) is a landscape pitted with smooth-sided soil-covered depressions and cone-like hills. Cone karst is a landscape with closely spaced conical hills – it is a type of cockpit karst. The Cockpit Country in Jamaica is a classic example of cone karst. The terms 'cockpit' and 'cone' karst are used almost interchangeably. Tower karst is a landscape characterised by upstanding rounded blocks set in a region of low relief. Although water is less able to dissolve carbon dioxide in tropical areas, the higher temperatures and the presence of large amounts of organic matter produce high amounts of carbon dioxide in the soil water.

Some geographers believe that there is an evolution of limestone landscapes that eventually leads to cockpit karst and tower karst (Figure 7.20). However, according to Marjorie Sweeting (1989), the distinction between cockpit karst and tower karst is fundamental, as the hydrological and tectonic conditions associated with each are quite different.

Polygonal or cockpit karst is characterised by groups of hills, fairly uniform in height (Figure 7.21). These can be up to 160 metres high in Jamaica, with a base of up to 300 metres. They develop mainly as a result of solution. They are as common to some tropical areas as dry valleys and dolines are to temperate areas. Polygonal karst tends to occur in areas:

- that have been subjected to high rates of tectonic uplift and
- where vertical erosion by rivers is intense.

Figure 7.19 Cockpit karst

Solution holes

The surface is broken up by many small solution holes but the overall surface remains generally level.

Cockpit karst

Cockpit karst is usually a hilly area in which many deep solution holes have developed to give it an 'eggbox' appearance.

Tower karst

The widening and deepening of the cockpits has destroyed much of the limestone above the water table. Only a few limestone towers remain, sticking up from a flat plain of sediments that have filled in the cockpits at a level just above the water table. Eventually the towers will be entirely eroded, and disappear.

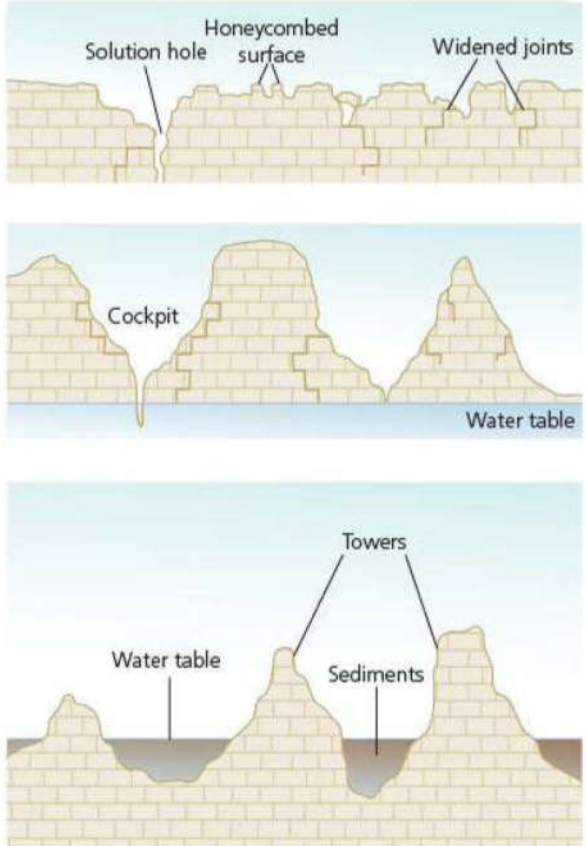


Figure 7.20 Cockpit karst and tower karst

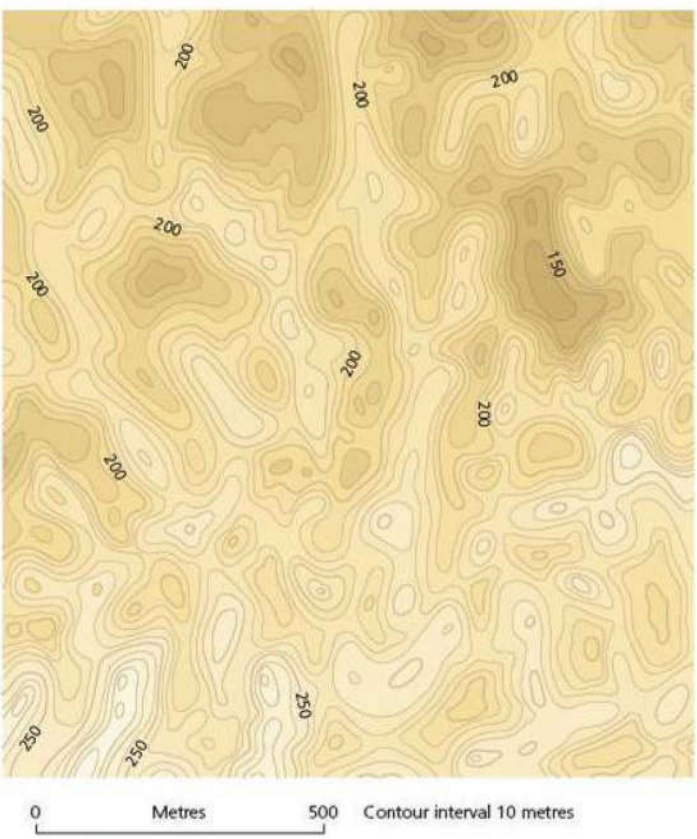


Figure 7.21 Cockpit karst in northern Puerto Rico, from a US Geological Survey map

The spacing of the cones may be related to the original stream network. Concentrated solution along preferred routes, such as wider joints, leads to accelerated weathering of certain sections of the limestone, especially during times of high flow, such as during a storm. Water will continue to weather the limestone as far down as the water table. This creates closed depressions and dolines. Once the water table is reached, water will flow laterally rather than vertically, so developing a flat plain.

An alternative theory suggests that the formation and subsequent collapse of cave systems is the main mechanism for cockpit-karst formation. Caves in limestone migrate upwards through the hillside. Collapse of the ceiling is due to the solution by water percolating downwards. Every time the ceiling collapses, the ceiling gets higher and the floor is raised by the debris, so the whole chamber gets higher. Eventually, the cave roof collapses.

By contrast, tower karst is much more variable in size than the conical hills of cockpit karst, and ranges from just a few metres to over 150metres in height in Sarawak. Other areas of tower karst include southern China, Malaysia, Indonesia and the Caribbean. They are characterised by steep sides, with cliffs and overhangs, and with caves and solution notches at their base. The steepest towers are found on massive, gently tilted limestone. According to Sweeting, tower karst develops in areas where:

- tectonic uplift is absent or limited
- limestone lies close to other rocks
- the water table is close to the surface.

In wet monsoonal areas, rivers will be able to maintain their flow over limestone, erode the surface and leave residual blocks set in a river plain. It is likely that there are other important processes. These include:

- differential erosion of rock with varying resistance
- differential solution along lines of weakness
- the retreat of cockpit karst slopes to produce isolated tower karst
- lateral erosion.

Why is China so important for tropical karst?

Southern China is one of the best areas in the world for the development of cockpit and tower karst (Figure 7.22). A number of conditions help explain this:

- large amounts of rainfall – over 2000 millimetres per annum (in the north of China where rainfall is low, limestone features include escarpments and dry valleys)
- long periods of slow uplift exposing broad, gently dipping plateaus
- thick beds of limestone, up to 3000 metres deep, allow spectacular landforms to develop.

Figure 7.22 Tower karst, China

Underground features

Underground features include caves and tunnels formed by carbonation-solution and erosion by rivers. Carbonation is a reversible process. When calcium-rich water drips from the ceiling, it leaves behind calcium in the form of stalactites and stalagmites. These are cave deposits formed by the precipitation of dissolved calcium carbonate. Stalactites (Figure 7.23) develop from the top of the cave, whereas stalagmites (Figure 7.24) are formed on the base of the cave. Rates of deposition are slow; about 1 millimetre (the thickness of a coat of paint) per 100 years. The speed with which water drips from the cave ceiling appears to have some influence on whether stalactites (slow drip) or stalagmites (fast drip) are formed.

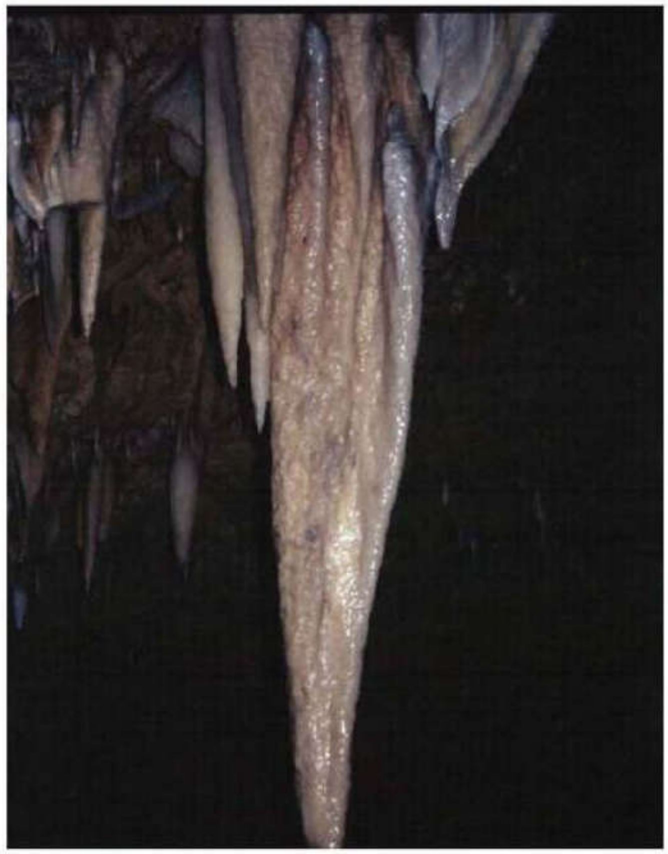


Figure 7.23 Stalactite, Harrison's Cave, Barbados

Figure 7.24 Stalagmite, Harrison's Cave, Barbados

Case Study: Blue holes in the Bahamas

Sea-level changes in the Caribbean have caused some limestone caves to be submerged, forming **blue holes** (Figure 7.25). These are a major tourist attraction in the Bahamas, for example. The Bahamas has a variety of blue holes (Figure 7.26). The islands' limestone has been carved out by carbonation-solution over millennia, during periods when the sea level fluctuated – the seas were some 130 metres lower 10 000 years ago, for example. As the sea level rose over the last 10 000 years, it submerged many of the limestone sinks, caves and tunnels. These drowned sinks became the blue holes. The classic form of a blue hole is circular, extending in a bell shape beneath the surface. However, some open into the edge of an oceanic wall or are simply openings in a shallow reef. Not all blue holes are oceanic – many are found inland. The deepest known blue hole in the Bahamas reaches down to over 200 metres, and many systems drop to around 100 metres and then extend into a network of caverns and caves at the bottom.

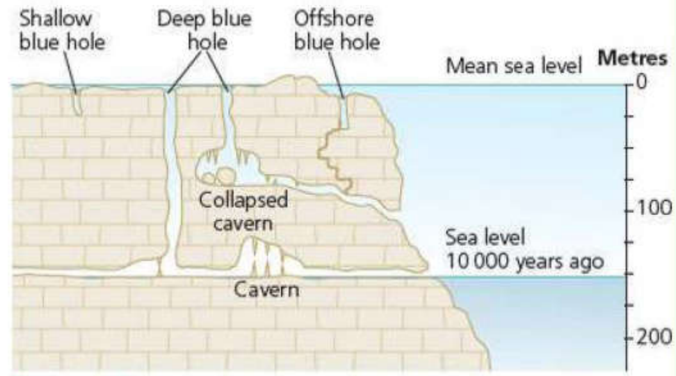


Figure 7.25 Formation of blue holes

Figure 7.26 Blue hole in the Bahamas

Section 7.2 Activities

1 How are blue holes formed?
2 Outline the differences between cockpit karst and tower karst.

7.3 Humid tropical (rainforest) ecosystems and seasonally humid tropical (savanna) ecosystems

An ecosystem is the interrelationship between plants and animals and their biotic and abiotic environment. In contrast, ecology is the study of organisms in relation to the environment, and biogeography is the geographical distribution of ecosystems, where and why they are found.

A community is a group of populations (animals and plants) living and interacting with each other in a common habitat (such as a savanna or a tropical rainforest). This contrasts with the term population, which refers to just one species, such as zebra.

The productivity of an ecosystem is how much organic matter is produced per annum. It is normal to refer to net primary productivity; that is, the amount of organic material produced by plants and made available to the herbivores (Table 7.3). Net primary productivity varies widely, and is affected by water availability, heat, nutrient availability and age and health of plant species. In contrast, biomass is a measure of stored energy. Forest ecosystems normally have much higher rates of biomass than grassland ecosystems, since much of the energy is stored as woody tissue.

Biodiversity refers to the variety of habitats, species and genetic diversity in an ecosystem. It is very high in tropical rainforests due to the high levels of productivity caused by year-round rainfall and high temperatures. It is also related to the long period of evolution without significant climate change. Biodiversity in savannas is also high due to the mosaic of habitats caused by physical and human factors.

Table 7.3 A comparison of mean net primary productivity and biomass for the world's major biomes

Ecosystem	Mean NPP ($kg/m^2/year$)	Mean biomass (kg/m^2)
Tropical rainforest	2.2	45
Tropical deciduous forest	1.6	35
Tropical scrub	0.37	3
Savanna	0.9	4
Mediterranean sclerophyll	0.5	6
Desert	0.003	0.002
Temperate grassland	0.6	1.6
Temperate forest	1.2	32.5
Boreal forest	0.8	20
Tundra and mountain	0.14	0.6
Open ocean	0.12	0.003
Continental shelf	0.36	0.001
Estuaries	1.5	1

Succession in plant communities

Succession refers to the spatial and temporal changes in plant communities as they move towards a seral climax (Figure 7.27). Each sere or stage is an association or group of species, which alters the micro-environment and allows another group of species to dominate. At the start of succession (pioneer communities), there are few nutrients and limited organic matter. Organisms that can survive are small and biodiversity is low. In late succession, there is more organic matter, higher biodiversity and longer-living organisms (Figure 7.28). Nutrients may be held by organisms, especially trees, so nutrient availability may be low. A well-documented case of succession is that following the eruption of Krakatoa in 1883 (Table 7.4). The climax community is the group of species that are at a dynamic equilibrium with the prevailing environmental conditions. On a global scale,

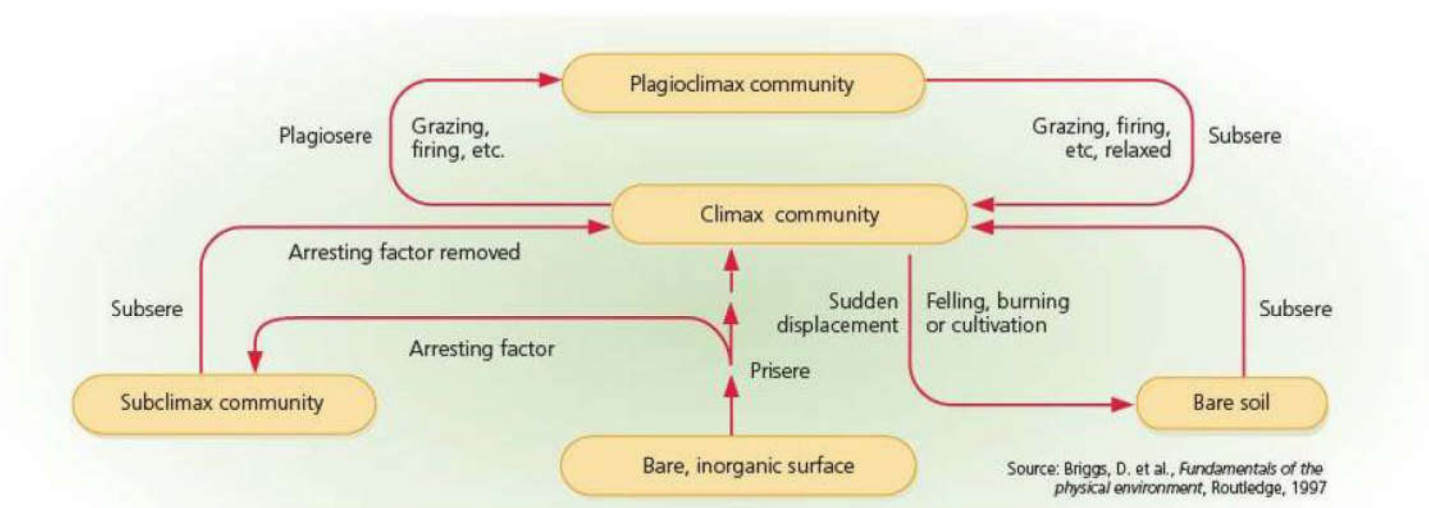


Figure 7.27 A model of succession

climate is the most important factor in determining large ecosystems or biomes such as tropical rainforest and temperate woodland (Figure 7.29). In some areas, however, vegetation distribution may be determined by soils rather than by climate. This is known as edaphic control. For example, in savanna areas, forests are found on clay soils, whereas grassland occupies sandy soils. On a local scale, within a climatic region, soils may affect plant groupings.

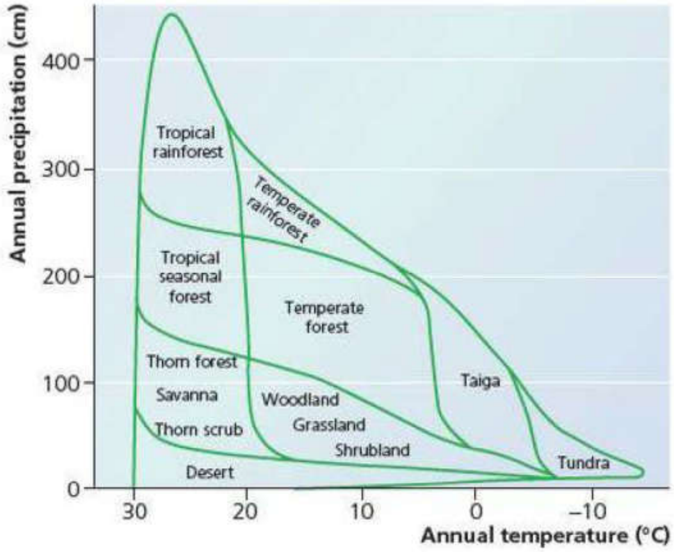
Attribute	Early	Late
Organic matter	Small	Large
Nutrients	External	Internal
Nutrient cycles	Open	Closed
Role of detritus	Small	Large
Diversity	Low	High
Nutrient conservation	Poor	Good
Niches	Wide	Narrow
Size of organisms	Small	Large
Life-cycles	Simple	Complex
Growth form	r species	k species
Stability	Poor	Good

Source: Briggs, D.et al., *Fundamentals of the physical environment*, Routledge 1997

Figure 7.28 Community changes through succession

Table 7.4 Primary succession on Krakatoa after the 1883 volcanic eruption

Year	Total number of plant species	Vegetation on the coast	Vegetation on the lower slopes	Vegetation on the upper slopes
1883	Volcanic eruption kills all life on the island			
1884	No life survives			
1886	26	9 species of flowering plant	Ferns and scattered plants; blue-green algae beneath them on the ash surface	Ferns and scattered plants; blue-green algae beneath them on the ash surface
1897	64	Coastal woodland develops	Dense grass	Dense grasses with shrubs interspersed
1908	115	Wider belt of woodland with more species, shrubs and coconut palms	Dense grasses to 3 m high, woodland in the larger gullies	Dense grasses to 3 m high, woodland in the larger gullies
1919			Scattered trees in grassland, single or in groups with shade species beneath; thicket development in large gullies	Scattered trees in grassland, single or in groups with shade species beneath; thicket development in large gullies
1928	214			
1934	271		Mixed woodland largely taken over from savanna	Woodland with smaller trees, fewer species taking over
Early 1950s		Coastal woodland climax	Lowland rainforest climax	Submontane forest climax



Source: *Advanced Geography: Concepts and Cases* by P. Guiness & G. Nagle (Hodder Education, 1999), p.441

Figure 7.29 The relationship between climate and vegetation

Sometimes a sub-climax occurs. This is often the case when a factor – such as a flood, hurricane or tsunami – prevents the climax community from forming or from remaining. It may, over time, form again, once the arresting factor has been removed. In contrast, a plagioclimax refers to a plant community permanently influenced by human activity. It is prevented from reaching climatic climax by burning, grazing, and so on. The maintenance of grasslands through burning is an example of plagioclimax.

Section 7.3 Activities

1 Briefly explain the meaning of the terms *succession* and *plagioclimax*.
2 Describe the main changes in plant species over time following the eruption of Krakatoa.
3 Suggest reasons for the differences between the vegetation on the coast, the lower slopes and the upper slopes.

Figure 7.30 shows a model of succession in a rainforest. A contemporary example of succession being affected by arresting factors is the rainforest of Chances Peak in Montserrat. In the early 1990s, Chances Peak had some of the finest tropical rainforest in the Caribbean region. It had a high biodiversity of plant life, insects, lizards, birds and bats. By January 1996, surveys indicated that vegetation loss from acid rain, gases, heat and dust on the top of Chances Peak and in the surrounding area was severe. The cloud forest had disappeared. Vegetation was gradually dying further down the mountain. On the east side, the lush forests of the Tar River valley were degraded from ash and gases, and were finally destroyed by lahars (mudflows) (Figure 7.31).

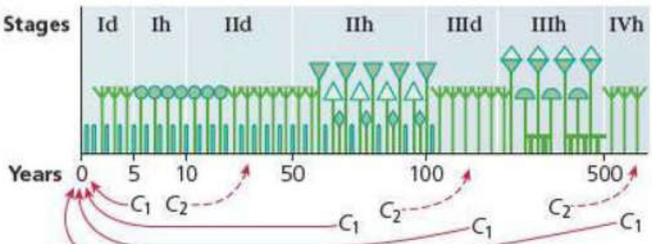


Figure 7.30 A model of succession in a rainforest from bare soil to primary forest

Figure 7.31 The effect of a volcanic eruption – Chances Peak, Montserrat

Volcanoes emit sulphurous gases. On a global scale, the amount of sulphur from active volcanoes is minor compared with that from other sources. On a local scale, the impacts from volcanic sulphur emissions have important consequences for plant and animal life. Acid rain increases leaching of some nutrients and renders other nutrients unavailable for uptake by plants.

By January 1996, the pH of the lake at the top of Chances Peak was 2.0 (1000 times more acidic than a pH of 5.0). Other lakes and streams measured about 1.5 at the same time.

Continued volcanic activity and erosion prevent reforestation. Sustained recovery will not take place until volcanic activity greatly reduces or stops. Recovery of the forest will start in two ways: seeds in the ground will start to germinate, and new seeds will blow in from surrounding areas. The rate of recovery will depend in part on the availability of seeds, which in turn depends on the proximity of other forest species and the availability of animals (for example, birds) to disperse seeds. In Montserrat, there is currently cloud forest in the Centre Hills and this may act as a source of new seeds for the southern Soufrière Hills close to the volcano. Pioneers will colonise the soil and make it suitable for other forest species. Early pioneer species must be able to tolerate high light intensities and high temperatures (because there is no longer any forest to provide shade). Species such as *Cecropia* are early pioneers: they are light tolerant, and their seeds are dispersed by a variety birds and bats (76 species of birds are known to feed on *Cecropia*). High light levels and high temperatures often stimulate the germination of these seeds. *Heliconia* and some palm species will colonise disturbed areas. Once these pioneer species have established, the shade they create often prevents other members of the same species from germinating and surviving. Thus new shade-tolerant species can now establish themselves. The forest therefore begins to increase in diversity. Studies in Puerto Rico have shown that some forests recover from hurricane destruction in about 40years.

Section 7.3 Activities

Suggest **two** contrasting reasons for the death of the trees shown in Figure 7.31.

Vegetation in tropical rainforests

There is a wide variety of ecosystem types in the humid tropics (Figure 7.32). The tropical rainforest is the most diverse ecosystem or biome in the world, yet it is also the most fragile. This stems from the conditions of temperature and humidity being so constant that species here specialise to a great extent. Their food sources are limited to only a few species. Thus when this biome is subjected to stress by human activity it often fails to return to its original state.

The net primary productivity (NPP) of this ecosystem is 2200 g/m²/year. This means that the solar energy fixed by the green plants gives 2200 grams of living matter per m² every year (Figure 7.33). This compares with the NPP for savanna of 900 g/m²/year, temperate deciduous forests of 1200 g/m²/year and agricultural land of 650 g/m²/year. Figure 7.33 shows the pattern of production and consumption in a typical undisturbed area of tropical rainforest. Only a minute amount passes through animals (and even less through hunter-gatherers). Most of the plant material falls to the forest floor to become litter. Although the forest contains many animals, it does not contain a large biomass of animals, in part because much of the plant material is inedible. The woody parts of plants are indigestible to animals. Leaves, fruits and seeds are digestible, but may contain chemicals that are poisonous to animals. Consequently, many animals specialise on particular plant species, upon which they feed successfully despite their toxicity. Many plants counter this with synchronised fruiting, sometimes as infrequent as once per decade, so that most of the time there is little food to support the animals that specialise in feeding on them.

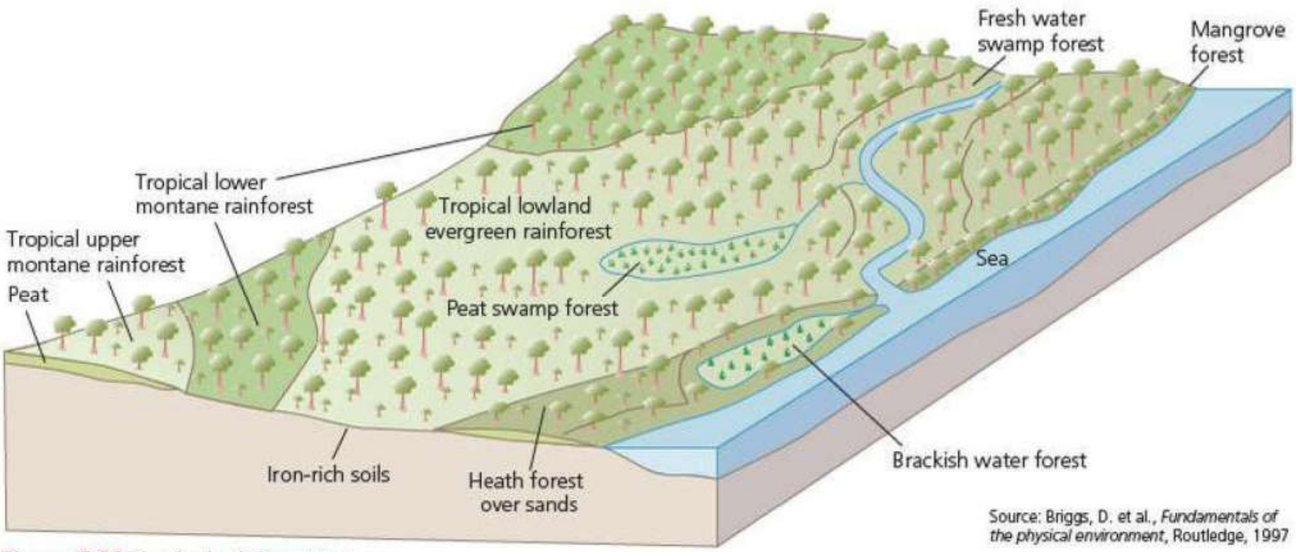


Figure 7.32 Tropical rainforest types

The hot, humid climate gives ideal conditions for plant growth and there are no real seasonal changes. The plants are therefore aseasonal and the trees shed their leaves throughout the year rather than in one season. There is a great variety of plant species – in some parts of Brazil, there can be 300 tree species in 2 km² (Figure 7.34). The trees are tall and fast growing. The need for light means that only those trees that can grow rapidly and overshadow their competitors will succeed. Thus trees are notably tall and have long, thin trunks with a crown of leaves at the top; they also have buttress roots to support the tall trees.

The trophic structure of the rainforest is similar to other ecosystems (including the savannas). Primary producers (the first trophic layer – including trees such as teak) trap energy from sunlight and convert it to food energy. This in turn is consumed by herbivores (the second trophic layer, such as tree squirrels), which in turn are consumed by primary and secondary consumers. Eventually, detritivores decompose dead material and return the nutrients to the soil. Given the high level of biodiversity in rainforests, the food web is complex.

There are, broadly speaking, three main layers of tiers of trees (Figure 7.35):

- **emergent**, which extend up to 45–50 metres
- a **closed canopy** 25–30 metres high, which cuts out most of the light from the rest of the vegetation and restricts its growth
- a limited **understorey** of trees, denser where the canopy is weaker; when the canopy is broken by trees falling, by clearance or at rivers, there is a much denser understorey vegetation.

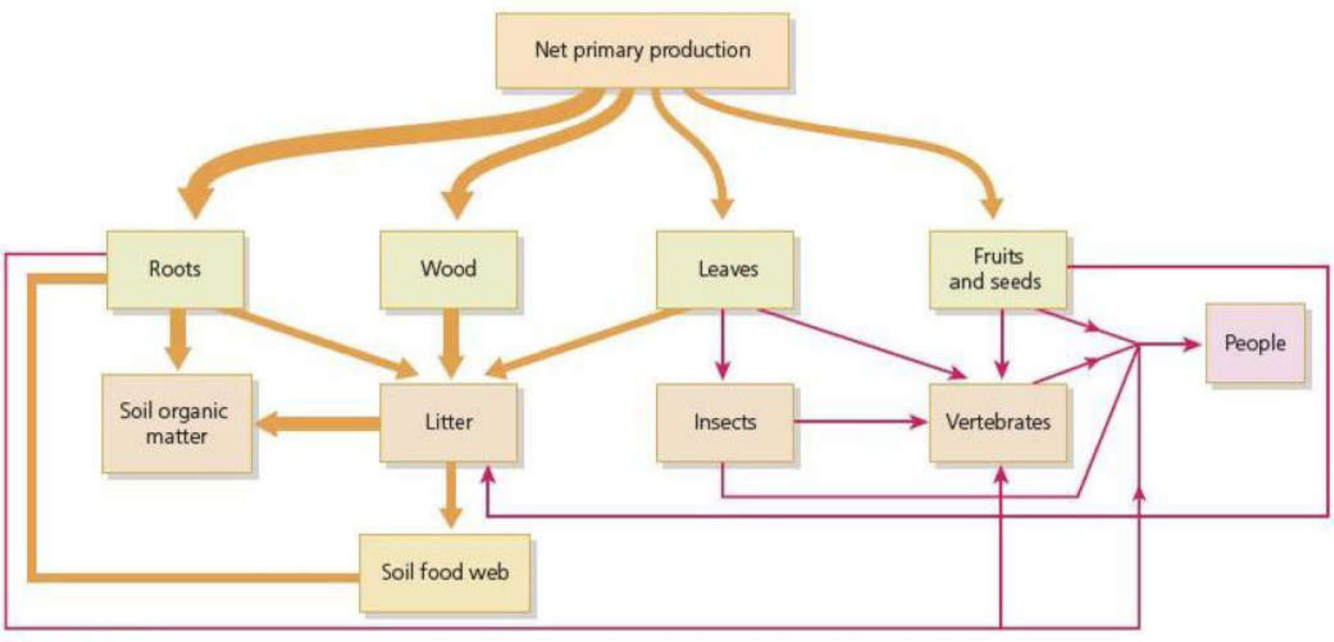


Figure 7.33 Energy flows in tropical rainforest – the width of the arrows indicates proportions

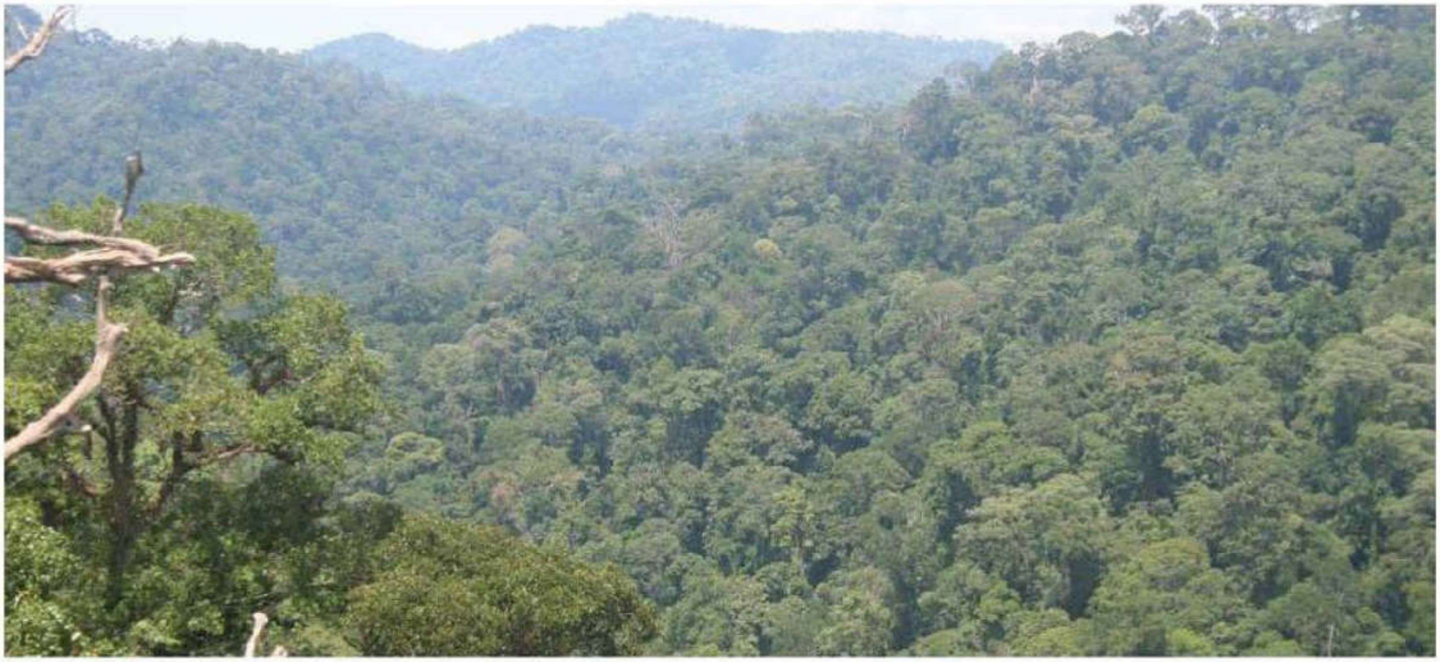
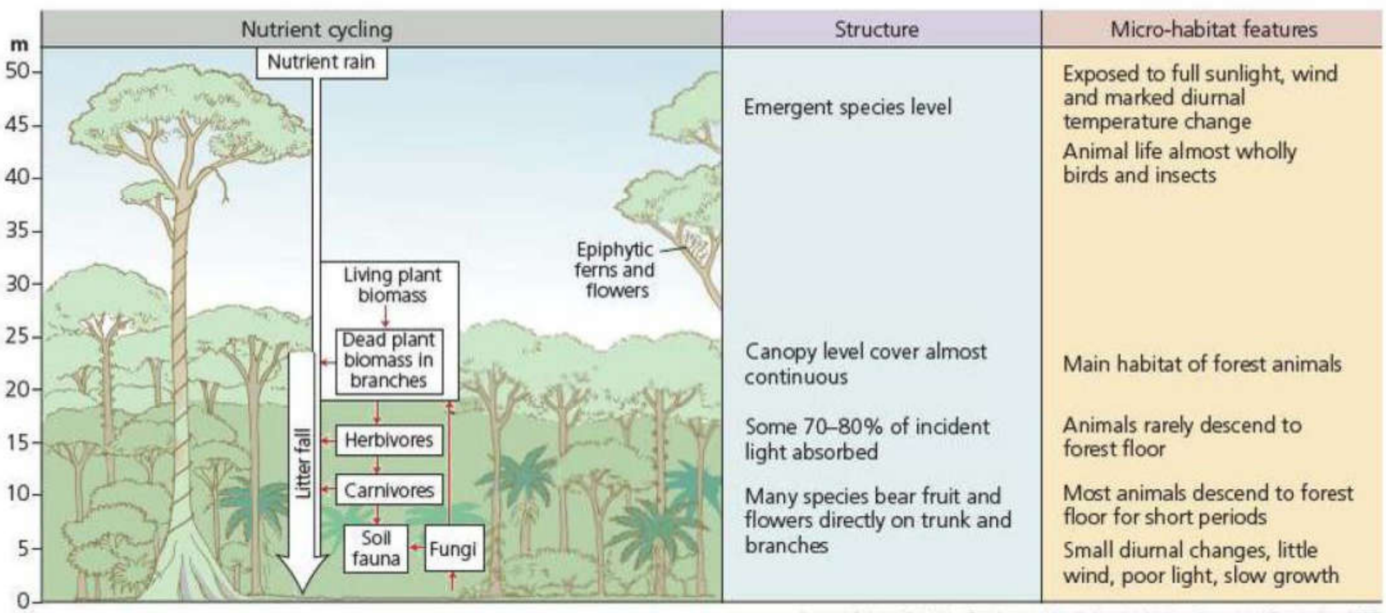


Figure 7.34 Tropical rainforests have vegetation in a number of different layers



Source: Briggs, D et al., *Fundamentals of the physical environment*, Routledge 1997

Figure 7.35 Vegetation structure in a rainforest

Trees are shallow-rooted as they do not have problems getting water. Other layers include lianas and epiphytes, and the final layer is an incomplete field layer limited by the lack of light. The floor of the rainforest is littered with decaying vegetation, rapidly decomposing in the hot, humid conditions. Tree species include the rubber tree, wild banana and cocoa; pollination is not normally by wind due to the species diversity – insects, birds and bats, which have restricted food sources.

Rainforest supports a large number of epiphytes, which are attached to the trees. Many of these are adapted to a system that requires only a small intake of nutrients. Some plants, such as the carnivorous pitcher plant (Figure 7.36), get their nutrients from insects and small mammals. There are also parasites taking nutrients from host plants, while those flora living on dead material are called 'saprophytes', an important part of the decomposing cycle. The fauna are as diverse as the flora.

Figure 7.36 A carnivorous pitcher plant, which takes its nutrients from insects and small mammals

Section 7.3 Activities

1. Explain why tropical rainforests have very high rates of productivity.
2. Suggest reasons why there are different types of rainforest as shown in Figure 7.32.
3. Describe and explain the vegetation structure of the tropical rainforest as shown in Figure 7.35.

Nutrient cycles

Nutrients are circulated and reused frequently. All natural elements are capable of being absorbed by plants, either as gases or soluble salts. Only oxygen, carbon, hydrogen and nitrogen are needed in large quantities. These are known as **macronutrients**. The rest are **trace elements** or micronutrients, such as magnesium, sulfur and phosphorus. These are needed only in small doses. Nutrients are taken in by plants and built into new organic matter. When animals eat the plants, they take up the nutrients. These nutrients are eventually returned to the soil when the plants and animals die and are broken down by decomposers.

All nutrient cycles involve interaction between soil and the atmosphere and involve many food chains. Nevertheless, there is great variety between the cycles. Generally, gaseous cycles are more complete than sedimentary ones as the latter are more susceptible to disturbance, especially by human activity. Nutrient cycles can be sedimentary based, in which the source of the nutrient is from rocks, or they can be atmospheric based, as in the case of the nitrogen cycle.

Case Study: Civil war and the Rwandan rainforest

In 1925, the Albert National Park, an area of lush tropical rainforest, was established by Belgian colonial authorities. In 1979, UNESCO declared the park, renamed Virunga National Park, as Africa's first National Park Heritage Site, on account of its biodiversity. However, Virunga has been plagued by problems for decades and the park is being deprived of its ecological treasures:

- Political and economic breakdown in the Democratic Republic of Congo has starved the park of funds.
- In the 1960s, much of the big game was killed by poachers, rebels and government soldiers during the civil war in the Congo.
- Tourism in the park is limited, thereby reducing the park's revenue.
- Poaching has halved the number of hippopotamuses and buffalo in the area.
- Villagers in the park have depleted the forest and overfished the lake.
- The Rwandan civil war (1990–94) intensified pressures on the land.

The park was looted by Rwandan refugees and Hutu soldiers from around the town of Goma in eastern Congo. Up to 300 km^2 of forest was destroyed in less than six months in 1994. Nearly 900 000 refugees lived within or near Virunga and up to 40 000 people entered the park daily, notably for food and fuel. Soldiers, too, cut wood to sell to the refugees. The rivers were polluted by human and animal waste and medical products, leading to a high risk of disease transmission.

Nutrient cycles can be shown by means of simplified diagrams (Gersmehl's nutrient cycles), which indicate the stores and transfers of nutrients (Figure 7.37). The most important factors that determine these are availability of moisture, heat, fire (in grasslands), density of vegetation, competition and length of growing season.

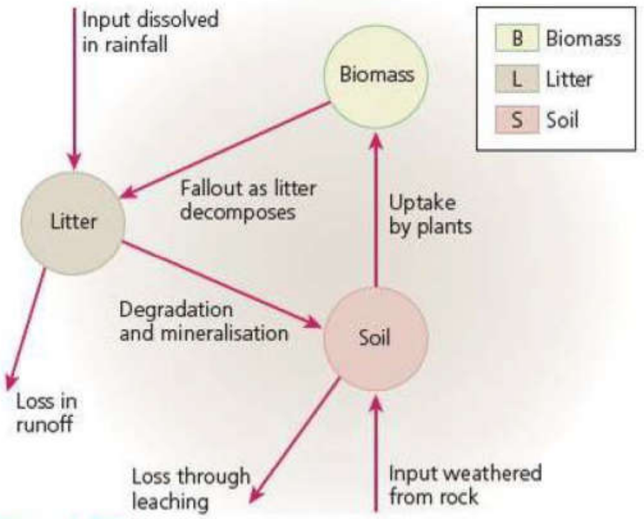


Figure 7.37 Gersmehl's nutrient cycle

The factors affecting the store of nutrients and their transfer are:

- the amount and type of weathering
- overland runoff and soil erosion
- eluviation
- the amount of rainfall
- rates of decomposition
- the nature of vegetation (woody species hold on to nutrients for much longer than annuals)
- the age and health of plants
- plant density
- fire.

Hence, explaining the differences between nutrient cycles in different ecosystems involves a consideration of many processes.

In the tropical rainforest, soil fertility is generally low. This can be explained by looking at the Gersmehl nutrient cycle model. The input of nutrients from weathering and precipitation is high (Figure 7.38) owing to the sustained warm wet conditions. However, most of the nutrients are held in the biomass due to the continual growing season. Breakdown of nutrients is rapid and there is a relatively small store in the soil. Where vegetation has been removed, the loss of nutrients is high due to high rates of leaching and overland flow.

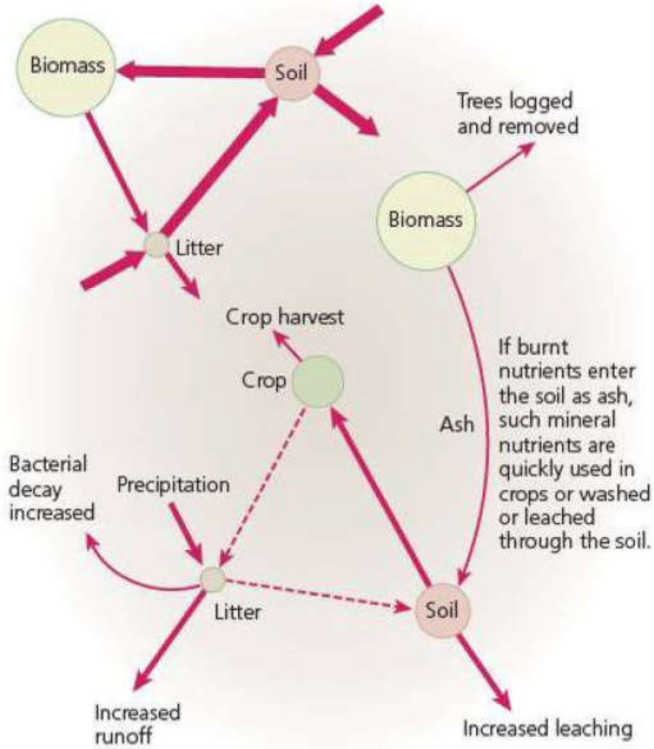


Figure 7.38 Nutrient cycle in a tropical rainforest

In contrast, in a savanna grassland ecosystem the biomass store is less than that of the tropical rainforest due to a shorter growing season. The litter store is also small due to fire. This means that the soil store is relatively large.

The savanna nutrient cycle differs from the tropical rainforest nutrient cycle because of the combined effects of a seasonal drought and the occurrence of fire. Consequently, there is:

- a lower nutrient availability
- a reduced biomass store
- a small litter store
- a relatively large soil store.

Section 7.3 Activities

1 Describe and explain the main characteristics of the nutrient cycle associated with tropical rainforests.
2 Outline the changes that occur as a result of human activity. Suggest reasons for the changes you have identified.

Savanna ecosystems

Origin

Savannas are areas of tropical grassland that can occur with or without trees and shrubs. Savannas are widespread in low latitudes, covering approximately one-quarter of the world's land surface – 18 million km² (compared with 2.6 million km² covered by tropical rainforest). Their origin is partly related to natural conditions and partly to human activities, especially burning. They occur between the tropical rainforest and the hot deserts, but there is not a gradual transition from rainforest through savanna to desert – rather, the savanna is a mosaic of plant communities influenced by many factors: climate, soils, drainage, geomorphology, geology and human factors, such as burning and animal grazing (Figure 7.39). Savannas are under increasing pressure from human activities. Trying to protect them is not proving easy.

According to Hills (1965), the factors affecting the development of savannas can be divided into predisposing, causal, resulting and maintaining. For example, in South America, climate predisposes vegetation to grassland rather than forest because grass is better able to survive the dry period. Landscape may be a causal factor as it affects drainage; laterite may be a resulting factor (being caused by drainage, but then in turn limiting the vegetation that can survive on impoverished soils), and fire a maintaining factor – human activity regulates the use of fire to produce grassland for grazing at the expense of forest.

Others suggest that edaphic (soil) characteristics may be important. Infertile soils with low water retention may only support grassland, whereas more fertile, moist soils may support forest. There is also a close relationship between soils and landscape – for example, soils at the base of slopes are often more moist and receive nutrients from further upslope.

Others suggest that savannas are the result of climate change in the Pleistocene period, when conditions were more arid. Many savanna trees are fire-resistant. Frequency of fire is important, as it allows fire-resistant species to invade. Woody species that take water from deeper may invade an area following overgrazing since the latter removes annual grasses and results in overland flow.

Climate

The climate that characterises savanna areas is a tropical wet/dry climate. However, there is great variation in the climate between savanna areas. The wet season occurs in summer: heavy **convectional rain** (monsoonal) replenishes the parched vegetation and soil. Rainfall can range from as little as 500 millimetres to as much as 2000 millimetres (enough to support deciduous forest). However, all savanna areas have an annual drought: these can vary from as little as one month to as much as eight months. It is on account of the dry season that grasses predominate. Temperatures remain high throughout the year, ranging between 23 and 28 °C. The high temperatures, causing high evapotranspiration rates, and the seasonal nature of the rainfall cause a twofold division of the year into seasons of water surplus and water deficiency. This seasonal variation has a great effect on soil development.

Climate and soils

The link between climate and soil could hardly be closer (Figure 7.40). Soils in the savanna are often leached ferralitic soils (ferruginous soils, tropical red earths). These are similar to soils of the rainforest but not as intensely weathered, are less leached and exhibit a marked seasonal pattern in soil process. They may have a concentration of iron and aluminium oxides in them, so are sometimes

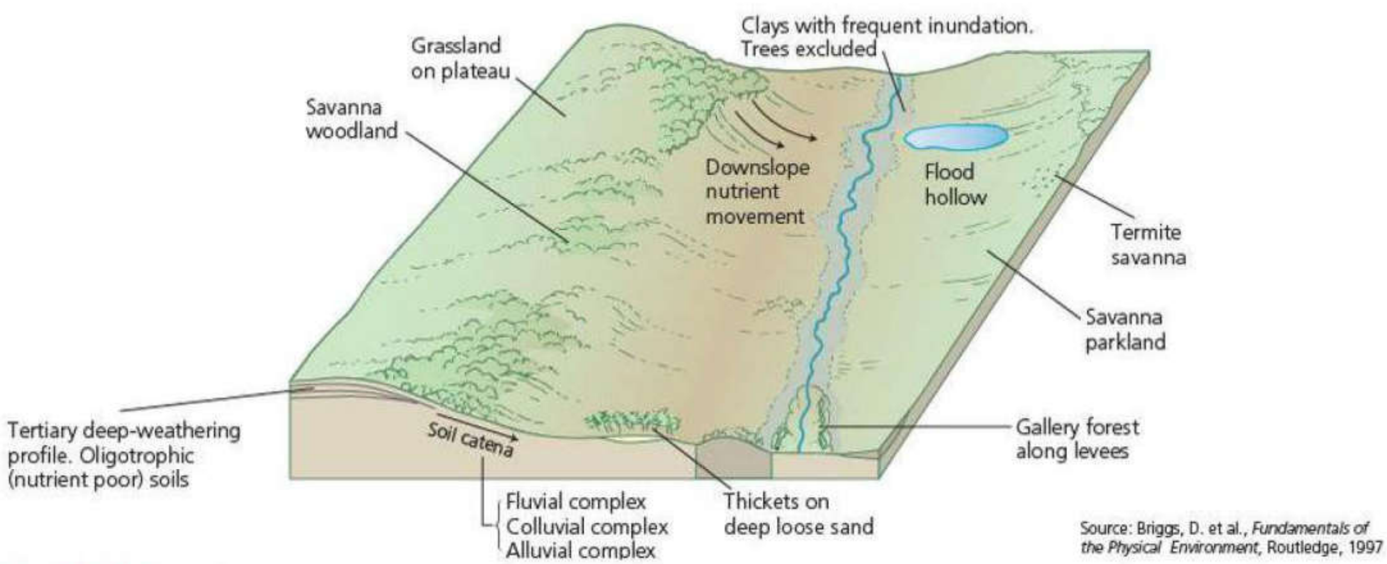


Figure 7.39 Types of savanna

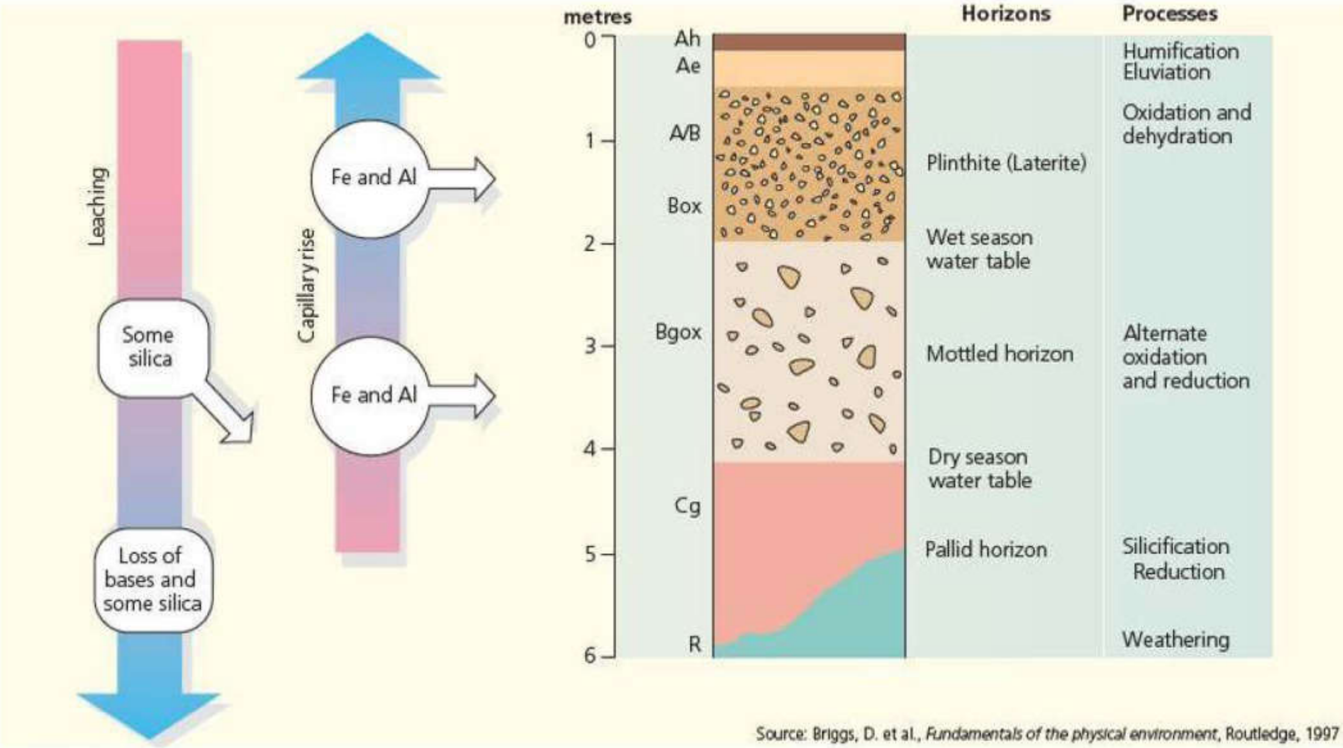


Figure 7.40 Savanna soils

referred to as red earths and tropical brown earths. During the wet season, the excess of precipitation (P) over potential evapotranspiration (E) means that leaching of soluble minerals and small particles will take place down through the soil. These are deposited at considerable depth. By contrast, in the dry season E > P. Silica and iron compounds are carried up through the soil and precipitated close to the surface. Capillary action also brings soluble bases to the surface. During the following wet season, leaching removes silicates, thereby leaving an upper horizon of iron and aluminium oxides, often in such a hard, compact layer that it forms an impermeable crust, known as 'laterite'. The bedrock tends to weather into a type of clay. This may become very plastic in the wet season, but very hard during the dry season. The soils are not fertile, and are poor for agriculture. They are certainly more suited for pastoral than for agricultural purposes. Soils with impermeable laterite have been called a 'pedological leprosy' and are subject to wind erosion.

Geomorphology plays an important role too. Some areas, notably at the base of slopes and in river valleys, are enriched by clay, minerals and humus that is deposited there. By contrast, plateaus, plains and the tops of slopes may be depleted of nutrients by erosion. The local variation in soil leads to variations in vegetation: this control by the soil is known as edaphic control. For example, on the thicker clay-based soils there is frequently woodland, whereas on the leached sandy soils, with poor water retention, grassland predominates. Savanna areas are frequently found on tectonically stable geological shields: these have therefore been weathered and are lacking in nutrients. Hence, even some river valleys may not be as fertile as their temperate counterparts.

A soil catena (Figure 7.41) can be observed in:

- thin, immature soils on the steep slopes close to the plateau top
- ferruginous soils on the freely drained slopes
- soils containing laterite where the lower part of the soil profile is affected by the water table
- vertisols (a vertical soil structure as a result of expansion of swelling clays) where the soil is largely beneath the water table.

Vegetation

Savanna vegetation is a mosaic including grasses, trees and scrub. All are xerophytic (adapted to drought) and therefore adapted to the savanna's dry season, and pyrophytic (adapted to fire). Adaptations to drought include deep tap roots to reach the water table, partial or total loss of leaves and sunken stomata on the leaves to reduce moisture loss. Those relating to fire include a very thick bark and thick budding that can resist burning, the bulk of the biomass being below ground level, and rapid regeneration after fire. Unlike shrubs, where growth occurs from the tips, the growth tissue in grasses is located at the base of the shoot close to the soil surface, so burning, and even grazing, encourage the growth of grass relative to other plants.

The warm wet summers allow much photosynthesis and there is a large net primary productivity of 900 g/m²/year. This varies from about 1000 g/m²/year where it borders rainforest areas to only about 200 g/m²/year

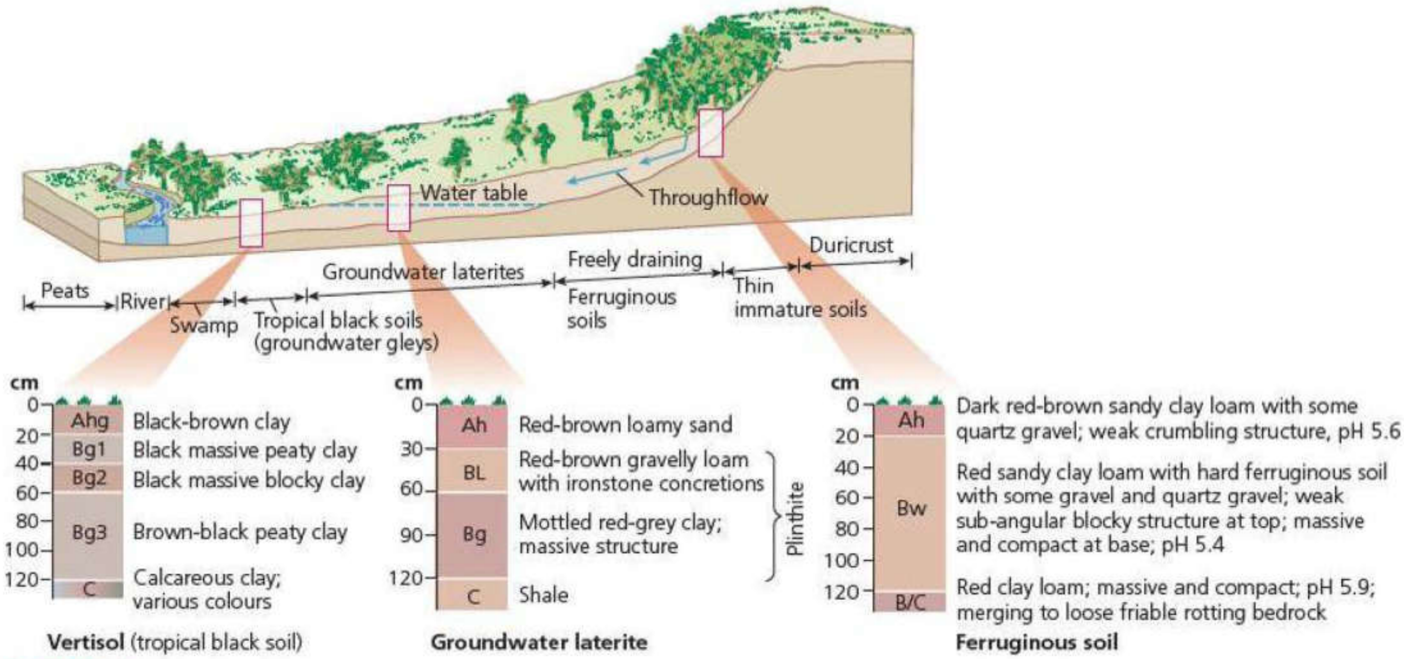


Figure 7.41 Soil catena in the savanna

where it becomes savanna scrub. By contrast, the biomass varies considerably (depending on whether it is largely grass or wood) with an average of 4 kg/m². Typical species in Africa include the acacia, palm and baobab trees (Figure 7.42) and elephant grass, which can grow to a height of over 5 metres. Trees grow to a height of about 12 metres and are characterised by flattened crowns and strong roots.

The nutrient cycle also illustrates the relationship between climate, soils and vegetation (Figure 7.43). The store of nutrients in the biomass is less than that in the rainforest because of the shorter growing season. Similarly, the store in the litter is small because of fire. Owing to fire, many of the nutrients are stored in the soil so that they are not burnt and leached out of the system. The role of fire, whether natural or caused by people, is very important (Figure 7.44). It helps to maintain the savanna as a grass community; it mineralises the litter layer; it kills off weeds, competitors and diseases; and prevents any trees from colonising relatively wet areas.

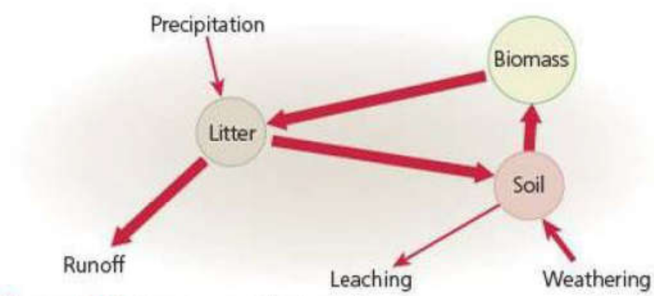


Figure 7.43 Savanna nutrient cycle

Figure 7.42 A baobab tree, Kruger National Park, South Africa

Figure 7.44 Fire is an important element of the savanna ecosystem

Other factors include the activities of animals. This includes locusts, for example, which can destroy large areas of grassland with devastating speed, and termites, which aerate the soil and break down up to 30kilograms of cellulose per hectare each year. In some areas, up to 600 termite hills per hectare can be found, thus having a significant effect on the upper horizons on the soil.

The fauna associated with savannas is diverse. The African savanna has the largest variety of grazers (over 40), including giraffe, zebra, gazelle, elephants and wildebeest (Figure 7.45). Selective grazing allows a great variety of herbivores: for example, the giraffe feeds off the tops of the trees, the rhinoceros the lower twigs and gazelle the grass beneath the trees. These animals are largely migratory, searching out water and fresh pastures as the dry season sets in. A variety of carnivores including lions, cheetahs and hyenas are also supported.

Figure 7.45 Savanna fauna – zebra

Section 7.3 Activities

1 Outline the ways in which **a** savanna vegetation and **b** savanna fauna are adapted to seasonal drought.
2 Explain why fire is important in savanna ecosystems.

Tropical rainforest soils

The soils of these tropical areas are usually heavily leached and **ferralitic**, with accumulations of residual insoluble minerals containing iron, aluminium and manganese (Figure 7.46). They are variously called **latosols**, **oxisols** and ferralitic soils. A distinction can be made between ferralitic soils (of the rainforest) and weathered ferralitic (ferruginous) soils that are found in savanna regions. The hot humid environment speeds up chemical weathering and decay of organic matter. This biome also covers ancient shield areas that have remained tectonically stable for a very long time and were unaffected by the Pleistocene glaciations. Not only are the soils well developed, but they have been weathered for a long time and are therefore lacking in nutrients and so are inherently infertile. More than 80 per cent of the soils have severe limitations of acidity, low nutrient status, shallowness or poor drainage. This is unusual given the richness of the vegetation that it supports. However, the nutrients are mainly stored in the biomass due to the rapid leaching of nutrients from the A horizon (see Figure 7.40). There is only a small store of nutrients in the litter or the soil itself.

Figure 7.46 Tropical red earth, Brunei

The rate of litter fall is high – 11 tonnes/hectare/year – and there is humus turnover of 1 per cent a day. At 25–30 °C, the breakdown and supply of litter is approximately equal. The rapid rates of decomposition and the rapid leaching of nutrients from the rooting area have led to an unusual adaptation in this ecosystem. The main agents of decay are fungi in mycorrhizal relationships with the tree roots. Nutrients are passed directly from the litter to the trees by the fungi (living on the tree roots). This bypasses the soil storage stage, when there is a strong chance that the nutrients will be lost from the nutrient cycle completely.

The rapid decay of litter gives a plentiful supply of bases. Clay minerals break down rapidly and the silica element is carried into the lower layers. Iron and aluminium sesquioxides, which are relatively insoluble, remain in the upper layers, as they require acidic water to mobilise them. These leached red or red–brown soils are termed ferralitic soils (Figure 7.40). Where it is wet, the iron may be hydrated and yellow soils develop. Deep weathering is a feature of these areas and the depth of the regolith may be up to 150 metres deep. Where a parent material allows free drainage and is poor in bases, such as a coarse sandstone, a tropical podsol will form. Catenas are very poorly developed under tropical rainforests.

These soils are not easy to manage. If they are ploughed, severe soil erosion may occur. Vegetation interrupts the nutrient cycle. In the rainforest, vegetation and soil are the major components in an almost closed nutrient cycle. The major store of plant nutrients is in the vegetation. The leaves and stems falling to the soil surface break down rapidly and nutrients are released during the processes of decomposition. These are almost immediately taken up by the plants. By contrast, the supply of nutrients from the underlying mineral soil is a small component. If the forest cover is removed, the bulk of the system's nutrient store is also removed. This leaves a well-weathered, heavily leached soil capable of supplying only low levels of nutrients.

Even when the forest is burnt, the nutrients held in the plant biomass store are often lost. During burning, there may be gaseous losses and afterwards rainfall may leach nutrients from the ash on the surface. In addition, the soils have a low cation-exchange capacity (CEC – see the following section). Unless a plant cover is rapidly established, most of the nutrients released from the plant biomass during burning will be lost within a short time. Thus, shifting cultivation can only take place for a few years before the overall fertility of the soil is reduced to such an extent that it is not worthwhile continuing cropping the plot. Indeed, farmers try to replicate the rainforest environment by intercropping. This provides shelter for the soil and protects it from the direct attack of intense rain (rainsplash erosion can otherwise be a serious problem). Compaction of the soil by heavy raindrops and the reduction of the infiltration capacity as a result will lead to overland flow and soil erosion even if there is only a slight slope.

Soils that are predominant in the region offer conditions only marginally suitable for most of these crops. They are often clayey textured, of low pH value, generally of less than medium fertility and offer only restricted rooting depths.

Changes to rainforest soils

Tropical rainforests are disappearing at an alarming rate and 'green jungles' are being changed into 'red deserts'. The loss of rainforest is up to 200 000 km²/year. By 2050, it is possible that there will be no extensive tracts of primary tropical rainforest, but simply isolated refuges of a few tens or hundreds of square kilometres. The tropical rainforest is a unique natural resource with a tremendous diversity of flora and fauna, much of which has still to be scientifically identified and studied.

To those who live within or close to the rainforest, the forest is a resource they are eager to exploit. To many economically marginal households, the land presently occupied by forest is seen as a way of improving their quality of their life, and to become self-sufficient in farming. Rainforests are areas of low population density, and in some areas are relatively unexploited. However, in some cases new farmers have little experience of the tropical environment. Some are the urban poor, while others are farmers familiar with very different environments. Table 7.5 shows the distribution of the different types of soil in the humid tropics.

Table 7.5 Distribution of the main types of soil in the humid tropics

	Million hectares
Acid, infertile soils	938
Moderately fertile, well-drained soils	223
Poorly drained soils	119
Very infertile sandy soils	104
Shallow soils	75
Total	**1459**

Source: S. Nortcliff, 'The clearance of the tropical rainforest', Teaching Geography, *April 1987*

Table 7.6 shows the characteristics of an oxisol (leached ferruginous soil) under tropical rainforest in Amazonas State, Brazil. The oxisol is deep and acidic (low pH). It has a low cation-exchange capacity and a low base saturation. The CEC is a measure of the soil's capacity to absorb and exchange positively charged ions (cations) such as potassium, calcium, magnesium, hydrogen and aluminium. The base saturation measures the proportion of the exchangeable cations that are bases (that is, not hydrogen and aluminium, which are acidic). A low CEC and low base saturation mean that the soil has a poor reserve of nutrients readily available to plants and that it also has an undesirable balance between ions for plant growth. Thus it is infertile. In the oxisol, the only horizon with a substantial CEC is the surface horizon, due to the presence of organic matter.

Table 7.6 Characteristics of an oxisol under tropical rainforest in Amazonas, Brazil

Depth (cm)	% organic matter	% sand	% silt	% clay	pH1 (H_2O)	CEC2 meq/100g	BS3 %
0–8	3.4	10	15	75	3.4	18	2
8–18	0.6	11	11	78	3.7	8	4
18–50	0.5	7	8	85	4.2	4	5
50–90	0.3	7	4	89	4.5	3	5
90–150	0.2	7	3	90	4.7	3	5
150–170	0.2	5	3	92	4.9	2	5

Notes:
1 pH determined in a 1:2.5 soil/water ratio
2 CEC expressed as milli-equivalents per 100g of soil
3 Percentage base saturation (sum of base cations/CEC 100).

Source: S. Nortcliff, 'The clearance of tropical rainforest', Teaching Geography, *April 1987*

Research near Manaus in Brazil investigated changes in the soil's physical characteristics that resulted when rainforest was cleared, first using traditional slash-and-burn techniques and second using a bulldozer (Table 7.7). Several observations of soil characteristics were made, including changes in soil surface, dry bulk density, moisture content and infiltration rate.

Table 7.7 Soil moisture contents – comparisons between uncleared forest, burned and bulldozed sites, Amazonas, Brazil

Depth below final soil surface (cm)	Virgin forest	Burnt	Bulldozed
	% soil moisture content		
0–10	52.1	40.8	40.8
10–20	44.4	40.4	39.4
20–40	41.4	40.4	38.6

On the site cleared by bulldozer, the change in soil surface height ranged from 2 to 9 centimetres, with an average of 5.7 centimetres. Thus much of the topsoil horizon was removed, leaving a denser subsurface horizon at or very close to the surface. The removal of the topsoil removes much of the soil organic matter, which is often the major store of plant nutrients within the soil.

There were increases in the soil dry bulk density resulting from the passage of heavy machinery over the surface, causing changes in the infiltration rate (the rate at which water can enter the soil) from over 200 centimetres/hour under uncleared forest, to 192 centimetres/hour at the slash-and-burn site and to 39 centimetres/hour at the bulldozed site.

The moisture content of the 0–10 centimetres and 10–20 centimetres layers of both burned and bulldozed sites were similar, and were significantly lower than the uncleared forest site. These differences reflect the removal of the organic matter during clearance. The organic matter acts both as a store of moisture and as a natural mulch restricting moisture loss.

Crop yields were higher in burnt plots because of the nutrient content of the ash (Table 7.8). The ash caused major changes in soil conditions. Soil acidity decreased and, compared with the bulldozed site, the organic matter was higher (although it was lower than that of the uncleared forest). The importance of ash to soil fertility and crop yield following clearance is substantial, especially in soils of low fertility.

Table 7.8 Crop response to forest clearance and different soil fertiliser applications, Vurimaguas in Peru

Fertility level	Slash and burn	Bulldozed	Bulldozed/ Burnt
	Yield tonnes per hectare		
Maize (grain yield)	0	0.1	0
NPK	0.4	0.04	10
NPKL	3.1	2.4	76
Soyabeans (grain yield)	0	0.7	0.2
NPK	1.0	0.3	34
NPKL	2.7	1.8	67
Cassava (fresh root yield)	0	15.4	6.4
NPK	18.9	14.9	78
NPKL	25.6	24.9	97

Fertiliser applications:
N = 50kg nitrogen/ha
P = 172kg phosphorus/ha
K = 40kg potassium/ha
L = 4 tonnes lime/ha

Sites labelled 0 received none of the above fertiliser applications.
Sites labelled NPK received applications of nitrogen, phosphorus and potassium.
Sites labelled NPKL received all applications.

Forest clearance in the tropics will continue in order to satisfy the demands of the growing population (see Topic 4, Section 4.1). The priority therefore should be to slow down the rate of clearance. This can be done by making the most effective use of the cleared land and by limiting the need for forest clearance to replace land cleared at an earlier stage. These aims can be achieved by:

- increasing the productivity of land already cleared by selection of suitable crop and land-management combinations
- minimising the damage that results from forest clearing methods by adopting methods of clearance and timing of clearance that produce the least detrimental effects
- restoring eroded or degraded land by the establishment of more appropriate land-management systems.

Section 7.3 Activities

1 Study Table 7.5. Explain why tropical rainforests have some of the world's most luxuriant vegetation and yet some of the world's least fertile soils.
2 Using examples, examine the effects of human activities on tropical soils.
3 With the use of an example, describe and explain the formation of a soil catena.

7.4 Sustainable management of tropical environments

Case Study: The Heart of Borneo

The forests of Borneo have suffered hugely in recent decades from rampant logging, slash-and-burn farming and cutting for oil palm and rubber plantations (Figure 7.47). The island's rich lowland forests have nearly vanished, with rates of forest loss still among the highest on Earth. There has also been widespread hunting. At Lambir Hills National Park in Sarawak, for example, half of the primate species, six of seven hornbill species and nearly all of the endangered mammal species have been hunted out. With the disappearance of its key seed dispersers, the fruits of many trees now just rot on the forest floor.

Figure 7.47a Rainforest converted to arable farming

Figure 7.47b Rainforest flooded to create HEP scheme

Figure 7.47c Cut trees choke a river

In 2007, the three governments of Borneo (Indonesia, Malaysia and Brunei) signed the Heart of Borneo (HoB) Declaration. The HoB was established in 2010 to protect the ecological, biological and cultural features of the Borneo rainforest. The Iban long house is part of the cultural tradition of Borneo (Figure 7.48). The HoB is largely in the central parts of Borneo (Figure 7.49), where the rainforest is mainly still intact. It covers 22 million hectares of rainforest, including some of the most biologically diverse habitats on Earth.

The forests of the HoB provide many benefits to the industries and communities of Borneo, such as clean water supplies, carbon sequestration, biodiversity benefits, economic revenues and important cultural services (Figure 7.50).

Figure 7.48 Iban long house

Figure 7.49 The location of the HoB

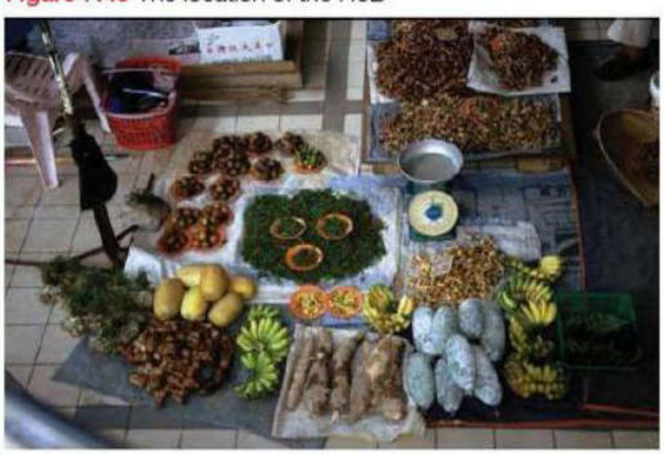


Figure 7.50 Food from the rainforest on sale at a market

Figure 7.51 Tourists boating – many rainforest sites are accessible only by river

Ecological services of the Heart of Borneo

Of the 20 major rivers in Borneo, 14 have their source in the mountainous forests of the HoB. The forests and peat lands of Borneo are particularly important because they are very effective carbon stores, with an average of 230 tonnes per hectare in above-ground biomass, and 2 400 tonnes per hectare in below-ground peat soils; most of this is released by deforestation and land degradation. Deforestation in Indonesia and Malaysia currently accounts for more than 80 per cent of their total carbon emissions, representing more than 2.5 Gt CO_2 per year; this is equivalent to almost four times the annual emissions from the global aviation industry.

Borneo has a rich biodiversity: more than 350 species of bird, 150 species of reptile and 15 000 flowering plants. Indeed, for every 10 hectares, there are over 700 species of trees.

The economic value of the HoB forests is equally significant. The HoB has rich natural resources in the form of timber and other forest products. If managed sustainably, these resources have the potential to provide continuous and long-term income. Sustainable forest management also maintains the flow of ecosystem services, such as water provision, pollination and local climate regulation.

Communities living within the forest depend on it for food, water, medicine and construction materials. Tourism also brings in a lot of money (Figure 7.51). In 2009, Sabah in Malaysia alone recorded more than 2 million arrivals, generating an estimated US$1.2 billion in tourism receipts.

Table 7.9 Extent of forestry, palm oil and coal mining concessions within the HoB

	Kalimantan (ha)	Malaysia (ha)	Brunei (ha)	Total (ha)
Palm oil	830 000	770 000	–	1 600 000
Palm oil RSPO certified	–	12 000	–	12 000
Forestry	2 600 000	3 200 000	138 000	5 938 000
FSC certified	424 000	215 000	–	639 000
Mining	1 100 000	–	–	1 100 000

Table 7.10 Potential environmental issues that can arise from poor management of forestry activities

Habitat loss	Logging natural forests	Clear-felling removes the whole forest ecosystem, resulting in severe reduction or complete loss of habitat and ecosystem values. The impacts associated with selective logging are less adverse, but can nevertheless be significant if managed poorly.
	Plantations	Plantations demand large areas, and their monocultures have very limited biodiversity. If plantations are built by clear-felling natural forest they lead to a severe loss of habitat and ecosystem values.
Carbon emissions		Borneo's forests are a carbon sink of global importance; however, deforestation releases this carbon. Fire is often used to clear forest, which can spread uncontrollably. The 1997–98 fires burnt 9.7 million ha of land, releasing huge quantities of carbon dioxide. Plantations on cleared land only sequester a small proportion of these emissions.
Land erosion	Logging natural forests	Clear-felling exposes the land to soil erosion, and poorly implemented selective logging can also result in serious soil degradation. Heavy rain and wind removes exposed and disturbed topsoil, rendering the land less productive for agriculture and severely impacting the prospects of forest regeneration in the area.
	Plantations	Without proper management, plantations suffer from soil erosion and land degradation, especially where large expanses of land are cleared and then not subsequently planted.
Degradation of watercourses	Logging natural forests	The clearance of watershed forest cover can degrade the quality of watercourses, leading to unpredictable and severe flash floods and mudslides that endanger downstream settlements.
	Plantations and processing operations	Plantations often use chemical fertilisers and pesticides. In addition, effluent waste from paper processing can contain high concentrations of bleaches that are toxic if not properly treated. This can leach into groundwater, affecting drinking supplies for the local communities and downstream urban areas. The overuse of water and diversion of watercourses can lead to shortages elsewhere.
Social issues		The allocation of logging and plantation concessions does not always take into consideration the traditional land rights of indigenous and other communities. These communities may use the land for crops and fruit trees, or for social activities. Logging and plantation expansion can result in conflict and displacement.

Source: WWF, Business solutions: delivering the Heart of Borneo declaration

However, growing populations and international demand have led to greater production from the palm oil, forestry and mining industries (amongst others), putting increasing pressure on Borneo's forests (Table 7.9). Moreover, the states of Borneo remain some of the poorest in the region, with an estimated 23 per cent of the population living below the poverty line in Sabah, for example.

Sustainable forestry

Changes in the production of Indonesia's and Malaysia's timber industry illustrate the need for an urgent shift towards a sustainable extraction model. The forestry sector manages the most land of any sector operating inside the HoB, and therefore has the greatest opportunities for sustainable use, but also the greatest risks in the absence of good practice (Table 7.10).

Sustainable logging of natural forests is a good example of how the standing forests can provide long-term revenues while maintaining a large proportion of the forests' values.

Plantation area is increasing across Borneo to meet the growing demand for timber and fibre for paper mills. It is essential that the expansion of mill capacity is matched by commensurate increases in sustainable plantations.

Sustainable forestry – the way forward:

- Logging activities should be avoided in high conservation-value forests; and elsewhere, reduced impact logging and sustainable forest management should be implemented to minimise environmental impacts.
- Plantations should not replace high conservation-value forests, and should instead be cultivated on the available idle land.
- Investors, traders and consumers should help drive **sustainable management** through financing and sourcing Forest Stewardship Council (FSC)-certified production.

Palm oil

The palm oil industry in Borneo has undergone rapid growth, and continues to expand to meet growing world demand. Indonesia's and Malaysia's palm oil production amounts to 85 per cent of the global supply, and production in Borneo in 2008 was 16.5 million tonnes, representing more than a third of this global supply. Oil palm plantations in Sabah grew from almost nothing in the mid-1980s to covering nearly 20 per cent of Sabah's land by 2010.

Palm oil plantations require the complete conversion of land use; if concessions are placed in high conservation-value areas, it can result in a significant loss of ecosystem value (Table 7.11). The challenge for the governments' vision enshrined in the HoB Declaration is to ensure that as the cultivated area increases, adequate protection is given to the HoB.

Palm oil – the way forward:

- Future revenues from the industry can be maintained and even increased by concentrating on increasing productivity, particularly amongst smallholders; by expanding plantations on idle lands; and by developing downstream processing industries. This adds value without increasing pressure to convert natural forests.
- Planners should ensure concessions are not allocated in high conservation-value areas of the HoB, but rather on idle land with low conservation values.

Table 7.11 Potential environmental issues that can arise due to inappropriate choice of locations or poor management of palm oil plantations

Habitat loss	Conversion of high conservation-value areas and their ultimate replacement with palm oil plantations results in reduced habitat and the loss of 80–90% of species, many of which may be endemic or threatened. Orang-utan habitat declined 39% in 1992–2002.
Carbon emissions	Borneo's forests are a carbon sink of global importance; deforestation releases this carbon, contributing to global climate change.
Fire	Despite its use being illegal across Borneo, fire is still used to clear forests. In 1997–98, fires burnt 9.7 million ha of land, releasing huge quantities of carbon dioxide; and fires can still be severe – most recently in May 2010.
Watershed degradation	Palm oil plantations often use chemical fertilisers and pesticides. Inappropriate use can result in polluting runoff entering watercourses and contaminating groundwater through leaching. This in turn can pollute drinking water for downstream communities and adversely affect aquatic wildlife and fishing yields. Inappropriate irrigation and diversion of watercourses can also lead to water shortages.
Land degradation	Deforestation, forest fires and peatland drainage expose the land to soil erosion. If land is left uncultivated, or is not effectively managed, soil erosion and land degradation can occur, particularly on sloped land. Heavy rain and wind remove topsoil, rendering the land less productive for agriculture and reducing the chance of forest regeneration. This can increase the frequency and severity of unpredictable flash floods, threatening lives, infrastructure and the environment.
Social issues	The allocation of palm oil concessions does not always take into consideration the traditional land rights of indigenous and other communities. These communities may use the land for crops and fruit trees, or for social activities. Plantation expansion can result in conflict and displacement.

- A shift to sustainable production, independently certified through the Roundtable for Sustainable Palm Oil (RSPO), will result in the improved environmental performance of existing and new plantations. Food suppliers and consumers are putting pressure on palm oil producers to guarantee that their palm oil is from sustainable sources. The RSPO was formed in 2004 to promote the growth and use of sustainable palm oil products through credible global standards and engagement of stakeholders. RSPO is a not-for-profit group that unites palm oil producers, processors and traders; consumer goods manufacturers; retailers; banks; investors; and environmental, social and development NGOs.
- Another approach has been adopted at the Yayasan Sabah forest. This was meant to be sustainably logged over an 80-year period. Instead, about 75 per cent of it was intensively logged. The director of forestry for the state of Sabah is trying to reverse the region's trend toward deforestation, moving forward with a plan to convert 10 per cent of Yayasan Sabah to palm oil plantations to generate revenue, and then gradually restore most of the rest of the tract so it can be sustainably logged. Palm oil plantations have been established on 100 000 hectares of land cleared for the pulp plantations. The revenue created by palm oil should generate the needed funds for Sabah's social programmes. The long-term plan is to restore the forests to a state of health where they can be logged again, albeit under the more stringent guidelines of the FSC.

Mining in Borneo

The Indonesian and Malaysian governments are both considering increasing their mining production, especially that of coal. In the short term, coal will remain an important and relatively low-cost source of energy for developing countries.

Legal and illegal coal and gold mining has significant social and environmental impacts (Table 7.12).

Table 7.12 Potential environmental issues that can arise from poor management of mining activities

Habitat loss	Open-cast mining is land intensive and requires the removal of large areas of terrestrial habitat and the loss of associated ecosystem value. There are also often secondary impacts that lead to habitat loss associated with both open-cast and underground mining activities. These include direct habitat removal and habitat fragmentation for construction of access roads or rail infrastructure.
Land removal and soil degradation	Large volumes of soil and overburden are extracted and processed in mining operations, and these can generate contaminated tailings as by-products. This can result in soil degradation, erosion and contamination, and also generate 'geohazards' such as subsidence and landslides.
Degradation of watercourses	Mine effluent can adversely affect water quality by increasing sedimentation in local watercourses and introducing contaminants. Even low levels of mercury and cyanide (used in gold processing) are toxic to most forms of wildlife and humans. Tailings (materials left over from mining and quarrying) can form acids through oxidisation that leach into the groundwater and enter watercourses.
Social conflict, health and displacement	Mining operations (both legal and illegal) attract large influxes of workers and associated temporary settlements and informal economies. This can encourage the spread of communicable diseases (e.g. HIV-AIDS) and diseases that thrive in poor-quality living quarters for workers (which can also spread to local communities). There is often high workforce turnover, caused in part by adverse health effects of mercury and cyanide where these are used. Mining activities can in some cases displace both indigenous and local communities, resulting in conflicts with mining companies over security and land rights.

Mining in Borneo – the way forward:

- Clear regulation and effective enforcement is needed across the region, for example of Environmental Impact Assessments and reclamation of land. Increased efforts are needed to control illegal mining and reduce the use of mercury by gold miners.
- Mining companies should identify high conservation-value forests before starting mining operations and ensure an adequate management plan is put in place to protect the value of the area during mining and after it is completed.
- Mine rehabilitation needs to be planned and implemented.

Conclusion

Success has been varied in terms of protecting areas of tropical rainforest. Sabah is still far ahead of Sarawak and Kalimantan, since surviving primary forest areas are being conserved; reforestation and forest restoration is happening; and encroachers have moved out of forest reserves. However, there is uncertainty as to whether a change in government may lead to a change in policies. Gains from conservation and reforestation could be reversed. Moreover, population growth and changes in standards of living will continue to put pressure on the forests of Borneo, and the land of Borneo, to provide for its people.

Source: The information in this Case Study has come from WWF, Business solutions: delivering the Heart of Borneo declaration

Section 7.4 Activities

1. Outline the consequences of the conversion of rainforest to palm-oil plantations.
2. Comment on the impacts of mining in rainforest areas.
3. Evaluate the attempts to manage Borneo's rainforest in the HoB.

Case Study: Sustainable agroforestry, Santa Rosa rainforest, Mexico

The Popoluca Indians of Santa Rosa in the Mexican rainforest practise a form of agriculture that resembles shifting cultivation, known as the **milpa system** (Table 7.13). This is a labour-intensive form of agriculture, using **fallow**. It is a diverse form of **polyculture** with over 200 species cultivated, including maize, beans, cucurbits, papaya, squash, water melon, tomatoes, oregano, coffee and chilli. The Popolucas have developed this system that mimics the natural rainforest. The variety of a natural rainforest is replicated in the form of shifting cultivation, for example lemon trees, peppervine and spearmint are **heliophytes** (light-seeking plants), and prefer open conditions, not shade. By contrast, coffee is a **sciophyte** (shade-tolerant plant), while the mango tree requires damp conditions.

The close associations that are found in natural conditions are also seen in the Popolucas' farming system, for example maize and beans grow well together, as maize extracts nutrients from the soil whereas beans return them to the soil. Tree trunks and small trees are left because they are useful for many purposes, such as returning nutrients to the soil and preventing soil erosion. They are also used as a source of material for housing and hunting spears, and for medicines.

As in a rainforest the crops are multi-layered, with tree, shrub and herb layers. This increases NPP per unit area, because photosynthesis is taking place on at least three levels, and soil erosion is reduced, as no soil is left bare. Most plants are self-seeded and this reduces the cost of inputs. The Popolucas show a huge amount of ecological knowledge and management. In all, 244 species of plant are used in their farming system. Animals include chickens and turkeys. These are used as a source of food, for barter and in exchange for money, and their waste is used as manure. Rivers and lakes are used for fishing and catching turtles. Thus it is not entirely a subsistence lifestyle, since wood, fruit, turtles and other animals are traded for some seeds, mainly maize.

Pressures on the Popolucas

About 90per cent of Mexico's rainforest has been cut down in recent decades, largely for new forms of agriculture. This is partly a response to Mexico's huge international debt and attempts by the government to increase its agricultural exports and reduce its imports. The main new forms of farming are:

- **cattle ranching** for export, and
- **plantations** of cash crops, such as tobacco, also for export.

However, these new methods are not necessarily suited to the physical and economic environment. Tobacco needs protection from too much sunlight and excess moisture, and the soil needs to be very fertile. The cleared rainforest is frequently left bare and this leads to soil erosion. Unlike the milpa system, the new forms of agriculture are very labour intensive. Pineapple, sugar cane and tobacco plantations require large inputs of fertiliser and pesticides. Inputs are expensive and the costs are rising rapidly.

Ranching prevents the natural succession of vegetation, because there is a lack of seed from nearby forests and the cattle graze off young seedlings. Grasses and a few legumes become dominant. One hectare of rainforest supports about 200 species of trees and up to 10000 individual plants. By contrast, 1 hectare of rangeland supports just one cow and one or two types of grass. However, it is profitable in the short term because land is available, and it is supported by the Mexican government. ⇨

Extensive **monoculture** is increasingly mechanised, and uses large inputs of fertiliser, pesticides and insecticides. However, it is very costly and there are problems of soil deterioration and microclimatic change. Yet there is little pressure to improve efficiency because it is easy to clear new forest.

The Mexican rainforest can be described as a 'desert covered by trees'. Under natural conditions it is very dynamic, but its resilience depends on the level of disturbance. Sustainable development of the rainforest requires the management and use of the natural structure and diversity; that is, local species, local knowledge and skills, rather than a type of farming that has been developed elsewhere and then imported.

Table 7.13 A comparison between the milpa system and the new forms of agriculture

	Milpa system	Tobacco plantation or ranching
NPP	High, stable	Declining
Work (labour)	High	Higher and increasing
Inputs (clearing and seeding)	Few	Very high: 2.5–3 tonnes fertiliser/ha/year
Crops	Polyculture (244 species used)	Monoculture (risk of disease, poor yield, loss of demand and/or overproduction)
Yield (compared to inputs)	200%	140% (at best)
Reliability of farming system	Quite stable	High-risk operation
Economic organisation	Mainly subsistence	Commercial
Money	None/little	More
Carrying capacity (livestock)	Several families/4 ha	1 family on a plantation (200 ha)
Ranching	1 ha of good land = 1 cow	20 ha of poor land = 1 cow

Section 7.4 Activities

Compare the Popolucas' methods of farming with the ecosystem of the natural tropical rainforest. What lessons can be learnt from this?

Case Study: CAMPFIRE, Zimbabwe – sustainable management in savanna areas

Almost 5 million people live in communal lands that cover almost half of Zimbabwe. Most of this land can be described as savanna land. CAMPFIRE (Communal Areas Management Programme for Indigenous Resources) is a programme designed to assist rural development and conservation. It works with the people who live in communal lands, supporting the use of wildlife as an important natural resource. CAMPFIRE is helping people in these areas manage the environment in ways that are both sustainable and appropriate.

National Parks

Approximately 12 per cent of Zimbabwe is protected as National Parks or conservation areas, such as Hwange National Park and the Matopas. Many local people were evicted from their homes when the Parks were created. Most now live in the surrounding communal lands. They are no longer permitted to hunt the animals or harvest the plants now found inside protected areas. However, animals frequently roam outside Park boundaries, destroying crops and killing livestock and sometimes people. This has created much conflict between local people and National Park staff, often resulting in illegal hunting.

Raising awareness and raising money

The CAMPFIRE movement began in the mid-1980s. It encourages local communities to make their own decisions about wildlife management and control. It aims to help people manage natural resources so that plants, animals and people – the whole ecosystem – all benefit. It helps provide legal ways for such communities to raise money by using local, natural resources in a sustainable way. As a result, many communities now actively protect local wildlife, seeing it as a valuable asset. In some areas, local people have even provided animals with emergency food and water in times of shortage.

Five particular activities help provide extra income to local communities:

- **Trophy hunting** – About 90 per cent of CAMPFIRE's income comes from selling hunting concessions to professional hunters and safari operators working to set government quotas. Individual hunters pay high fees to shoot elephant (US$15 000) and buffalo and are strictly monitored, accompanied by local, licensed professionals. Cecil the lion, a 13-year-old male, was a major tourist attraction in Hwange National Park (Figure 7.52). He was shot and killed in 2015, by a North American dentist. The killing caused an international outrage. **Trophy hunting** is considered to be the ultimate form of ecotourism as hunters usually travel in small groups, demand few amenities and cause minimal damage to the local ecosystem, yet provide considerable income.
- **Selling live animals** – This is a fairly recent development. Some areas with large wildlife populations sell live animals to National Parks or game reserves. For example, Guruve district raised US$50 000 by selling ten roan antelope.
- **Harvesting natural resources** – A number of natural resources, for example crocodile eggs, caterpillars, river-sand and timber are harvested and sold by local communities. Skins and ivory can be sold from 'problem animals' (individual animals that persistently cause damage or are a threat can legally be killed).

- **Tourism** – In the past, most revenue from tourists has not gone to local communities. During the 1990s, pilot projects were set up and five districts now benefit from tourism. There has been development of specialist tourist areas, such as culture tourism, bird watching and visits to hot springs. Some local people are employed directly as guides, or run local facilities for tourists.
- **Selling wildlife meat** – Where species are plentiful, for example impala, the National Parks Department supervises killing and selling of skins and meat. However, this raises relatively small sums of money.

Figure 7.52 Cecil the lion

Organisation

Each village taking part in the CAMPFIRE project has a wildlife committee responsible for counting animals, anti-poaching activities, conflicts that arise through 'problem animals' and environmental education. Game scouts are trained to help stop poaching and manage wildlife.

Quotas

For hunting concessions to be granted and wildlife managed sustainably, local communities need to monitor their wildlife populations and manage their habitats, protecting them from poaching or alternative forms of land use, for example farming. Every year, the Department of National Parks helps to estimate the wildlife population totals so that sustainable quotas can be set.

Tour operators must, by law, keep detailed records of animals killed – their size, weight, length of certain animals and/or horns and tusks. This helps check that young animals are not being taken, which would put future numbers at risk. New quotas are not issued until operators produce these records for analysis by the Department for National Parks.

Up to 80 per cent of the money raised is given directly to local communities, which collectively decide how it should be spent. Money is used for the community, for example for building and equipping clinics and schools, constructing fences, drilling wells and building roads. In bad years, usually drought years, money may be used to buy maize and other foodstuffs. Since 1989, over 250 000 Zimbabweans have been involved in CAMPFIRE projects.

In 1980, Binga District in north-west Zimbabwe had just 13 primary schools, and most of its people lived in poverty. Money from hunting concessions, fishing and tourism was used by Sinkatenge village (near Matusadona National Park) to build a 12 kilometre length of electric fencing to enclose their fields, preventing animals from trampling their crops and providing full-time work for two local people to maintain it. Today, partly as a result of income from CAMPFIRE projects, the District has about 80 primary and around 40 secondary schools, and several health clinics and wells.

Masoka in the north-east was one of the first to join CAMPFIRE. Local people now receive more than four times their previous income via hunting concessions, using it to buy maize and other food in drought years, building a clinic, buying a tractor and funding their football team. For the first time here, local rural women were employed, working on CAMPFIRE projects. CAMPFIRE is also actively encouraging women to participate in community decision-making, something that has been traditionally dominated by men. Women have also been encouraged to attend workshops and take part in training schemes.

Nyaminyama District, on the southern edge of Lake Kariba, is introducing land-use zoning, with specific areas for wildlife conservation, tourism, crocodile breeding and hunting. A recent WWF report estimated that CAMPFIRE has increased incomes in communal areas by up to 25 per cent.

The future

There are many advantages of CAMPFIRE's activities in Zimbabwe:

- It creates jobs – local people are trained and become involved as environmental educators, game scouts, and so on.
- It prompts environmental education and promotes the benefits of wildlife conservation to communities.
- It provides an incentive for people to conserve wild species.
- It generates funds, which are used for community projects or to supplement household incomes.
- Communal lands can act as game corridors between existing National Parks, protecting the genetic diversity of wild species.

Rural communities benefit from secure land tenure and rights over their wildlife. The ability of CAMPFIRE to assist wildlife conservation in Zimbabwe depends on two broader factors:

- the acceptance of hunting as a wildlife management tool by the international community
- placing economic value on wild species.

Section 7.4 Activities

1 Briefly explain the difficulties in developing tropical environments.
2 With the use of examples, outline opportunities for sustainable development in tropical environments.