Chapter 1

What is fire?

This chapter serves as an introduction not only to Part One but also to the book as a whole. It considers many of the fundamentals of fire. We introduce here a number of concepts that are developed throughout the text and, where relevant, the chapter numbers or parts are given for reference. In addition, some areas are dealt with here because there is no space to develop them more fully within this book, as to do so would make it too long and unwieldy. Due to this, we have tried to provide a wide range of illustrative material here, as well as more extensive references for further reading.

1.1 How fire starts and initially spreads

Simply put, fire – generally called combustion – is a rapid chemical oxidative reaction that generates heat, light and produces a range of chemical products (Torero, 2013). However, in the context of vegetation fires, it is important to consider not only the range of materials that may be combusted, but also the conditions under which fire may occur and even be ignited.

It is obvious, therefore, that the basis of a fire is the nature of the fuel that will be combusted and the type of ignition source. The general principle for vegetation fires is that there is an initial high-temperature heat source. This may be produced by lightning, volcanic activity, a spark from a rock fall or, of course, by humans. Plants contain a range of organic compounds that include cellulose, a carbohydrate that is a linear polysaccharide polymer found in many cell walls. The high initial temperature causes a breakdown of the cellulose molecule and produces a range of gaseous components that include ammonia (NH_3), carbon dioxide (CO_2) and methane (CH_4). These gases mix with atmospheric oxygen and undergo a rapid exothermic reaction – combustion. This rapid increase in heat, together with the readily available oxygen, allows the reaction to continue and a fire is started (Cochrane and Ryan, 2009). These features may be characterized by the use of a fire triangle (Figure 1.1, Fire fundamentals).

Each element will be discussed in more detail below, but it is worth making a few general points at the outset.

- First, the fuel needs to be as dry as possible. This is because the initial heat may be dissipated by the need to evaporate water. If dry, then the heat can begin to break down the cellulose in the plant material. The moisture value of the fuel will depend on whether the plant is alive or dead. If alive, then the plant may contain moisture in the leaves, branches and trunk. If dead, the plant may be more prone to drying out.
- The second element is the fuel itself. For a fire to spread, it is necessary to have sufficient fuel to burn. Extreme build-up of litter that is dry would obviously be conducive to the spread of fire. However, how the fuel is arrayed and how quickly it is combusted is also important (Van Wagtendonk, 2006). There are also differences in the ways in which woody and non-woody vegetation burn, as well as other features such

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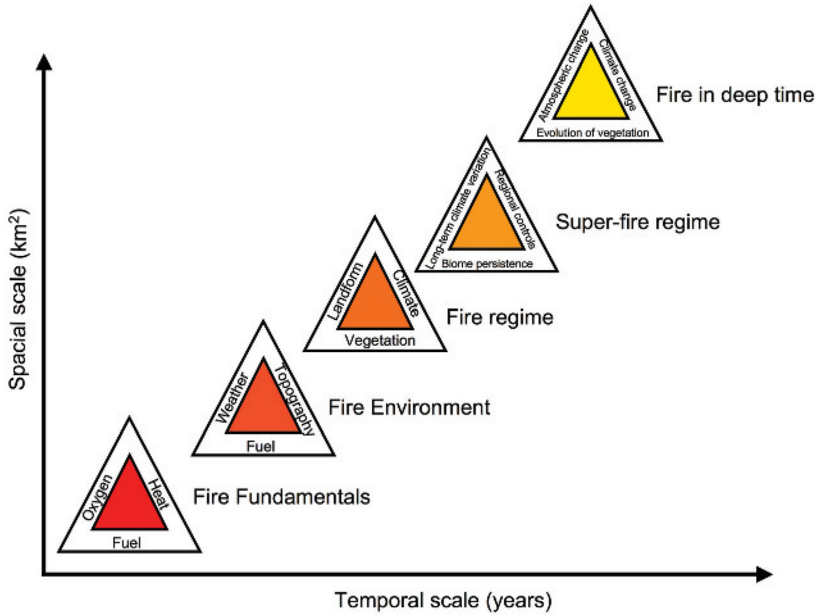

Figure 1.1 Fire triangles. The importance of different elements of fire is shown in relation to different scales, from the initial starting of a fire to the controls on fire in deep time. (This figure is compiled from a range of different authors' work including S. Pyne, M. Oritz, C. Whitlock, A. C. Scott).

as calorific value, the rate of fire spread and its intensity (see Chapter 14, Part Four).

- Third, a key element is readily available oxygen. In today's atmosphere, where the air contains 21% O_2, then combustion and fire spread is possible. For fire to be maintained, oxygen must continue to arrive at the burning point or the fire will be exhausted. This is why wind is so dangerous, as it not only drives the fire, but also replenishes the oxygen at a faster rate.

The implications of the above are also that to put a fire out, water may be added to the fuel to stop flame spread; or, in a confined space, oxygen may be excluded by smothering the fire by the use of inorganic materials such as sand or CO_2 to replace the oxygen-rich air.

1.2 Lightning and other ignition sources

Of all the natural ignition sources for a wildfire, lightning, volcanic eruptions and sparks from rock falls, it is lightning that is the most important. Human sources of ignition will be considered elsewhere in this book (see Part Three).

Lightning occurs when there is electrostatic discharge from the atmosphere. The most significant is sky-to-ground lightning (Figure 1.2). Here, a strong electrical charge is transferred from a cloud to the ground. Where the lightning hits the ground, there is a sudden increase in temperature, creating temperatures sometimes in excess of 30 000 °C. Lightning may or may not occur associated with rainfall.

Lightning may strike across many parts of the Earth's surface, but it is found concentrated in particular regions (see map, Figure 1.3). One problem with lightning maps, however, is that they show all lightning, including cloud-to-cloud lightning, not just cloud-to-ground lightning. It is significant that there may be as many as eight million lightning strikes every day.

When not associated with rain, the lightning may be referred to as 'dry lightning' and may occur in cumulonimbus clouds, which then may produce pyrocumulus clouds that create more lightning as a result of a warming ground surface from fire and is, therefore, a result of part of a positive feedback mechanism.

Not all lightning gives rise to a wildfire. In many cases, when trees are struck, this may result merely in scorching. However, if the tree is dead or dry because of drought, the great heat allows combustion to occur. This is equally the case with herbaceous vegetation,

Figure 1.2 Lightning strike. Dry lightning (not associated with rain) is one of the major ignition sources for fire (Courtesy valdezrl/Fotolia).

but sufficient fuel also needs to be available for a fire to spread.

The occurrence of fire may, therefore, be limited because of the amount or nature of the fuel (fuel limited) or because of moisture content of that fuel (moisture limited). In the tropics, this can lead to a single tree on fire, as it is unable to spread because of fuel moisture (Figure 1.4).

In regions of grassland, however, such as in savannas in Africa, fire may start just hours following a

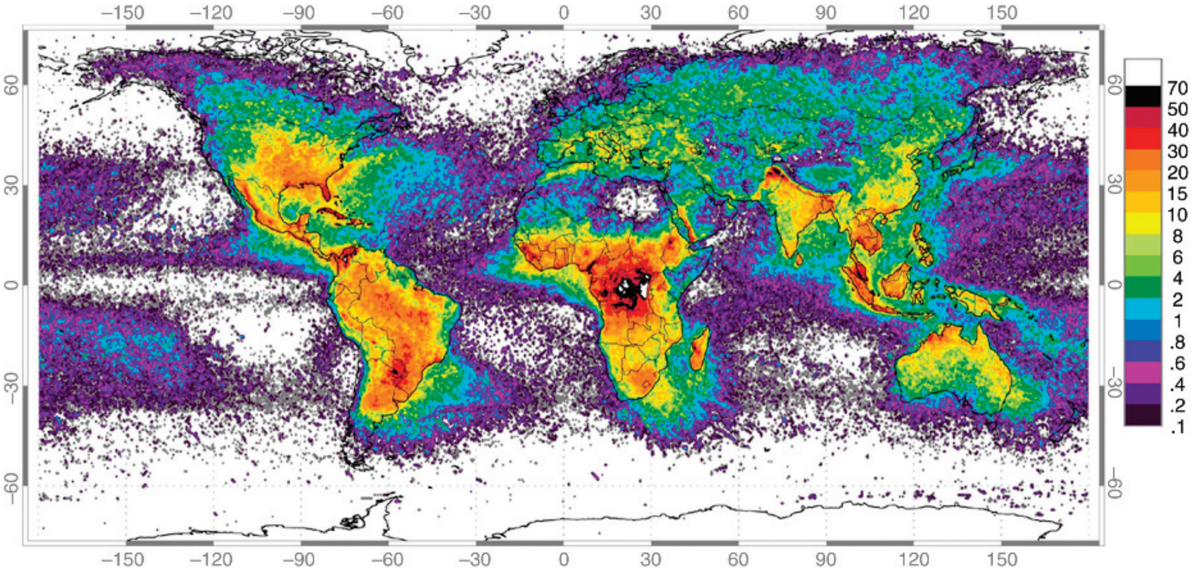

Figure 1.3 Global lightning activity (number of flashes/km^2 per year). Data available from Global Hydrology Resource Center (http://ghrc.msfc.nasa.gov). (From Bowman, 2005).

Figure 1.4 Fire burning a solitary tree in the Amazon rainforest. (Photo: M. Cochrane).

rainstorm, as the atmosphere is warm and dry, which allows the fine fuels to dry out very quickly. All of these facts are of particular significance to those producing fire potential maps (Figure 1.5).

1.3 The charring process

Most plant material comprises of a range of organic compounds, including a variety of macromolecules. For example, wood is composed of cellulose and lignin, but also includes hemicelluloses. Leaf coatings contain cutin, whereas spores and pollen are composed of the inert macromolecule sporopollenin. All of these compounds, including those from other organic sources (e.g. chitin from fungi), will break down upon heating. Of particular significance are aliphatic compounds such as cellulose, a carbohydrate, and lignin, which is an aromatic compound that is heavily cross-linked.

When heated in the absence of air this pyrolysis process results in the decomposition of the biomacromolecules to produce liquid and gaseous materials. The resultant residue is termed charcoal, and this is highly aromatic, with an increased

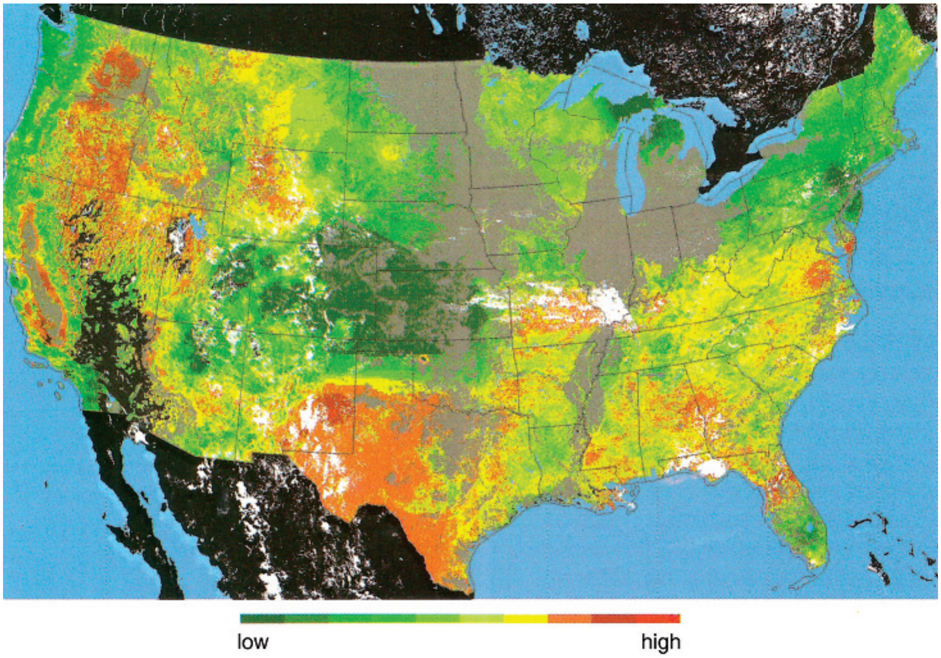

Figure 1.5 Fire potential index map of the United States for August 13, 1998. White areas are cloud cover; grey are agricultural lands (not rated). (From USGS factsheet 125–98, 1998).

proportion of carbon over the starting material. Some tar-like liquids may be produced, along with other volatile components and other gases. These materials may be mixed with oxygen in the air and combustion results, which, in turn, generates more heat for the process to continue.

The burning of plants is, therefore, a two-stage process in which:

1. pyrolysis occurs in the absence of oxygen, whereby the bio-macromolecules are charcoalified (Scott, 2010), releasing volatile components;
2. combustion then follows, representing an oxidative process whereby these components mix with oxygen in the air to allow burning.

Temperatures in the process are variable. For charcoalification to begin, the temperatures generally of 275 °C are required but higher temperatures will create a broad range of pyrolysis products that may be combusted.

1.4 Pyrolysis products

The result of the pyrolysis and combustion process leads to the production of a number of materials and compounds from charcoal: inorganic ash, volatile gases and compounds (aerosols), and soot (Santín *et al.*, 2012). Most fires generate this full range of material, and this may have a significant impact on the environment. Many of these products may be incorporated into the smoke plume of the fire and be transported considerable distances (Figure 1.6). Each of these products will be briefly examined in turn.

The products of a fire can be divided into two main groups: the material that remains in place after a fire

Figure 1.6 Smoke from fires.

A. White smoke columns from the Las Conchas Fire, New Mexico, USA, 2011 (see also Figure 1.42).
B. Grey smoke from the Norton Point Fire, Wyoming 2011.

(Photos from National Interagency Fire Center, https://picasaweb.google.com).

has passed (including mineral ash and charcoal); and the material that is transported away from a fire within a smoke plume. White or grey smoke (Figure 1.6) will depend on a range of factors, from fuel type to moisture content to temperature.

Usually the first visible evidence of a wildfire is its smoke plume. This may include water vapour which will be dependent on the water content of the fuel, small charcoal particles, usually less than 125 μm, but in some fires, significantly larger pieces may be lofted with the plume. Perhaps more important is the presence of soot, volatile components and aerosols (Artaxo *et al.*, 2009).

1.4.1 Soot

Soot, together with charcoal, is often referred to as black carbon. There is considerable disagreement among researchers on the nomenclature of these products. Some use the term 'black carbon' to mean only soot, whereas others include any combustion product that is recalcitrant in the biosphere (see Chapter 2 and Glasspool and Scott (2013)). Soot is formed by the recombination of vaporized organic molecules to form a new carbon material. Chemically, it is nearly pure carbon, and it is morphologically distinctive. Under the scanning electron microscope, it can be seen to have a range of morphologies, with a particle size less than 1 μm (see Figure 2.5g). Soot may also be produced by a range of other combustion processes (including petroleum), but that from vegetation fires may have this particular morphology.

Small cenospheres may also be produced from the burning of fossil fuels such as peat and coal. This soot may be widely dispersed into the atmosphere and may subsequently be deposited across the globe, even into deep-sea sediments (see Chapter 2). The soot may also be associated with micro-sized charcoal particles.

1.4.2 Volatile gases and compounds

A range of gases and aerosols may also be incorporated into the smoke plume. These include CO_2, carbon monoxide (CO), CH_4 and oxides of nitrogen (NO_x). Fire is therefore a significant producer of greenhouse gases. Most of the CO_2 is recaptured from the atmosphere by the re-growth of vegetation. If a fire results in the burning of peat, however, then this may become a significant issue for climate forcing.

Other important compounds include complex organic molecules such as pyrolitic polycyclic aromatic hydrocarbons (PAHs). These compounds may be produced in large quantities and their composition may depend of the type of vegetation being burned and the temperature involved. The higher the temperature, the larger the number of carbon rings found in the molecule. Table 1.1 shows a list of these compounds and their origin. The most common of these are cadanene and retene, but they also include phenanthracene, fluoromethene and chrysene, pyrene and coronene. Laevoglucosan derived from cellulose is widely used as a biomarker for vegetation fires. These compounds may also stay

Table 1.1 Major biomarker tracers in smoke from biomass burning. (From Simoneit, 2002).

Compound	Structure	Composition	Indicator for source
Anisic acid (p-methoxy-benzoic acid)	V	$C_8H_8O_3$	Gramineae lignin
Vanillic acid	II	$C_8H_8O_4$	Lignin
Syringic acid	IV	$C_9H_{10}O_5$	Angiosperm lignin
Matairesinol	VII, $R = O$	$C_{20}H_{22}O_6$	Conifer lignin[a]
Shonanin	VII, $R = H_2$	$C_{20}H_{24}O_5$	Conifer lignin[a]
Divanillyl	VIII	$C_{16}H_{18}O_4$	Lignin dimer
Divimillylmethane	IX	$C_{17}H_{20}O_4$	Lignin dimer
Divanillylelhane	X	$C_{18}H_{22}O_4$	Lignin dimer
Vanillylsyringyl	XI	$C_{17}H_{20}O_5$	Angiosperm lignin dimer
Disyringyl	XII	$C_{18}H_{22}O_6$	Angiospyrm lignin dimer
Dianisyl	XIII	$C_{16}H_{18}O_2$	Gramineae lignin dimer

Table 1.1 (*Continued*)

Compound	Structure	Composition	Indicator for source
Levoglucosan	XIV	$C_6H_{10}O_5$	Cellulose
Mannosan	–	$C_6H_{10}O_5$	Hemicellulose
Galactosan	–	$C_6H_{10}O_5$	Hemicellulosc
1,4:3,6- Dianhydro-β-D-glucopyranose	–	$C_6H_8O_4$	Cellulose
Dehydroabielic acid	XV	$C_{20}H_{28}O_2$	Conifer resin
n-Nonacosan-10-ol	–	$C_{29}H_{60}O$	Wax[a]
3- Methoxyfriedelane	XVI	$C_{31}H_{54}O$	Angiosperm[a]
Abietic acid	XVII	$C_{20}H_{30}O_2$	Conifer resin[a]
Pimaric acid	XVIII	$C_{20}H_{30}O_2$	Conifer resin[a]
iso-Pimaric acid	XIX	$C_{20}H_{30}O_2$	Conifer resin[a]
Sandaracopimaric acid	XX	$C_{20}H_{30}O_2$	Conifer resin[a]
Cyclopenta[c,djpyrene	XXI	$C_{18}H_{10}$	PAH all burning
Retene	XXII	$C_{18}H_{18}$	Conifer
Pimanthrene	XXIII	$C_{16}H_{14}$	Conifer
Simonellite	XXIV	$C_{19}H_{24}$	Conifer
Acetosyringone	XXV, $R = C_2H_3O$	$C_{10}H_{12}04$	Angiosperm lignin
Syringyl acetone	XXV, $R = C_3H_5O$	$C_{11}H_{1404}$	Angiosperm lignin
Oleana-2,l2-diene	XXVI, $R = CH_3$	$C_{30}H_{48}$	Angiosperm
Uraina-2,12-diene	XXVII, $R = CH_3$	$C_{30}H_{48}$	Angiosperm
Oleana-2,12-dien-18-oic acid	XXVI, $R = CO_2H$	$C_{30}H_{46}O_2$	Angiosperm
Ursana-2,12-dien-18-oic acid	XXVII, $R = CO_2H$	$C_{30}H_{46}O_2$	Angiosperm
Allobclul-2-ene	XXVII	$C_{30}H_{48}O$	Birch *(Betula)*
β-Sitosterol	XXLX, $R = \beta C_2H_5$	$C_{29}H_{50}O$	Vegetation[a]
1-Palmitin	XXXV	$C_{19}H_{38}O_4$	Fauna (flora)
1-Stearin	–	$C_{21}H_{42}O_4$	Fauna (flora)
Cholesterol	XXIX, $R = H$	$C_{27}H_{46}O$	Fauna algae
Campesterol	XXIX, $R = \alpha CH_3$	$C_{28}H_{48}O$	Gramineae
Stigmasta-3,5-diene	XXX	$C_{29}H_{48}$	Vegetation[a]
Lupa-2,22-diene	XXXI	$C_{30}H_{48}$	Angiosperm
Stigmaslerol	XXXII	$C_{29}H_{48}O$	Vegetation[a]
Ferruginol	XXXIII	$C_{20}H_{30}O$	Some conifers
1,6-Anhydro-2-acetamido-2-deoxyglucose	XXXVI	$C_8H_{13}NO_5$	Chitin
17α(H),21 β(H)-Hopanes	XXXIV	e.g., $C_{30}H_{52}$	Petroleum, lignite
Moretanes (βα-hopanes)	XXXVII	e.g., $C_{30}H_{52}$	Petroleum, lignite
α-Amyrone	XXXVIII, $R = O$	$C_{30}H_{48}O$	Angiosperm
β-Amyrone	XXXIX, $R = O$	$C_{30}H_{48}O$	Angiosperm
α-Amyrin	XXXVIII, $R = \beta OH$	$C_{30}H_{50}O$	Angiosperm[a]
β-Amyrin	XXXIX, $R = \beta OH$	$C_{30}H_{50}O$	Angiosperm[a]
β-Oxodeliydioabietic acid	XL	$C_{20}H_{26}O_3$	Conifer resin
7-Oxodehydroabictit acid	XLI	$C_{20}H_{26}O_3$	Conifer resin

Source: Reproduced by permission of Elsevier.

[a] Natural product, compound (unaltered).

Figure 1.7 Photos of different types of fire.

A. Surface fire in grassland at edge of forest in Gibbon Meadows, Yellowstone National Park 1988 (photo: Jim Peaco, 12048 National Park Service (www.nps.gov/features/yell/slidefikle/fire/wildfire88)).
B. Surface fire in grassland. (http://cedarcreek.umn.edu/high res.savanna-fire.jpg). Reproduced with permission of Cedar Creek Ecosystem Science Reserve.
C. Surface to crown fire in conifer forest. Trees torching at Grant village junction, July 1988, Yellowstone National Park (Jeff Henrey: Slide 12064 (www.nps.gov/features/yell/slidefikle/fire/wildfire88)).
D. Large crown fire in conifer forest (Arrow fire, 1976, Yellowstone National Park. Slide 11818 (www.nps.gov/features/yell/slidefikle/fire/wildfire)).

in the atmosphere for a considerable time and result in the prevention of rain formation, hence prolonging a wildfire event. The compounds may be washed out of the atmosphere and be incorporated into sediments (Simoneit, 2002).

Other gases that may occur in the smoke plume are the hazardous nitrous oxides that have an impact upon human health. Studies have shown that human populations regularly subjected to smoke from wildfires have a susceptibility to a range of diseases, especially lung diseases (Johnston *et al.*, 2012). Significantly, the toxicology of wildfire smoke is different, and more harmful, than the vehicle emissions that cause smoke in urban airsheds.

1.5 Fire types

Fire may occur where there is sufficient build-up of fuel that is dry enough to burn. Most often, a fire starts on the surface, where litter and duff and herbaceous plants and shrubs may occur (Figure 1.7). With forest systems, such surface fires (Figure 1.8A) may only burn the fuel on the forest floor (Figure 1.7A). These fires tend to burn relatively coolly – often less than 400 °C – and some relatively slowly. However, some shrubby vegetation, such as chaparral in California, may burn much hotter – up to 900 °C at the ground surface (Figure 1.7F) and spread faster (Figure 1.7C). Grass fires (Figure 1.7A,B) may also burn more at a

E. Crown fire in coniferous forest, Castle Rock fire, Ketchum, Idaho, USA, August 2007 (National Interagency Fire Center).
F. Crown fires in Chaperral, East Basin Complex, California, USA, July 2008 (National Interagency Fire Center).
G. Peat Fire in Indonesia. Although the fire above ground is out, the peat underground continues to burn (photo: S Page).

much faster rate. In the case of grass or scrub fires, wind may drive the fire to move faster.

If there is a thick humic layer within the soil and it is sufficiently dry, a fire may spread to burn this layer. In such a case, with restricted oxygen supply, the fire may then smoulder. The movement of such a fire may be quite slow, as much fuel may be consumed. Such a fire is termed a ground fire (Figure 1.8C). Ground fires may also burn thick peat layers (Figure 1.7G), where the water table has been lowered and the peat has dried out. In such circumstances, water may not be sufficient to extinguish such a fire, as this may introduce

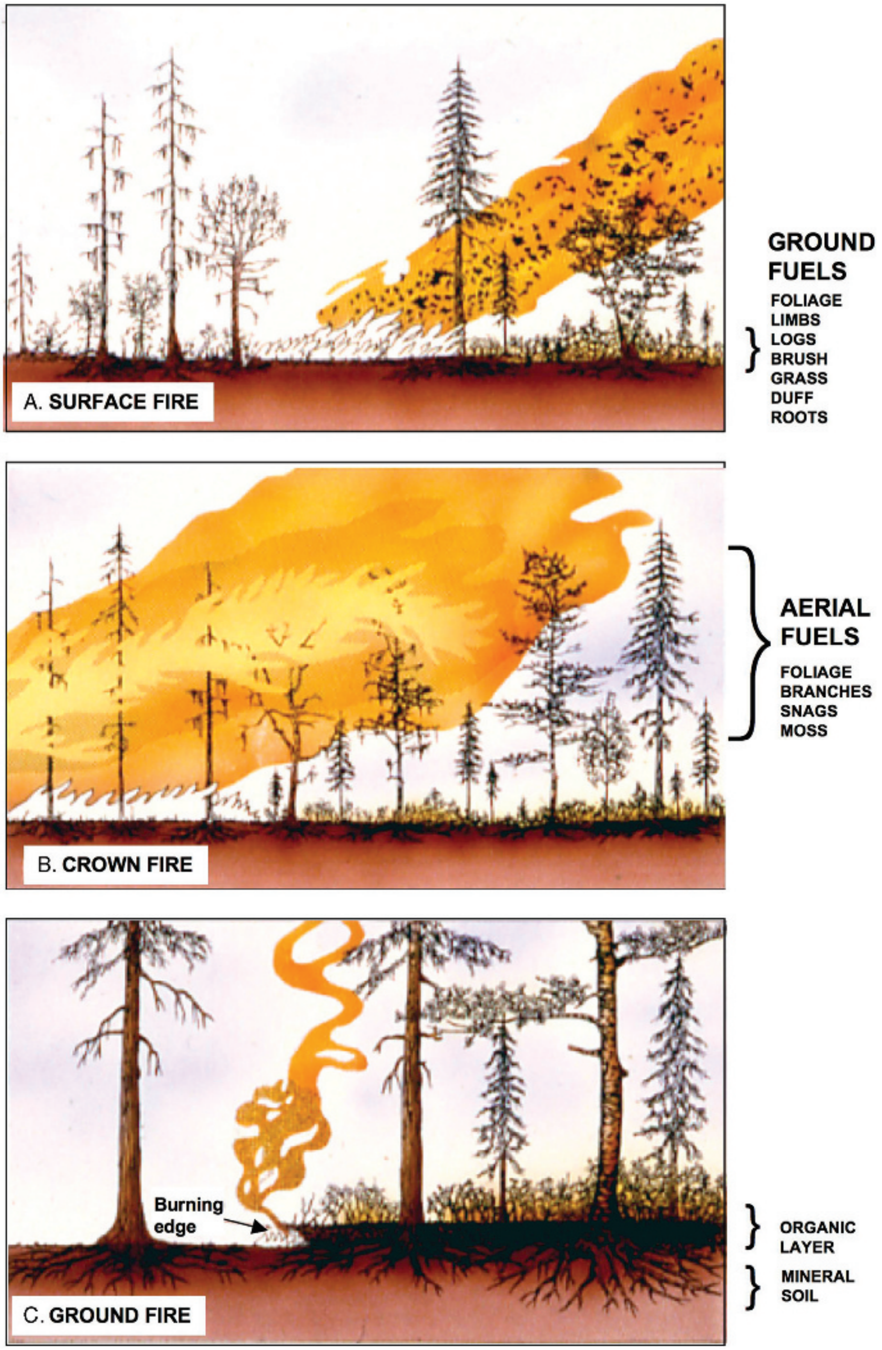

Figure 1.8 Types of wildfire and fuel sources. (From Scott, 2000, modified from Davis, 1959).

oxygen to the system and the fire may actually flare up in response.

If there is a significant build-up of surface fuel within a forested ecosystem, then fire temperature may increase. Here, the fire may spread up the trunks of the tree and into the crowns of the forest trees (Figure 1.7C). This type of fire is referred to as a crown fire (Figure 1.8B). The energy release of a

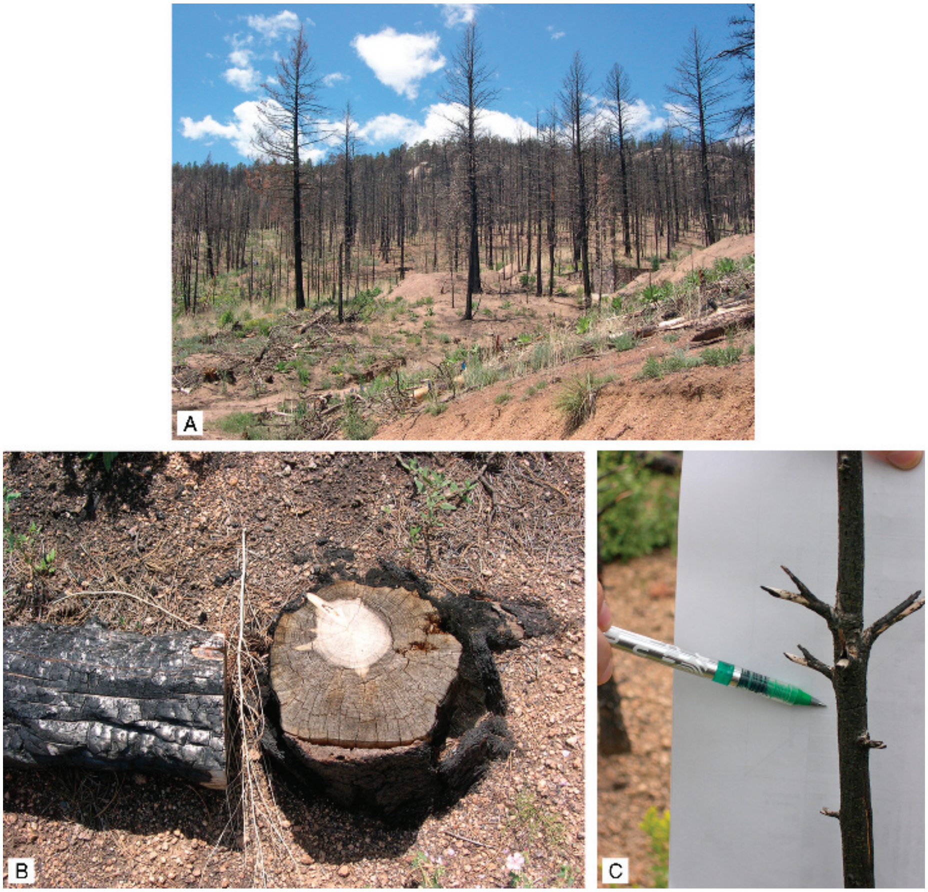

Figure 1.9 Ponderosa Pine forests of Colorado, USA after fire. (All from Scott, 2010).

A. Standing trees remaining after fire. Most of the trees remain (Buffalo Creek (1996) fire, Colorado, USA). Reproduced with permission from Elsevier.
B. Cut charred stump from the Hayman (2002), Colorado, USA fire, showing that only the outside of the trunk was charred. Reproduced with permission from Elsevier.
C. Leaves and fine twigs have been removed in the fire, leaving even small branches intact. (Hayman, Colorado, USA fire, 2002). Reproduced with permission from Elsevier.

fire and its spread relates to fire intensity, and it is this factor that partly controls the spread of a fire from the surface to the crown. The leaves and fine branches appear to be the major source of fuel for the fire (as well as dead dry trees), as large upright trunks may still be visible after such a fire (Figure 1.9). When cut down, often only the outermost bark and trunk will show signs of burning (Figure 1.9B).

Crown fires (Figure 1.7D-F) may burn much hotter. While many crown fires produce temperatures only around 800–900 °C, in some cases where there is abundant dry fuel and wind to feed into the fire with oxygen, temperatures may rise to 1200 °C. It is important, however, to distinguish the temperature at the flame tip and that a metre above the tip, which may be higher. Most often it is the Fire Radiative Power (FRP) that is measured, using infrared data from satellites (see section 1.13). Crown fires may separate from surface fires and move much more quickly (Figure 1.8B). Glowing embers may be lofted up into the atmosphere (Figure 1.10) and set fire to other vegetation, causing the spread of the fire and developing many fire fronts. The result of this may be a mosaic burn pattern in the forest (Figure 1.11). In extreme fire, gas balls may explode above the fire front.

Figure 1.10 Glowing embers from burning trees.

A. Fire at tops of palm trees, Orange County, California (Courtesy LA Times. Photographer Glenn Koenig).
B. Glowing embers from burning crown of palm tree, Santa Barbara California (Photo: Ray Ford – ray@sb-outdoors.com).

1.6 Peat fires

The extreme ends of ground fires are peat fires. In such wetland mire systems, natural wildfire may be relatively rare. Studies have shown that, globally, less than 5% of the peat is charcoal formed by fire. However, when there are very dry periods, even in these ever-wet systems, a surface fire may burn away the peat layer. This may have a dramatic effect upon the environment and will be discussed in a later chapter (see Part Two). Two of the effects may be to cause a switch in the vegetation cover or, in some cases, to develop into a lake when the water table is restored to its original level.

Figure 1.11 Mosaic burn in Yellowstone National Park, USA after fire. This shows the patchy nature of a fire. North side of Willow Creek Fire, August 1974. (www.nps.gov/features/yell/slidefikle/fire/wildfire 1358).

While peat fires may occur naturally in some ecosystems, it is the action of humans that creates particular problems. Peatland drainage, such as is seen in Kalimantan, Indonesia, may create the conditions for peat fires (unintentional or intentional) to take hold and may produce significant emissions (Figure 1.7 G) (Page *et al.*, 2002, 2009; see also Parts Two and Three).

Recent studies of biomass burning across peat areas in Indonesia have shown the release of up to 2.5 Gt of carbon per year, which is significant to the global carbon budget. Unlike in other systems, where perturbations in the system can be reversed, the habitat may be permanently changed within these tropical peat systems. These peat-burning fires may also create a significant smoke hazard that is deleterious to human health (Johnston *et al.*, 2012; see Figure 1.12).

Temperatures within peat fires may be very variable. Most of these are smouldering fires, and temperatures reached may be up to 900 °C (Rein, 2013). Often, combustion is near complete, with a total conversion of the biomass to CO_2. This is important, as combustion completeness is a significant factor in the calculation of carbon emissions from wildfire.

1.7 Fire effects on soils

A significant impact on the environment relates to the temperatures that occur within a fire. It is important to stress that how and when a temperature is measured is particularly significant. Temperature figures are often quoted that have very little relevance to the issue being discussed. For example, temperatures within crown fires may bear little relation to the effect of surface fires upon soil systems. In addition, the length of exposure to a particular temperature may also be important (Table 1.2), as it may create increased temperatures at different depths (Figure 1.13). In the context, therefore, of the fire effects on soil, the temperature reached in surface fires is particularly significant (Ubeda and Outeiro, 2009; see Table 1.2).

There are three important concepts that need a brief introduction here:

- First, the term 'fire intensity' refers to the amount of energy released from a fire, usually expressed as the amount of energy per unit flame length (in kW/m).
- Second, the term 'fire severity' is related to the loss or damage to vegetation that may be determined through either ground observations or by satellite data.
- Third, related to this is 'burn severity', which is often measured by the loss of organic matter in the soil and is, therefore, related to the impacts of the fire on a range of properties of the ecosystem that are concerned with the land surface.

We have already seen that both the nature of the fuel (wood/grass/dry litter, living trees), as well as its

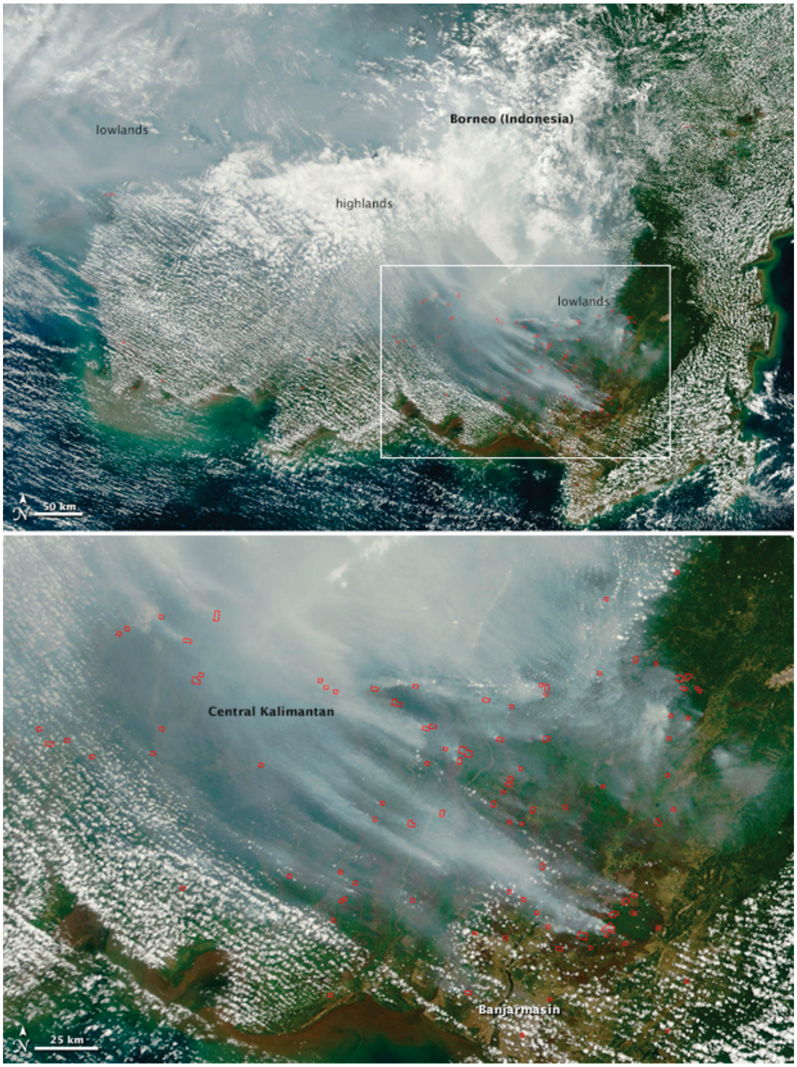

Figure 1.12 Smoke from peat fires in Indonesia, seen from NASA's Terra satellite on September 15 2009. Individual fire areas shown with red spots (http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=40182).

structure (closely or sparsely packed) and biomass, may influence fire temperature. Instead of considering the fire temperature above the burning fuel (the flame tip temperature and that measured above 1–3 m above the flames may also be significantly different), the temperature at the fuel burn-soil interface and within the soil layer needs to be considered.

The temperature reached at the soil-burn interface will depend upon a number of factors. Importantly, these include fuel load, which has implication for forest management and prescribed burns (see Chapter 16, Part Four). A significantly high surface fuel load may create the conditions for a fire not only to burn hotter but also to remain at a particular point longer, which can impact upon soil temperatures (Figure 1.13A).

The condition of the fuel within a soil may also be important, as combustion occurs differently in wet fuels, as opposed to dry fuels. The type and distribution of the fuel load should also be considered – whether it comprises fine fuels or slash logs, for example. Finally, different species of plants have different calorific values and mineral contents, and some contain resins or other volatile compounds that may cause a fire to burn hotter (Figure 1.13B). The ecological consequence of burn temperature will be considered in a later chapter (Chapter 8, Part Two). Two

Table 1.2 Soil temperatures measured during fires. (From Ubeda and Outeiro, 2009).

Temp (°C)	Depth (cm)	Vegetation
135	0.32–0.64	Pines
550	Surface	Grassland
250	2.5	Dense forest
105	7.5	
60	15	
538	Surface	Scrubland
149	3.8	
700	Surface	Savanna
438	Surface	Conifers
27	3	
17	7	
590	Surface	Scrubland
399	1	
177	Surface	Grassland
93	1.3	
1150	Surface	Pines
500	3	
900	Surface	Eucalyptus
100	5	
400–200	Surface	Shrubs
510	Surface	Dense forest
44		
666	Surface	Eucalyptus
112		
245	Surface	Grassland
68	1.3	
716	Surface	Dense forest
166	2.5	(by afternoon)
66	5	
316	Surface	Dense forest
66	2.5	(by night)
43	7.6	
93	Surface	Pines
800	Surface	Scrubland
500	1	
250	Surface	Scrubland
125	2.5	
50	5	
700–250	Surface	Scrubland
200–90	2.5	
250	Surface	Different kinds
100	2	Black ashes
500–750	Surface	Different kinds
350–450	2	
150–300	3	
< 100	5	
388–442	Surface	Masticated fuel
170–330	Surface	Wheat
700	Surface	Pines
300	15	
340	Surface	Pines
740	Surface	*Cistus*
280	Surface	No vegetation
180	Surface	Scrubland
50	2.5	
475	Surface	Low dense
90	2.5	Scrubland
40	5	
600	Surface	Grassland
50	1	
702	Surface	*Ulex parviflorus*
22	5	

Source: Reproduced by permission of Taylor & Francis.

areas will be discussed here: the conversion of the plant biomass to ash (i.e. both mineral ash, charcoal and other pyrolysis products – see Santín *et al.*, 2012); and temperature reached and its impact within the mineral soil profile.

An important feature of soils is what is termed soil hydrophobicity (DeBano, 2000). In simplest terms, this relates to how quickly or slowly water infiltrates a soil. Hydrophobic soils are ones where drops of water remain on the soil surface for a considerable time. Techniques have been developed to measure this by timing the absorption of a measured water droplet into a soil. When water falls upon a soil surface, it may be absorbed into the top surface of the soil or flow off the surface by overland flow. Equally, the water may be absorbed into the upper layers of a soil but then flow laterally within the soil profile.

The burning of the surface fuels by a surface fire has two major impacts. First, there is the temperature rise within the topmost layer of the mineral soil. Organic matter may combust and the soil structure altered. This may be seen by a change in colour, from browns and blacks to yellows, oranges and reds (Figure 1.18A). In some extreme cases, some clays may be baked into red

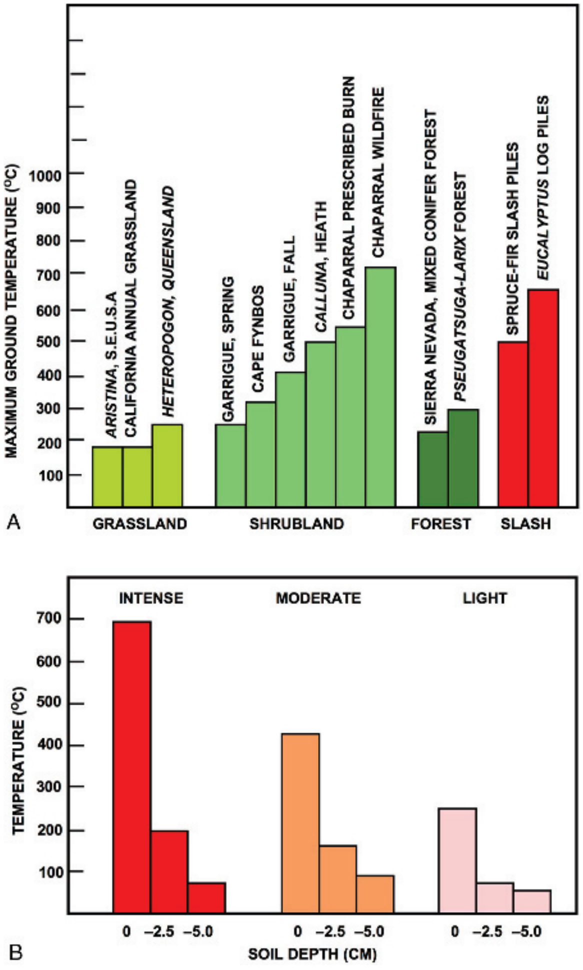

Figure 1.13 Ground temperature of fires.

A. Maximum ground temperatures reached during natural wildfires (modified from Rundel, (1981)). Reproduced with permission from Springer Science+Business Media B.V.
B. Profiles of maximum temperature with soil depth for three intensities of chaparral fires (after DeBano *et al.*, 1977). USDA.

brick-like fragments. The pyrolysis of the organic matter may generate liquids that may be freed into the soil layers coating the soil particles.

The effect of these changes is to change or introduce a hydrophobic layer. The strength and position of the hydrophobic layer plays a major role in post-fire erosion (Figures 1.14, 1.15). Clearly, the impact of a surface fire upon soil properties depends on a large array of variables and these are subject to considerable on-going research (see Doerr and Shakesby, 2013).

1.8 Post-fire erosion-deposition

The impact of a surface fire upon the landscape may be severe. This will depend on three principal factors:

- the amount of fuel built-up on the land surface;
- the intensity and severity of the fire; and
- the timing between the fire and the first rainstorm.

Surface fires with minimal fuels may burn at relatively low temperatures. Their speed will depend on a range of factors, including the wind speed. A fast-moving low-temperature surface fire may have little effect upon the underlying soil or plant roots. A build-up of fuel may mean that the fire burns hotter, remaining at a single site for longer, despite the fire front moving and have a greater effect on the soil.

The fire may play two major functions. It may impact on the binding of soil particles by destruction of their organic content and, more importantly, it may have an impact on soil hydrophobicity. We have seen how a fire may enhance soil hydrophobicity by primarily precipitating volatile compounds within the soil. The effect is that the uppermost layer of the soil becomes more porous, but a more water-impenetrable layer forms beneath (Figure 1.14, 1.15).

The impact of a fire upon the soil may also depend on the nature of the soil itself, so that immature granite soils that contain rock fragments and little organic matter, for example, may behave differently from mature sandy or clay soils or those with a high organic content. Fire can remove organic chemicals leached from some vegetation types that make soils hydrophobic.

If there is a delay between the fire and significant rainfall, this may allow some plants to re-sprout. This may be helped by slight rainfall where, in some settings, ferns and grasses may re-sprout within a few days or weeks of fire (Figure 1.16). This will help in the stabilization of the soil and will prevent its movement and removal from the environment. Even if there is significant ash production (including mineral ash and charcoal), growth of plants may stabilize the sediment.

If, however, there is a significant rainstorm soon after the fire, this may have a devastating effect upon the environment (Figure 1.17). This is particularly the case if there is any significant topography. The rain in such circumstances will not fall on living vegetation

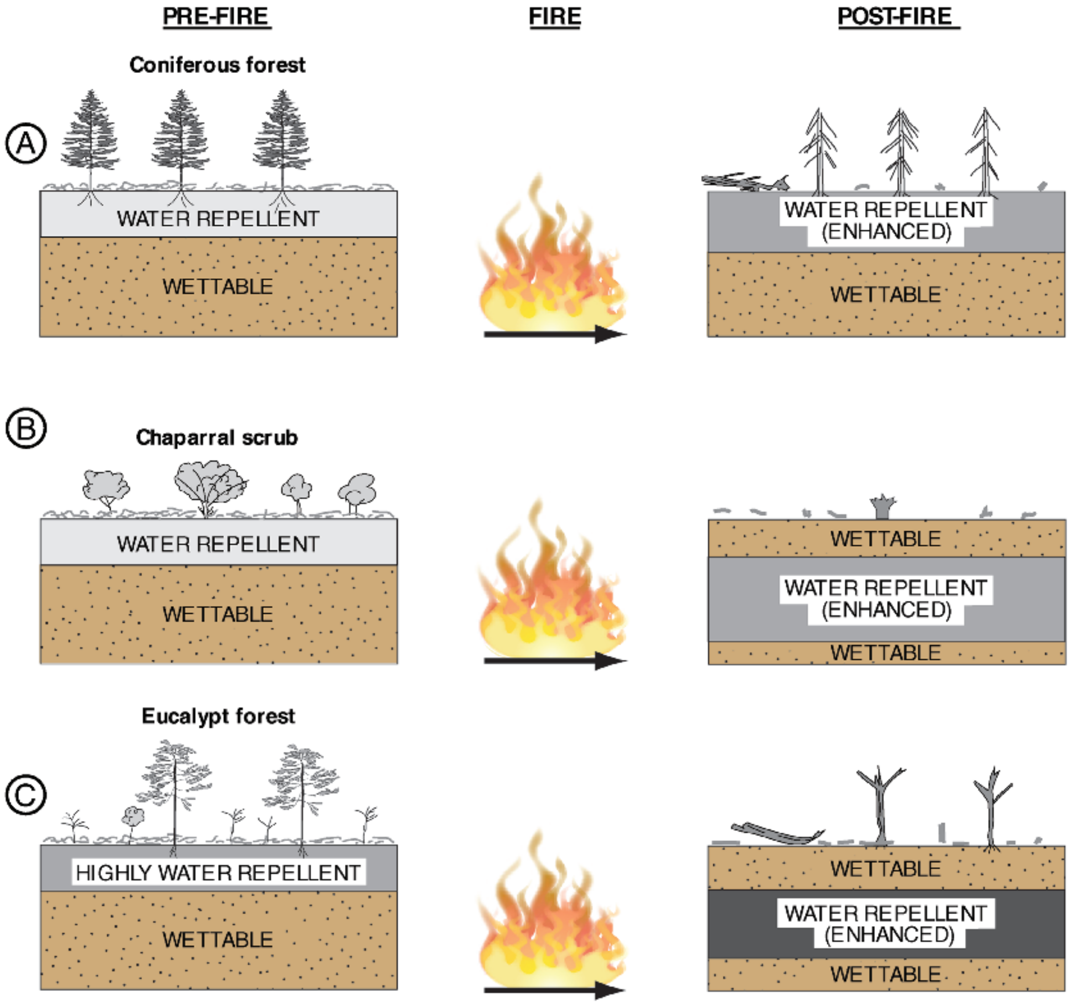

Figure 1.14 Soil water repellency changes following fire of moderate or high severity for:

A. coniferous forest in the north-western United States;
B. Californian chaparral;
C. Australian eucalypt forest.

Darker shading represents more severe repellency.
(After Doerr *et al.*, 2009). Reproduced by permission of Stefan Doerr.

and be absorbed by the plants, but will fall instead upon a bare landscape. We can consider if this landscape comprises bare soil, where there is little ash residue, or if there is a significant layer of ash and charcoal.

In zones of high burn severity, there may be little residue of ash/charcoal on the soil surface. The rain will tend to pound on the soil surfaces, as the presence of a strong hydrophobic layer may prevent rapid infiltration of the water (Figure 1.18).

The water will, therefore, move by overland flow. The hydrophobic layer, however, may be discontinuous, so that water may penetrate beneath the layer. In such circumstances, small rills are produced that may widen into very large erosional channels (Figure 1.19). Sediment may move very quickly and in large quantity (Moody and Martin, 2009).

In cases where there is significant topography, this may not only trigger the erosion of large catastrophic channels, but sediment may come to rest at a change

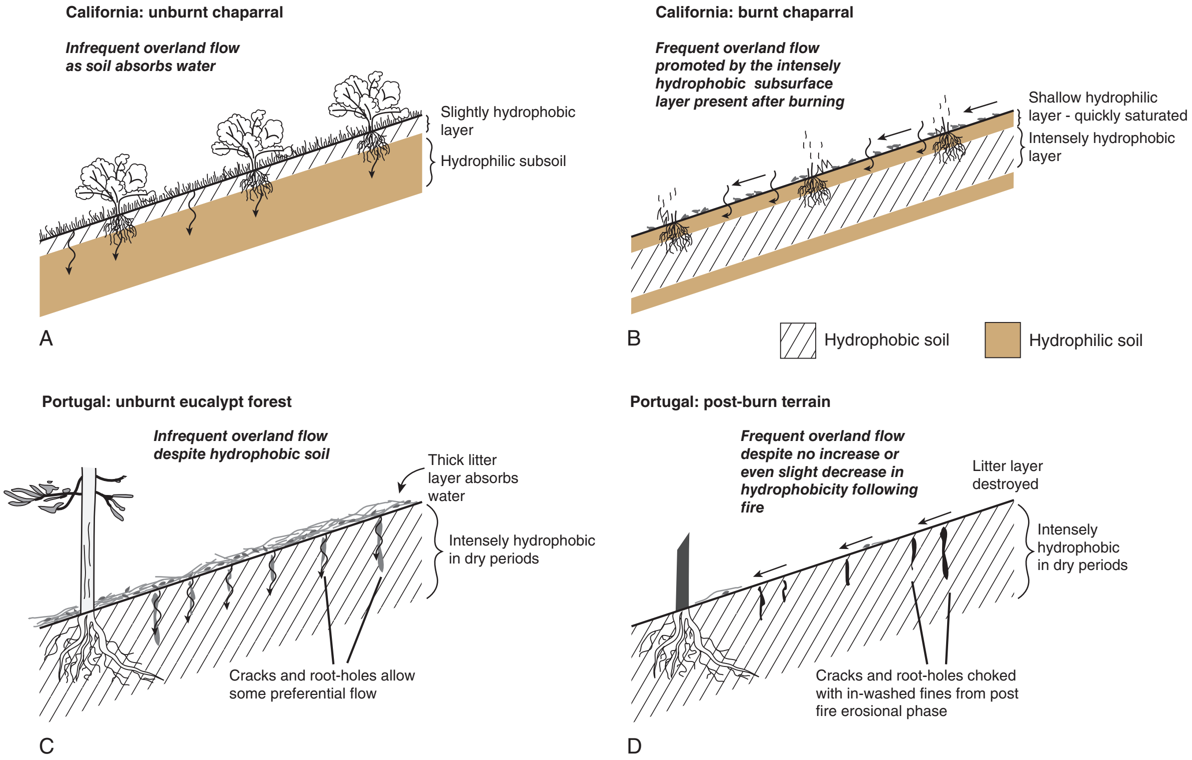

Figure 1.15 Impact of rainfall on a burnt soil. Hydrological response of forested terrain with high natural levels of coil water repellency for (A) unburnt and (B) burnt conditions following fire in California chaparral and (C, D) in eucalypt forest in Portugal. (From Doerr *et al.*, 2000). Reproduced with permission from Elsevier.

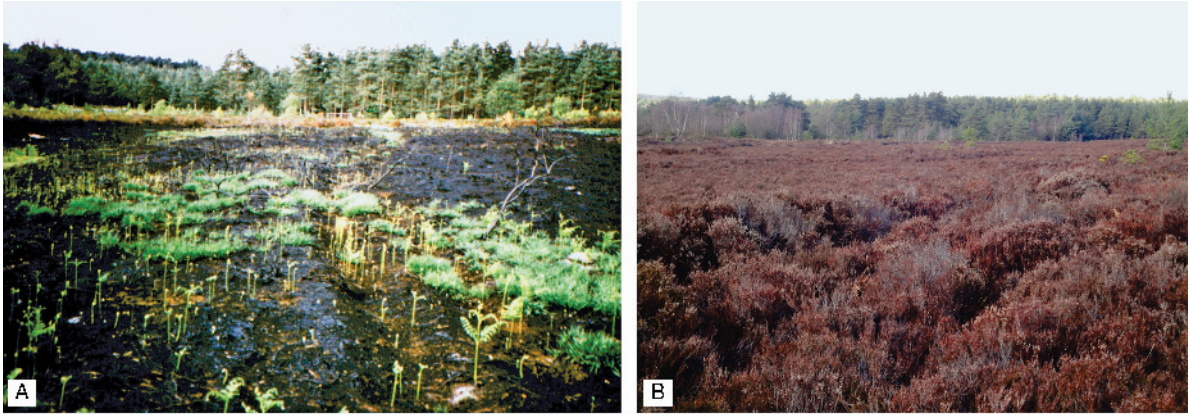

Figure 1.16 Burning and recovery of heather heathland in southern England (see Scott *et al.*, 2000).

A. Frensham, Surrey after fire showing re-growth of ferns and grass after two weeks (photo: A. C. Scott). Reproduced with permission from Elsevier.
B. Same area after ten years of re-growth of heather (*Calluna*) (photo: A. C. Scott). Reproduced with permission from Elsevier.

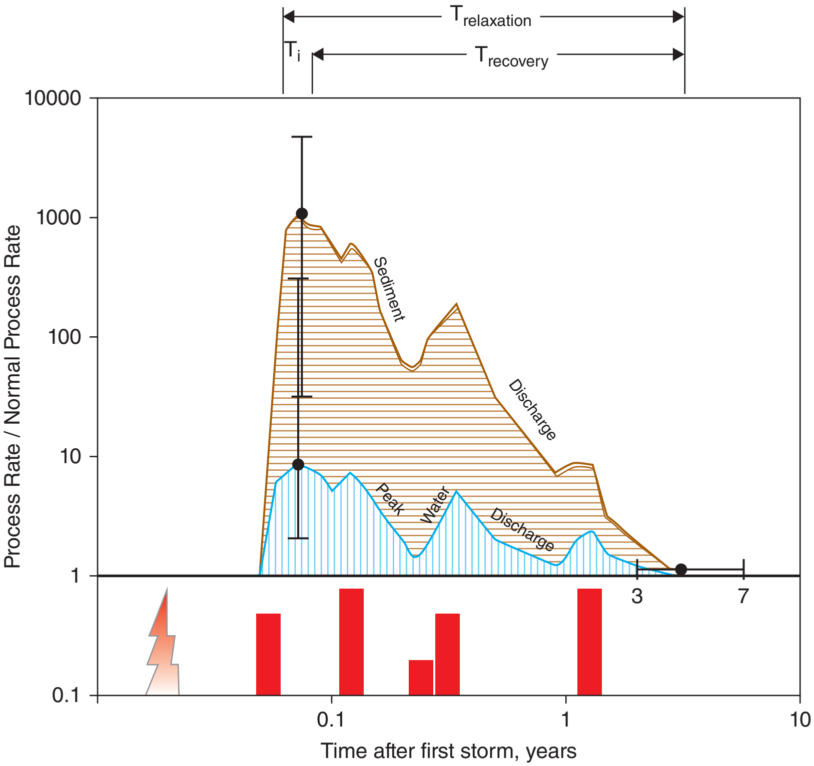

Figure 1.17 Conceptionalization of the response for one fire-flood cycle. The pre-fire process rates have a magnitude of 1.0, so that the process rates for peak water discharge and sediment transport are relative rates. The time of the fire is shown by the 'lightning bolt' (modified from Moody and Martin, 2009). Reproduced with permission from Taylor & Francis.

of slope in the form of an alluvial fan (Figures 1.19, 1.20). Fan thicknesses of more than one metre may form following single thunderstorms events.

This sediment, now released into the depositional system, may be fluvially reworked and be deposited many kilometres downstream, or it may find its way into lakes or even on to flood plains (Figure 1.21). In some cases, it may even reach the sea.

If there is a significant ash/charcoal layer, this may also have an impact upon the erosion depositional cycle. It has been suggested recently that a thick layer of ash may be effective in reducing hill-slope responses to surface run-off and erosion following a fire. The ash may develop a significant storage capacity. In some cases, the charcoal in the ash will float and may be transported both within the burnt area and out of the burnt area by overland flow (Figure 1.22).

The nature of the ash produced by the fire may also be significant in a range of geomorphic processes (Doerr and Shakesby, 2013). Ash may include various types, from black to grey to white ash that may be composed of a range of soluble and insoluble materials, from pure mineral ash (i.e. the organic materials have been largely combusted, but inorganic compounds that were present in the plant remain after combustion, leaving a residue that is, therefore, white) to ash that includes a greater amount of organic matter, often in the form of charcoal, and hence is more grey or black in colour. On some burnt surfaces, a layer of grey or black ash may underlie a coating of white ash (Figure 1.23).

Within the burn site, charcoal may be transported into local hollows or be dammed up against fallen trees (Figure 1.24).

Extensive water run-off may transport sediment, charcoal and even uncharred litter, as a slurry, out of the burn area (Figure 1.22). This charcoal-rich sediment may be deposited many kilometres from the burn site, in some cases filling channels or even lakes (Figure 1.22). A range of studies has shown

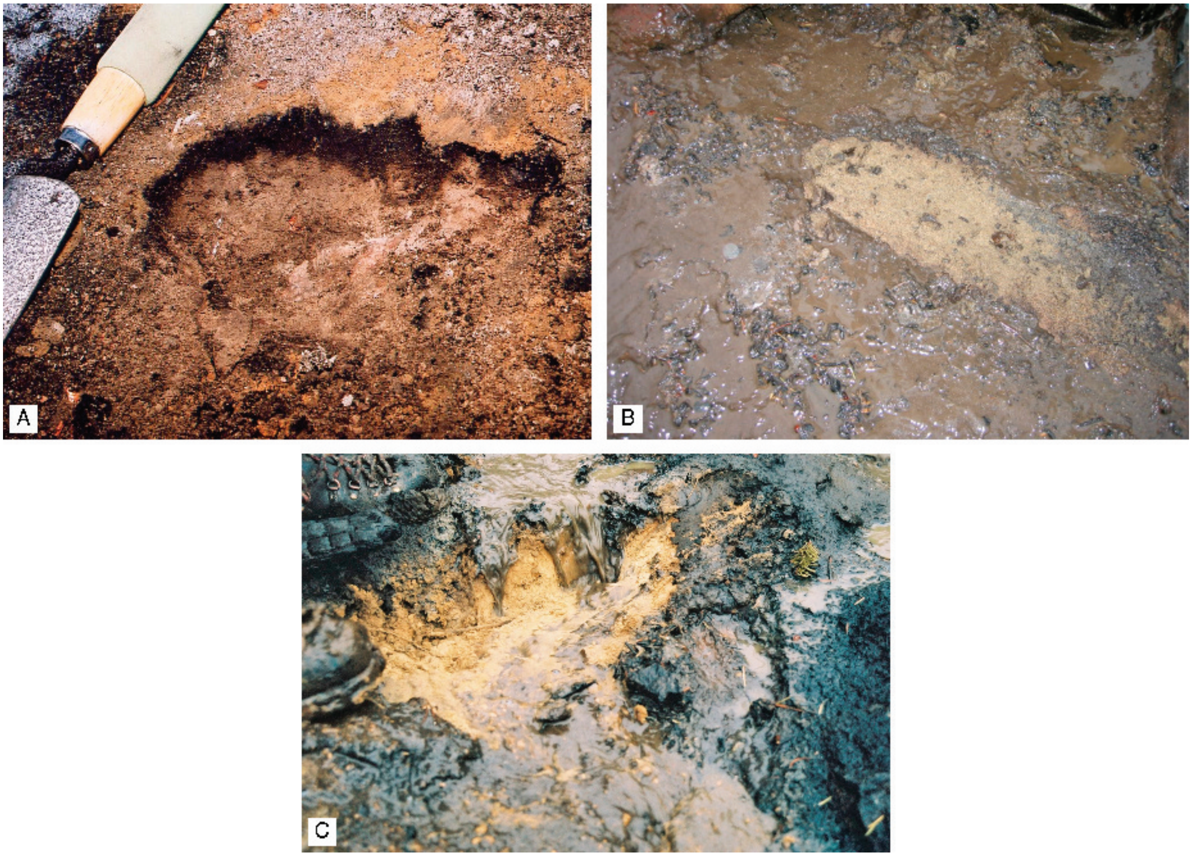

Figure 1.18 A burnt soil surface and the impact of rain after fire in Canadian Conifer forest. (Photos: D. F. Scott). Photos were taken in Okanagan Mountain Park, Kelowna, BC during a light rain event in October 2003, roughly six weeks after the passage of a late summer wildfire through old mountain pine forest (predominantly *Pinus contorta*). Dead and down fuel loads were high as the area was long unburnt and unharvested.

A. Burnt soil surface.
B. Water saturated upper layer with un-wettable hydrophobic layer beneath.
C. Water moving by overland flow eroding gulley.

that depositional rates, in some deposits, and setting may increase more than 30 fold (Swanson, 1981; Moody and Martin, 2009). As yet, we have rather limited understanding of this transport depositional process or how to recognize how it has occurred from the nature of the sediments. The occurrence of charcoal, especially in sediments that have been rapidly deposited, may provide a significant clue.

The significance of fire as a trigger for alluvial fan deposition was first studied in sediments from Yellowstone National Park in the USA. Further investigations in the historic records there and elsewhere, has demonstrated the widespread nature of this phenomenon (Meyer and Pierce, 2003; Cannon *et al.*, 2001). Most studies have involved forested ecosystems, and there is a need for more studies in grassy ecosystems. There is a growing understanding that not only the vegetation, but also the hydrology and hill slope, will play a part in the erosion deposition process (Figure 1.21).

1.9 Fire and vegetation

Another key element in wildfire is the nature of the vegetation and fuel. There are fundamental differences in fires within forests, for example, and those in grasslands. The different vegetation types result not

Figure 1.19 Geomorphic impacts of fire.

A. Channel incised after the Cerro Grande Fire near Los Alamos, New Mexico, USA, 2003.
B. Wide gully eroded after Buffalo Creek Fire, Colorado, USA, 1996.
C. Alluvial fan created following Buffalo Creek Fire and first rainstorm, Colorado, USA, 1996.

(All photos: John Moody, USGS).

only in different fuel loads and flammability, but also in the influence of wind and speed of fire spread. Even fires within similar types of vegetation (e.g. shrubs) will differ because of both fuel structure and calorific value of the fuel.

Shrubs and grasses are burnt predominantly by surface fires (Figure 1.7). However, it is useful to know that Mediterranean-type shrublands (e.g. chaparral, fynbos, matorral) are usually described as crown fire systems (Figures 1.7, 1.8). The build-up and moisture content of the fuel is critical in how they burn. In grasslands, fuel may grow rapidly and dry dead fuel may accumulate quickly in significant quantities. Fires in such vegetation may be of cool to moderate temperatures (less than 600 °C) and move rapidly through the vegetation. Because of this, the roots of the plants may not be killed, nor the seeds in the soil bank destroyed. A key for grassland fires relates to the fire return interval (FRI) (see below), whereby any small tree sapling could be killed if the FRI is less than ten years. If there is too long between fires, it is possible that the nature of the vegetation will change to growth of shrubs and trees, thereby changing the nature of subsequent fires (Bond *et al.*, 2005).

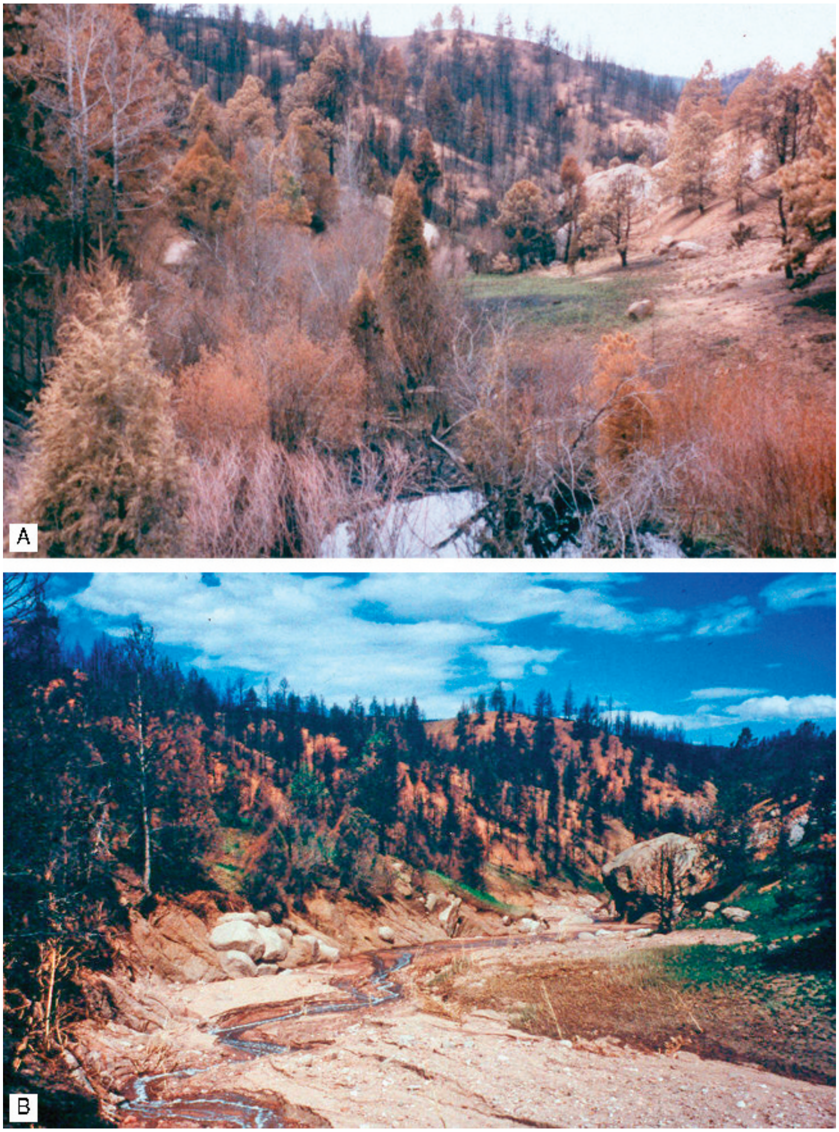

Figure 1.20 Impact of the Buffalo Creek Fire, Colorado, USA, 1996.

A. Area after fire before first rain storm (June 1996).
B. Area as above but after first rain storms, showing large area of sediment accumulation (16 July 1996).

(All photos: John Moody, USGS).

Ground cover vegetation, ranging from ferns through to shrubs, will also burn by surface fires. Heather heathland in Europe is a prime example of this (Scott *et al.*, 2000, Figure 1.16). In such cases, much of the fuel comes from the living vegetation rather than a build-up of litter. In other cases, such as chaparral, the fuel load comprises a combination of dead and fine fuel. This vegetation, however, burns particularly hot and may be spread by stormy winds.

As we have seen, though, the important result of a fire relates to its intensity and severity. Fire must be considered in the context of the ecosystem, as pointed out by Keeley *et al.* (2012) and, hence, the factors involved may be thought of in terms of a fire diamond (Figure 1.25).

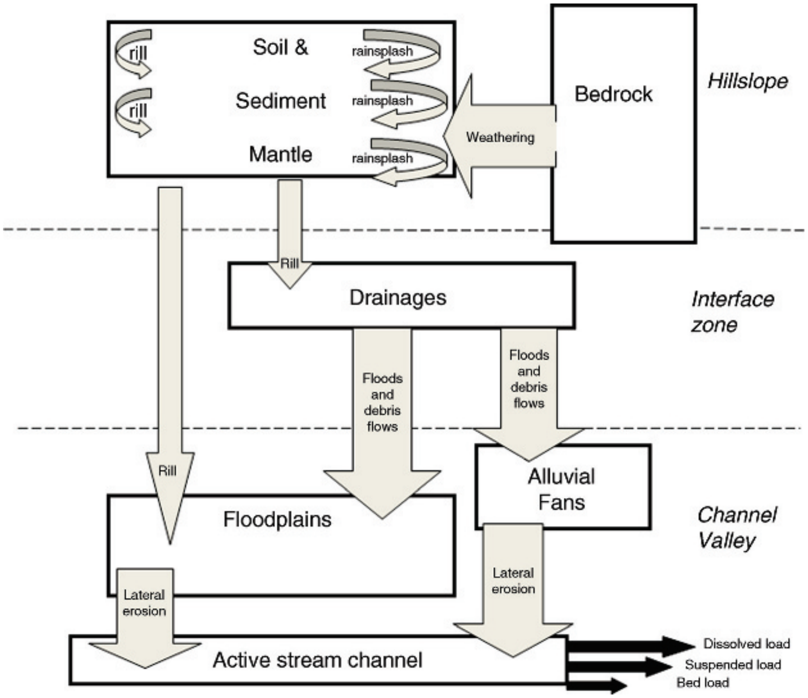

Figure 1.21 Components of a burnt landscape. Sediment storage reservoirs are shown as rectangles and transfer processes as grey-green arrows. (Modified from Moody and Martin, 2009). Reproduced by permission of Taylor & Francis.

Here, not only is the amount and distribution of the fuel important, but also climate seasonality. Within forest systems, the fires may be more complex. The majority of wildfires in forests start as surface fires that consume the on-ground fuel load, typically comprised of dead litter, logs and duff, as well as living herbaceous plants and shrubs (Figure 1.8). This fuel build-up is key. If surface fires burn regularly through many types of forest ecosystems (e.g. ponderosa pine forests of western North America), then the temperature and flame height may be insufficient for the fire to either kill the roots of the plants or spread into the canopy layer as a crown fire.

Key elements in the nature of the surface fuels will be not only the moisture content of the plants but also the size, distribution and type of fuel available to burn. Both from field and laboratory observations, it can be shown that logs, twigs and leaves have different flammability and different rates of drying. Even different shapes and sizes of leaves can ignite differently and can also produce different fire spread rates (Belcher *et al.*, 2010a). Obviously, there are some surface fires within woodlands or forests that may have a significant impact upon that ecosystem, but in forests where fires are a regular feature, such as in ponderosa pine forests of western North America, regular burning of surface fuel is important in preventing fuel load build-up. Consequently, a surface fire may spread into the tree canopy as a crown fire if the surface fuel loads are very high (Figure 1.7; Roos and Swetnam, 2012).

Where there is a significant build-up of soil litter, an organic-rich soil layer may form. In extreme circumstances, such as in a normally waterlogged environment (e.g. mire), this organic-rich layer may dry up and a fire may not only burn surface litter but also begin to burn humus or peat layers in a ground fire. In some cases, these fires may change from quick-moving flaming surface fires to slow-moving smouldering fires that are relatively starved of oxygen. These fires may last hours, days, months or even years after the surface fire has moved away and been extinguished (Rein, 2013). Putting out such fires may be problematic, as exposing the fire to air may induce flaming and, in some cases, water may only act to introduce oxygen into the system, making the fire worse rather than

Figure 1.22 Moss movement and deposition of charcoal following fire and rain.

A. Charcoal-rich flows after rainstorm, from a forest fire by overland flow from the Rodeo-Chediski Fire, Apache-Sitgreaves National Forest, Arizona, USA, 2002 (photo: D. Neary, US Forest Service).
B. Charcoal-rich flows after rainstorm, from a forest fire by overland flow from the Rodeo-Chediski Fire, Apache-Sitgreaves National Forest, Arizona, USA, 2002, and into a nearby river (photo: D. Neary, US Forest Service).
C. Charcoal filling channel from the Hayman fire, Colorado, USA, 2002 (photo: Greg Smith, USGS).

(From Scott, 2010).

putting it out. An extreme example of such fires are underground lignite and coal fires, which can smoulder for decades and cover thousands of square kilometres (Figure 1.26).

As will be shown later, the frequent occurrence of surface fires in some forest ecosystems has led to the evolution of some fire-resistant traits in some plants and even, in some cases, the need for fire as part of their reproductive strategy. With some plants, features of their growth and composition may even promote fire. Most eucalypts, for example, have evolved a re-sprouting ability from root stocks, so even if all of the main above-ground biomass is consumed in the fire, the plant will still survive (see Chapter 7, Part Two for a discussion of flammable traits).

Different tree shapes, densities and even wood type may all affect the nature and type of a fire. This wide range of variables makes the prediction of wildfire occurrence and behaviour very difficult (Chapter 15, Part Four).

1.10 Fire and climate

However much fuel build-up there is, it is climate that provides one of the ultimate controls on wildfire

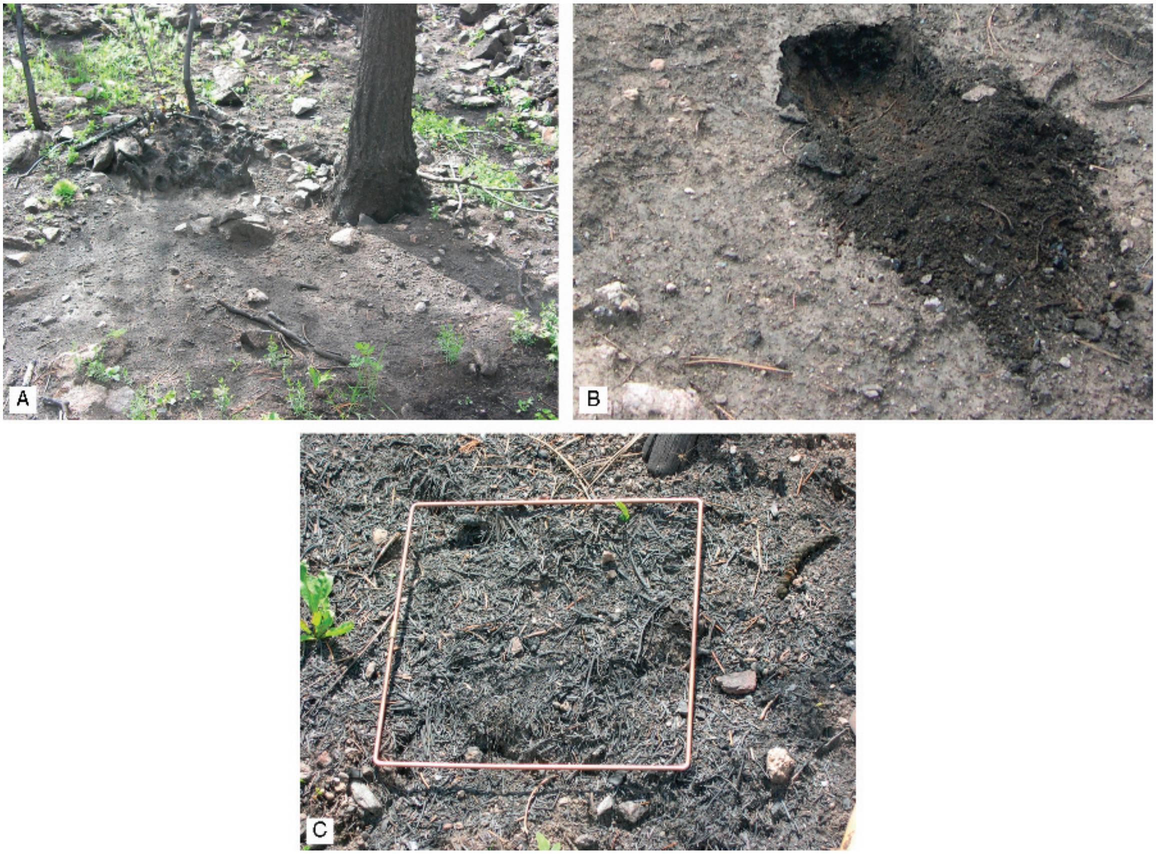

Figure 1.23 Charcoal and ash from wildfire in forest, Colorado, USA (from Scott, 2010).

A. Ash on forest floor from the Overland fire (2003). Reproduced by permission of Elsevier.
B. Pale upper ash layer and thick dark charcoal layer beneath (photo: A. C. Scott).
C. Area with only charcoal-rich ash on forest floor from the Hayman fire, 2002. Quadrat is 20 × 20 cm. Reproduced by permission of Elsevier.

(Figure 1.1), both in the ignition and spread, as well as in the extinguishing of, a major fire (see Chapter 9, section 9.16, Part Two). As we have seen, fuel moisture content is critical for fire ignition through a lightning strike (or even through a human agency). Simply wet plants do not burn (at least under the present oxygen composition of the atmosphere). A lengthy hot-dry period has two effects: to dry out the dead fuel making it available to burn and to reduce the moisture content of living vegetation to allow at least the finer leaf/twig fraction to more easily combust (Figure 1.19).

However, one of the observations from the Yellowstone fires of 1988 was that living plants were fully hydrated, despite long preceding drought. Fire risk will therefore be a combination of the condition of fuel, the moisture content of the air and also the temperature. There is no doubt that hotter temperatures promote increased fire. Aspects of fire weather are detailed later in this book (Chapter 14, Part Four), but it is important to grasp that climate (and hence climate change) plays a particularly significant role in wildfire activity. Small changes in the timing of snow melt or summer length may have a profound affect upon the occurrence or length of a fire season. Such small climate shifts have been noted in western North America, which has been claimed to lead to a significant increase in wildfire activity (Westerling *et al*., 2006; Figure 1.27).

In parts of the world where fire is not a common element in the natural vegetation, periods of drought can lead to an increase in wildfire activity (e.g. southern England), even if a number of the fires are started

Figure 1.24 Charcoal from surface fires in heathland and conifer forest.

A. Charcoal after fire across heathland in southern England (from Scott *et al.*, 2000). Reproduced by permission of Elsevier.
B. Charcoal from Hayman fire, Colorado, USA (2002). Scale is 1 cm (from Scott, 2010). Reproduced by permission of Elsevier.
C. Charcoal washed up against downed tree trunk that is acting as a trap. Hayman fire, Colorado, USA, 2002 (from Scott, 2010). Reproduced by permission of Elsevier.

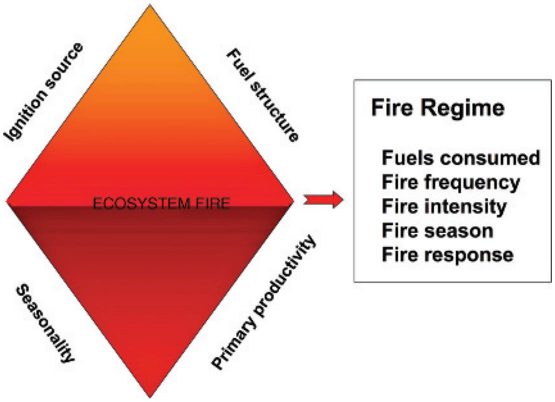

Figure 1.25 Ecosystem fire. Fire diamond schematic of factors necessary and sufficient for predicting the distribution of fire as an ecosystem process. Fire regimes are controlled strongly by ignition frequency and fuel structure, with important feedback loops between all four factors shown on the sides of the diamond. (Modified by J. Keeley from Keeley *et al.*, 2012. Courtesy USGS)

by human activity. Strong winds can fan fires, even under mild temperatures.

An additional impact of climate are the southern oscillations, such as El Niño/La Niña cycles. This leads to periods of more drought and increased fire activity, such as seen in the south-western USA (Swetnam and Betancourt, 1990). Such weather cycles also affect other regions, such as Indonesia, where a combination of the human draining of peat lands and exceptionally dry years led to extensive peat fires such as those seen in 1983 and 1992 (Page *et al.*, 2002, 2009).

Together, therefore, climate and weather play a major role in wildfire activity. Fires, however, unlike other disturbances such as floods, cyclones, but very like herbivores in ‘eating’ vegetation, play a major role in selecting for particular plant traits (Bond and Keeley, 2005). Without the organic matter, fires would not exist. We emphasize the importance of the biology in the fire ecology chapters later in this book (see Part Two).

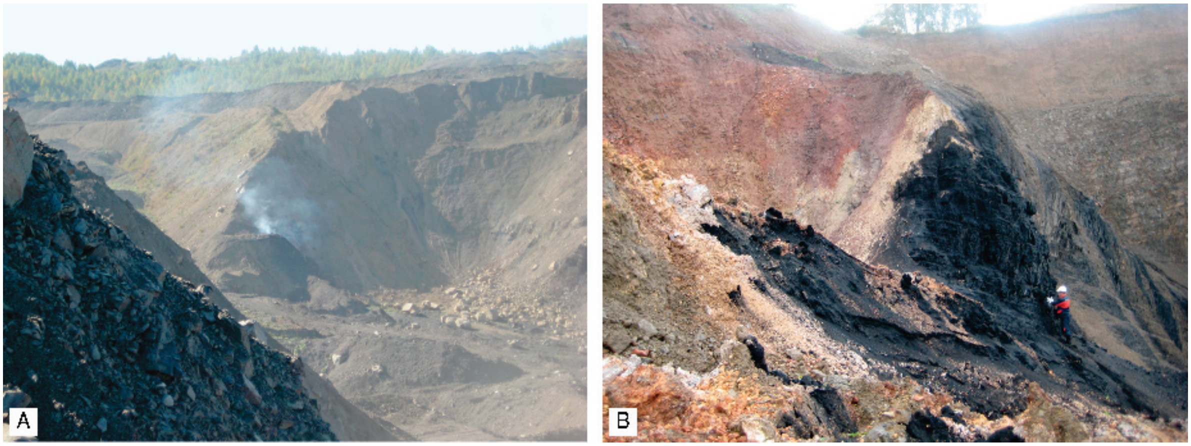

Figure 1.26 Russian coal fires. (Photos A. C. Scott).

A. Coal fire, Permian coals, Kusnetsk Basin, Siberia, Russia.
B. Burnt coal after coal fire, Permian coals, Kusnetsk Basin, Siberia, Russia.

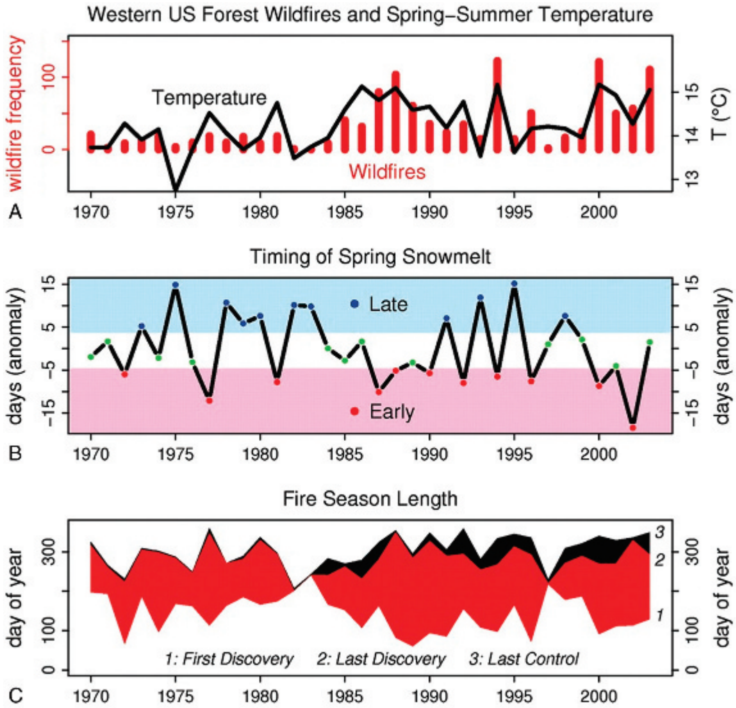

Figure 1.27 Western USA forest fires 1970–2005. (From Westerling *et al.*, 2006). Courtesy TW Swetnam.

A. Annual frequency of large (9400 ha) western US forest wildfires (bars) and mean March through August temperature for the western United States (line).
B. First principal component of centre timing of streamflow in snowmelt-dominated streams (line). Low (pink shading), middle (no shading) and high (light blue shading) tercile values indicate early, mid- and late timing of spring snowmelt, respectively.
C. Annual time between first and last large fire ignition, and last large fire control.

1.11 Fire triangles

Traditionally, a range of characteristics of fires has been expressed in the form of fire triangles (Figure 1.1). These have the advantages of helping to simplify the fundamental aspects of fire, but the disadvantage in some cases is restriction of other elements. In this chapter, so far, we have considered two of these triangles. The first considers plant combustion, with fuel, oxygen and heat being the key elements. Lightning is a source of heat and the fuel is ignited, but oxygen availability is key to fire spread. The second triangle fire considers fundamental aspects of fire spread. This considers the fuel, its condition as determined by weather, and also topographic variation.

Yet these triangles are not sufficient to fully define all of the variables of fire (see, for example, the fire diamond in Figure 1.25). As will be discussed later, there is also a time dimension to consider (see Chapters 4 and 5). In today's world there is increasing interest in modelling fire both on a local and global scale. New approaches of fire science add aspects of scale and a consideration of the 'mega-fire' (Figure 1.1). These approaches have been driven by the need to understand the longer-term aspect of fire suppression. An important additional element in our discussion concerns the fire return interval.

1.12 Fire return intervals

A key element in understanding fire is the concept of fire return interval. This is the re-burning of vegetation that has been burnt at some time in the past. The significance of this factor is manifold, but it has particular importance with regard to fire intensity or severity, and also in ecological maintenance or succession. There is a complete spectrum between fire return intervals, from less than ten years in many grassland savannas to several hundreds, or even thousands, of years in some forested ecosystems (Table 1.3).

The fire return interval may be influenced both by the vegetation type and climate regime. In addition, the resistance of vegetation to fire may also play an

Table 1.3 Fire return intervals. FRI has been classified using a number of scales (see Pyne *et al.*, 1996) and here that of Davis and Mutch (1994) is followed. (Modified from Pyne *et al.*, 1996).

Class A	Natural fires rare or absent. Examples: Wetter regions of Eastern USA deciduous forest; Southern USA deserts; Inland cypress communities of Florida.
Class B	Infrequent, low intensity surface fires with more than a 25-year return interval. Most fires are small. Examples: Eastern USA deciduous forest; Subalpine forests; Pinyon-juniper woodlands of USA and some montane meadows in western USA.
Class C	Frequent low intensity surface fires with 1- to 25-year return intervals for small areas. They are often combined with sporadic, small-scale fires with long or very long return fires and/or high intensity surface fires with a 200– to 1000–year interval. Typical burns are a few hundred to a few thousand acres. Examples: Sierra mixed conifer forests with giant sequoia, ponderosa pines etc, western USA. Prairies of USA; Sawgrass everglades of Florida.
Class D	Infrequent, severe surface fires with more than a 25 -year interval. These are usually combined with long return intervals of 300 years, sporadic crown fires, and/or higher intensity surface fires killing most but not all stand elements. Many fires can cover large areas from 1000 to 10 000 acres with some portions of still larger crown fires that belong to other regimes. Examples: White and red pine forests of Canada; Lodgepole pine forests of Rockies; Redwoods in northern California; Pinyon-pine and mixed juniper communities in USA.
Class E	Shorter to medium length return interval crown fires and/or stand-killing, high-intensity surface and ground fires with 25- 100-yearr return intervals. Most stand elements are killed over large areas. Ecologically significant fires are generally 5000 to 10 000 acres or more in area. Examples: Boreal forest of Eastern Canada; Coastal chaparral in California.
Class F	Long and very long return intervals sporadic crown fires and high intensity surface fires that kill most but not all stand trees, often over large areas. Return intervals are often 100–300 years or more and probably are longest at higher elevations. Fire areas are often 5000 to 50,000 acres, but smaller in subalpine forests. Examples: Most Douglas fir, and red cedar forests in western USA and Canada; High sub-alpine forest of the Rockies; Rainforest of Hawaii; Coastal redwood forests.

important role. In a grassland savanna ecosystem, for example, rapid fuel build-up, together with periods of drought, encourages frequent fires. These fires, however, generally burn rapidly and do not affect the soil seed bank, so that the vegetation may quickly regenerate. The fire may also have a flame height that may kill any tree saplings. In such circumstances, if there is no fire at the same location for more than ten years, the trees may grow to a height where they are not killed by the fire. In such a case, the vegetation may be transformed from a savanna to a woodland/forest (Bond *et al*., 2005; see Chapters 7, 8, Part Two).

Frequent burning of some shrubby vegetation, such as heather heathland in Europe, may also help in the maintenance of the ecosystem. In some ponderosa pine forests in western North America, the return of surface fires at regular intervals may maintain the ecosystem, as these fires are often of low intensity and severity, burning only dead surface fuels. In such systems, if the fire return interval is too long, the build-up of fuel will allow for both a more intense surface fire and possibly a stand-replacing crown fire. In many temperate forest ecosystems, fire return intervals may vary between 40–400 years (Roos and Swetnam, 2012).

Some ecosystems may become vulnerable to devastating mega-fires on the sites of recently burnt areas, such as in California. In such cases, the initial fire may have killed, but not consumed, all of the woody vegetation. The dead trees and shrubs will then become a large fuel load for a fire if the return interval is too short. Table 1.3 shows typical fire return intervals for a range of vegetation types.

Climate change may play an important role in altering fire intervals. However, humans may also exert an influence, both in setting fires in vegetation that rarely experiences fire naturally (e.g. Indonesian peats) or in suppressing fire (e.g. the forests of western USA) (Parts Two and Three) in which case a future fire may be much larger and more damaging. A significant new threat is that of plant invasives. This is where plants (often, but not always, grasses such as Gamba and Cheat grass) has been introduced and spread (see Part Two). The spread of flammable grasses into a vegetation that rarely burns, or with a long fire return interval, can be devastating. Equally, these plants may change the fire frequency or timing of a fire, which also may have a major impact on the native ecosystem (Balch *et al*., 2013).

1.13 How we study fire: satellites

For much of the past two centuries, our understanding of fire has come from direct on-the-ground observations and manage reports following wildfires. In such cases, observations may be limited because of both access and safety considerations. In some cases, awareness of a fire has come only after a fire has been extinguished. Over the past 50 years, there has been an increase in aerial observations of wildfire, often as a result of both aerial dropping of fire retardants and from firefighters in the air. However, even in such cases, direct observations of fires may be made much more difficult because of smoke plumes (see Figure 1.6).

There are several important drivers for the need for a range of broader scale observations of fires. These include the need to access fire damage and impact upon the land environment, and also to access the atmospheric impact of a fire, including smoke, aerosol and as emissions. For many years, aerial photography of burn sites, together with surface observations, have provided much valuable data, especially concerning burn severity. Burn severity assessments are, for example, regularly carried out by the US Forest Service (Figure 1.28).

In recent years, satellite monitoring of fires and effects, not just locally but also on a global scale, has proved invaluable in advancing the understanding of wildfire (Figure 1.29). Early assessments of global wildfire activity were undertaken using Landsat imaging techniques (Figure 1.30). These were undertaken at a variety of scales, using both normal light photography and imagery using other bands, such as infrared. Such techniques have proven very useful in assessing not only the extent of a wildfire, but also the severity of the fire, as the occurrence of dead vegetation may become particularly visible using non-visible spectra (Graham, 2003).

Satellite images of fires over parts of the globe have become commonplace and dramatic (Figure 1.31). The 1980s saw the development of the Advanced Very High Resolution Radiometer (AVHRR) that is used to scan the Earth's surface (Table 1.4).

There are a number of channels that can be used to measure different wavelengths, too – for example, determining smoke plumes from fires, as well as the occurrence of fire, using thermal infrared data from which temperatures can be derived. The latest instrument version is AVHRR/3, with six channels, which

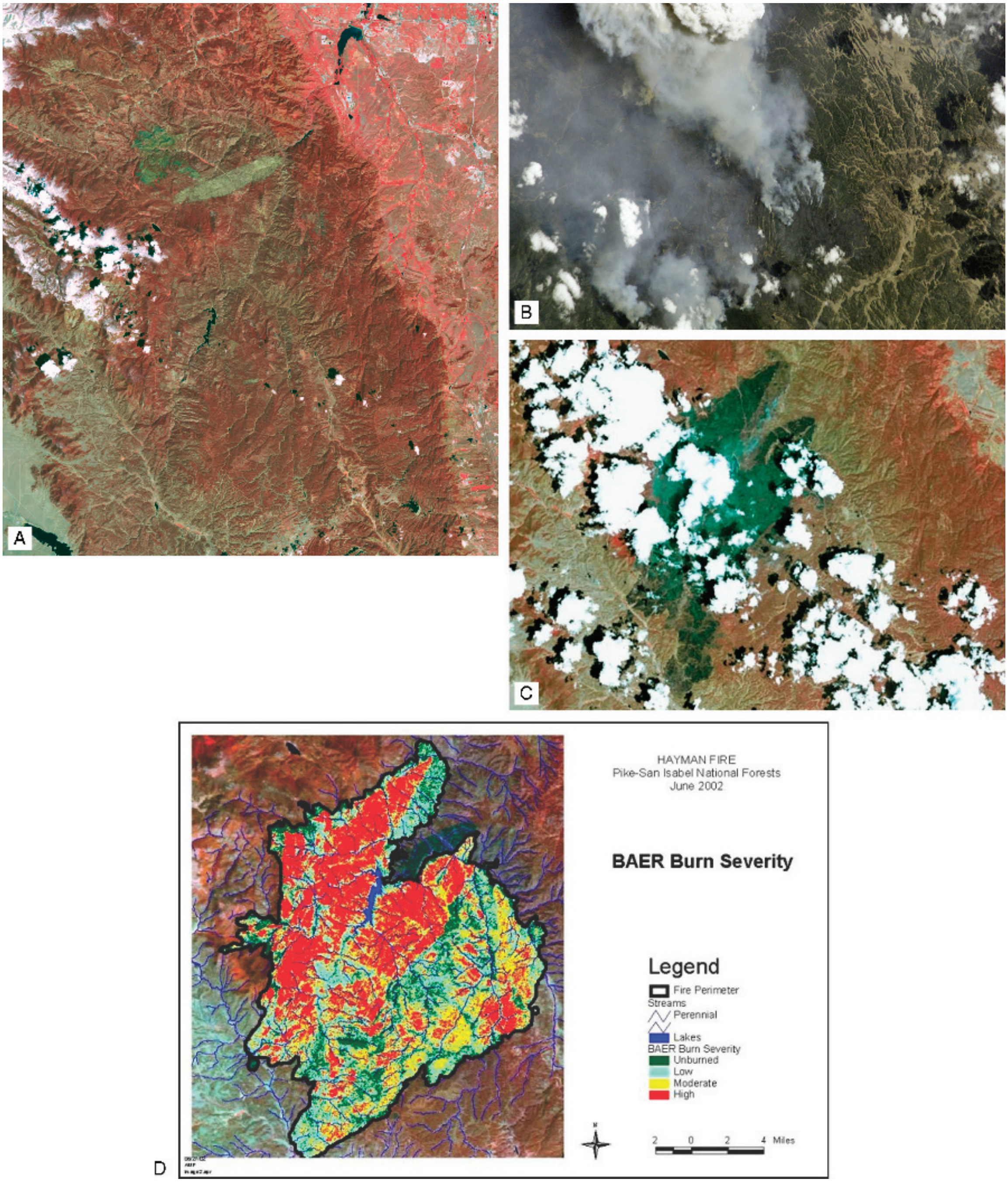

Figure 1.28 Satellite and Landsat images of before, during and after the 2002 Hayman Fire, Colorado, USA.

A. Landsat image of the Hayman Fire area in early 2002 before the fire. Vegetation appears red in the false-colour image (http://earthobservatory.nasa.gov). NASA.
B. Photo taken by in International Space Station crew on Tuesday 19 June 2002, showing the eastern flank of the Hayman fire (http://earthobservatory.nasa.gov). NASA.
C. Landsat image of burn scar. Clouds are shown in white. The burnt area shows in black, June 16 2002. (http://earthobservatory.nasa.gov). NASA.
D. Burned Area Emergency Response (BAER) burn severity map of the Hayman fire (from Graham, 2003). USDA.

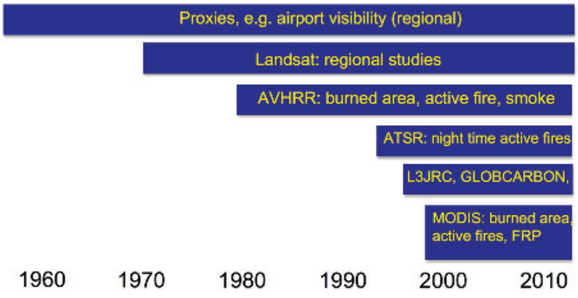

Figure 1.29 Development of the remote sensing of fire showing satellites and products. (Data from G. van der Werf).

was launched in 1998. In all such data gathering equipment, it is not simply the obtaining of the data that is important but also its processing into usable products (Roy *et al.*, 2013). For example, a database of fire activity in Russia was derived from 1 km resolution remote sensory imaging using AVHRR that was itself largely derived from active fire observations.

Table 1.4 Satellites and sensors used for monitoring fires

Satellite type	Satellite	Sensor
Polar orbiting	NASA Terra and Aqua	MODIS (Moderate Resolution Imaging Spectroradiometer)
Polar orbiting	NOAA POES	AVHRR (Advanced Very High Resolution Radiometer)
Polar orbiting	ERS	ATSR (Along Track Scanning Radiometer)
Polar orbiting	ENVISAT	AATSR (Advanced Along Track Scanning Radiometer)
Polar orbiting	TRMM	VIRS (Visible and Infrared Scanner)
Polar orbiting	NASA Terra	ASTERR (Advanced Spacebourne Thermal Emission and Reflection Radiometer)
Geostationary	Meteosat SG	SEVIRI (Spinning Enhanced Visible and Infrared Imager)
Geostationary	GOES East and West	GOES (Geostationay Operational Environmental Satellite Imager)

There has been an increasing need to monitor active fires, both during the day and at night, and to build databases to examine fire frequency within different areas and different types of vegetation, in order to help develop an understanding of how fire may be related both to climate and to human activities (Figure 1.32).

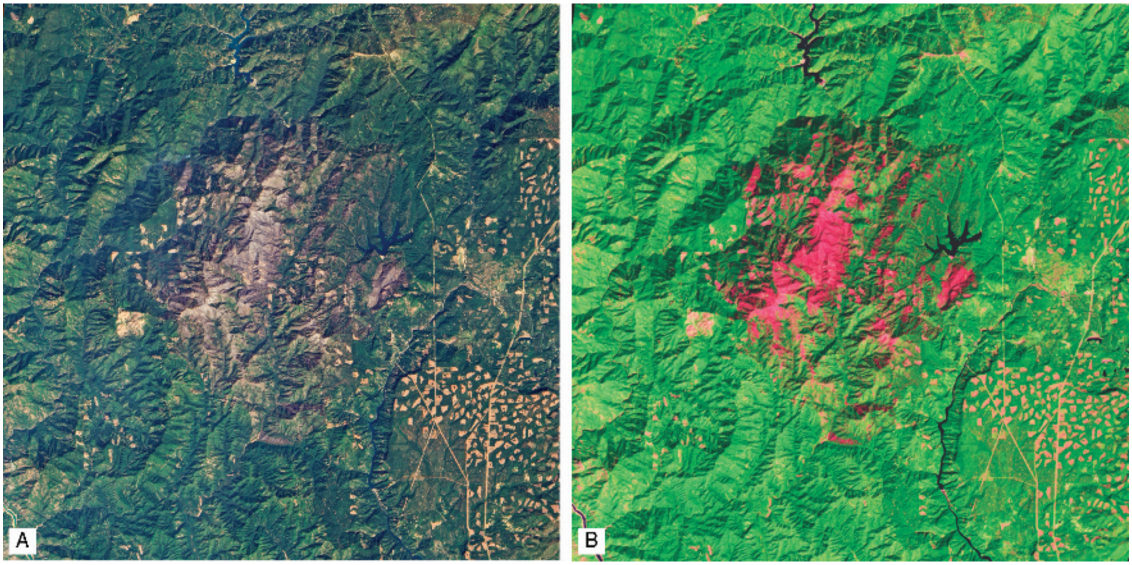

Figure 1.30 Landsat images of fire scar, Bagley Fire, Californian, August 2012. The Advanced Land Image (ALI) on the Earth Observing-1 (EO-1) satellite acquired these images on September 11, 2011.

A. Showing natural colour with the burn scar in brown.
B. Showing the burnt vegetation in red.

(http://earthobservatory.nasa.gov). NASA.

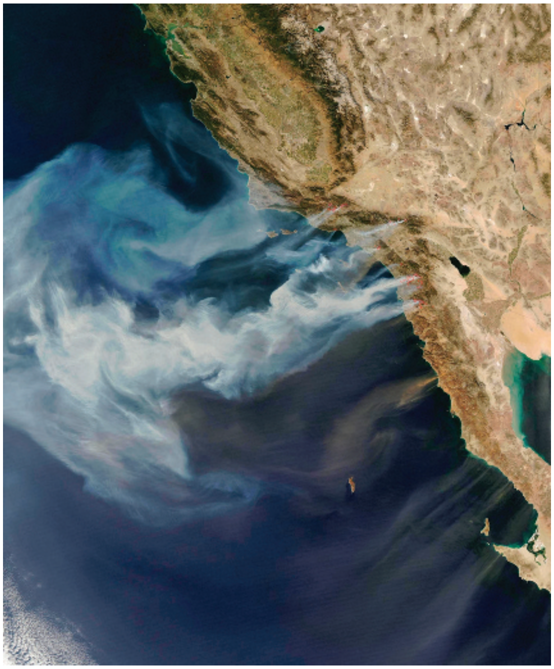

Figure 1.31 Smoke plumes from Californian fires between Los Angeles and San Francisco in October 2007 billowing out over the Pacific Ocean. Red spots indicate active fires. (Modis Rapid Response Project at NASA/GSFC, image 1163886). NASA.

Another important development during the 1990s was the ability to monitor night-time active fires (Figure 1.33).

The European Space Agency launched its satellite ENVISAT in 2002 to continue the work of ERS satellites to monitor environmental and climate changes. ENVISAT flies in a sun-synchronous polar orbit of about 800 km altitude, and the repeat cycle is 35 days. The satellite carries the Advanced Along-Track Scanning Radiometer (AATSR), following on the ATSR-1 and ATSR-2 on board ERS-1 and ERS-2. The AATSR has a resolution of 1 km at nadir and measurements are derived from reflected and emitted radiation: 0.55 μm; 0.66 μm; 0.87 μm; 3.7 μm, 11 μm and 12 μm.

The data from this satellite has been used, for example, to develop a fire atlas. Each year, the fire atlas requires the processing of 80,000 images. All hotspots with a temperature higher than 312 °K at night are precisely located (better than 1 km). Information concerning the fire atlas is available online. The satellite also allows monitoring of smoke base in addition to fire (Figure 1.34). The orbiting space station has also provided both large and smaller scale images of smoke plumes, such as those from human-set peat fires across Indonesia (Figure 1.12).

Other developments were L3JRC and Glob carbon. These are products developed by a consortium of universities and the European Commission to image and classify burnt areas. This data was derived from the Earth Observation system SPOT VEGETATION.

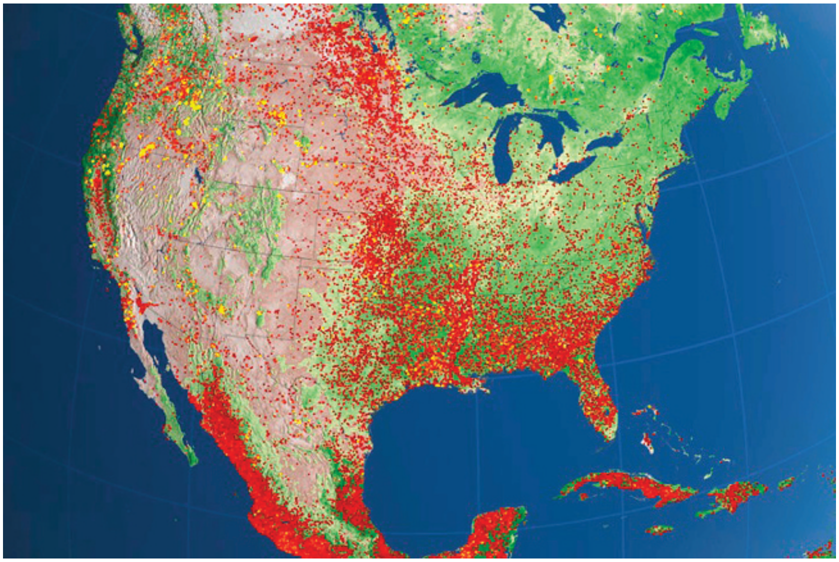

Figure 1.32 Fires across the USA from January 1 to October 31, 2012, as detected by MODIS instruments (http://earthobsevatory.nasa.gov). NASA.

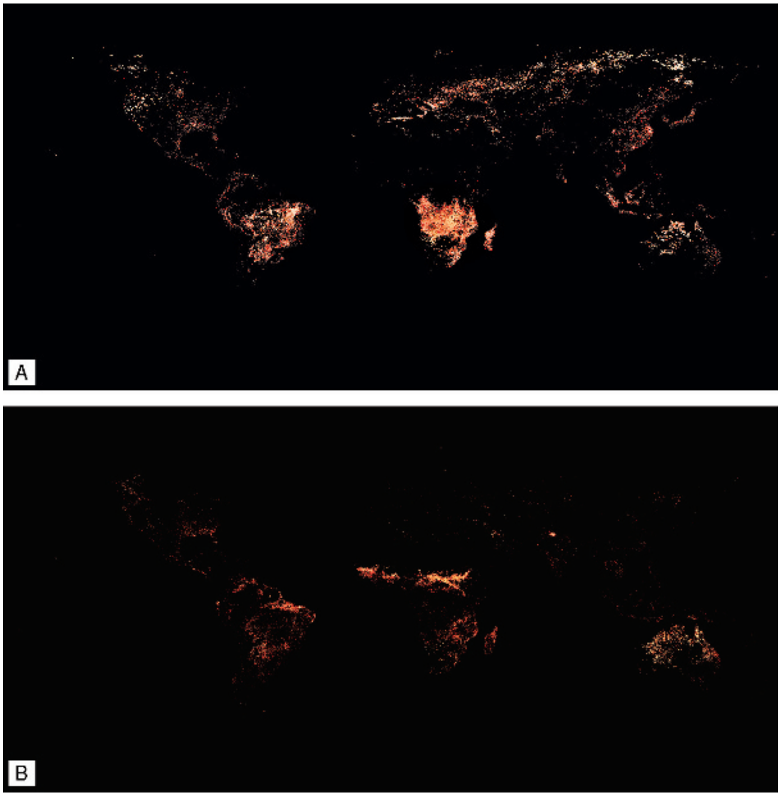

Figure 1.33 Active fires imaged at night. NASA.
A. This image, using MODIS on the Terra satellite, shows the fires seen from Aug 1 - Sept 1 2012.
B. This images shows fires from Nov 1 to Dec 1, 2012 (http://neo.sci.gsfc.nasa.gov).

Figure 1.34 Smoke plumes from fires across Russia on 29 July, 2010, with a resolution of 300 m. This image was taken by the European Space Agency's ENVISAT Earth-observing satellite. Moscow is in the lower left hand corner. (http://esamultimedia.esa.int/images/EarthObservation/images_of_the_week/forest_fires_MoscowMER_FR_20100729_43977.jpg (Aug 10, 2010)). European Space Agency.

Perhaps the most significant development over the past 10–15 years is the development of MODIS products (and FRP). Fire Radiative Power (FRP) is estimated from active fire observations and is the rate at which a fire emits radiant energy. Fire Radiative Energy (FRE) is a temporal integer of FRP over the period of observations. The units are Joules. This data can be used to retrieve fire temperature. In general, the greater the amount of fuel, the greater the amount of energy that is released, and the heat released is also related to both the fuel consumption and the heat content of the fuel.

The Moderate Resolution Imaging Spectra-radiometer (MODIS) is aboard the Terra satellite launched by NASA. The amount of data collected by this satellite is astonishing, and a wide range of products has been developed to utilize this vast quantity of data. For example, the Fire Information for Resource Management System (FIRMS) integrates remote sensing and GIS technologies to deliver global MODIS hotspot fire locations and burnt area information to a variety of end users (Figures 1.35, 1.36, 1.37). This builds upon a mapping interface, *Web Fire Mapper*, which delivers near real-time hotspot-fire information and monthly burnt area information (see van der Werf *et al.*, 2006).

It is possible to receive a fire alert from the NASA data site. It should be noted that this fire data relates to fires within 1 km pixels. It should also be noted that this fire data might be viewed using Google Earth, but size restrictions may mean that not all the data is

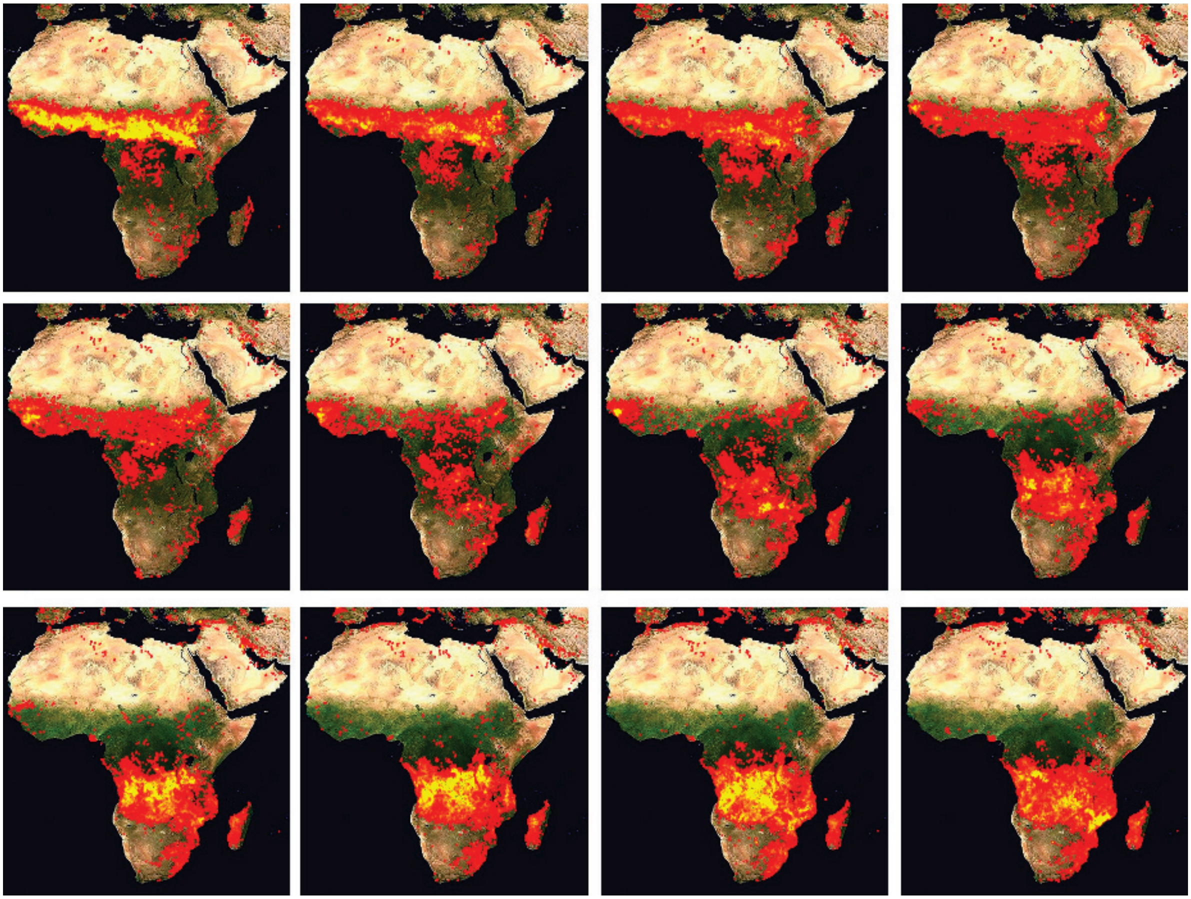

Figure 1.35 Variation of fire across Africa in 2005. Each image was processed from a ten-day period within a month from Jan to August (Jan 1–10; Jan 21–30; Feb 10–19; Mar 2–11; Mar 22–31; April 11–20; May 1–10; May 20–30; Jun 10–19; Jun 30–Jul 9; Jul 20–29; Aug 9–18). Successive images show the shift of fire through the year. Red indicates a single fire in an area over the period and yellow indicates more. These images were processed using data from MODIS on NASA's Terra and Aqua satellites. (http://earthobsevatory.nasa.gov). NASA.

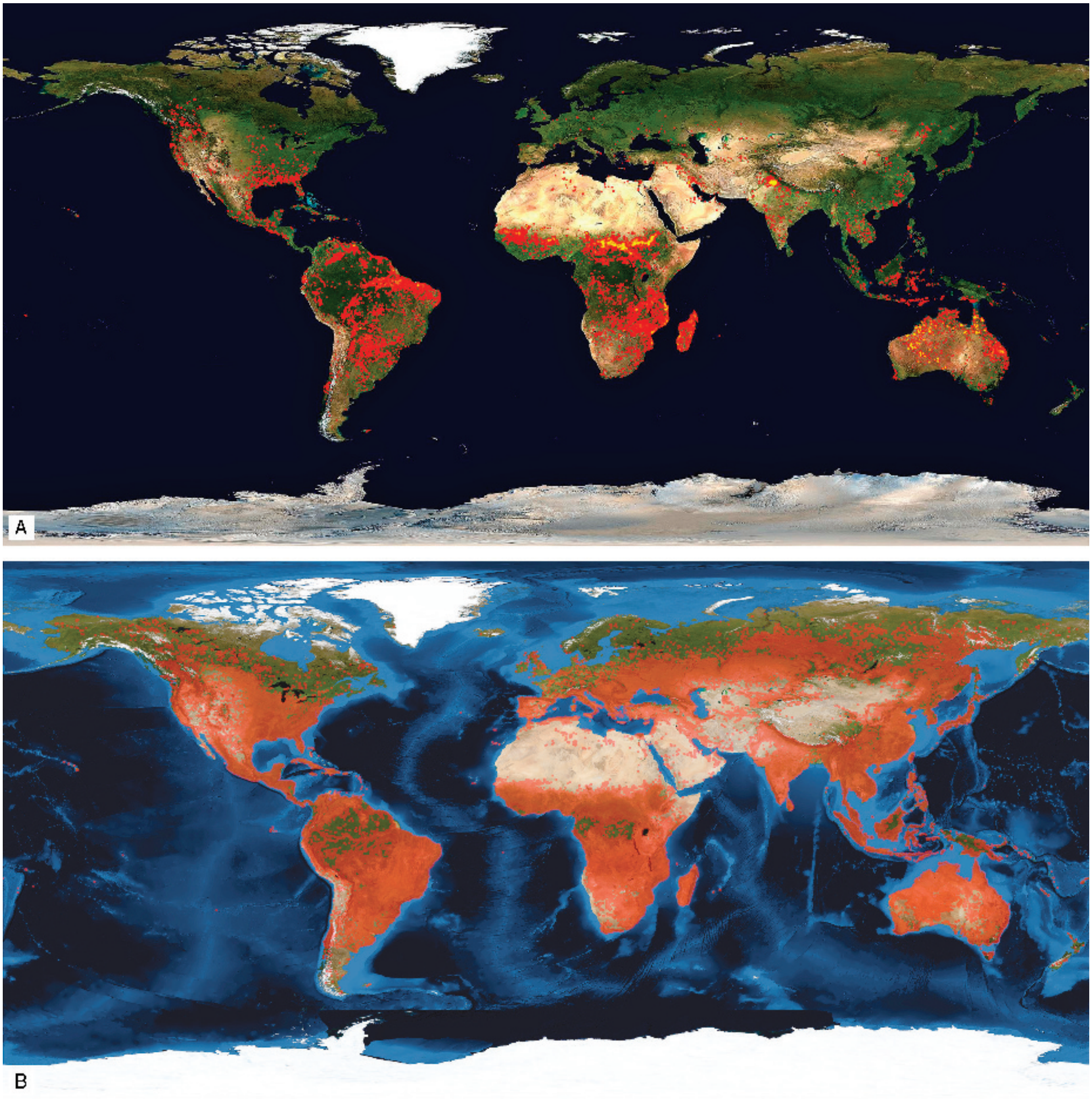

Figure 1.36 Fire across the world.
A. This image is a composite of active fires in part of a single year. Areas of red show a single fire in a ten-day period and yellow shows multiple fires, Jan 1–10, 2013). This image was collected using MODIS on NASA's Terra and Aqua satellites (http://lance-modis.eodis.gov).
B. This map has all fires collated through the year for 2012 (NASA FIRMS 2012. MODIS Active Fires Detections Data Set. Available online http://earthdata.nasa.gov/firms). (Map made and provided by Min Minnie Wong, Department of Geographical Sciences, University of Maryland, USA).

displayed (http://activefiremaps.fs.fed.us). These new data also allow information such as burnt area as well as carbon emissions to be calculated (see Chapter 6, Part Two).

It is not only the fires themselves that can be imaged. The effects of not only smoke (e.g. using the Calipso satellite; Figure 1.38) but also other gases and aerosols derived from fires (Figures 1.39, 1.40),

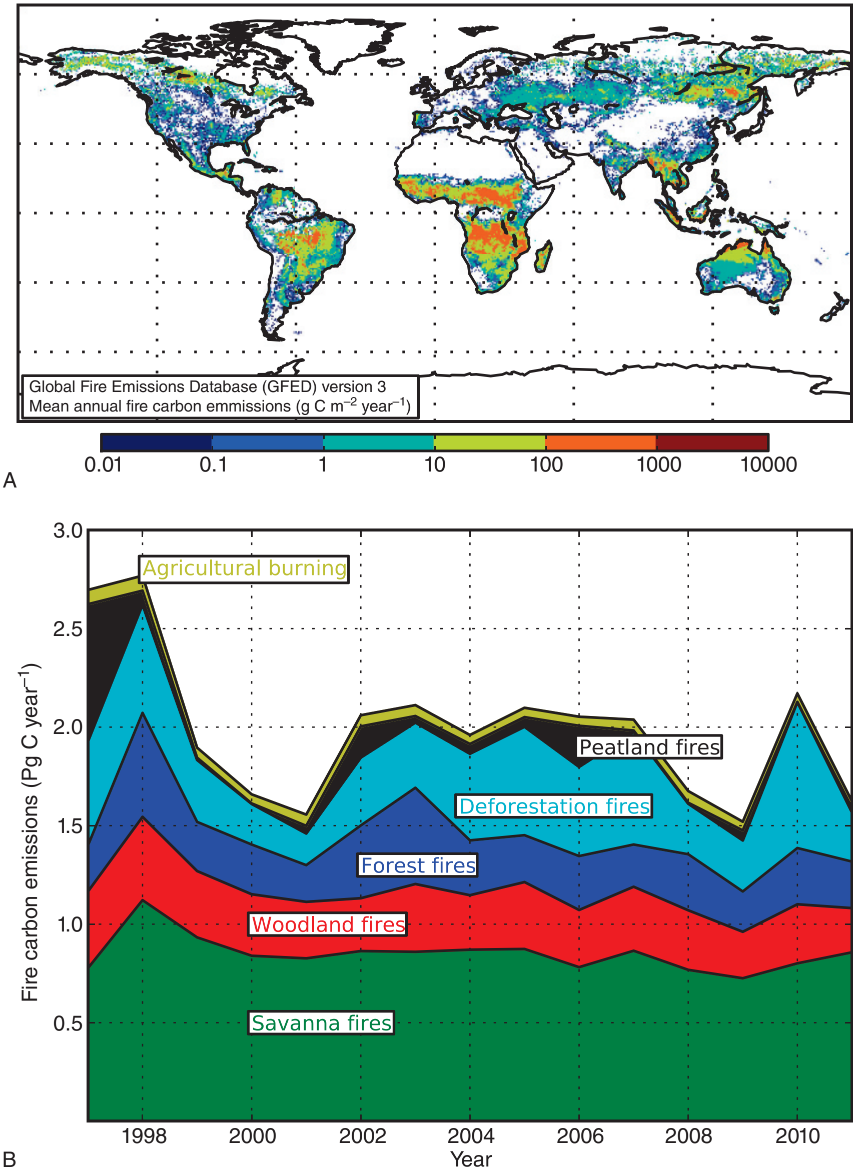

Figure 1.37 Emissions from fires from mid 1997 - mid 2010 shown on a global map (A) and through time related to vegetation type (B). (Diagrams supplied by G. van der Werf).

such as carbon monoxide (CO; Figure 1.41) and oxides of nitrogen (NO_x; Figure 1.42) can be seen spreading into the upper atmosphere, and this emphasizes the global impact of fire (Part Three).

The new fire data available using satellite monitoring techniques (Roy *et al.*, 2013) has revolutionized our understanding of global fire and also of the impact that humans play in both starting and suppressing fires (Part Three).

1.14 Modelling fire occurrence

The ability to map fires at an increasingly fine resolution in both space and time has led to the development of fire models that simulate the observed patterns. The fire occurrence data can be linked together with fuel data and also meteorological data, including

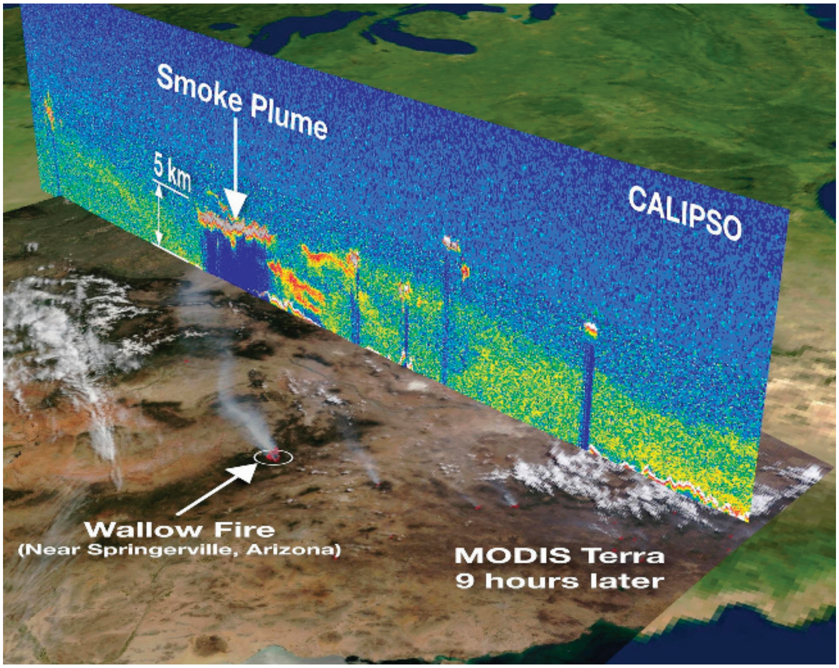

Figure 1.38 Smoke plume from the Wallow fire (Arizona, USA), June 2011, as seen from NASA's CALIPSO satellite. This vertical profile from space shows the smoke plume reached heights of 5 km (3 miles) high. Photo: Jason Tacett and Calipso team (www.nasa.gov). NASA.

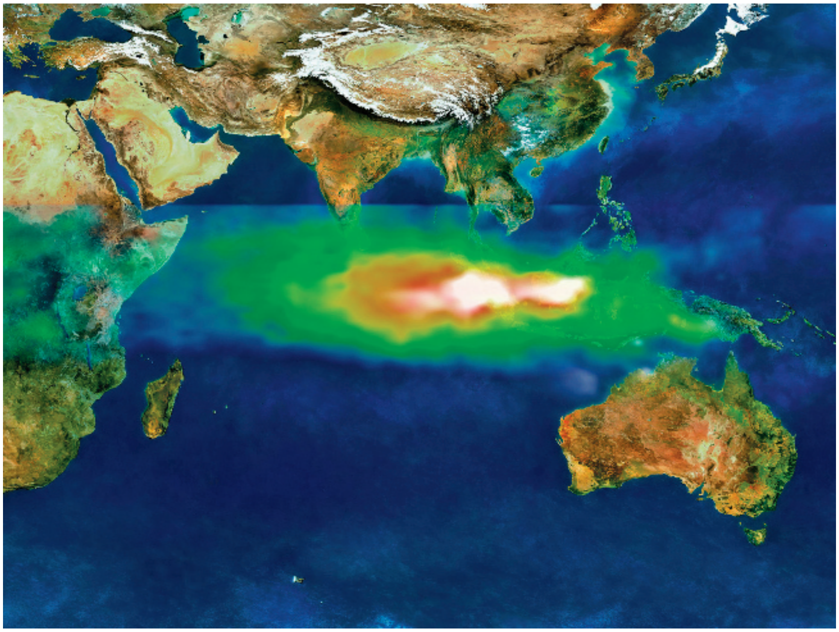

Figure 1.39 Aerosol emissions from fires in Indonesia, October 1997. White represents smoke near the fire and colours indicate smog being carried in to the Troposphere by high altitude winds. This was taken using NASA's Earth Probe Total Ozone Mapping Spectrometer (TOMS) satellite instrument (http://visibleearth.nasa.gov). NASA.

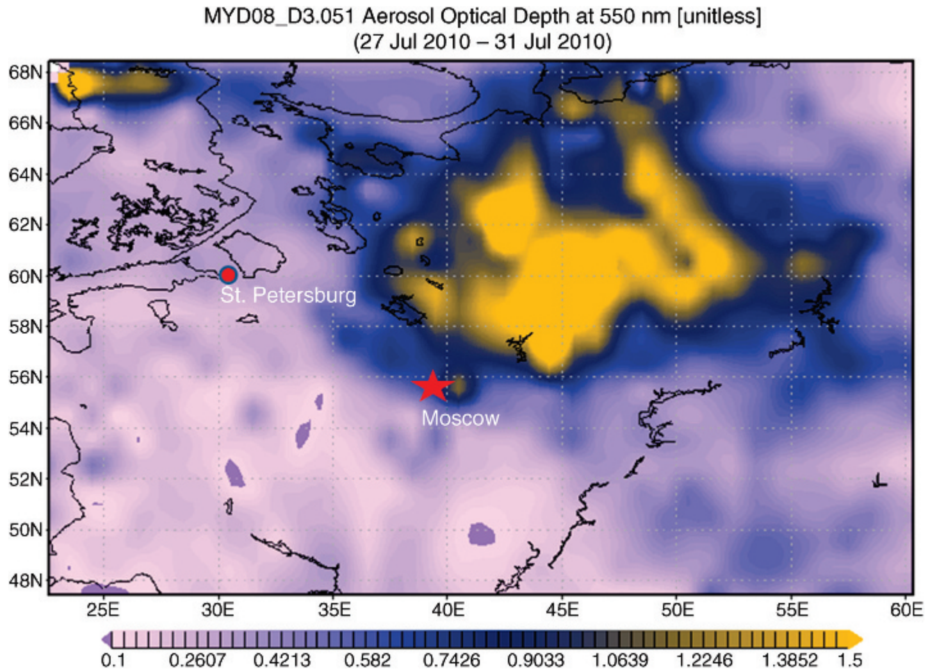

Figure 1.40 Smoke pollution from fires near Moscow, Russia in July 2010. This image used the MODIS sensor on the EOS Aqua satellite and was averaged over a five-day period (July 27–31, 2010) (see Keywood *et al.*, 2013). (Image from www.earthdata.nasa.gov). NASA.

temperature, humidity and wind speeds. For the short term, this may lead to the prediction of fire occurrence through fire danger maps that may consider overall risk to an area through to daily forecasts (Figure 1.5).

The development of powerful climate models also has allowed the integration of fire prediction to consider not only the relationship of fire and climate (also fire, vegetation and climate) in the present but also in the future. This approach is at an early stage, and several research groups have developed computer models allowing prediction of fire and climate. The computing power needed for such models is considerable, so most of these models tend to be global and fairly large scale.

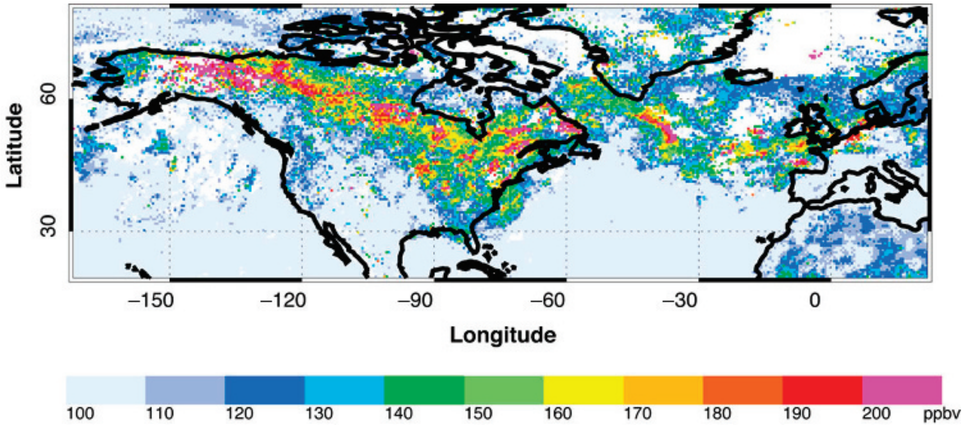

Figure 1.41 Carbon monoxide plumes from Alaskan fires of 2004. Using NCAR MOPITT (Measurements of Pollution in the Troposphere) (UCAR, University Corporation for Atmospheric Research (D101890).

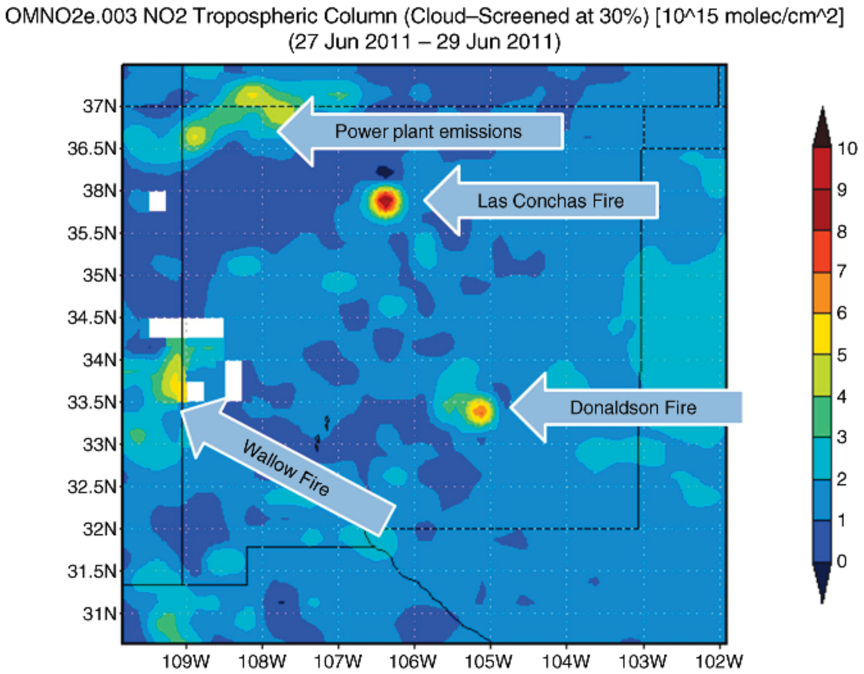

Figure 1.42 Levels of nitrogen dioxide (NO_2) levels from fires across New Mexico and Arizona in June, 2011, using Ozone Measuring Instrument (OMI) on NASA's Aura Satellite (NASA and James Acker: www.nasa.gov.20110701). NASA.

There are two main approaches to the construction of fire-climate models. One is correlative and, therefore, based on statistics of past fire events. The other is an attempt to build a mechanistic model analogous to the GCMS for predicting entirely new combinations of vegetation and climate of the future. SPITFIRE is currently the most advanced attempt to build a mechanistically based simulation model for application at a global scale.

One correlative model (Krawchuk and Moritz, 2011) constructed multivariate statistical, generalized additive models (GAMS), combining existing fire occurrence, climate, net primary productivity (NPP) and ignition data (see Chapter 6, Part Two). In addition, data such as global vegetation distribution was included. This data used spacial data at a spacial resolution of 100 km (10 000 km) and mapped global vegetation fire using the ATSR fire atlas (Figure 1.36). Such an approach allows for a consideration of a range of climate scenarios, from the most conservative estimates of climate change to the most extreme (Figure 1.43).

The results of such analyses may allow analysis of whether fire will become more or less likely within a region, or if fire may retreat or invade an area. These

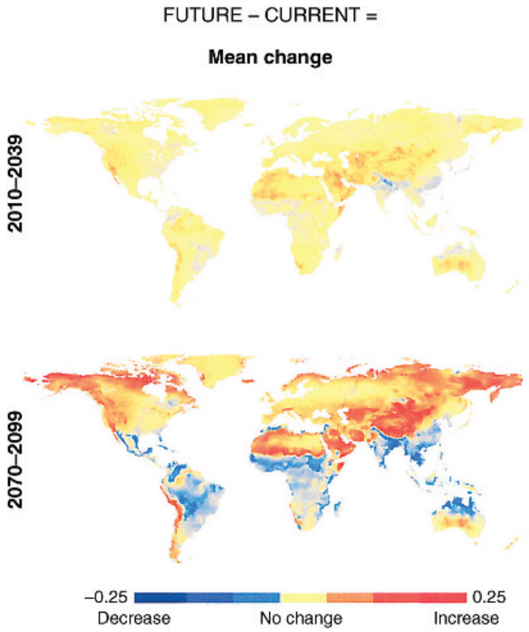

Figure 1.43 Modelling fire in relation to climate change showing particularly strong increases in fire in some areas in the later part of the 21st century. Note: in some areas, fires decrease. (From Moritz *et al.*, 2012, with permission from the authors).

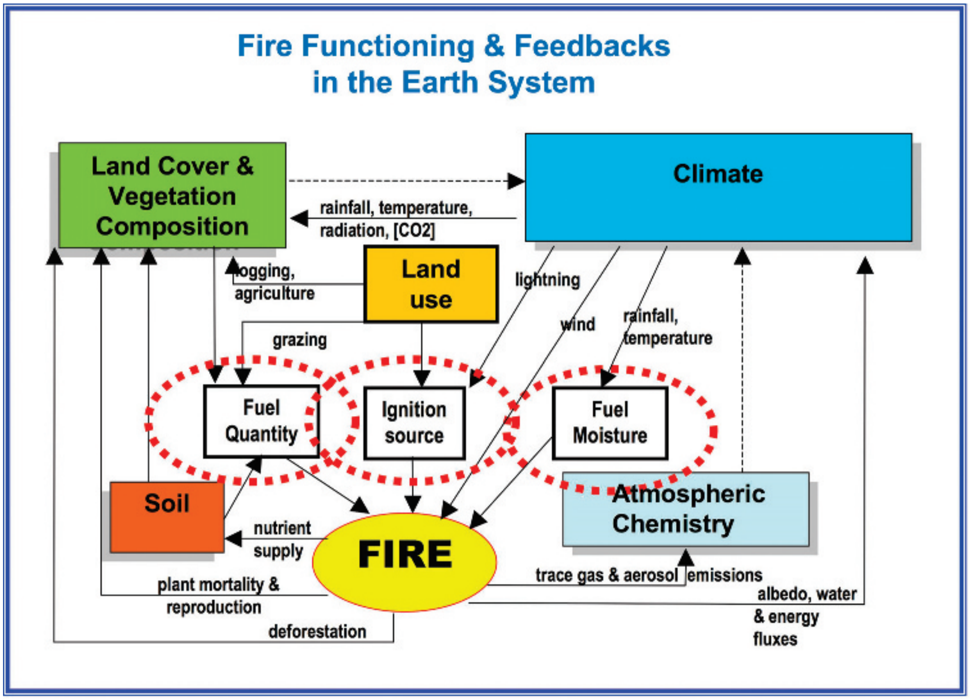

Figure 1.44 Fire functioning and feedbacks in the Earth system used as a basis of the development of the SPITFIRE model. The three key factors of fuel quantity, moisture and ignition are highlighted. (Supplied by Spessa *et al.*, 2012). Reproduced with permission from Springer Science+Business Media B.V.

models should alert planners to future fire risk and they should also link into major considerations of discussions concerning future global biodiversity assessments (Shlisky *et al.*, 2007).

The other recent approach using a mechanistically based simulation model has also involved simulating climate-vegetation-fire interactions using regional applications of the LPJ-SPITFIRE model (Figures 1.44, 1.45). This research is concerned with the long-term changes in vegetation and global carbon storage, as well as quantifying different trace gasses from biomass burning (CO_2, etc.) at regional and global scales. The model also allows the effect of regional climate phenomena such as El Niño on fire activity, vegetation and emissions, and it tries to distinguish between patterns of natural versus human fire ignition patterns (Thonicke *et al.*, 2010).

1.15 Climate forcing

An increased understanding of the distribution of fire on Earth has led to a consideration not only of how fire is influenced by climate change, but also how fire may be involved in climate forcing. Fire may produce increased CO_2 in the atmosphere, adding to the total of greenhouse gases and contributing significantly to global warming. In contrast, smoke emissions may have an effect upon the atmosphere that creates a cooling effect. Burning of a region may also change albedo, so that green vegetation may become black. Fire suppression may change a reflective grassland to an absorbent forest, thereby heating the planet (while supposedly sequestering carbon). In addition, soot particles may cover a snowfield, again adding to that effect. Such positive and negative impacts make the overall contribution of fire to climate change difficult to calculate.

Recent global analyses of fire and its effects on climate change have been published. Some of these publications consider the effect of regional fire activity on global emission data. For example, the major peat fires in Indonesia are shown to have had a significant effect upon the global carbon cycle. A particular problem is separating natural and human-caused fire effects.

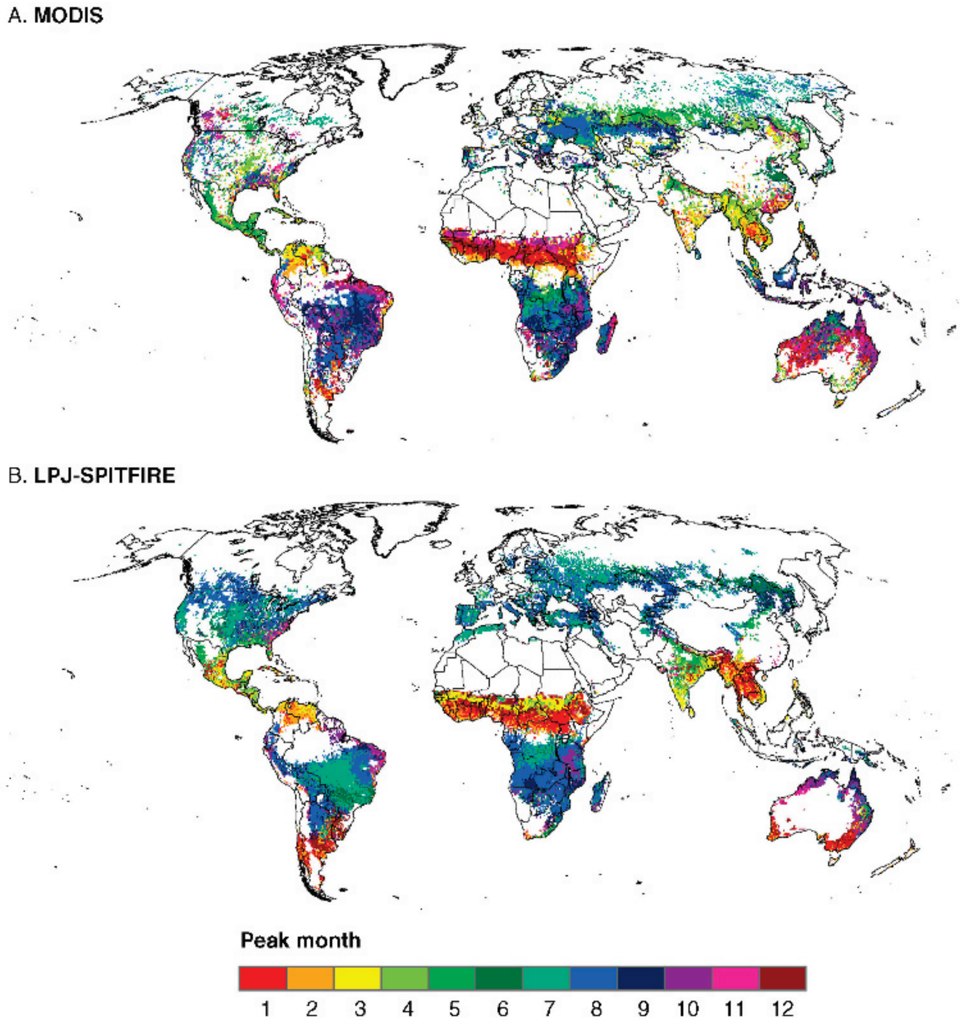

Figure 1.45 Simulating fire using the SPITFIRE model. These simulations can be matched with actual data (MODIS) to indicate the power of the model. (From Thonicke *et al.*, 2010).

Bowman *et al.* (2009) provides a detailed analysis of climate forcing and fire (see Chapter 6, Part Two). Radiative forcing is defined by the Intergovernmental Panel on Climate Change (IPCC), as the change in stratospherically adjusted radiative influx at the tropopause, compared with 1750 AD (Forster *et al.*, 2007). Positive forcing will increase global mean surface temperature, while negative forcing will decrease it. Fires change radiative forcing through altered atmospheric composition and/or changes in surface albedo.

The calculations involve a number of assumptions to be made. These include an understanding of the extent and frequency of fire in the pre-industrial era. Some assumptions also consider that fire emissions (e.g. from tropical forest regions) are directly related to deforestation, and that the peat fires in south-east Asia represent a new anthropogenic emission source. All of the data combined provide an estimate that fires have contributed to about 19% of the anthropogenic radiative forcing since the pre-industrial era.

Unravelling CO_2 emissions from natural fires is complex. It is considered that fires contribute a constant 50% of total carbon emissions through time from deforestation. Fires represent an important source of ozone precursors, such as NO_x, especially in tropical regions. There are, however, many uncertainties in the calculations. Basically we can calculate:

$$\begin{aligned}\text{Emissions} = {} & \text{Burnt area} \times \text{Fuel(biomass)} \\ & \times \text{Combustion completeness} \\ & \times \text{Emission factor}\end{aligned}$$

As has been indicated, surface albedo can be changed by fire. Burning may cause short-term warming of the surface due to blackening or cooling of the surface due to especially increased exposure of snow at high latitudes. Black carbon on snow warms the surface by decreasing albedo. However, only 20% of this effect may be attributed to fires.

The direct aerosol effect is both positive and negative. A small cooling effect (< 2%) is associated with light-scattering sulphate aerosols. Black carbon, however, has a tropospheric warming effect. Aerosol particles emitted by fires also have a significant impact on clouds, which has been termed an 'indirect aerosol effect'. There are two opposing effects of aerosols on clouds: the cloud condensation (microphysical) and black carbon (radiative). Where there is heavy smoke, there is an increase in cloud cover but a decrease in cloud droplet size. In contrast, large bouts of black carbon increase the susceptibility of low clouds to evaporation, which inhibits cloud formation and development. Quantification of these effects is difficult (see Chapter 9, Part Two).

One aspect of fire that is often forgotten is the production of charcoal (Figure 1.24B) As this is relatively inert, it may be buried and survive not only for thousands of years but for millions of years (Scott, 2010). In such cases, this may contribute to the long-term draw down of CO_2 in the atmosphere. It is this feature that has encouraged the production and use of bio-char to help in the reduction of current carbon dioxide levels (Lehmann *et al*., 2006; Chapter 2).

1.16 Scales of fire occurrence

While the majority of fires are small, there has been an increasing concern over mega-fires (> 20 000 ha) in the past few years. This is particularly significant, not only in terms of the impact to the ecosystem or on humans, but especially in relation to emissions as discussed earlier. Most fires burn areas of a few to a few hundred hectares. In some regions, there may be many fires that are burning at the same time, as was the case during the fires in Yellowstone National Park (USA) in 1988. In total, more than 570 000 ha burnt, of which 400 000 ha were in the National Park.

There is also a relationship between fire size and ecosystem impact. Many large fires burn areas that have been previously burnt, and this may have a devastating ecological effect. Large fires may burn for a much longer period and are difficult to

Figure 1.46 Fires threatening the Jet Propulsion Laboratory. The fires raged in the foothills around NASA's Jet Propulsion Lab (JPL). The 'Station Fire' broke out on August 26, 2009, in La Cañada Flintridge, California, just a few miles from the JPL. It was started by a combination of factors: triple-digit temperatures; extremely low humidity; dense vegetation that has not burned for several decades; and years of extended drought. The blaze burnt 145 000 acres (227 square miles) of the Angeles National Forest, destroyed 64 houses, forced tens of thousands of people to evacuate their homes and caused the deaths of two firemen who were involved in a crash while trying to escape rapidly advancing flames. (Photo: Brent Buffington, JPL, NASA).

extinguish, and they also may have a much greater atmospheric and, hence, global impact. These impacts may also include human health (Johnston, 2009; Johnston *et al*., 2012).

In California, the Santa Ana wind may contribute to the size of a fire, in addition to human fire suppression policies, so that some fires may expand from 100 000 ha to over one million ha in events that may last several days and even weeks (Keeley *et al*., 2011). In populated regions, fire size may be limited by habitat fragmentation and effective fire suppression measures. However, the problem of fire at the wildland-urban interface is becoming increasingly important (Figure 1.46; see Parts Two and Three).

An understanding of the scale of fire is important for fire modelling and the assessment of future fire with climate change. Recent studies in the western USA have found that mega-fires did not occur in the past, as non-catastrophic small fires reduced fuel load and, over the past century, fire suppression has reduced fire size. Climate change is, however, leading to an increase in the occurrence of mega-fires, and this trend may continue in the future.

Further reading

Artaxo, P., Luciana V. Rizzo, L.V., Paixão, M., de Lucca, S., Oliveira, P.H., Lara, L.L., Wiedemann, K.T., Andreae, M.O., Holben, B., Schafer, J., Correia, A.L., Pauliquevis, T.M. (2009). Aerosol Particles in Amazonia: Their Composition, Role in the Radiation Balance, Cloud Formation, and Nutrient Cycles associated with deposition of trace gases and aerosol particles. *Amazonia and Global Change*. Geophysical Monograph Series **186**, 233–250.

Bowman, D.M.J.S., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M.A., D'Antonio, C.M., DeFries, R.S., Doyle, J.C., Harrison, S.P., Johnston, F.H., Keeley, J.E., Krawchuk, M.A., Kull, C.A., Marston, J.B., Moritz, M.A., Prentice, I.C., Roos, C.I., Scott, A.C., Swetnam, T.W., van der Werf, G.R., Pyne, S.J. (2009). Fire in the Earth System. *Science* **324**, 481–484.

Cerdà, A. and Robichaud, P. (eds) (2009). *Fire Effects on Soils and Restoration Strategies*. Science Publishers Inc., New Hampshire.

Cochrane, M.A. and Ryan, K.C. (2009). Fire and fire ecology: concepts and principles. In: Cochrane, M.A. (ed). *Tropical fire ecology: Climate change, land use and ecosystem dynamics*, pp. 24–62. Springer, Berlin.

Doerr, S.H., Shakesby, R.H. (2013). Fire and the Land Surface. In: Belcher, C.M. (ed). *Fire phenomena and the Earth System: An interdisciplinary guide to fire science. 1st edition,* pp 135–155. J. Wiley & Sons, Ltd, Chichester.

Fites-Kaufman, J., Bradley, A.F., Merril, A.G. (2006). Fire and plant interactions. In: Sugihara, N.G., Van Wagtendonk, J. W., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (eds). *Fire in California's ecosystems*, pp. 94–117. University of California Press, Berkley, CA.

Keeley, J.E., Bond, W.J., Bradstock, R.A., Pausas, J.G., Rundel, P.W. 2011. *Fire in Mediterranean Climate Ecosystems: Ecology, evolution and management*. Cambridge University Press.

Roy, D.P., Boschetti, L., Smith, A.M.S. (2013). Satellite remote sensing of fires. In: Belcher, C.M. (ed). *Fire phenomena and the Earth System: An interdisciplinary guide to fire science. 1st edition*, pp. 97–124. J. Wiley & Sons, Ltd, Chichester.

Rundel, P.W. (1981). Fire as an ecological factor. In: Lange, O.L., Nobel, P.S., Osmond, C.B., Ziegler, H. (eds.), *Physiological plant ecology I, Response to the physical environment*, pp. 501–538.

Shakesby, R.A., Doerr, S.H. (2006). Wildfire as a hydrological and geomorphological agent. *Earth Science Reviews* **74**, 269–307.

Spessa, A., van der Werf, G., Thonicke, K., Gomez-Dans, J., Lehsten, V., Fisher, R. & Forrest, M. (2012). Modelling Vegetation Fires and Emissions. In: Goldammer, J. (Ed.) *Fire and Global Change*, Chapter XIV.

Sugihara, N.G., Van Wagtendonk, J.W., Fites, Kaufman, J. (2006). Fire as an ecological process. In: Sugihara, N.G., Van Wagtendonk, J.W., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (eds). *Fire in California's ecosystems*, pp. 58–74. University of California Press, Berkley, CA.

Van Wagtendonk, J.W. (2006). Fire as a physical process. In: Sugihara, N.G., Van Wagtendonk, J.W., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (eds). *Fire in California's ecosystems*, pp. 38–57. University of California Press, Berkley, CA.