1 Introduction to dryland environments

1.1 EXPLORATION AND AWARENESS OF DRYLANDS

Drylands, simply defined, are areas where potential evaporative water loss balances or exceeds the meager annual rainfall; a shortage of water inherently plagues these regions. The drylands comprise one-third of the global land surface; they support 14% of the world's inhabitants and a significant share of world agriculture. The climates of the drylands attracted little attention until the 1970s, when the combination of recurrent drought and intense land use demonstrated both the fragility and the importance of these ecosystems. The effects of climatic fluctuations and human-induced pressures have been especially adverse in semi-arid lands: agricultural regions of the American Midwest and Central Asia, India, the African Sahel, and much of southern Africa regularly have to contend with severe and often persistent drought. In the Sahel unusually dry conditions prevailed from the late 1960s until the turn of the twenty-first century. In some dryland regions climatic fluctuations and human mismanagement have interacted to initiate the process of desertification, a long-term degradation of the environment. Concern for the future is enhanced by the expansion of development into drylands as population growth continues, and by the prospect of global and regional climatic change. More unsettling are claims that human activities, including land use, may induce climatic change.

Initially, knowledge about the world's drylands was achieved in the context of exploration and exploitation, rather than scientific inquiry. German geographers such as Passarge (1904) and Jaeger (1921) wrote extensively about Namibia and South Africa. Missionaries such as Moffat and Livingstone (Fig. 1.1) kept detailed diaries that chronicled year-to-year environmental events at mission stations. French geographers and explorers, such as Capot-Rey (1953), Monod (1958), and Tilho (1911), vastly expanded our geographical knowledge of the Sahara. Huntington (1907) and Hedin (1904–5) journeyed into the Gobi Desert and other Asian regions. Powell (1875) and Gilbert (1975) surveyed the American West. Their journals included information on climate and weather, but the focus was on description, not physical processes. The field of meteorology was likewise slow to focus on dryland climates, understand their dynamics, or put them into a global context.

Fortunately, this picture has changed. A number of developments have brought deserts and semi-arid regions into the mainstream of modern meteorological and ecological research. Electronic data-recording systems have extended meteorological networks into more remote areas. Remote sensing techniques have vastly expanded global information gathering and have provided a means of monitoring the status of drylands. The catastrophic Sahel drought of the early 1970s and synchronous droughts elsewhere evoked worldwide interest in climatic fluctuations in dryland areas. Recurrent El Niño episodes have produced dramatic, newsworthy events, from floods in Peru and California to snow in Israel, as well as drought in many semi-arid areas. Scientists began expressing concern that human activities could influence global climate and numerous studies suggested that drylands would be the regions most severely affected. Finally, the concurrent development of theories of global climate and sophisticated numerical models to test these theories served both to increase our understanding of climate and its variability and to point out the necessity of including the world's drylands in this new global perspective on climate.

The result is an increased awareness of drylands. These regions are now recognized as a dynamic component of the global environmental system. They are also recognized as an endangered global resource with importance in areas as diverse as global economics, worldwide agriculture, and dynamic climatology. The need for protection and proper management, in order to maintain the drylands as renewable resources in the face of potential climatic changes and increasing land-use pressure, is clearly acknowledged. Some of the specific concerns include climatic changes induced by increased greenhouse gases; groundwater depletion by extensive irrigation; and long-term effects of desertification and land-use change. These concerns are supported by evidence that in some dryland regions

Fig. 1.1 (left) The Kuruman (South Africa) mission station of Robert Moffat, whose daughter married the missionary and explorer David Livingstone. (right) Plaque commemorating the Livingstone mission at Kolobeng, near Gaborone, Botswana.

the combination of climatic variability and imprudent land use can adversely alter the region's climate.

The demand for development in drylands will continue. At the same time, global climate change could reduce the potential resources of the drylands. In view of this, *Dryland Climatology* focuses on the climates of arid and semi-arid regions with the aim of underlining their environmental potential and limitations. Common dryland characteristics include low and highly variable rainfall, seasonal water availability, thermal extremes, and sensitivity to both climatic fluctuations and human intervention.

These characteristics represent the potentials of, and limitations to, developing and sustaining drylands. The differences associated with the diverse climatological characteristics (e.g., tropical and temperate) are of secondary importance. The common features determine the strategies suitable for coping with these less than optimal environments. An understanding of these environments, their characteristics and their dynamics, can lead to better management practices that will help preserve the dryland regions as a global "resource."

1.2 GEOGRAPHIC EXTENT OF DRYLANDS

Drylands, semi-arid and arid regions where evapotranspiration potentially balances or exceeds rainfall, comprise about one-third of the earth's land surface. Precise climatic limits have been prescribed by numerous authors in order to define an arid or a semi-arid environment (e.g., Wallén 1967; Koeppen 1931; Thornthwaite, 1931), but such a definition remains a complex problem compounded by the inconstancy of climatic parameters.

The key factor – the one that limits human activities, vegetation growth, land use, and surface hydrology – is moisture availability. This, in turn, is dependent on a number of climatic and environmental factors, the most important of which are rainfall, its concentration in time and space, and evaporation. Quantitative assessments of moisture availability by a variety of schemes, as discussed in Chapter 9, provide the basis for classifying dryland regions. Unfortunately, these schemes produce quite divergent distributions of arid and semi-arid lands. Similarly, there is little consensus on the criteria establishing boundaries on the basis of vegetation, soil, or streamflow, although these features are more constant than climatic parameters.

Meigs' (1957) system, developed for UNESCO, is the best-known and most widely accepted dryland classification scheme. It distinguishes semi-arid, arid, and extremely arid regions; the last two classes being considered the true deserts. Meigs' criteria are based on the Thornthwaite moisture index (TMI, Thornthwaite 1948), which compares rainfall and potential evapotranspiration. According to this system, 4% of the world's land surface is extremely arid, 15% is arid, and 14.6% is semi-arid.

Despite diversity in the dryland boundaries established by various classification schemes, the principal deserts recognized by Meigs are universally accepted as arid lands, if not true deserts. These include the Kalahari-Namib, Somali-Chalbi and Sahara on the African continent; the Arabian, Iranian and Turkestan deserts and the Thar, Taklamakan and Gobi regions of Asia; the Monte-Patagonian and Atacama-Peruvian deserts of South America; the Australian desert; and the North American desert, including the Great Basin and the Sonoran, Mojave and Chihuahuan deserts (Fig. 1.2). Of these, only the Sonoran, Peruvian, Arabian, Taklamakan, Sahara and Namib deserts include lands classed as extremely arid. Vast tracts of semi-arid land, including the American Great Plains and the African Sahel, border each of the deserts. Extensive semi-arid regions exist also in Europe (on the Iberian Peninsula) and in Northeast Brazil. Thus, dryland areas are found on six continents (Table 1.1), although they are concentrated in Africa, Asia and Australia, where about half the land is arid or semi-arid.

Drylands, especially true deserts, tend to be situated in subtropical latitudes. This is partially a consequence of the prevailing subtropical high-pressure cells. However, other factors, such as topography or coastal effects, produce dryland climates.

Table 1.1. *Area (million km²), by continent, of arid lands (from Meigs 1957). Final column indicates the percentage of the continent that is arid or semi-arid.*

Continent	Extremely arid	Arid	Semi-arid	Total	Percentage of continent
Africa	4.56	7.30	6.08	17.94	60
Asia	1.05	7.91	7.52	16.48	37
Australia	–	3.86	2.52	6.38	84
North America	0.03	1.28	2.66	3.97	16
South America	0.17	1.22	1.63	3.02	17
Europe	–	0.20	0.80	1.00	10

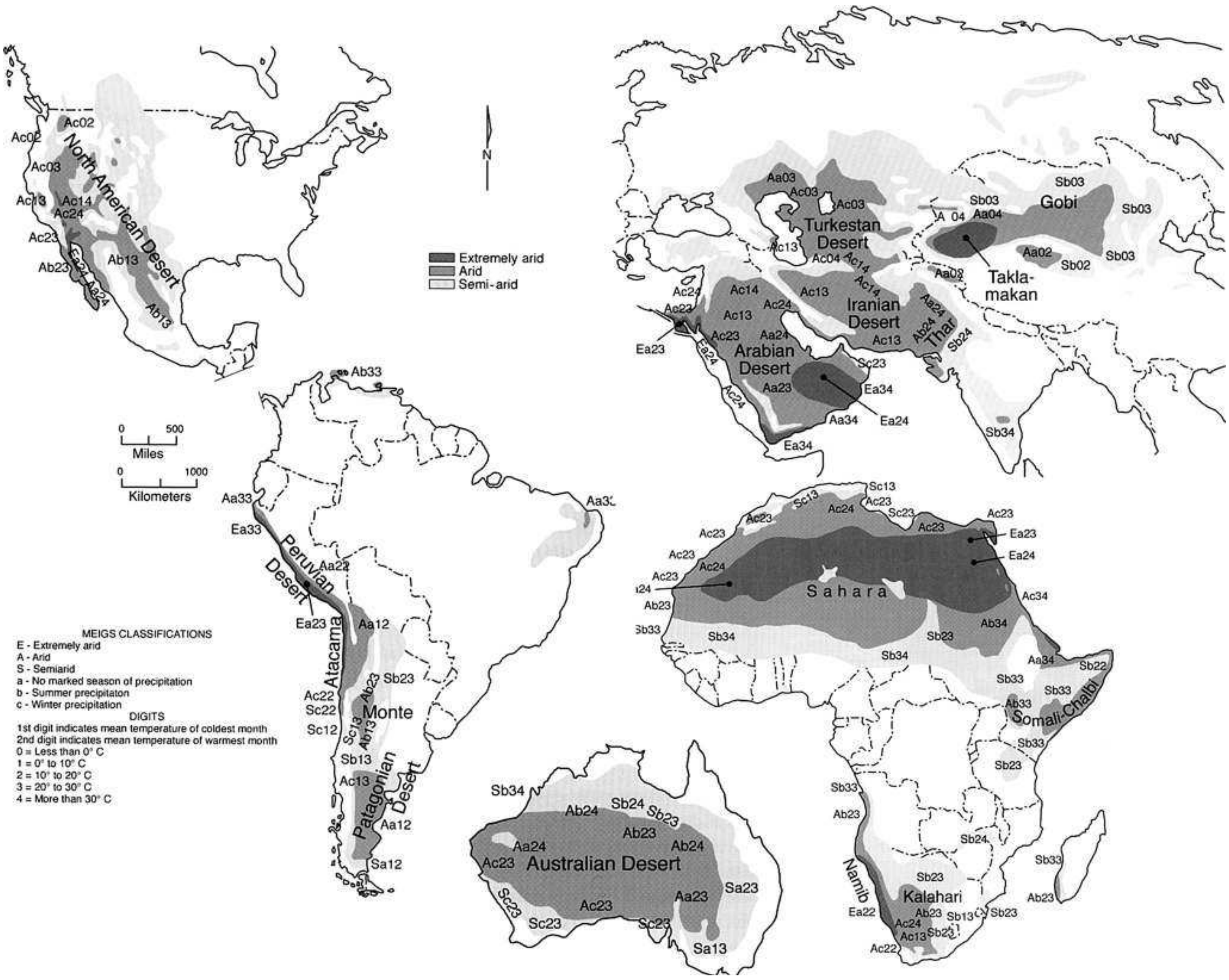

Fig. 1.2 Global extent of arid lands according to Meigs (1966).

As a result the latitudinal location and extent of the drylands vary greatly. In Africa, they lie approximately between 15° and 30° N and 6° and 33° S. Major Asian deserts are concentrated between 15° and 35° N in Arabia, 22°–48° N over southeastern and Middle Asia, and 36°–46° N in Central Asia (Petrov 1976). Together, the African and Asian systems constitute a subtropical lower–mid-latitude dry zone, extending longitudinally over nearly half a hemisphere. The North American desert region extends from about 22° to 44° N; the Australian from 15° to 30° S. The South American deserts have the greatest latitudinal

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extent (1°–52° S) but the east–west extent is small because they are largely confined by coasts and mountains to narrow zones.

There are, of course, dry climates created by extreme altitude and near-polar location. These differ from those discussed so far in two basic respects: the limited moisture supply is primarily the result of cold conditions, and evapotranspiration is inherently low and of minor importance in determining water availability. In consequence, other aspects of their climatic environments differ greatly from those dryland areas discussed above. For this reason, generalizations in this text concerning dryland regions and common environmental concerns do not apply to polar or altitudinal deserts. Such regions are therefore omitted from this book.

1.3 PHYSICAL FEATURES OF DRYLANDS

The climatic and surface characteristics of the world's drylands are extremely diverse. Petrov (1976) points out that deserts fall within temperate, subtropical, and tropical climatic zones, even when cold deserts (high latitude or high altitude) are ignored. Similarly, Tricart and Cailleux (1969) distinguish between those with seasonal precipitation, sporadic precipitation, or a humid atmosphere (high relative humidity because of a coastal location), as well as those with seasonal or sporadic freezing. Shmida's (1985) classes are somewhat broader: warm deserts, cold deserts, and fog deserts (i.e., the coastal deserts) (Fig. 1.3). Clearly, both the moisture and thermal regions are very diverse within the earth's drylands, as are the atmospheric dynamics governing these climates.

There are, however, distinctive environmental characteristics common to dryland areas, and it is these traits to which human use of the ecosystem must adapt. The most general, and most important, are the extreme moisture and thermal regimes and their pronounced and rapid fluctuations. Water supply is limited and highly variable in time and space; the rhythm of moistening and desiccation is generally irregular, or at least brief and highly seasonal. Rainfall is generally in the form of short, intense showers that can suddenly flood a desert landscape. The thermal climate is extreme because the factors that moderate the thermal environments in humid climates – vegetation, cloudiness, and soil moisture – are inherently sparse or almost absent in dryland regions. The sparse vegetation cover also leads to relatively windy conditions that, like extreme temperatures, favor high evaporation.

The intensity and rhythm of these climatic extremes vary greatly within the diverse dryland habitats. In the subtropical savanna, where summer rains usually prevail and temperatures are relatively constant, seasonal cycles of rainfall and aridity are dominant determinants of flora, fauna, and agriculture. In the low-latitude deserts, aridity and the irregular timing of the rare rainfall events are the most characteristic features. Torrential rains break long periods of drought. The harshness of the environment is accentuated by the diurnal cycles of temperature: extreme heat during the day and extreme cold at night. In mid-latitude deserts the seasonal cycle of temperature is equally extreme, but deserts in the low latitudes have no cold season, with night being the only analog to winter. The semi-arid steppes (temperate-latitude grasslands) experience hot summers, cold winters, and low annual rainfall that occurs mainly in summer. Thus, the harsh environment is dictated by marked annual cycles of rainfall and drought, heat and cold, and longer or shorter days.

Climate is the prime determinant of the vegetation, hydrology, and soils of the arid land surface. The combination of climatic, hydrologic, and geomorphic processes, together with the sparse vegetation cover, determines the surface materials and landforms in the very arid environments. Wind and water are the primary forces in landscape development. Unhindered by dense vegetation cover, they become effective geomorphic agents and create distinctive desert landforms and surfaces (Fig. 1.4). In the absence of a vegetative canopy to break the force of raindrops and root networks to bind materials, soil material cannot accumulate, so that desert soils are rare. The action of wind is likewise accentuated. In humid areas, vegetation cover reduces

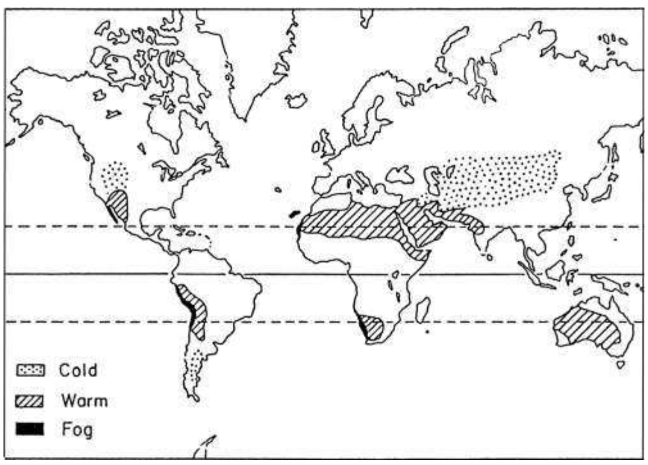

Fig. 1.3 Location of cold, warm and fog (coastal) deserts (after Shmida 1985).

Fig. 1.4 Erosional landform in the Libyan Desert of Egypt.

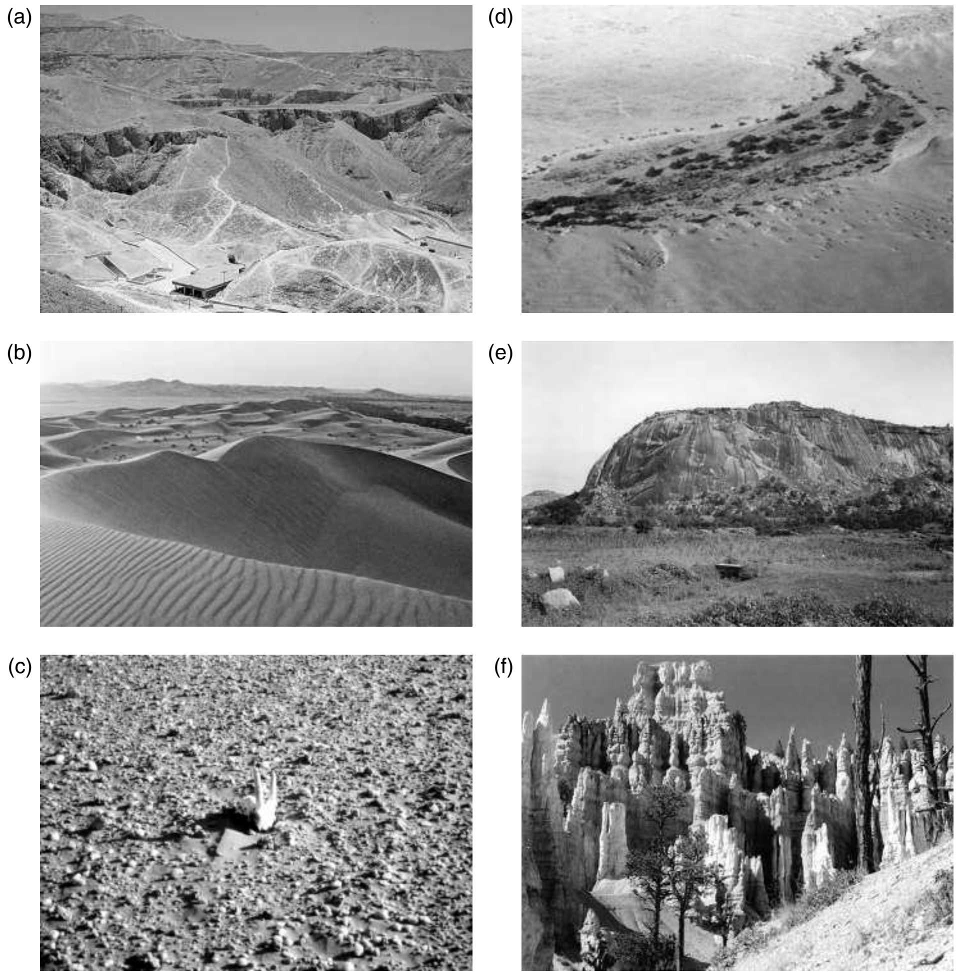

Fig. 1.5 Typical desert surface features: (a) bedrock in the Egyptian Sahara, (b) Namib dunes, (c) stone pavement in the Namib, (d) ephemeral stream channel of the Kuiseb River, Namibia, (e) inselberg in the savanna of northern Nigeria, (f) badlands in Bryce Canyon of the western USA.

wind velocity near the surface, absorbs the force of the wind, and prevents it from being directed against the land surface: it also protects surface material from the full erosional force of wind and water.

Contrary to the common perception of deserts as vast sand seas, sand dunes and ergs constitute a relatively small proportion of desert surfaces. Australia has the largest proportion of sand and that is only 30%. Other highly distinctive surface types result from the characteristic hydrologic and geomorphic processes operating in drylands (Fig. 1.5). These include bedrock (hamada desert), stone pavements (e.g., reg and serir), desert crusts, and depositional flats (such as playas) (Fig. 1.6). These are discussed more fully in Chapter 2. Sand fields are common in the Sahara and the Australian deserts, but the Syrian and Gobi deserts are largely hamada and reg. As the desert gives way to semi-arid landscape, soils become more common and widespread. The surface also contains hydrological networks: ephemeral stream channels and exotic streams (those originating in wetter, external regions) in deserts, and drainage systems in semi-arid regions. Other common landscape features include alluvial fans deposited by streams, pediments (eroded bedrock platforms at the foot of hillslopes), inselbergs (huge, isolated, steep-sided rock outcrops), and erosional features such as mesas and badlands.

Fig. 1.6 Playa surface in southern Africa.

Landforms and surfaces represent the combined forces of weathering (which breaks down materials), wind and water erosion (which transports and removes finer materials), and depositional processes. Stone pavements – fields of coarse material and rock fragments set in or on finer materials – are erosional features formed when water and wind strip away finer, more transportable material. Sand surfaces are depositional, left behind when the forces of the water or wind transporting the sand ebbs. Deposition by water also produces alluvial fans and desert flats, the residue left after water has evaporated.

Playas are characterized by repeated cycles of inflow and evaporation, which leave behind crystalline materials such as chlorides, carbonates, and sulfates (e.g., rock salt, gypsum, lime, and sodium salts). Cycles of moistening and evaporation also produce the desert crusts, but these result from smaller-scale processes within desert soils. Vertical water movement, which is preferentially upward in dry regions, leaves crusts of hard materials such as gypsum, lime, laterites (iron-rich material), and silicates. Although these can accumulate in lower soil horizons, they are commonly at or near the surface.

1.4 ACQUISITION OF DATA AND INFORMATION

1.4.1 *IN SITU* CLIMATIC AND METEOROLOGICAL DATA

The availability of climatic and meteorological data is relatively limited in most dryland regions because observing stations are mainly situated in areas of dense population. This is illustrated by the station network in the Global Historical Climatology Network (GHCN) data set compiled by the National Climatic Data Center in the USA (Fig. 1.7). This data set is one of the most widely used in climatic research. The decrease in station density toward the dry interiors of Africa, Australia and Asia and along the coastal deserts is clearly apparent.

The trend in modern climatological research is to use gridded global data sets. This includes both analyses solely based on station data (e.g., Legates 1995; New *et al*. 2002) and "blended" analyses that combine station data with remotely sensed data and modeling analysis. Examples of the latter are the NCEP/NCAR Reanalysis data (Kistler *et al*. 2001) and ERA-40 (Uppala *et al*. 2005). These are electronically available and easy to use. However, these data sets have large error bars where station data are sparse. This includes most arid and semi-arid regions. Figure 1.8 illustrates the large apparent differences in mean annual rainfall over the Namib coastal desert, as evaluated from three different data sets.

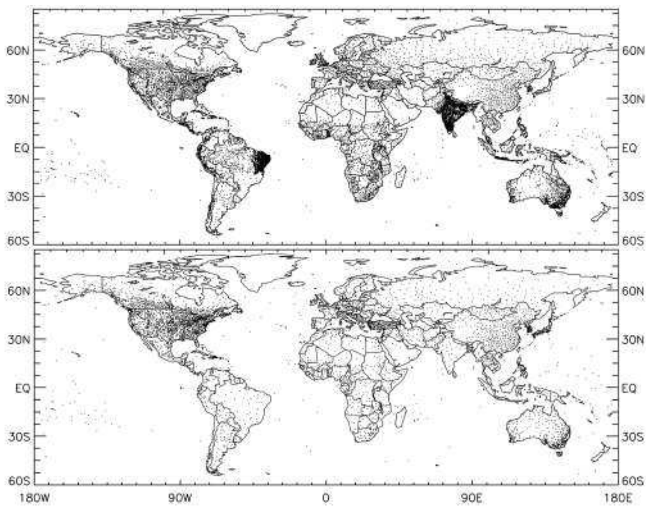

Fig. 1.7 Precipitation (top) and temperature (bottom) station network of the Global Historical Climatology Network (GHCN).

Unfortunately, in most regions the reporting networks have declined over the last few decades. There are many reasons for this, ranging from changing economic conditions in many developing countries and decreased international data exchange to increased reliance on satellite data for weather information. Whereas meteorological data were once freely exchanged and regularly published in monthly bulletins and annual reports, many countries in Africa and South America have started to charge exorbitant sums even for routine information on temperature and precipitation.

As a consequence, much of the best climatological information comes from sources compiled many years ago. These include such sources as the multi-volume series *Ecosystems of the World* (Goodall 1983–2000), *World Climatic Data* (Wernstedt 1972), the six volumes of meteorological tables published by the British Meteorological Office (1958–1967), works by Dubief (1959, 1963), Meigs (1966), Hastings and Humphrey (1969a, 1969b), Amiran and Wilson (1973), and the multi-volume series *World Survey of Climatology* (Landsberg 1971 onward) and *World Weather Records* (see NOAA website below). Useful data sets can also be found online from various websites of the US National Oceanographic and Atmospheric Administration (NOAA) (e.g., www.ncdc.noaa.gov/), and NASA (http://rain.atmos.colostate.edu/CRDC/) and in the monthly publication *Monthly Climatic Data for the World*. A few national or regional precipitation data sets have also been compiled, such as those for the Middle East (Yatagai *et al*. 2008), Australia (Lavery *et al*. 1997), Africa (Nicholson 1986), China (Hong *et al*. 2005), the Former Soviet Union (Groisman *et al*. 1991) and Siberia in particular (Yang and Ohata 2001), the USA (Di Luzio *et al*. 2008, Guirguis and Avissar 2008), Mexico (Graef *et al*. 2000), and South America (Liebmann and Allured 2005), Brazil in particular (Silva *et al*. 2007).

A wealth of climate information was also compiled over the years by various arid lands research institutes. Some of the major ones include the Repetek Desert Research Center in Turkmenistan; the Training and Research Centre Gobabeb, Namibia; the Arid Lands Office at the University of Arizona; the Lanzhou Institute of Desert Research in China; the Arid Lands Ecosystem Research Center at the Hebrew University in Jerusalem; the Blaustein Institute for Desert Research at Ben-Gurion University in Tel Aviv; and the Institute for Arid Zone Research at the University of the Negev in Beer Sheva. Our knowledge of arid lands was also rapidly advanced by UNESCO's Arid Lands Research Programme, which commenced in 1951.

Various field programs have also contributed to our understanding of arid lands. One of the first took place in the Pampa

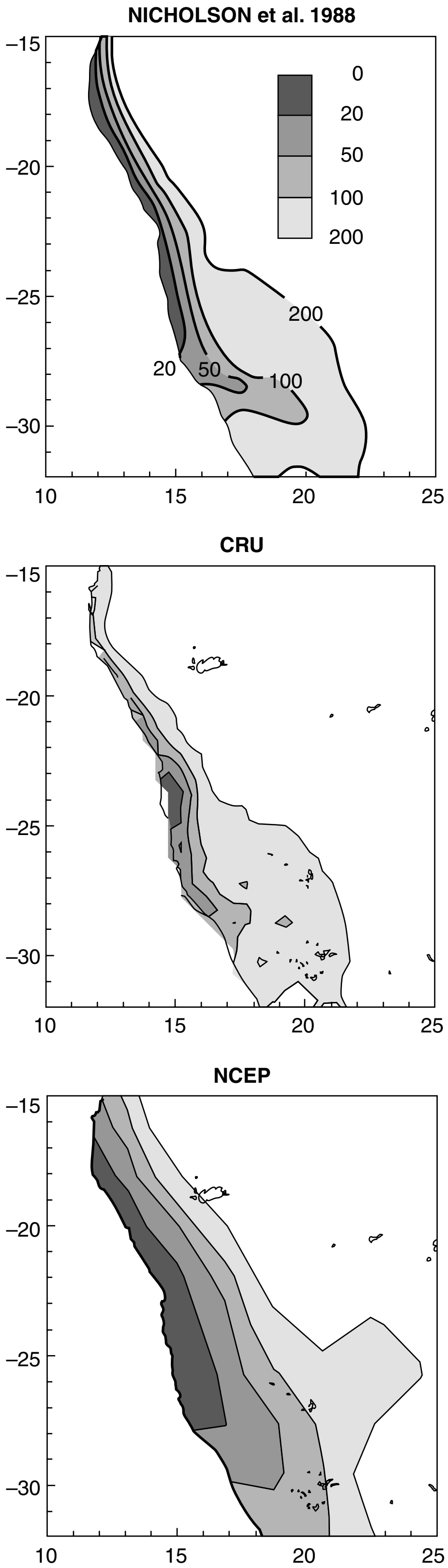

Fig. 1.8 Comparison of mean annual rainfall (mm) in the Namib coastal desert, as assessed with data from an expanded, local gauge data set (top; Nicholson *et al.* 1988), the East Anglia (CRU) gridded data set (center), and NCEP Reanalysis data (bottom).

de la Joya in Peru in the early 1960s (Lettau and Lettau 1978). Conducted by the University of Wisconsin, it provided unprecedented information on the causes of coastal aridity, desert energy balances, and dune dynamics. With the development of remote sensing, numerous field experiments in dryland regions emphasized the creation of algorithms for assessing the land surface from space and deriving ground-truth for observations from aircraft, radar, and satellites. The impetus for many of the field experiments was concern about desertification, as well as an emerging interest in land–atmosphere interactions.

A landmark international experiment, the FIFE campaign (First ISCLSCP Field Experiment) took place in the US Great Plains during 1987–1989 (Sellers and Hall 1992), setting the stage for a similar ground-truth/remote sensing campaign in the African Sahel in 1990–1992. Termed HAPEX-Sahel, this international effort emphasized hydrology in this semi-arid region (Goutorbe 1997). Elsewhere in Africa, the TRACE-A and SAFARI experiments in southern Africa (1992), and later SAFARI-2000 (Privette and Roy 2005; Swap *et al.* 2003), investigated the impact of savanna fires on atmospheric chemistry. Numerous field experiments relating land surface and climate took place in the American Southwest in the 1990s: Monsoon '90 (Kustas and Goodrich 1994), Walnut Gulch '92 (Moran *et al.* 1994), and JORNEX (Ritchie *et al.* 1998). Concerted cooperative field efforts in drylands have also taken place under the auspices of programs such as SALSA (Semi-Arid Land–Surface Atmosphere program; Goodrich and Chehbouni 1998), the Kalahari Transect (Scholes and Parsons 1997), and the Miombo Network (Desanker *et al.* 1997).

1.4.2 REMOTE SENSING

The development of remote sensing techniques during the last three decades has markedly enhanced our ability to investigate and monitor environmental parameters on a large scale, especially in regions where conventional data acquisition networks are not extensively employed. These techniques have been particularly important for drylands in developing countries, where the demise of the influence and activity of colonial powers, together with economic and practical factors, has led to a breakdown of conventional monitoring programs. The methods of remote sensing rely on large-scale data collection from airborne and space-borne platforms.

The central principles in remote sensing are that all natural substances vary in their relative capacities to absorb, reflect, emit, and transmit electromagnetic radiation and that these capacities vary with the wavelength of the incident or emitted radiation. These techniques involve the measurement of (1) *reflected* solar radiation, (2) radiation *emitted* from the earth's surface, and (3) *reflected* microwave radiation. Solar radiation spans the visible and adjacent ultraviolet and infrared portions of the electromagnetic spectrum. Earth, or terrestrial radiation, is in the thermal infrared or microwave wavelengths.

Natural surfaces have a unique "spectral signature": the reflectivity and emission of radiation vary systematically and

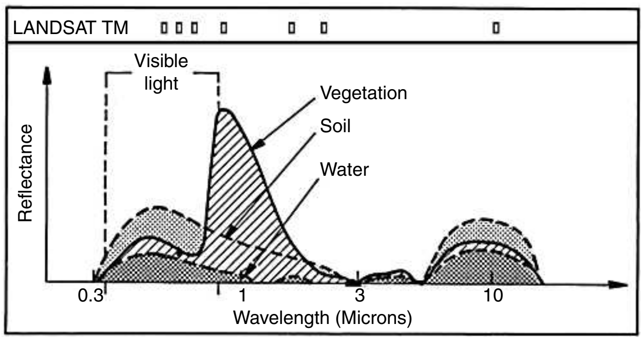

Fig. 1.9 Spectral reflectance signatures of various natural surfaces, along with the spectral detection bands of the Landsat thematic mapper (TM).

characteristically with wavelength (Fig. 1.9). This signature provides a means to identify the nature of the surface material being monitored, many of its physical properties, and many properties of the atmosphere. The brightness of a radar image, for example, depends on the intensity of microwave backscatter, which in turn depends on the physical and electrical properties of the targeted surface. The former include slope, roughness, and vegetation cover, while electrical properties (chiefly conductivity) are affected by such factors as soil porosity and water content. The reflection of visible and near-infrared solar radiation from the earth's surface is most strongly dependent on chemical composition. The emission and reflectivity of longer, thermal infrared wavelengths are functions of temperature and heat capacity. The intensity of emitted microwave radiation varies with chemical and physical properties. This is useful, for example, in distinguishing between ice and water. New techniques used to derive quantitative interpretations of radar and satellite imagery are rapidly expanding their applicability. Some of the characteristics that can be determined include surface cover (e.g., soil, vegetation, water, sand, even rock type), surface topography, soil moisture, and soil and air temperatures.

Satellites have become the most useful and sophisticated tool for remote sensing. These fall into two broad categories: environmental satellites and earth resources satellites. The former are generally geostationary, i.e., in an equatorial orbit, they remain over a selected geographic location. Examples are the American geostationary operational environmental satellites (GOES) and the European Meteosat. The resolution of environmental satellites is relatively low, however, ranging from about 1 to 11 km. The earth resources satellites, designed for monitoring a slowly varying land surface, provide high-resolution but relatively infrequent coverage at individual locations. An example is the American Landsat, launched in 1972. The earth resources satellites are useful tools for environmental mapping.

Most satellites rely on three kinds of sensor systems: cameras, radiometers, and radar. Cameras provide visual images usually derived from visible light or infrared radiation. Radiometers measure the amount of radiation reflected or emitted by the targeted area; individual sensors detect radiation within narrow bands of the spectrum. Radar emits microwaves or radiowaves and detects the amount of backscatter. Recently LiDAR (light

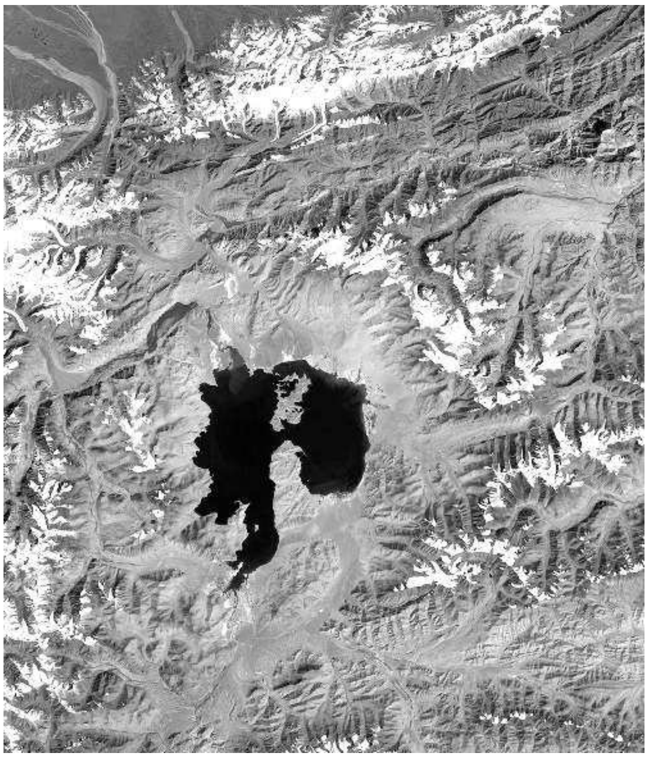

Fig. 1.10 Landsat image of Lake Kara Kul, a water-filled volcanic crater in Tajikistan. White areas are snow cover (from USGS, http://landsat.usgs.gov/).

detection and ranging), which emits light via laser pulses instead of radio waves, has also been used.

Monitoring techniques can be simply illustrated with the multispectral scanner (MSS) instrument carried aboard the first Landsat. This includes sensors that detect radiation in four bandwidths, two in the visible range (a red and a green channel), one at the visible/near-infrared transition, and one near-infrared channel. Four separate images, each corresponding to one of these bands, are transmitted from the satellite. The "green" band is best able to penetrate water and determine turbidity, to distinguish green vegetation, and to identify geologic structures, while the "red" band can distinguish various vegetation types, topographic features, and areas of human settlement. The red/infrared band ratio is useful in monitoring land use and vegetation cover. The near-infrared helps to delineate land–water and soil–crop boundaries. Figure 1.10 shows a composite image of the four bands: Lake Kara Kul in Tajikistan shows up clearly, as does snow cover on the surrounding mountains.

Advancement came with the development of Landsat's thematic mapper, which included the seven bands indicated in Fig. 1.9. The current satellite, Landsat-7, uses a more advanced instrument termed the ETM+ (enhanced thematic mapper plus). It measures radiation in eight bands, with spatial resolution varying from 15 to 60 m, depending on the band. Other earth resources satellites include the French SPOT (with up to 10 m resolution), the European ERS, and the Russian RESURS. The latter, with 160 km resolution, fills the gap between the geosynchronous satellites and the high-resolution earth resources satellites. A commercial satellite, IKONOS, provides resolution of 1 m or better.

In 1999 an instrument specifically designed for land surface monitoring was launched into space aboard the Terra satellite, a joint venture between the USA, Canada and Japan. Termed MODIS (moderate resolution imaging spectroradiometer), this instrument detects radiation in 36 spectral bands and has a spatial resolution of 250–1000 m, depending on the band. MODIS transmits information on surface reflectance, snow cover, surface temperature, land cover and dynamics, vegetation indices, fire, burned areas, leaf area index (LAI), photosynthetically active radiation, net photosynthesis, and vegetation cover change (Justice *et al*. 2002). It provides particularly useful information for savanna regions.

Radar systems have certain advantages over cameras and radiometers. Because of the long wavelength of the beam, radar can penetrate through clouds, and often to some depth below the land surface. This depth is proportional to the wavelength of the signal and is strongly dependent on soil moisture, so that a penetration of several meters is possible in very arid regions, compared with a few centimeters in humid regions. Also, because the intensity of the backscattered signal is highly sensitive to varying physical properties, microwave radar is equally suited for mapping landforms, drainage systems, and geologic features, especially in arid regions. Topography, for example, is best observed when the illumination is almost perpendicular to the direction of the topographic trend. Unlike solar illumination, the direction and angle of incidence of the radar beam can be varied to optimize the detection of individual features. The device is so sensitive to topography that a change of slope of a few degrees can change the radar backscatter by a factor of two or more. For similar reasons, microwave radar is highly sensitive to surface roughness, making it a useful tool in detecting such features as erosional processes (rough surfaces), "desert varnish" (smooth), or sheets of sand (highly reflective and smooth). Thus, it shows excellent promise for the environmental mapping of arid and semi-arid regions.

Early space-borne radar systems were flown on the Seasat spacecraft in 1978 and on the Columbia space shuttle flight of November 1981. These produced surprising observations of several arid regions. The salt pans in the Great Kavir region of the Iranian desert were clearly visible as wavelike patterns and ellipses. Images of sand dunes in the North American desert showed that the brightness in the microwave region of the spectrum varies with the direction of illumination and vegetation cover. The shuttle imaging radar (SIR-A) system aboard the Columbia space shuttle (Elachi *et al*. 1982) produced images of the Lake Chad Basin with clearly discernible dune ridges, interdunal flats, former drainage channels, lake beds, playas, and vegetation. In some cases, even desert wadis were visible. The most striking result was obtained in the hyper-arid eastern Sahara, where the lack of soil moisture allowed the microwaves to penetrate several meters beneath the vast sand fields. The radar detected buried stream channels (some nearly as wide as the Nile) and other subsurface drainage features, as well as possible Stone Age occupation sites (McCauley *et al*. 1982).

1.4.3 ENVIRONMENTAL APPLICATIONS OF REMOTE SENSING IN DRYLAND REGIONS

Both satellite and radar imagery can be applied to a broad range of environmental situations. In dryland regions, remote sensing is especially useful for deriving information on soils, vegetation, and water resources and for monitoring environmental changes, dust outbreaks, and fire. In true deserts, detailed pictures of dunes and other surface materials, and even surface features, can be derived. The accuracy and resolution of remote sensing techniques are still insufficient to provide a complete substitute for aerial photography and field observations, but they provide an important tool for surveying and monitoring remote regions where more conventional data are scarce. Similarly, they provide excellent weather information (rainfall, cloudiness, winds, surface and air temperatures) for remote dryland regions where there is no network of observing stations.

Remote sensing in dryland regions presents special challenges because of the sparseness of the vegetation cover and the spatial heterogeneity of surface features. Most satellite pixels include a combination of vegetation, soil, and other features and special techniques must be developed to unravel the various components. The size of the areas of spatially homogeneous surface is on the order of meters to tens of meters (Bhark and Small 2003). Useful reviews of the challenges and approaches are provided by Okin and Roberts (2004), Ustin (2004), Asner (2004) and Jafari *et al*. (2007).

GEOLOGY, SURFACE FEATURES, AND SOILS

Multispectral scanners and microwave radar have three primary geologic applications. They can discern topography and landforms, provide basic data for geologic mapping, and produce information useful in locating mineral deposits. New techniques used to derive quantitative information from radar images are rapidly expanding its geologic applicability, especially in delineating surface features. The sensitivity of visible and near-infrared reflectivity to chemical composition is sufficient to allow individual rock types to be discerned.

Remote sensing has numerous applications in the identification of soils, soil processes, and soil characteristics such as salinity (Huete 2004). Roughness is the main factor determining soil reflectance and this is highly variable among desert soils (Ustin 2004). The spectral signatures of soils in arid regions are also distinct, sufficiently so that the Landsat image mosaic can serve as a base map for soil types (Satterwhite and Ponder Henley 1984). Landsat has been used for this purpose in the Big Desert of Idaho and in the Indo-Gangetic plain of northern India. SPOT has been used in the Chihuahuan Desert of the USA (Franklin *et al*. 1993). Satellite imagery is also useful in monitoring soil erosion (e.g., Omuto and Vargas 2009), soil moisture, and irrigation. Techniques for assessing soil moisture are described in a later section. In dryland areas, where evaporation is generally high and fields are often irrigated, satellites can identify salt-affected areas and problematic saline soils. A good review is provided by Metternicht and Zinck (2003).

Techniques have also been developed to study dunes (Stephen and Long 2005; al-Dabi *et al.* 1997), sand transport (Ramsey *et al.* 1999), and other features of arid lands. Biogenic crusts, which can be early signals of environmental change (Ustin *et al.* 2005), can be detected from their spectral signature (Karnieli 1997). Space-borne radar facilitates the determination of dune forms and morphology and even the internal structure of dunes (e.g., Bristow *et al.* 2005).

VEGETATION

The remote sensing of vegetation is based on a simple physical principle: while most natural substances show a gradual increase in reflectivity with wavelength in the solar bands of the spectrum, green vegetation shows a dramatic increase between the red and near-infrared wavelengths (Fig. 1.9). This differential reflection in the two bands is described by a number of indices (e.g., Huete *et al.* 2002), the most common of which is the normalized difference vegetation index (NDVI), generally derived from data from the NOAA satellites. It is defined as:

$$(CH_2 - CH_1) / (CH_1 + CH_2) \quad (1.1)$$

where CH_1 is the reflectance in channel 1 (visible/red, 0.55–0.68 microns) and CH_2 is the reflectance in channel 2 (near-infrared, 0.73–1.1 microns).

NDVI is ultimately a measure of the total absorption of photosynthetically active radiation (PAR), but in semi-arid regions it correlates well with such parameters as percentage surface cover, biomass, and leaf area index, as well as rainfall (Fig. 1.11). In wetter regions, however, the index tends to saturate, leveling off to some maximum value. In most of Africa this tends to happen in regions where annual rainfall exceeds about 1000–1200 mm, but in parts of southern Africa, the limit can be as low as about 500 mm/year (Fig. 1.12).

The apparent vegetation signal is altered by such factors as satellite calibrations, changes in orbit, and atmospheric effects such as clouds and dust. The use of a ratio minimizes these effects. Sophisticated models have been developed to deal with such problems and to resolve and interpret images with more than one major surface component (e.g., bare soil and vegetation or grass and tree cover).

In arid and semi-arid regions the effect of the underlying soil has a large impact on the vegetation index. When vegetation cover falls below 40%, the soil dominates the reflectance signature (Smith *et al.* 1990). The effect of soils is threefold. Soils vary greatly in overall brightness, or magnitude of reflectivity (Fig. 1.13). This problem is greatly reduced by the use of ratios, such as the NDVI. The secondary variation of soils is associated with "color" differences, i.e., the shape of the spectral

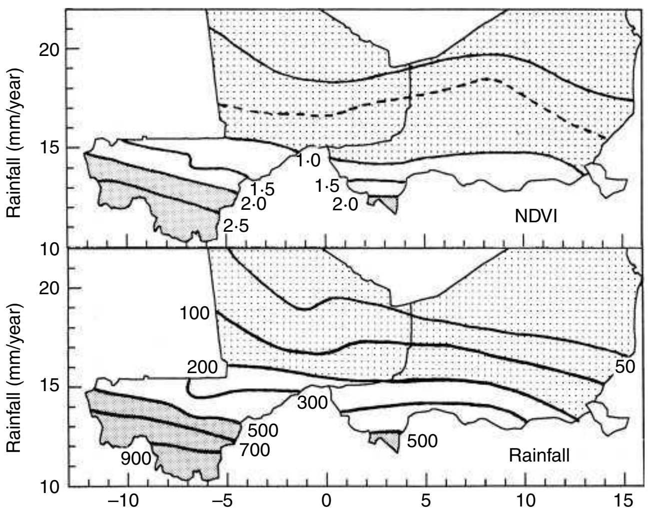

Fig. 1.11 Maps of rainfall (mm/year) (lower panel) and annually integrated NDVI (upper panel) over West Africa (Malo and Nicholson 1990).

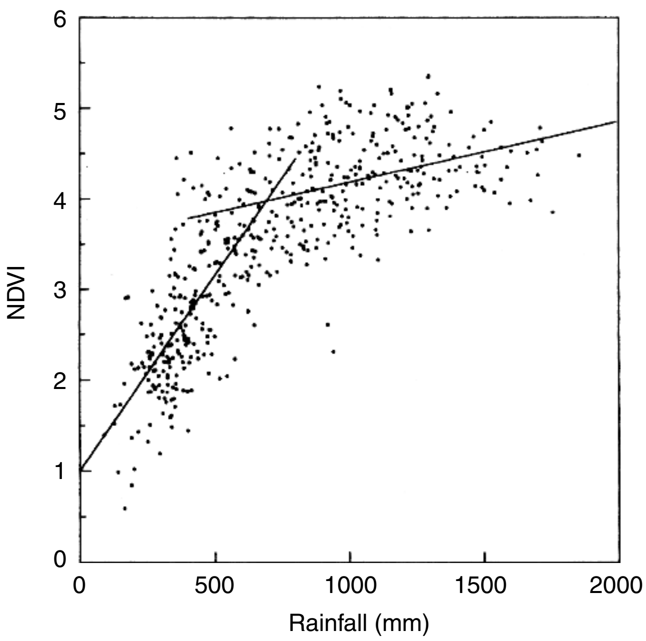

Fig. 1.12 Monthly rainfall (mm) versus monthly NDVI for dryland locations in western, eastern and southern Africa (Nicholson *et al.* 1996). This indicates the "saturation" of NDVI (point where the lines cross) as an index of either rainfall or vegetation growth.

signature; this is related to soil biochemistry and its effect on the absorption of solar radiation. The third problem relates to cases of mixed vegetation and bare soil and is due to multiple scattering. Much of the radiation incident on the bare ground has already been reflected by the vegetation layer. Since the vegetation layer absorbs relatively more of the red than near-infrared (NIR), the light that is scattered toward the ground is "enriched" in the NIR wavelengths, so that, when re-reflected, it gives anomalously high values of NDVI. The effect can be