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Chapter 3: Deserts and the Planet — Linkages between Deserts and Non-Deserts

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Satellite image of the Algerian Desert
Source: QINETIQ/Still Pictures

This chapter addresses the linkages and interactions between deserts and the rest of our planet. While desert climate is controlled by processes taking place outside deserts, processes in deserts also affect climate away from deserts. Deserts and non-deserts are linked by dust generated in deserts that travels away from deserts, and rivers that originate outside deserts dramatically affect deserts while flowing through them. People from outside deserts migrate or visit deserts, while desert people export minerals and fossil energy to non-desert economies. Deserts also serve as corridors through which goods travel and cultures are exchanged, and desert corridors serve bird migration and locust invasions. Finally, though most deserts are remote from leading centres of science, research carried out in deserts has enriched knowledge of the history of our universe and planet, of life on earth, and of peoples and their cultures.

The Physical Tele-Connections — Climate, Dust and Rivers

Deserts are not only highly constrained by water, but their water supply greatly depends on climatic processes operating away from them, either those involved in the generation of desert rainfall, or in generating flows of rivers that enter deserts. Deserts also have effects on climate beyond their boundaries, either directly or through the dust they generate.

DESERTS AND GLOBAL CLIMATE

Ocean-atmosphere linkages maintain desert climate

The intense solar radiation hitting the earth of the tropical belt (between latitudes 23° South and 23° North) sets off air currents bringing dry winds to sub-tropical areas (within latitude 25° and latitude 35°, either North or South), thus denying them precipitation and making them deserts. The western seaboard sections of the African and American continents are deserts due to dry inland conditions induced by upwelling of deep cold seawater, driven by ocean coastal currents. Deserts also occur on the leeward sides of mountain ranges that are deprived of ocean-generated moisture. It is rather paradoxical that the forces which induce highly productive conditions next to deserts — the high solar radiation in the tropical rainforests, the cold and nutrient-rich upwelling of western coastal seawaters, and the moisture-laden tropical trade winds reaching tropical continental mountains — are also all factors maintaining the aridity of deserts.

Rainfall patterns within deserts also depend on climatic processes outside deserts. When the desert surface is cold, moisture blown from the sea condenses and generates winter rains; when the surface is warm, the moisture drawn into the atmosphere from various sources condenses to generate summer rains. Rainfall can be also augmented by of fog, formed when water droplets kept in suspension over the ocean are blown into the desert.

The great year-to-year variations in desert rainfall are modulated by processes away from deserts, such as the Southern Oscillation — a global weather cycle associated with a fluctuation of atmospheric pressure between the South Pacific and tropical Indian Oceans, and expressed in alternating 3–7 year cycles of El Niño Southern Oscillation (or ENSO) and La Niña events. Within this cycle, El Niño develops when the warm water that accumulates in the eastern equatorial Pacific Ocean decreases the upwelling of cold water along the coasts of North and South America; the sea surface then warms-up, resulting in an increase in coastal winter rainfall. After a few months, El Niño conditions begin to recede, paving the way for La Niña: a strong westward flow of surface currents forces the upwelling of cold waters along the coasts of the American continent, thus inducing drought along the coastal deserts. This cycle affects the coastal deserts of Atacama and Baja California, Namibia, Western Australia, and Atlantic Morocco. Paradoxically, since deep seawater upwelling also modulates the productivity of coastal water, the pulse of rainfall-induced high desert productivity coincides with a pulse of low coastal ocean productivity, and vice versa (see also Chapter 1).

Because the El Niño-induced coastal rainfall occurs when moist air moves from warm oceans onto cooler land, the increase in precipitation occurs mostly in coastal fog deserts such as the

southern Namib or the Atacama deserts. Inland, summer-rain deserts such as central Australia, the Thar Desert in India and Pakistan, or the Brazilian Caatinga, however, tend to become drier during El Niño years but enjoy increased precipitation during La Niña years, due to the differential in temperatures between these desert lands and the surrounding seas. Because deserts are so limited by scanty rainfall, these year-to-year climatic oscillations produce pulses of abundance and scarcity of resources with immense ecological repercussions. This highlights the importance of tele-connections in global ecology: a gradient of air pressures developing over the sea critically affects the ecological dynamics of the driest of lands.

Global climate change affects desert climate

Global climate change, the directional change induced by anthropogenic emissions of greenhouse gases (to be distinguished from long-term or short-term climate variations not caused by global-scale human impact on the climate system) also affects deserts. Deserts warmed-up between 1976 to 2000 at an average rate of 0.2–0.8°C/decade — an overall increase of 0.5–2°C (Table 3.1), much higher than the average global temperature increase of 0.45°C, which has been attributed to the increase in atmospheric concentrations of greenhouse gases (IPCC 2001). Global warming is expected to induce an overall increase in rainfall; but high latitudes are projected to warm more than the mid- and low-latitudes, resulting in more rainfall in higher latitudes linked to reduced rainfall in subtropical ones. Indeed, in most deserts within the subtropical belt, rainfall has already been decreasing in the last two decades (Table 3.1).

Table 3.1: Changes in desert temperatures and rainfall

Observed and projected changes in surface temperatures (OT, °C) and annual precipitation (O#rainfall, per cent) over twelve desert regions. A2 and B2 are IPCC SRES scenarios (IPCC 2001). Empty cells indicate no data. Values in bold highlight deserts for which no decrease and/or an increase in precipitation is predicted. Values given for observed changes per decade are the average of two values: (i) the difference between 1981-1990 mean values and 1976-1980 mean values, and (ii) the difference between 1991-2000 mean values and 1981-1990 mean values (percentage diffferences for rainfall).

	Observed changes 1976-2000		Projected changes (means of values projected for 2071-2100 relative to means of observed 1961-1990 data)			
			OT (°C)		O#rainfall (%)	
Desert (country)	OT (°C/decade)	O#rainfall (%/decade)	A2 scenario	B2 scenario	A2 scenario	B2 scenario
Sahara (Algeria, Tunisia, Morocco)	–	–	+4	+3	-20	-10
Libya (Libya)	+0.8	–	+3	+2	-10	-10
Western Desert (Egypt)	+0.8	+4	+4	+2	**0**	**0**
Rub' al Khali (Saudi Arabia)	–	–	+4	+3	**+2**	**+2**
Kalahari (South Africa)	+0.8	-12	+4	+3	**+10**	**0**
Namib (Namibia)	-0.4	–	+3	+2	**0**	-5
Gobi (China)	+0.8	–	+6	+4	**+15**	**+10**
Kizil Kum (Afghanistan)	+0.6	+8	+7	+5	-5	**+5**
Dashti Kbir (Iran)	+0.6	-16	+5	+4	-10	**+10**
Great Victoria (Australia)	+0.8	–	+3	+2	-10	-5
Colorado and Great Basin (USA)	+0.4	-4	+5	+3	-15	-5
Atacama (Chile)	+0.2	-8	+2	+1	-10	-5

Source: IPCC 2001

As for the future, using two global emissions scenarios developed by the IPCC (2001), projected deviations of temperature and precipitation for the period 2071 to 2100 relative to the period 1961–1990, are expected as follows: temperature increases of 2–7°C or 1–5°C (scenarios A2 and B2, respectively), and 5–15 and 5–10 per cent precipitation decrease for most deserts, but also no change, or 2–15 and 2–10 per cent precipitation increase for a few deserts. Moreover, global climate change is expected to increase year-to-year variations in desert rainfall, including an increase in desert droughts induced by a negative feedback between the ENSO cycle and the global atmosphere (Tsonis and others 2005). Hence as the global atmosphere continues to warm, the frequency of El Niño events is expected to increase, bringing more rainy pulses to winter-rain deserts and more drought pulses to summer-rain deserts.

Global change (climate and atmospheric CO_2) will impact the ecology of deserts

The global climate change-induced desert warming is bound to increase evapotranspiration. This water loss may be greater than the water gain in those deserts where global climate change also increases precipitation. In most deserts, the combined effect of higher evapotranspiration, lower precipitation, and more severe and protracted droughts will reduce soil moisture — the limiting resource on which desert productivity depends — resulting in an overall reduction of desert vegetation cover (Lioubimtseva and Adams 2004). Since all other life-forms directly or indirectly depend on plants, desert biodiversity is expected to be impacted too. While animal species of low mobility and plant species of low dispersal ability may decline in numbers or become locally extinct, those with dispersal rates faster than the expected rate of warming advance will extend their ranges into areas that had been cooler previously. Thus, for each local desert area a turnover of species will take place. For example, nearly half of the Chihuahua Desert bird, mammal and butterfly species are projected to be replaced by other species by the year 2055 (Peterson and others 2002). Increasing aridity will also lead to the loss of grasses in favour of shrubs, reinforcing a new stable ecosystem state with “islands” of fertility beneath shrubs and relatively nutrient-poor soils in the barren areas in-between (Schlesinger and others 1990).

The increase in global atmospheric CO_2 concentration, the major driver of global warming, is also the major plant resource, absorbed through the stomata (microscopic pores in the leaf surface of plants) for manufacturing plant carbohydrates through the process of photosynthesis. Interestingly, the direct effect of global CO_2 on desert plants may counteract its indirect effect on them as a driver of desert aridity. This is because increased atmospheric CO_2 enables plants to open their stomata less, thus reducing the amount of water lost during photosynthesis and hence increasing their water-use efficiency. Indeed, most experiments demonstrate that water-use efficiency of desert vegetation increases at high CO_2 concentrations. Depending on differences in the biochemical pathways of photosynthesis, some species within a desert plant community are more responsive to elevated CO_2 than others in the same community, and this would lead to changes in plant community structure (Morgan and others 2001). Furthermore, it was found that increased growth under elevated CO_2 is most likely in wet rather than in dry years (Naumberg and others 2003), which suggests that the effect of the predicted increased droughts will be further amplified by this differential plant response to elevated CO_2. In addition, since the increased productivity is carbon-based, it is associated with an increased carbohydrate-to-protein ratio, making plants less nutritious and less digestible. Also, increasing CO_2 encourages alien invasive species such as annual grasses that are prone to wildfire. This would eliminate shrubs and leave barren desert soils (Smith and others 2000).

Deserts affect non-desert climate

It is rather paradoxical that while anthropogenic warming of the global atmosphere already warms and dries deserts, deserts habitually cool the adjacent global atmosphere — a state that is also projected to further intensify, due to global warming. This is due to the desert albedo (the direct reflection of solar radiation by the earth’s surface back to outer space). In contrast to the intuition that views the long hours of intense solar radiation reaching the bright desert surface through the dry atmosphere as a cause of enhanced warming, the actual effect of deserts is that of cooling the global atmosphere (Charney 1975). The typical desert albedo is 20–35 per cent of

solar radiation reflected back to space (much higher than the 15% of the savannah and the 5% of the rain forest; Pinty and others 2000). With little water available for evaporation from the dry desert surface, most of the remaining solar radiation heats the desert surface, and the generated thermal radiation escapes to space through a dry atmosphere. The heated dry air cools at the rate of 10°C km^{-1} as it rises to 3–4 km, such that the tropospheric air column above deserts is cooled. This high-altitude cooled air is dispersed by the winds over great distances away from deserts, at least as far as the adjacent non-desert drylands, which become cooler and drier.

Global warming is projected to increase desert albedo, through reducing desert vegetation cover, which will further amplify the effect of cooling the non-desert atmosphere and drying adjacent non-desert drylands. Thus, whereas global climate change makes the desert drier, deserts make the global atmosphere cooler, and the drier the desert becomes, the more its cooling effect will increase. The same logic applies also in the opposite direction. "Greening the desert" by restricting grazing or by irrigation would reduce the albedo of the Sahara desert and enhance precipitation over the Sahel; it will also decrease the cooling effect of the desert on the global temperature, thus contributing to anthropogenic global warming.

Will deserts mitigate global warming?

On average, more CO_2 is absorbed than is released by global vegetation, which thus functions as a "carbon sink" by permanently binding this net amount, through the process of photosynthesis, into organic compounds that make up the plants' tissues and organs. This makes the overall mass of the global vegetation a "carbon reserve". After generations and millennia, much of the carbon stored in plants moves to the soil, such that currently the global soil carbon sink is about three times larger than that of global standing live vegetation. Carbon sequestration in vegetation and soils counteracts the currently much faster process of carbon emissions, responsible for global warming. But under the current influence of deforestation, land use change, and climate change, part of the soil and vegetation reserve can function as a source, and further exacerbate global warming. The uptake of atmospheric CO_2 stored in desert plant biomass is among the lowest of the world's biomes. Moreover, in most desert areas where there has been no recent change in vegetation, no further net storage of carbon in vegetation takes place. Desert soils are relatively poor in organic carbon and much richer in soil inorganic carbon, in the form of "secondary carbonates" — carbonate minerals precipitated from the calcareous soil solution rather than inherited from the soil parent material (Monger and Martínez-Ríos 2000). Lack of soil water for most of the time means slow weathering of the carbonates and little organic carbon accumulation.

Yet, since deserts cover a quarter of the earth's land surface, it is worth assessing the carbon storage and sequestration potential of all deserts combined (Table 3.2). Soils sequester carbon in inorganic and organic compounds. It is the organic carbon that is most readily sequestered — rainfall allowing — with rates of accumulation of 5-10 g C m^{-2} y^{-1} under best-practice rain-fed farming in arid-semiarid regions (Lal 2002). The

Table 3.2: Area-weighted, mean stocks of soil carbon in the world's deserts[a]

Area	Units	SOC[a]		SIC	TotC
		0-30 cm	0-100 cm	0-100 cm	0-100 cm
Deserts[b]	kg C m^{-2} Gt[c] C	2.1-2.3 72-80	4.0-4.3 136-149	8.7-11.0 298-372	- 434-521
Global	Gt[c] C	684-724	1 465-1 551	591-739	2 056-2 290

[a] Calculated using soil organic carbon (SOC) and soil inorganic carbon (SIC) data per FAO soil unit using the ISRIC-WISE database (Batjes 1996). TotC stands for total soil carbon; that is, the sum of soil organic (SOC) and inorganic (SIC) carbon
[b] Global Deserts as defined for *Global Deserts Outlook*, which excludes cold deserts
[c] One Giga tonne (Gt) C is 10^{15} g or 1 PgC

average rate of accumulation of the inorganic carbon is considerably slower — some 0.1–0.6 g C m^{-2} y^{-1} (Schlesinger 1985). Yet, though the rate at which atmospheric CO_2 is precipitated as soil carbonate is slow, and the rate at which it can be sequestered as soil organic matter is relatively fast, the global desert ecosystem has accumulated much inorganic carbon but only little organic carbon. Thus, only 9–10 per cent of global soil organic carbon is held in deserts. Therefore, in spite of their large extent, deserts do not play a significant role in the global carbon cycle.

However, if some desert regions do become significantly moister under global warming, they have the potential to function as a globally significant sink that could tangibly mitigate global warming (Lioubimtseva and Adams 2004). On the other hand, those deserts that become drier, with their vegetation only weakly responding to CO_2 enrichment, will not become a significant sink. These deserts are also not likely to act as a significant source driven by land degradation, because the turnover rate of the large desert sink of inorganic soil carbon is too slow to generate significant CO_2 emissions. Also, although the turnover of soil organic carbon is fast and land degradation in deserts might increase CO_2 emissions (as the carbon in eroded soil is oxidized), the pool of soil organic carbon that might be affected by land degradation is too small to make this a significant contribution to global atmospheric CO_2. Between-ecosystem comparison (Batjes and Sombroek 1997) suggests that under the scenario of further desert warming and reduced precipitation, the ratio of soil organic carbon to soil inorganic carbon in deserts will be reduced. This will further reduce the role of deserts in the modulation of global climate change, unless drastic human interventions for increasing desert productivity take place.

DESERTS AND DUST

How, where and when is desert dust formed and where does it travel to?

Deserts generate dust, much of which travels great distances into non-desert areas, with diverse and often unexpected effects. Far-travelled dust particles are usually less than 2 micrometres (µm) in size, and are mostly made up of an alumino-silicate minerals. The major desert dust production mechanism is "saltation", a process triggered when larger wind-blown particles bounce on the desert soil's surface, thus releasing smaller dust particles from the surface. Dust is emitted from the Sahara, Arabian, Gobi, Taklimakan, Australian and South American deserts; but, quantitatively, most dust in the global atmosphere is emitted from the hyperarid northern African (50–70%) and Asian (10–25%) deserts.

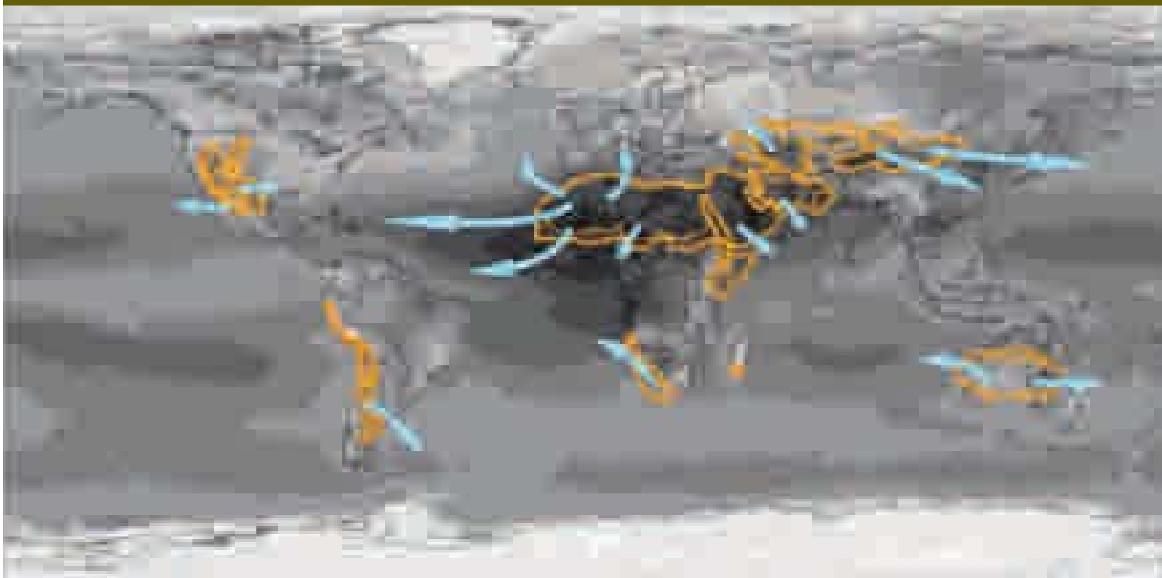
Frequent dust events are observed in enclosed depressions (Prospero and others 2002): from lake sediments deposited during wetter climate periods (like the Paleo-Lake Chad on the Saharan–Sahelian border, which contains the most active dust source on earth) or from the end-points of riverine transport of fine particles (like the Murray-Darling Basin in Australia). Global annual dust emissions are estimated to range from 1 000 to 3 000 million tonnes per year (IPCC 2001), less than 10 per cent of which is likely to result from human activities in the drylands (Tegen and others 2004).

Dust can be carried over thousands of kilometres by strong winds (Figures 3.1 and 3.2). Dust emitted in the Sahara can be carried across the North Atlantic to North and Central America, and even to the Amazon basin. Large amounts of Asian dust are carried over the North Pacific toward the mid-Pacific islands and North America. The lifetimes of atmospheric dust range from less than a few hours for particles larger than 10 µm, which are quickly removed by gravitational settling, to 10–15 days for submicron particles that are mostly removed by wet deposition (Jickells and others 2005).

Desert-generated dust affects productivity of land and ocean away from deserts

Dust generated in deserts adds essential nutrients to terrestrial and marine ecosystems away from deserts, such as phosphorus and silicon, which enhance growth in oceanic phytoplankton otherwise often limited by these minerals. Iron is a micronutrient whose shortage limits the uptake and assimilation of nitrogen, phosphorus and silicon. Enrichment by dust-carried iron can stimulate oceanic plankton growth, and therefore increase CO_2 uptake in ocean regions, where iron is limiting. In nutrient-poor regions, dust-borne iron

Figure 3.1: Atmospheric dust



Twelve-year annual average of the Absorbing Aerosol Index (AAI) from the Total Ozone Mapping Spectrometer (TOMS) satellite instrument. The shading provides a qualitative measure of the atmospheric dust content: dark shade – high aerosol concentration. The TOMS AAI is an indicator of the load of absorbing aerosols in the atmosphere, which are mostly dust particles with some contribution of smoke particles. The desert areas are marked by contours, main transport pathways of dust out of the deserts are marked by arrows.

Source: NASA's "Blue Marble" website

Figure 3.2: Travelling dust storms

Dust storm moving over the Mediterranean from the northern Sahara to southern Europe.

Source: NASA's "Blue Marble" website, http://earthobservatory.nasa.gov

can enhance the fixation of molecular nitrogen by phytoplankton. However, because the specific iron compounds required by phytoplankton are at low concentration in dust and are not easily soluble in water, the role of dust-borne iron in ocean productivity is not yet clear (Jickells and others 2005). Transported dust may also have negative oceanic effects: some authors argue that increased dust deposition in the western Atlantic over the past 25 years could have significantly contributed to coral reef decline by carrying bacterial or fungal spores (Shinn and others 2000). On the other hand, phosphate deposited by dust enhances forests of the south-eastern United States, and the Saharan dust deposited in the Amazon basin replenishes the phosphorus lost through the intense leaching caused by high rainfalls in this area (Okin and others 2004).

Desert dust affects atmospheric properties, rainfall, visibility, and health away from deserts

Depending on their size, distribution and refractive properties, dust particles in the atmosphere partly reflect and partly absorb incoming solar radiation (Sokolik and others 2001). Thus, dust blown away from deserts and over oceans increases the reflectance in an area in which the dark ocean surface would otherwise be absorbing radiation, and thus the atmosphere over the oceans is cooled. When desert dust reaches heights above 5 km, it absorbs and reflects back to space

some of the solar radiation, and so warms the mid-troposphere (Kishcha and others 2003) at the expense of cooling the lowest levels. This generates a downward airflow that exacerbates desert conditions. The added dryness can lead to more desert dust, thus amplifying the initial effect. Desert dust particles can impair precipitation from potential rain clouds, and keep the desert drier, dustier and even less favourable to precipitation in a reinforcing feedback loop, which further increases dust generation by deserts and the likelihood of its transport to non-deserts. Far away from deserts, the transported dust may suppress precipitation from convective clouds by inhibiting the formation of raindrops (Rosenfeld and others 2001). Finally, desert-generated dust may reduce visibility to the point of seriously interfering with ground and air traffic away from deserts. Persistent dust storms also increase the incidence of respiratory diseases (Gyan and others 2005).

Desert dust and global climate change

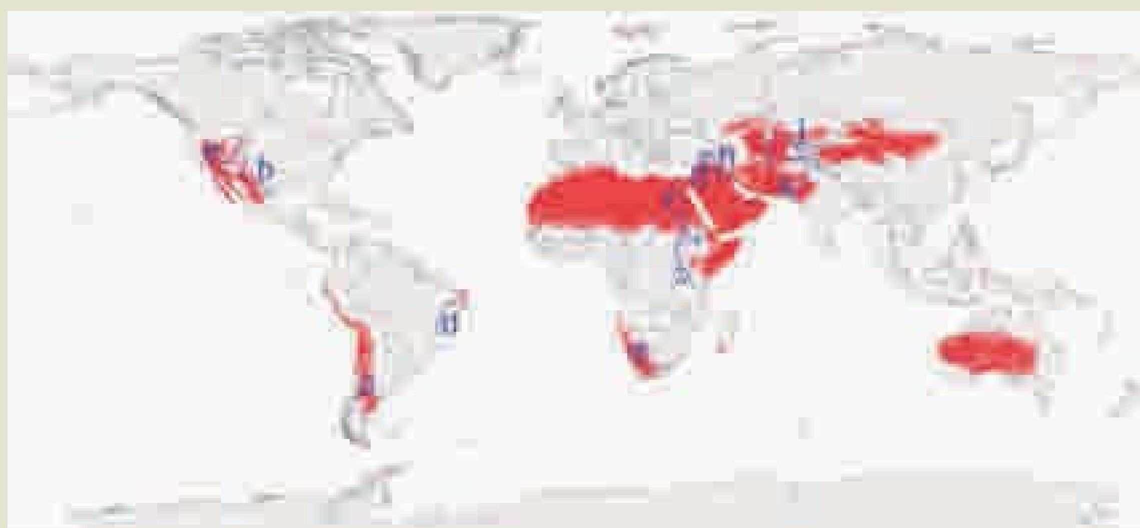
In general, both climate change-induced increasing aridity of deserts and increasing wind speeds will increase overall dust emissions from deserts. In deserts where rainfall is predicted to decrease, concurrent loss of vegetation cover will allow more dust emissions to non-desert areas. In deserts where rainfall is predicted to increase, desert dust flux will be reduced, sustaining, in turn, wet conditions away from deserts (Lioubimtseva and Adams 2004). Yet, due to uncertainties, projections of dust emissions for the next 100 years range between a 60 per cent decrease to a 50 per cent increase in dust emissions (Mahowald and Luo 2003).

CROSS-DESERT RIVERS OF NON-DESERT SOURCES

The significance of rivers to the deserts they cross

Low and variable precipitation and high evaporation are not conducive to generating perennial rivers in deserts. Rather, the source of perennial rivers in deserts is from upland, non-desert areas. The headwaters of the Nile which crosses the eastern Sahara Desert, the Gariep river of the Kalahari, the Tigris and Euphrates in the Syrian Desert, the Indus of the Thar Desert, and other desert rivers, are far from the desert edge, up in humid highlands (Figure 3.3). At a certain point of their course these rivers cross a desert to eventually discharge into the sea (like the Colorado and the Tigris rivers), or into a desert lake (like the Amu Darya and Syr Darya rivers). While flowing through the desert, the riparian banks function as elongated, winding oases, a non-desert island within the desert. Cross-desert rivers provide fish, plants, and animals that comprise the base of

Figure 3.3: Desert rivers of the world



(a) Colorado and (b) Rio Grande/Río Bravo in North America; (c) Río Negro in the Argentine Monte; (d) Saõ Francisco in the Brazilian arid northeast; (e) Gariep in southern Africa; (f) Nile in the Sahara; (g) Tigris and (h) Euphrates in Mesopotamia; (i) Amu Darya and (j) Syr Darya in Central Asia; and (k) Indus in India and Pakistan.

Source: ESRI World Map database, and regional maps

livelihoods for people concentrating along their courses (for example, 97 per cent of the Egyptian population lives along the Nile). River water is often diverted to irrigate extensive agriculture and to support pasture, and it carries sediment that fertilizes or generates soil. Desert rivers have cultural and spiritual significance for desert people, nurturing ancient civilizations.

Climate away from deserts modulates the flow of desert rivers

The flow of perennial rivers in deserts totally depends upon the upland headwaters, non-desert wetlands and lakes, and on their pre-desert course. For example, the Egyptian population, most of which lives under climatically hyperarid conditions with far less than 100 mm of annual rainfall, totally depends on a rainfall regime of more than 1 600 mm that precipitates some 3 000–4 000 km away. The Mesopotamian rivers cross a desert of less than 200 mm of annual rainfall, but depend on precipitation of more than 1 000 mm, much of which is snowfall maintaining seasonal peaks of desert flow, depending on the timing and rate of snowmelt 900 km away. Desert flows of rivers such as the Nile and the Colorado are extremely sensitive to variations in rainfall interception within their small headwater catchments outside the desert (Degens and others 1990).

Water diversion away from deserts reduces cross-desert flow

The amount and quality of river water reaching deserts often depend more on people than on nature. The river flows in the Egyptian and Iraqi deserts depend on the management of their headwaters in Ethiopia and Turkey, respectively. In countries like Pakistan, with both desert and non-desert areas, desert people depend on the way water is managed in the non-desert sections of the Indus river, which has a denser population and a greater impact on the river-flow. Damming that diverts water for irrigation and generation of electric power in the upland non-desert courses of rivers reduces the amount of water reaching the desert. Conflicts between highland and lowland water users are becoming common globally, but they are more apparent in desert-crossing rivers, because most deserts are in the lower river reaches, where water is more precious and population growth is often high; most dams in the Tigris-Euphrates basin are in the Turkish, non-desert course of the two rivers, while few lie in the desert Syrian and Iraqi sections, where flow has been much reduced. Yet, such conflicts have not escalated into armed confrontations; rather they often motivate cooperation among the riparian countries.

Water quality of cross-desert rivers depends on humans away from deserts

Deforestation and overgrazing at the source enriches river water with minerals leached or transported with eroded soils (Hanspeter and others 1998). Residual pesticides and fertilizers, irrigation-generated salinity, and industrial and organic wastes are also drained into river flows. Much of the organic pollution dumped in the non-desert section oxidizes before it reaches the desert; but other pollutants do reach the desert flow, which lacks incoming tributaries to dilute pollutants or spring floods to wash them away. Since the damming of most desert rivers, chiefly off-desert, reduces sediment load in the river flow and hence nutrients, fisheries and wildlife have been impacted. For example, the demise of the Mesopotamian Marshlands is in part due to such reduced flows (Richardson and others, 2005).

Effects of global climate change in the non-desert source areas

Global climate change will affect the remote sources of desert rivers more than deserts themselves. Those rivers with headwaters in snow-capped mountains that depend almost exclusively on snowmelt from glaciers — such as on both sides of the Andean range (Atacama and Monte) — will be the most affected, because accelerated melting of most glaciers is predicted with high confidence (IPCC 2001). The Himalayan glaciers, surrounded by relatively dry areas and sustained due to the high elevations where water is stored as ice, are highly vulnerable; melt will first generate increased flow and the eventual loss of the glaciers would reduce desert flow dramatically. With most of Pakistan's inhabitants dependent upon an irrigation network now fed by the Indus river, the effects of climate change in its basin could be devastating (Nianthi and Husain 2004). The Nile catchment is located at the boundary

between climatic zones, hence minor shifts of this boundary could have dramatic consequences on its desert flow, as already happened when the last glacial age terminated (Conway 2005). However, rainfall behaviour in the Nile catchment under future climate change scenarios is still unclear.

People of Deserts and Non-Deserts are Interlinked

Deserts are linked to non-desert areas not only through the global physical processes modulated by the atmosphere, such as climate, dust transport and river flow, but also through linkages between people, such as the two-way flow of goods and people between deserts and non-deserts. In the following section we highlight only the flow of goods and nature's assets from deserts and the flow of people into deserts.

ECONOMIC EXPORTS FROM DESERTS

A sizeable share of minerals and fossil energy used globally is exported from deserts

Given their low productivity and harsh climate, deserts are only expected to support a relatively small human population. Yet, the conditions of deserts make them rich in a few non-renewable mineral resources, in quantities much larger than are required to satisfy the local population. These resources are often exported to non-desert regions. Water-soluble salts, which readily accumulate in desert deposits due to the ambient dryness, such as gypsum, borates, table salt, and sodium and potassium nitrates, have been historically a product of deserts (Walker 1997). Before the widespread use of industrially-fixed atmospheric nitrogen, nitrates used as fertilizers and explosives were mainly obtained from the Atacama Desert, whose saltpetre and salt beds also contain 40 per cent of the world's reserves of lithium, used in medicine and technology (Crawford 1990).

Several minerals, highly significant in the global economy, are mined in deserts, where they occur not because of current aridity but rather due to geological history. While the low vegetation cover in deserts may have facilitated mineral deposit discovery, heat and the lack of infrastructure make mining and transportation difficult. Thirty-eight percent of the global supply of bauxite (an aluminium source) is mined in Australian drylands (Venkatesh 2003). Fifty-two percent of the world's copper extraction in 2004 was mined from deserts in Chile, Australia and Mexico; 33 per cent of the world's diamonds were extracted in the drylands of Botswana and Namibia; and the deserts of South Africa, northwest China, Australia, Uzbekistan, and Mali accounted for at least 35 per cent of the world's production of gold. Twenty percent of global iron ore production and 35 per cent of its exports came from Australia, where many mines are located in the desert. Phosphate rock is mined in the deserts of Morocco (16 per cent of world production), Senegal (9%), Tunisia (6%), Jordan (5%), Australia (4%), and Israel (3%), adding up to 43 per cent of global production. Finally, half the world's uranium ores are mined in deserts (Kazakhstan, Niger, Namibia, Uzbekistan, South Africa; BGS 2006). The most important contribution of deserts to mineral wealth is their deposits of evaporite minerals — soda, boron, and nitrates (e.g. Chile saltpetre), which are not found in other ecosystems.

More than for their mineral exports, deserts are renowned for the provision of biologically-derived but non-renewable energy resources, which dramatically boost the political standing and the per capita GDP of several desert countries. Thus, deserts contribute slightly above 50 per cent of world oil production and contain 75 per cent of its reserves, while 28 per cent of the world's natural gas reserves are found in the West Asia, North Africa and Central Asia (IEA 2005).

Deserts also export biological products to the rest of the world

Renewable resources — agricultural and other biological products — are also exported from deserts to non-desert areas. This may sound surprising, since usually the low biological productivity of deserts hardly even provides for the needs of desert inhabitants. Yet, some desert countries, such as Turkmenistan and Uzbekistan, practice irrigation agriculture and export much of their produce, like cotton. Also, due to the mild winter temperatures of many deserts, it pays to invest in water resource development for the intensive production of vegetables, fruits and cut

flowers, which fetch high prices when exported to non-desert areas, where and when temperatures are significantly lower and inappropriate for the production of these crops. Thus, dates, vegetables and cut flowers cultivated in the Negev Desert of Israel are exported to Israel's non-desert markets serving 90 per cent of its population, and part of this production is also exported to European markets.

Another type of non-conventional desert export is derived from aquaculture practiced in Arizona and Israel. This includes crustaceans and fish that, when raised in closed systems that reduce evaporation, are paradoxically more efficient in water use than desert plants, and cheaper to cultivate due to mild winter temperatures and the low cost of land. Also, biologically-derived valuable chemicals, produced by micro-algae, are manufactured in deserts by capitalizing on their year-round high solar radiation, and exported to global markets (see Box 5.5).

Many countries with large deserts, such as China and India, export herbal and medicinal plants (Koocheki and Nadjafi 2003). Germany, for example, imports some 1 500 plant species for medicinal purposes, fewer than 100 of which are cultivated on a large scale, while the others are collected from the wild (Plant Talk On-Line 1997). Since deserts harbour large numbers of medicinal and herbal plants traditionally used by desert and non-desert people — for example, 95 per cent of disease treatments of the Thar Desert are provided through the use of 85 desert plant species (Ahmad and others 2004) — it is likely that in this export desert plants play a significant role.

Deserts hold a potential for bioprospecting

Besides exporting wild or cultivated herbal and medicinal plants from deserts to non-deserts, desert plants can be expected to catalyse the global pharmaceutical industry. The assertion that desert flora can be bioprospected for chemicals derived or extracted for medicinal use is rooted in findings that many evolved adaptations to the stressful desert conditions are chemically-based, such as compounds of anti-oxidative or of anti-herbivory action extracted from desert plants. Indeed, recent screening of plants in the Negev Desert led to the identification of a few species with cytotoxic and antimalarial activities (Golan-Goldhirsh and others 2000), and some plant species from deserts in Argentina and Arizona and arid regions in Morocco have demonstrated activity against human diseases (for example, uterine cancer and infectious microbes), while their activity against a non-cancerous cell line was much lower, thereby indicating that disease-specificity may be prevalent (Donaldson and Cates 2004). It was also found that essential oils from two plants of Morocco's deserts, active against certain cancer cell lines and microbes, enhance poultry growth, reduce mortality, and increase the efficiency of feed conversion. They can be therefore used to replace antibiotics in poultry feeds, thereby reducing the evolution of antibiotic resistance (Donaldson and others 2005).

Yet, none of the known active compounds of desert plants have yet worked up to the level of a certified pharmaceutical in worldwide clinical use, though there are several patented claims for medicinal properties of such compounds, and a dryland plant-derived dietary supplement (the Kalahari Desert *Hoodia gordonii*, alleged to control appetite) is commercially marketed. Thus, the pharmaceutical potential of desert plants has yet to be tapped.

MOVEMENT OF PEOPLE FROM NON-DESERTS TO DESERTS

Job creation encourages immigration to deserts and desert urbanization

The dimension of human migration from non-desert regions into deserts cannot be precisely quantified. But, because desert cities and towns do not normally have an agricultural hinterland from which they can draw rural migrants, their population growth can be attributed to both natural growth and to migration from outside the desert (Portnov and Erell 1998). The growth of desert cities, clearly evidenced in industrial countries in the mid-20th century, is an indicator for migration of people from non-deserts to deserts. This migration is usually employment-driven. New jobs are created in the desert when governments encourage military and industrial dispersal from densely-populated non-desert areas to the open spaces of deserts, as well as large-scale development projects. These attract services — catering, restaurants, hotels, transportation, travel agencies, shopping,

housing developers, etc. — which create additional employment opportunities for desert newcomers.

Migration to the desert may also take place for security considerations. Thus, during WWII, major industries were relocated from the western part of the former Soviet Union, occupied by Nazi Germany, to its eastern regions, including the deserts of the Kazakh and Turkmen republics. This relocation was followed by a major migration of technical personnel and employees of these industries. In recent years, the government of China established incentives promoting primary and military industries to boost the economy of its western and northern desert regions, driven by the discovery of oil in these regions and by a policy of encouraging development of the inland parts of the country. Other policy-encouraged immigration into deserts, which may affect smaller desert societies, their lifestyles, cultures and environment, are the immigration of Han Chinese into the Uyghur-inhabited Xinjiang (Nellemann 2005), and the immigration of Delta-inhabiting Egyptians into the small Bedouin societies of the Sinai, as well as the settling of Egyptian university graduates in remote desert localities charged with reclaiming them for cultivation (Divon and Abou-Hadab 1996).

In industrial countries, migration from non-desert to desert areas is driven by the availability of cheap housing (development towns in the Negev Desert of Israel), including for retired citizens (the Sun Belt localities in the US, or the Canary Islands) who are attracted to desert towns by the dry and sunny climate. In developing desert countries, specifically in Sub-Saharan Africa, periodic droughts in non-desert drylands draw thousands of rural migrants and nomads to local cities, many of which are located adjacent to deserts, in search of food and employment (Pedersen 1995) (see also Chapter 2).

Tourist influxes to deserts encourage migration to deserts

In recent years, many desert areas south of the Mediterranean basin (e.g., Canary Islands, Eilat in Israel, Sharm-al-Sheikh in Egypt), have become popular destinations for tourists from northern countries, who are attracted by the balmy climate of the desert. Many desert resorts in the Mediterranean spur their attractiveness by combining recreational facilities for vacationers with visits to adjacent archaeological and geological parks. Rehabilitation centres for patients suffering from diseases, such as asthma or arthritis, have also been established in desert regions (Golany 1978). Desert tourism boosts the economy of desert countries (11 per cent of Egypt's gross national income is from tourism; WRI 2003), and services for the desert tourism industry also create new jobs and attract immigration into the growing desert cities.

Deserts as Corridors

The common denominator of trading caravans and migratory birds is that both use deserts only as corridors linking non-desert starting points with non-desert destinations. However, while using the desert corridor, both often interact with the desert environment, its biota and its human population. And, just as desert corridors have been used by armies to reach their non-desert destinations for assault, so it is often the case with locusts that use deserts as a corridor for invading non-desert areas.

CROSS-DESERT TRANSPORTATION OF GOODS AND CULTURES

Deserts are wedged between, and thus hinder exchanges among, civilizations. In response, desert people developed a livelihood that capitalized on this need for commercial exchanges, the livelihood of transportation — guiding and servicing the cross-desert caravans. This expertise in safely and efficiently moving goods through deserts channelled a flow of income from non-desert to desert people, and at the same time economically and culturally benefited the non-desert areas at both ends of the cross-desert transportation routes. This trade often made desert people knowledgeable of the politics of Europe and Asia, more than the other way around. Though the great trade empires founded on cross-desert transport are long gone and desert routes are now far less significant, transport and trade still support desert livelihoods.

Deserts have been crossed by trade routes through millennia

Most deserts have been crossed by trading roads through millennia (Figure 3.4). The Silk Roads were already active in the late Bronze Age, though

Figure 3.4: The Silk Road: trans-desert trade route in Eurasia, 3rd–15th century

Source: Modified from Donnus Nicolaus Germanus, Cosmographia: Claudins Ptolemaeus; Leonhart Holle, Ulm, 1482

intensive use of cross-desert roads was triggered by the domestication of the camel. The trade through the trans-Saharan roads took off only with the Islamic conversion of West Africa. The two main roads, made of a network of shorter segments between oases, led from Morocco to the Niger Bend and from Tunisia to Lake Chad. Guided by Berber guides to ensure safe passage, caravans included on the average a thousand camels, sometimes reaching 12 000 animals, and runners were sent ahead to oases to ship out water when the caravan was still days away. West African gold and slave servants were exchanged for North African salt and slave soldiers, thus enriching kingdoms and empires of Ghana and Mali south of the Sahara, and Tuareg cities north of it. Similarly, through the Silk Road network goods to and from Xinjiang province of China travelled through Central Asian deserts either to West Asia or to Russia.

Trade through these roads declined (as of the 16th and the 12th centuries in Africa and Asia, respectively) due to political unrest, incursions, and wars, on the one hand, and the development of maritime routes on the other. The independence of African nations in the 1960s and rebellions and civil wars of the 1990s halted the cross-Saharan roads at the national boundaries, and trade through the Silk Road was disrupted by the wars of Genghis Khan. Today most cross-desert transport is through an extensive tarmac road network in addition to transport by air and sea; yet, Tuareg camel caravans still travel on the traditional Saharan routes, carrying salt from the desert interior to communities on the desert edges.

Cross-desert trade routes encouraged significant cultural exchange

The transfer of goods between non-desert lands through deserts enriched desert people, both economically and culturally. The Nabatean Kingdom was moulded and subsisted on controlling roads crossing West Asian deserts, moving spices from southern Arabia and goods from India to their capital Petra, and then to the Mediterranean port of Gaza, to be shipped to Greece and Rome. Other desert trading cultures include those of the Saharan Tuaregs, Fulani and Songhai and the Central Asian Uyghurs and Kazaks.

The cross-desert trading routes functioned as communication and information channels between non-desert regions, and between these and the desert people. Through the Sahara rumours of West African treasures prompted the Portuguese to reach Guinea, and West Africans became acquainted with the Arab and Mediterranean world long before the adoption of Islam. Books

from Europe travelled to Africa through the trans-Saharan roads, the only means for their transport until the 15th Century, exposing sub-Saharan countries to knowledge generated in Europe (Masonen 1997). European traders met trading partners in Africa and Asia with information far surpassing their own. Along with luxury goods and weapons, religions and knowledge moved through and out of the Asian deserts, such that the cultural scene of Central Asia was moulded by Indian, Greek, Chinese, Tibetan and Arabian cultures and the Buddhist, Christian and Muslim religions. Cross-desert trade routes also promoted gene flow among populations isolated from each other by the desert's reproductive barrier. Shared gene pools among camels, horses and goats on both sides of deserts (Jianlin and others 2004) are attributed to Pleistocene migrations along corridors later to become the Silk Road. Human populations in Europe, Northern Africa, the Arabian Peninsula, East Asia and North America share a common genetic history, attributed to cross-desert travel and trading (Yao and others 2004).

Cross-desert transport continues to affect desert and non-desert people

While the trade across the desert today is small, cross-desert pipelines, trains and trucks move minerals and oil from the desert to non-desert destinations. Firewood and charcoal as fuel for desert inhabitants is transported from non-desert areas through desert roads. Altogether, ground transport now provides for a significant transportation sector in deserts. Better road systems have also opened up for tourism, one of the fastest growing economic sectors. This modern transport goes through oases and sky-islands and facilitates the urbanization of major oases, thus contributing to the economy of desert regions but also presenting risks to traditional lifestyles. Desert roads, however, are vulnerable to flash-floods and drifting sand, and programmes directed toward the construction of physical wind barriers or establishing vegetation to reduce drifting sand exist (Figure 3.5).

The use of modern cross-desert roads is also often constrained by armed bandits and guerrilla warfare that may include road mining, making travel and trade dangerous and uncertain. Although no statistics are available, much of the cross-desert trade and road use is currently of an illegal nature — drugs, arms and slavery (mostly for prostitution); 80–90 per cent of the heroin consumed in Europe comes from the deserts of Afghanistan, and 60 percent of Afghan opium and heroin travels through Central Asian or West Asian deserts. Products from poaching of endangered species also travel through deserts (Nellemann 2005).

Figure 3.5: Desert road protection

Desert roads are protected from moving sands with irrigated road-side plantations. Taklimakan Desert, China.
Source: Wang Tao

CROSS-DESERT ANIMAL MIGRATION

Trans-desert bird migration

Thousands of bird species are migratory, performing a north-south, often cross-equatorial, seasonal migration between northern and southern homes (Figure 3.6), of which the one north of the subtropical region is used for breeding. A migratory bird is an integral component of these two distinct ecosystems, linked only by migration routes, used for reaching its destination in the fastest and safest way. Since most deserts are wedged within the subtropical latitudes, since many regions within subtropical latitudes are deserts, and since competition for resources at either end favors early arrival, most migrants select the shortest route, which is very likely to include a desert-crossing section serving as a corridor for the migration of large numbers of birds.

Migrating is always costly, but more so on desert crossing, because migrants spend most of their life outside the desert and hence are not as well-

Figure 3.6: Major migratory bird routes of the world

The red areas show the world's deserts.

Source: Perrins and Elphick 2003

adapted to deserts as resident birds. Yet, since crossing deserts rather than circumventing them evolved as an adaptation to reduce travel time, the added cost is reduced by specific adaptations. The fuel used for travel is fat—light in weight and rich in energy —stored under the skin. A 10g warbler needs fat stores approximately a *quarter* of its body mass to complete the flight across the Sahara Desert, which can take 40 hours (Carmi and others 1992). Burning this fat during the intensive and exhaustive flight generates much heat and the rapid breathing during flight removes body water. To reduce the risks of overheating and dehydration, most small cross-desert migrants fly at night. When the desert tract to be crossed is short, birds may make it in a single flight, but otherwise birds conduct intermittent flights between stopovers (Biebach and others 2000); they alight at dawn, seeking shaded and concealed refuges, even as small as a shading rock or a single bush if nothing better is in sight, where they minimize water loss and rest prior to taking off again when night falls.

Migrants can do even better when stopping-over in desert oases, which function as stepping stones for *en route* energy replenishment (Safriel and Lavee 1988). But because oases are rare (for example, the combined area of Saharan oases is only 2 per cent of this desert), scattered and hence difficult to spot, many migrants use routes along desert rivers such as the Nile (Box 3.1). Combined, all desert oases and riparian corridors comprise a critical habitat for a hugely disproportionate number of migratory species. Yet, the richer an oasis or a riparian tract is, the more it is likely to be impacted by people (two-thirds of the human population of the Sahara concentrate in oases) who can pose a threat to the migrants; the intensification of irrigated agriculture in natural and man-made oases, for example, may add open water and some locally abundant sources of food, which does attract migrants, but agrochemicals and other pollutants may harm the migrants, either directly, or through damage to the insects they might feed on (e.g., Evans and others 2005).

Cross-desert bird migration is also being impacted by global climate change. Cues such as day length, which are independent of climate, are involved in determining the onset of migration. These have evolved to synchronize with changes in seasonal abundance of plant and insect food resources in the two far-apart "homes" of the migratory birds; in contrast with the day-length cues, these changes in food availability are highly dependent on climate. Climate change will decouple the synchrony between non-climatic cues and climatic events. This synchrony is critical for cross-desert migrants, many of which time their migration such that they arrive at their feeding ground, just prior

Box 3.1: The trajectory of a white stork, a soaring cross-desert migrant, tracked from space

The white stork (*Ciconia alba*) is a soaring, cross-desert daytime migrant, with a breeding home in Europe and a wintering one in southern Africa. The map describes the trajectory of "Princess", a female white stork fitted with a satellite-tracked transmitter. When at least nine years of age, Princess left her breeding grounds (red circle) in northern Germany (51.7°N) on 25 August 2002, arrived at the northern desert edge (the Negev in Israel, 31.5°N) after 15 days, then travelled south across the Sinai and along the Nile Valley. After exiting the Sahara Desert, thus ending a 9 days cross-desert journey, Princess stayed for 58 days in the southern part of the Nile basin, within the semi-arid area next to the desert edge (white rectangle) to replenish reserves spent on the first leg of the voyage and to store for the post-desert second leg towards her wintering home (white circle). She then travelled 20 days, more leisurely than the desert crossing, and arrived at her winter grounds, which included Zimbabwe, Botswana and eventually the Cape Province at the southernmost tip of the African continent.

Princess wandered within her wintering grounds for 115 days of the southern summer. She started her journey back to Germany on 30 March 2003, travelling rather quickly and arriving at the desert edge five days later. Here, she again stayed for restocking, this time only for 11 days. The northbound desert crossing was longer than the southbound one, taking 15 days. Upon leaving the desert she stayed in the semi-arid area of Israel (red rectangle) for 15 days of replenishment following the desert crossing. It then took her 25 days to travel through Lebanon, Turkey and Europe until reaching her breeding home in northern Germany rather late, on 9 June, then spending only 65 days there, and again taking off on 14 August 2003.

Altogether, Princess covered 12 600 km in 102 days of her southbound migration, of which 2 440 km were through a desert, yet close to riparian habitats of the Nile. Her northbound voyage was shorter – 8 250 km in 71 days. Yet, her late arrival and short stay in the breeding grounds attest to an unsuccessful breeding. In the previous year she arrived on April 12, and stayed for 98 days, a period sufficient for completing successful reproduction.

Source: Migratory Birds Know No Boundaries, International Center for the Study of Bird Migration, Israel Ornithological Center, http://www.birds.org.il/show_item.asp?levelId=457

to entering, or just after exiting the desert when the food supplies there peak, which enables them to replenish their fat reserves for the remaining journey (Vickery and others, 1999). Compounding that problem is the projected "expansion" of deserts, which would increase the distance of that flight, perhaps beyond that which birds are already adapted to, or to which they might rapidly adapt. Furthermore, even if climate change does not jeopardize the voyage itself, it may reduce the benefits of migration. Since migrants have only a small margin of safety of energy reserves during migration, the condition in which they arrive at their destination, where they may encounter intense competition, substantially determines their survival.

To conclude, the cross-desert migration of birds, many of which are both familiar and important to people living far from deserts, is sensitive to human impact, climate-change included. Since this migratory network can only be as strong as its weakest link, the conservation of desert sites used by alighting migrants, as well as off-desert ones on which the success of cross-desert migration depends, is urgently required (Hutto 2000).

Locusts moving through deserts

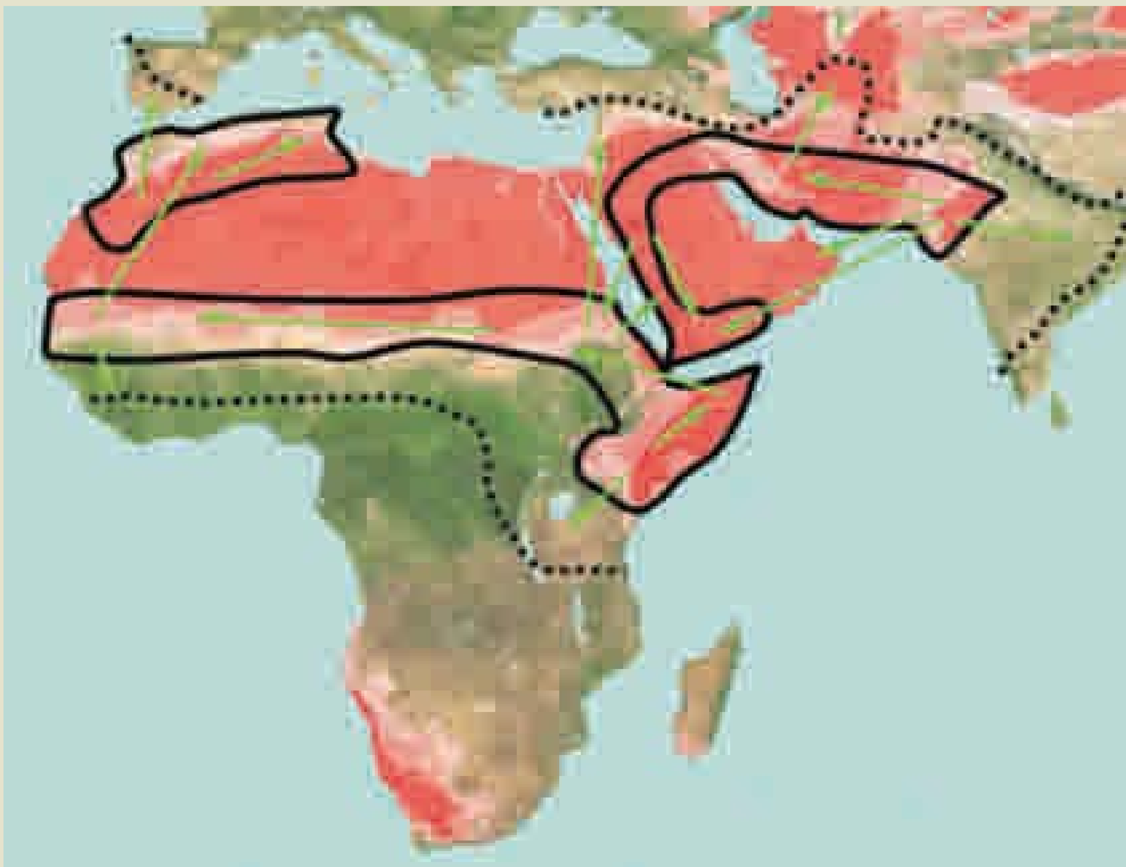
Though there are many more insect species than bird species, the number of migratory insects is smaller than that of migratory birds and only one small group of migratory insects is associated with deserts — the locust. Unlike migratory birds which cross deserts in a regular, seasonal two-way migration, locusts cross the desert in a unidirectional, irregular pattern. And, whereas the arrival of migratory birds is often welcome, the sighting of locust swarms is always ominous. Several locust species spend part of their lives in deserts and many locust swarms cross deserts. Most significant is the desert locust (*Schistocerca gregaria*) of the least dry parts of deserts — arid (but not hyperarid) regions in 25 countries of the Sahel (including Burkina Faso, Chad,

Mali, Mauritania and Niger), the Arabian Peninsula, along the coast of the Red Sea, and along the coast of ROPME Sea Area (Regional Organization for the Protection of the Marine Environment — Kuwait Regional Convention, 1978) up to the India-Pakistan border (Simpson and others 1999). The desert locust in the solitary phase poses no threat to crops; its small populations are dispersed in patches of suitable habitat, with little movement between them (Ibrahim and others 2000).

When spells of good rainfall occur in several successive rainy seasons, the soil becomes moister and vegetation grows more quickly. In response the animals also grow more quickly and egg-laying in holes dug in the soft, moist soil intensifies. Each of the formerly isolated populations increases, and their movement downwind leads to a concentration of several crowded, fast-growing populations (Despland and others 2004). Once the aggregated population is large and crowded, the individuals change in colour, physiology and behaviour which, combined, helps them to aggregate and reproduce intensively (Pener 1991) especially when rains persist, thus increasing pressure on resources. When, eventually, vegetation is decimated at the source, a large-scale directional, downwind flight of whole swarms is initiated (Culmsee 2002).

This movement can bring the swarms to other desert arid or hyperarid areas, or to non-desert areas (Figure 3.7) — the "outbreak areas" (as distinct from the areas they inhabited prior to the massive movement — the "recession areas", Pedgley 1981). Carried by the wind which takes them to where it takes the rain too (Waloff 1960), swarms that may contain 50 000 million individuals, migrate from deserts into non-desert areas, where they can spread over more than 20 per cent of

Figure 3.7: Distribution and movements of the desert locust



The solid black lines bound the areas where solitary locusts transform into the gregarious phase, out of which swarming invasions of gregarious locusts are generated. These invasions may occur in any location within the area bound by the dotted lines. The green arrows indicate typical flight directions of most swarms.

the land surface of up to 65 countries including in the Sahara and the Arabian Desert. They can reach southern Spain, Turkey, West Africa, India, Bangladesh, Tanzania and the Democratic Republic of Congo, consuming 100 000 tons of vegetation a day. Swarms originating in deserts can even cross oceans; during the 1986–89 plague, swarms escaped extermination in western Africa and crossed 5 000 km over the Atlantic Ocean, reaching the West Indies and the eastern coast of Venezuela. Swarms migrating to outbreak areas rarely return to the original recession areas (Ibrahim and others 2000): they die out, or are destroyed by cold weather or pest control measures. Since it is the desert edges that are often the source of locust plagues, it is there, in countries such as Algeria, Somalia, Sudan and Iran, where the battle against locusts can be most-effectively fought, in order to save crops in other areas, in countries such as Mali, Niger, Chad and Yemen (Showler 2002).

The Impact of Desert Research on Global Science

Though remote, isolated and of harsh climatic conditions, deserts attract scientists of every discipline. Most of them carry out scientific research on deserts, but some perform scientific research in deserts, capitalizing on some desert attributes that make the research there more productive than if carried out elsewhere. Both research on deserts, striving to generate knowledge of this specific environment, and research in deserts, which makes use of this environment for increasing general knowledge, have made an impact on global science. This is because both types of research carried out in deserts benefit from the desert's clean atmosphere, sparse human settlements, dry climate, sparse vegetation cover, and often thin soil cover — features that contribute to good preservation conditions, visibility, and high detectability of scientifically-relevant objects and phenomena.

RESEARCH IN DESERTS CONTRIBUTES TO SPACE EXPLORATION

Since the desert environment is most reminiscent of that of several barren, apparently lifeless planetary bodies, deserts have been used as simulators for testing planetary exploration equipment. For example, NASA conducted experiments in US southwestern deserts to test communication rovers and to improve human-robot interactions in conditions similar to those on the Moon and Mars (Volpe 1999). The Nomad robot, designed for long-distance planetary exploration, successfully traversed the Atacama Desert, and a remotely-guided rover explored the distribution and diversity of life in this desert as an analogue to Mars, not only because it is extremely dry, but also, because, like Mars, it experiences high levels of ultraviolet radiation, due to its altitude and atmospheric transparency (Wettergreen and Cabrol 2005).

Just as deserts are used for research that helps to send vehicles and sensors to explore distant planets, meteors arrive on earth from outer space; here deserts play a role too, serving as a repository of space debris and meteors reaching the planet's surface and remaining there as meteorites, well-preserved due to the slow rate of desert rock erosion. Indeed, most collected meteorites have come from deserts, though many are now also collected in Greenland and Antarctica.

Unlike the use of deserts for testing technologies for space exploration and for detecting meteorites, astronomical observations can theoretically be conducted in any environment, but conducting them in deserts is advantageous. This is because the background "noise" relative to the "signal" emitted by faint celestial sources is minimized in deserts, except where and when dust storms are often generated. This is because, beside the obvious low cloud cover, deserts minimize light pollution from human settlements, atmospheric water vapour, and air turbulence close to the telescope. It is easy to find desert sites where flat, treeless areas reduce the turbulence of airflow and in which urban encroachment is highly unlikely. Indeed, some of the largest and most expensive astronomical instruments of the international astronomical community are placed on desert mountain tops, where also the layers of atmosphere present between the telescope and any celestial object are minimized, such as, for example, the Very Large Telescope array (VLT) of the European Southern Observatory (ESO) on Cerro Paranal in the Atacama high desert of Chile, the Sutherland site in the Karoo of South Africa

where the SALT telescope started operations in 2005, and other observatories currently being planned for other desert sites.

FINDINGS IN DESERTS SHED LIGHT ON THE EARLY HISTORY OF ANIMALS, PEOPLE AND EARTH

Deserts are treasures of paleontological findings

The world's deserts serve as a natural laboratory for investigating the history of life, be it that of plants and animals or of humankind. This is because the desert's sparse vegetative cover, lack of thick soils, and aridity combine to provide large areas of exposed rock. This, together with the scant precipitation that reduces chemical leaching by groundwater, promotes the preservation and the detection of fossils that allow deciphering the evolutionary history of animals and plants, and of early man (Figure 3.8). Although ultimately it is the distribution of appropriate aged sedimentary rocks that determines where fossils will (and will not) be discovered, deserts probably have produced a disproportionate number of major paleontological finds.

Figure 3.8: Desert fossils

A fossil ammonite shows-up in the sandy surface of the Chihuahuan Desert, at 1500 m altitude, as a silent record of past geologic ages and of the power of tectonic forces that brought the floor of the ancestral Atlantic Sea into the contemporary Chihuahuan Plateau.

Source: Patricio Robles-Gil

Particularly noteworthy examples include the badland terrains of the Gobi Desert where a great diversity of late Cretaceous (65 million year-old) dinosaurs and mammals have been unearthed; the Sahara's Ténéré Desert in Niger where excavations in lower Cretaceous — 10 Ma (million years ago) — rocks recently recovered over 25 tons of dinosaur fossils; the Karoo Desert of South Africa and its exposures of upper Permian (250 Ma) through lower Triassic (220 Ma) rocks containing abundant remains of mammal-like therapsid reptiles; Egypt's Fayum Desert, which preserves important Eocene-age (40 Ma) fossil treasure of early cetaceans and sirenians; the Pisco Basin, a coastal desert in Peru, where an exposed stratigraphic sequence of Miocene to Pliocene (20 to 2 Ma) rocks has produced spectacular assemblages of fossil marine mammals; and the Colorado desert in south-eastern California, that harbours one of the most complete records of late Cenozoic land mammal evolution in North America.

Findings in deserts shed light on the origins of mankind and its culture

Some fossils of hominids found in deserts in recent years were instrumental in reconstructing the evolution of humans. The early hominid *Sahelanthropus tchadensis*, a new genus and species of hominid that lived 6–7 million years ago (Vignaud and others 2002) was discovered in 2001 in the Saharan Djurab Desert of northern Chad. This finding suggests that the divergence between the human and chimpanzee lineages was earlier than indicated by most molecular studies. *Australopithecus garhi*, who lived 2.5 million years ago, was found in 1996–9 in the Afar Desert of Ethiopia. *Australopithecus garhi* might have been the world's earliest maker of stone tools, used to scrape bones of hunted mammals (Asfaw and others 1999). The oldest found fossilized remains of modern humans, who lived 160 000 years ago, was found in 1977 in the desert sands near the Ethiopian village of Herto (White and others 2003).

Most desert attributes that conserve fossils also apply to preservation of prehistoric and archaeological remains; and the low level of surface disturbance by humans has also preserved prehistoric sites. These attributes have resulted in a large number of archaeological discoveries in

Figure 3.9: Archeological remains in the Negev Desert

Aerial photo of an ancient threshing-floor 'Uvda Valley, southern Negev, Israel. The larger grey oval (18 × 36 m) was built on the rock surface in the 5th millennium BCE, while the smaller structure (14 × 17 m) was dug into the rock in the early 3rd millennium BCE. Silos and a flint workshop were built next to it.

Source: Uzi Avner

deserts, many of which are of global significance. For example, the earliest stone plough-tips, the largest and oldest cluster of threshing floors (Figure 3.9) and the earliest run-off irrigation system supporting large cultivated fields, belonging to early farming communities which evolved from hunter-gatherers since 6 000 BCE, were found in the Negev Desert (Avner 1998). Among hundreds of prehistoric cult sites in West Asian deserts, shrines of standing stones representing deities have been found (Figure 3.10), erected first in the 12th millennium BCE and becoming very common from 6 000 BCE. These suggest that while peoples

Figure 3.10: Prehistoric desert shrines

A shrine with standing stones facing east, representing a group of seven deities, 5th–3rd millennia BCE, 'Uvda Valley', Negev Desert, Israel.

Source: Uzi Avner

of the fertile lands of that region worshiped gods in figurative, human or animal forms, natural, unshaped stones represented gods to the desert people. Millennia later, this abstract, non-figurative theology was also adopted by the Jewish, Nabatean and Islamic religions (Avner 2000). Another rather famous desert finding with religious implications, that of the Dead Sea Scrolls, preserved for 2 000 years due to the desert's dry climate and discovered since 1947, shed new light and contributed insights into the history, philosophy and evolution of Judaism and early Christianity. Less widely known but of far-reaching impact is the desert origin of alphabetic writing, which first appeared in West Asian desert rock inscriptions around 2 000 BCE. While the ancient Egyptian and Mesopotamian scripts consisted of hundreds of complex signs (Figure 3.11), a group of people in the Sinai desert adopted only 28 (mostly Egyptian) symbols, each representing a single consonant. Later, these signs evolved into the Phoenician and the Hebrew script, then to the Greek and Latin and finally into the present-day Western European scripts.

Figure 3.11: Hieroglyphs and the development of alphabetic script

A painted wall of the tomb of Prince Sirempút II (12th Dynasty) in Aswan, Egypt. The encircled hieroglyphs are two of the five presented in the table inset. The table shows examples of proto-Sinaitic letters engraved by Semitic desert people around 2 000 BCE in rock inscriptions discovered in western Sinai.

Sources: Carpiceci 1997 (painted wall) and Yadin 1963 (table)

Desert research generated knowledge on the earth's geology

The low soil and vegetation cover of deserts has also attracted geologists and geomorphologists, whose research in deserts has contributed to our basic understanding of the processes that shape and mould the surface of the earth. The wealth of excellent rock exposures in the rocky deserts is outstanding, providing scientists and visitors with a glimpse into geological windows. Deep canyons, fault escarpments and rift valleys in deserts often exhibit sequences of rock strata that disclose chapters of hundreds-of-millions of years of earth history. Deserts have also been pivotal to the development of geomorphology, largely because their landforms are also easy to see. John Wesley Powell's report on the Grand Canyon (Powell 1875) opened geological science to the power of rivers, and Gilbert's (1877) work in North American deserts, are the foundational studies of modern geomorphology.

DESERT BIOLOGICAL RESEARCH CONTRIBUTES TO SEVERAL BIOLOGICAL SCIENCES

Desert research and the notion of convergent evolution

Being an environment as remote as imaginable from the aquatic origin of life, deserts attracted early life scientists eager to uncover the adaptations of desert organisms to this challenging setting. These endeavours had a profound impact on the disciplines of evolutionary biology, physiology and ecology. Regarding evolution, it was found that both desert annual plants and sedentary animals respond with extremely rapid growth to the short bouts of resource abundance, and by quiescence of life processes during the intervening long periods of shortage (Philippi 1993), whereas both perennial plants (Cabin and Marshal 2000) and mobile animals survive periods of low resource abundance by either moving to more favourable areas (animals), or by physiological means such as suppressing resource allocation to temporarily less important activities (plants). That groups with such different evolutionary ancestry as plants and animals display similar adaptations to the extreme and random fluctuations in resource availability convinced biologists that, in the living world, divergent genetic makeups have the potential to generate convergent solutions to a wide array of environmental challenges and selection pressures (Smith and Wilson 2002) (see also "Biological Adaptations to Aridity" in Chapter 1).

Desert physiological adaptation as a model for life under stress

Desert research revealed that physiological adaptations enable mammals and birds to live in environments where water is limiting and temperatures are high, while human adaptations are exclusively behavioural and cultural. This prompted researchers to study the physiological responses of humans to desert conditions. These studies demonstrate the potential of people to acclimatize, rather than adapt, to stressful conditions (Shkolnik and others 1980). The fact that humans and their livestock do live in deserts has also compelled physiologists to examine the deleterious effects of high temperatures, chronic dehydration and food shortages on humans, and on the animals they domesticated due to their ability to live in deserts, such as camels (Schmidt-Nielsen and others 1967), goats, and donkeys (Izraely and others 1989).

What determines the number of links in a food chain? — A desert insight

Two features make deserts ideal for ecological research. The low plant cover enables one to easily explore animal activity either directly, or indirectly, by observing the tracks they leave on the bare soil surface. More importantly, since in deserts only one major factor, precipitation, governs ecological processes, and since the number of species in deserts is relatively low and the sizes of their populations are small, the desert ecosystem appears simpler, hence easier to understand than other ecosystems. These features encouraged the use of deserts as an outdoor laboratory, where hypotheses and theories developed in non-desert environments lend themselves to testing.

For example, a prevailing notion that evolving specializations for partitioning a limiting resource enables many species to avoid competition and coexist, thus leading to high diversity, is challenged by the finding that annual plants and darkling beetles (the blackish beetles of the family *Tenebrionidae*) exhibit high diversity in deserts, but subsist on resources not amenable for partitioning;

since soil moisture is restricted to its thin top loayer, the coexistence of so many annual plant species cannot be attributed to each of them drawing water from a different depth. Similarly, the rather physically and chemically homogenous plant litter cannot be partitioned and is indiscriminately consumed by all darkling beetles. This desert observation supports the notion that species diversity can be maintained not only by competition that generates specialization, but also by predation (Ayal and others 2005).

This leads to challenging yet another central paradigm of current ecological theory, that food chain length is determined by the productivity of its first link, the primary productivity of plants, and that high primary productivity maintains long food chains. In deserts, however, long food chains with several predation links on top have been observed repeatedly, in spite of the desert's overall low primary productivity. Several related observations explain this finding. Most of the desert's primary productivity is not consumed by herbivores but becomes plant litter; plant litter in deserts is not readily decomposed by soil micro-organisms, which are constrained by the desert's protracted periods of low moisture. Hence, much litter accumulates on the surface and is consumed by a large number of arthropods. Being relatively small, these litter-consuming arthropods are preyed upon by only slightly larger small predators, such as arachnids and reptiles, which in turn are preyed upon by birds and mammals, which are larger still. Thus, desert food chains are long and size-structured, yet are supported by a base of low primary productivity (Ayal and others 2005). Desert research then implies that it is the body size of the primary consumers rather than the quantity of primary production that determines the length of food chains, a conclusion that undermines the high productivity–long food chain paradigm, and which may apply to other, non-desert ecosystems.

Why are linkages important?

Exploring how deserts are linked to the rest of the planet, this chapter highlights the importance of deserts. It also underscores why the more than 6 000 million people who live outside the desert biome need to take an interest in what happens in deserts, even though only 144 million people currently live there. This is not only because so much of the oil and so many of the diamonds come from deserts; there are more subtle aspects of human culture that for inexplicable reasons have been nurtured in deserts, such as the advent of the alphabetic script or the emergence of monotheistic religions that, respectively, catalyzed human development and largely dominate human relations the world over. Yet, it is not the signature of a desert's remote past that matters most. Rather, much of human well-being in its broadest and most global sense depends in several ways on what happens in deserts today.

For example, the climate system of the areas beyond the desert affects that of the deserts themselves, but some of the desert climates' responses to these then affect the climate of the non-desert world. This in turn much depends on global climate change, mostly generated by non-desert people. Deserts may respond to these changes, among other things, by increased emissions of cross-boundary dust storms with far-reaching negative (as well as positive) implications. Another example is derived from the dependence of non-desert birds on cross-desert migration. Birds are directly, but people are indirectly, affected, because when not on the move these birds are intimately involved in the provision of services in the non-desert ecosystems in which they live, services that support life in general and human well-being in particular, at local and global scales, and which will not be provided if the cross-desert migration is impaired. Hence, this migration depends on what people both in deserts and outside of deserts do, either to protect or to disrupt these trans-desert migrations. Furthermore, these two groups of people, the desert and the non-desert, are inter-connected too. The livelihoods of many desert people, upon which the flow of benefits from deserts to the rest of the world depends, is often linked to the ways non-desert people manage the non-desert headwaters of major rivers that cross into deserts, nourish their life and nurture their societies.

To conclude, our understanding of global processes, the development of much of our modern research, our ability to cope with global environmental change, and the preservation of much of our global heritage depends to a large

extent on the way we manage and preserve the world's deserts. What happens in deserts affects every one of us, wherever we are. What happens outside deserts impacts deserts, changes the way they function, and what they can contribute to the rest of the planet.

REFERENCES

Ahmad, H., Bhatti, G.R., and Latif, A. (2004). Medicinal flora of the Thar Desert: An overview of problems and their feasible solutions. *Zonas Áridas* 8: 74–84

Asfaw, B., White, T., Lovejoy, O., Latimer, B., Simpson, S., and Suwa, G. (1999). *Australopithecus garhi*: A New Species of Early Hominid from Ethiopia. *Science* 23: 629–635

Avner, U. (1998). Settlement, Agriculture and Paleoclimate in Uvda Valley, Southern Negev Desert, 6th–3rd Millennia B.C. In *Water, Environment and Society in Times of Climate Change* (eds. A. Issar and N. Brown) pp. 147–202. Dordrecht, Netherlands

Avner, U. (2000). Nabatean Standing Stones and Their Interpretation. *ARAM* 11–12, 97–122

Ayal, Y., Polis, G.A., Lubin, Y., and Goldberg, D.E. (2005). How can high animal biodiversity be supported in low productivity deserts? The role of macrodetrivory and physiognomy. In *Biodiversity in Drylands* (eds. M.Shachak and R.Wade). Cambridge University Press, Cambridge

Batjes, N.H. (1996). Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science* 47: 151-163

Batjes, N.H., and Sombroek, W.G. (1997). Possibilities for carbon sequestration in tropical and subtropical soils. *Global Change Biology* 3: 161–173

BGS (2006). *World Mineral Production 2000–2004*. British Geological Survey, Keyworth, Nottingham

Biebach, H, Biebach, I., Friedrich, W., Heine, G., Partecke, J., and Schmidl, D. (2000). Strategies of passerine migration across the Mediterranean Sea and the Sahara Desert: a radar study. *Ibis* 142: 623–634

Cabin, R.J., and Marshall, D.L. (2000). The demographic role of soil seed banks. I. Spatial and temporal comparisons of below- and above-ground populations of the desert mustard *Lesquerella fendleri. Journal of Ecology* 88: 283–292

Carmi, N., Pinshow, B., Porter, W.P., and Jaeger, J. (1992). Water and energy limitations on flight duration in small migrating birds. *Auk* 109: 268–276

Carpiceci, A.C. (1997). *Art and History of Egypt: 5000 Years of Civilization*, Bonechi Books, Florence, Italy

Charney, J.G. (1975). Dynamics of deserts and drought in the Sahel. *Quarterly Journal of the Royal Meteorological Society* 101: 193–202

Conway, D. (2005). From headwater tributaries to international river: observing and adapting to climate variability and change in the Nile basin. *Global Environmental Change* 15: 99-114

Crawford, L. (1990). Amax Pulling Out of Lithium Project. *Financial Times,* pp. 36, 8 November 1990

Culmsee, H. (2002). The habitat functions of vegetation in relation to the behaviour of the desert locust *Schistocerca gregaria* (Forskål) (Acrididae: Orthoptera) — a study in Mauritania (West Africa). *Phytocoenologia* 32: 645–664

Degens, E. T., Kempe, S., and Richey, J. (eds.) (1990). *Summary: Biogeochemistry of Major World Rivers.* In *Biogeochemistry of Major World Rivers.* SCOPE Report 42, John Wiley & Sons, Chichester (available online at www.icsu-scope.org)

Despland, E., Rosenberg, J., and Simpson, S.J. (2004). Landscape structure and locust swarming: a satellite's eye view. *Ecography* 27: 381–391

Divon H., and Abou-Hadab, F. (1996). *Collaborative Agricultural and Rural Development of Settlement in the Nubariya Region, Egypt.* Jewish Virtual Library. http://www.jewishvirtuallibrary.org/jsource/Peace/egmashav.html [Accessed 19 April 2006]

Donaldson, J.R., and Cates, R.G. (2004). Screening for anticancer agents from Sonoran Desert plants: A Chemical Ecology Approach. *Pharmaceutical Biology* 42: 478–487

Donaldson, J.R., Warner, S.L., Cates, R.G. and Young, D.G. (2005). Assessment of antimicrobial activity of fourteen essential oils when using dilution and diffusion methods. *Pharmaceutical Biology* 43: 1–9

Evans, M., Amr, Z., and Al-Oran, R.M. (2005). The status of birds in the proposed Rum Wildlife Reserve, Southern Jordan. *Turkish Journal of Zoology* 29: 17–26

Gilbert, G.K. (1877). *Report on the geology of the Henry Mountains*. United States Department of the Interior, United States Government Printing Office, Washington, D.C

Golan-Goldhirsh, A., Sathiyamoorthy, P., Lugasi-Evgi, H., Pollack, Y., and Gopas, J. (2000). Biotechnological potential of Israeli desert plants of the Negev. *Acta Hort.* 523: 29–37

Golany, G. (1978). Planning Urban Sites in Arid Zones: The Basic Considerations. In *Urban Planning for Arid Zones* (ed. G. Golany) pp. 3–21. John Wiley & Sons, New York.

Gyan, K., Henry, W., Lacaille, S., Laloo, A., Lamsee-Ebanks, C., McKay, S., Antoine, R.M., and Monteil, M.A., (2005). African dust clouds are associated with increased paediatric asthma accident and emergency admissions on the Caribbean island of Trinidad. *International Journal of Biometeorology* 49: 371–376

Hanspeter, L., Weingartner, R., and Grosjean, M. (1998). *Mountains of the World: Water Towers for the 21st Century.* Institute of Geography, University of Berne and Swiss Agency for Development and Cooperation (available online: Mountains of the World website www.mtnforum.org/resources/library/magen98a2.htm)

Hutto, R. L. (2000). On the importance of *en route* periods to the conservation of migratory land birds. *Studies in Avian Biology* 20: 109–114

Ibrahim, K.M., Sourrouille, P., and Hewitt, G.M. (2000). Are recession populations of the desert locust (*Schistocerca gregaria*) remnants of past swarms? *Molecular Ecology* 9: 783–791

IEA. (2005). *World Energy Outlook 2005 — Middle East and North Africa Insights*. International Energy Agency, Paris

IPCC (2001). "Climate Change 2001. Working Group I, Third Assessment Report". Cambridge University Press, Cambridge

Izraely, H., Choshniak, I., Stevens, C.E., and Shkolnik, A. (1989). Energy digestion and nitrogen economy of the domesticated donkey (*Equus asinus*) in relation to food quality. *Journal of Arid Environments* 17: 97–101

Jianlin, H., Ochieng, J.W., Lkhagva, B., and Hanotte, O. (2004). Genetic diversity and relationship of domestic Bactrian camels (*Camelus bactrianus*) in China and Mongolia. *Journal of Camel practice and Research* 11: 97–99

Jickells, T. D, An, Z.S., Andersen, K.K., Baker, A.R., Bergametti, G., Brooks, N., Cao, J.J., Boyd, P.W., Duce, R.A., Hunter, K.A., Kawahata, H., Kubilay, N., LaRoche, J., Liss, P.S., Mahowald, N.M., Prospero, J.M., Ridgwell, A., Tegen, I., and Torres, R. (2005). Global iron connections between desert dust, ocean biogeochemistry, and climate. *Science* 308: 67–71

Kishcha, P., Alpert, P., Barkan, J., Kirchner, I., and Machenhauer, B. (2003). Atmospheric response to Saharan dust deduced from ECMWF reanalysis (ERA) temperature increments. *Tellus* B, 55: 901–913

Koocheki, A., and Nadjafi, F. (2003). *The status of medicinal and aromatic plants in Iran and strategies for sustainable utilization* Medicinal Plants Network. http://www.medplant.net/modules/DownloadsPlus/uploads/Publications/Nadjafi_Paper_on_Medicinal_Plants.doc [Accessed 19 April 2006]

Lal, R. (2002). Carbon sequestration in dryland ecosystems of West Asia and North Africa. *Land Degradation and Development* 13: 45–49

Lioubimtseva, E., and Adams, J.M. (2004). Possible implications of increased carbon dioxide levels and climate change for desert ecosystems. *Environmental Management* 33 (Supplement 1), S388–S404

Mahowald, N., and Luo, C. (2003). A less dusty future? *Geophysical Research Letters* 30(17): 1903

Masonen, P. (1997). Trans-Saharan Trade and the West African Discovery of the Mediterranean World. From: Sabour and Vikør, *Ethnic encounter and culture change*, pp.116–42. Bergen/London 1997

Monger, H.C., and Martínez-Ríos, J.J. (2000). Inorganic carbon sequestration in grazing lands. In *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect* (eds. R.F. Follett, J. Kimble and R. Lal) pp. 87–118. Lewis Publishers, Boca Raton, Florida

Morgan, J.A., Lecain, D.R., Mosier, A.R. and Milchunas, D.G. (2001). Elevated CO_2 enhances water relations and productivity and affects gas exchange in C3 and C4 grasses of the Colorado shortgrass steppe. *Global Change Biology* 7: 451

Naumberg, E., Housman, D.C., Huxman, T.E., Charlet, T., Loik, M.E., and Smith, S.D. (2003). Photosynthetic responses of Mojave Desert shrubs to free air CO_2 enrichment are greatest during wet years. *Global Change Biology* 9: 276–285

Nellemann, C. (ed.) (2005). *The fall of the water: Emerging threats to the water resources and biodiversity at the roof of the world to Asia's lowland from land-use changes associated with large-scale settlement and piecemeal development*. UNEP/GRID-Arendal, Arendal, Norway (available online at www.globio.info)

Nianthi, K.W.G.R., and Husain, Z. (2004). Impact of climate change on rivers with special reference to river-linking project. In *Regional Cooperation on Transboundary Rivers: Impact of the Indian River-linking Project,* (eds. M.F. Ahman, Q.K. Ahmad, and M. Khalequzzaman) pp. 263–278. Bangladesh Environment Network. http://www.ben-center.org/ConfPapers-2005/Rekha,doc [Accessed 19 April 2006]

Okin, G.S., Mahowald, N., Chadwick, O.A., and Artaxo, P. (2004). Impact of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems. *Global Biogeochemical Cycles*, 18, Art. No. GB2005

Pedersen, J. (1995). Drought, migration and population growth in the Sahel: the case of the Malian Gourma: 1900–1991. *Population Studies* 49: 111–126.

Pedgley, D. (1981). *Desert Locust Forecasting Manual.* Centre for Overseas Pest Research, London

Pener, M.P. (1991). Locust phase polymorphism and its endocrine relations. *Advances in Insect Physiology* 23: 1–79

Perrins, C.M., and Elphick, J. (2003). *The complete encyclopedia of birds and bird migration.* Chartwell Books, Inc., Edison, N.J

Peterson, A.T., Ortega-Huerta, M.A., Bartley, J., Sánchez-Cordero, V., Soberón, J., Buddemeier, R.H., and Stockwell, D.R.B. (2002). Future projections for Mexican faunas under global climate change scenarios. *Nature* 416: 626–629

Philippi, T. (1993). Bet-hedging germination of desert annuals – beyond the 1st year. *American Naturalist* 142(3): 474–487

Pinty, B., Roveda, F., Verstraete, M.M., Gobron, N., Govaerts, Y., Martonchik, J.V., Diner, D., and R. Kahn (2000). Surface Albedo Retrieval from METEOSAT. *Journal of Geophysical Research* 105: 99–134

Plant Talk On-Line (1997). *Plants in traditional and herbal medicine.* http://www.plant-talk.org/Pages/PFacts10.html [Accessed 19 April 2006]

Portnov, B.A., and Erell, E. (1998). Long-term Development Peculiarities of Peripheral Desert Settlements: The Case of Israel, *International Journal of Urban and Regional Research* 22(2): 216–32

Powell, J.W. (1875). *Exploration of the Colorado River of the West (1869-72)*. Reprinted by University of Chicago Press, Washington, D.C

Prospero, J. M., Ginoux, P., Torres, O., Nicholson, S.E., and Gill, T.E. (2002). Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 TOMS absorbing aerosol product. *Reviews of Geophysics* 40, Art. No. 1002

Richardson, C.J., Reiss, P., Hussain, N.A., Alwash, A.J., and Pool, D.J. (2005). The Restoration Potential of the Mesopotamian Marshes of Iraq. *Science* 307: 1307–1311

Rosenfeld D., Rudich, Y., and Lahav, R. (2001). Desert dust suppressing precipitation — a possible desertification feedback loop. *Proceedings of the National Academy of Sciences* 98: 5975–5980

Safriel, U., and Lavee, D. (1988). Weight changes of cross-desert migrants at an oasis — Do energetic considerations alone determine the length of a stopover? *Oecologia* 76: 611–619

Schlesinger, W.H., (1985). The formation of caliche in soils of the Mojave Desert, California. *Geochimica et Cosmochimica Acta* 49: 57-66

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A., and Whitford, W.G. (1990). Biological feedbacks in global desertification. *Science* 247: 1043-1048

Schmidt-Nielsen, K, Crawford, E.C. Jr, Newsome, A.E., Rawson, K.S., and Hammel, H.T. (1967). Metabolic rate of camels: effect of body temperature and dehydration. *American Journal of Physiology* 212: 341–346

Shinn, E.A., Smith, G.W., Prospero, J.M., Betzer, P., Hayes, M.L., Garrison, V., and Barber, R.T. (2000). African dust and the demise of Caribbean coral reefs. *Geophysical Research Letters* 27: 3029–3032

Shkolnik, A., Taylor, C. R., Finch, V., and Borut, A. (1980). Why do Bedouins wear black robes in hot deserts? *Nature* 283: 373–375

Showler, A.T. (2002). A summary of control strategies for the desert locust, *Schistocerca gregaria* (Forskål). *Agriculture, Ecosystems and Environment* 90(1): 97–103

Simpson, S.J., McCaffery, A.R., and Hägele, B.F. (1999). A behavioural analysis of phase change in the desert locust. *Biology Reviews* 74: 461–480

Smith, B., and Wilson, J.B. (2002). Community convergence: Ecological and evolutionary. *Folia Geobotanica* 37, 171–183

Smith, S.D., Huxman, T.E., Zitzer, S.F., Charlet, T.M., Housman, D.C., Coleman, J.S., Fenstermaker, L.K., Seemann, J.R., and Nowak, R.S. (2000). Elevated CO_2 increases productivity and invasive species success in an arid ecosystem. *Nature* 408: 79–82

Sokolik, I.N., Winker, D., Bergametti, G., Gillette, D.A., Carmichael, G., Kaufman, Y., Gomes, L., Schuetz, L., and Penner, J.E. (2001). Introduction to special section: Outstanding problems in quantifying the radiative impacts of mineral dust. *Journal of Geophysical Research* 106: 18015–18027

Tegen, I., Werner, M., Harrison, S. P., and Kohfeld, K. E. (2004). Relative importance of climate and land use in determining present and future global soil dust emission. *Geophysical Research Letters* 31

Tsonis, A.A., Elsner, J.B., Hunt, A.G., and Jagger, T.H. (2005). Unfolding the relation between global temperature and ENSO. *Geophysical Research Letters* 32

Venkatesh, G. (2003). The Aussie mining sector. *Minerals and Metals Review* 29: 121–134

Vignaud, P., Duringer, P., Mackaye, H.T., Likius, A., Blondel, C., Jean-Boisserie, R., De Bonis, L., Eisenmann, V., Etienne, M-E., Geraads, D., Guy F., Lehmann, T., Lihoreau, F., Lopez-Martinez, N., Mourer-Chauviré, C., Otero, O., Rage, J-C., Schuster, S., Viriot, L., Zazzo, A., and Brunet, M. (2002). Geology and palaeontology of the Upper Miocene Toros-Menalla hominid locality, Chad. *Nature* 418: 152–155

Volpe, R. (1999). Navigation Results from Desert Field Tests of the Rocky 7 Mars Rover Prototype. *International Journal of Robotics Research, Special Issue on Field and Service Robots* 18(7), July 1999

Walker, A.S. (1997). *Deserts: Geology and Resources.* United States Geological Service. http://pubs.usgs.gov/gip/deserts/ [Accessed 19 April 2006]

Waloff, Z.V. (1960). The fluctuating distributions of the desert locust in relation to the strategy of control. *Report of the 7th Commonwealth Entomological Conference*, London 6–15 July 1960, pp. 132–139 (available online at ispi-lit.cirad.fr/text/Waloff60a.htm)

Wettergreen, D., and Cabrol, N. (2005). Investigation of Life in the Atacama Desert by Astrobiology Rover. *EOS Transactions,* American Geophysical Union*,* 86(52), Fall Meeting. Supplement, Abstract P41D-04

White, T. D., Asfaw, B., DeGusta, D., Gilbert, H., Richard, G.D., Suwa, G., and Howell, C.H. (2003). Pleistocene *Homo sapiens* from Middle Awash, Ethiopia. *Nature* 423: 742–746

Yadin, Y. (1963). *The Art of Warfare in Biblical Lands*, McGraw-Hill, Toronto

WRI (2003). *EarthTrends.* World Resources Institute, Washington D.C

Yao, Y.G., Kong, Q.P., Wang, C.Y., Zhu C.L., and Zhang Y.P. (2004). Different matrilineal contributions to genetic structure of ethnic groups in the Silk Road region in China. *Molecular Biology and Evolution* 21(12): 2265–2280