PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

The Geography of Semi-Arid Lands [and Discussion]

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The geography of semi-arid lands

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[Plate 1]

Semi-arid lands were at times during the last 20000 years more humid and at other times more arid than at present, with important consequences for the soil and water resources of the present day. These lands were the scene of the beginnings of pastoralism, the cultivation of cereals, and urban living between 10000 and 5000 years ago. The environment has always been attractive to man but it is liable to deteriorate towards desert with long-lasting consequences. Development possibilities diversify according to environmental conditions which vary from place to place and also according to the economic and other characteristics of the States in which these lands are situated. The States can be regarded as falling into four categories: there are on the one hand wealthy countries – either industrialized or rich in minerals; on the other hand there are poor countries – some with land outside the arid zone as yet not fully developed, others with no land of this kind. In response to the differences in economic opportunity, migratory movements are taking place, notably from the impoverished semi-arid regions to the towns, particularly those in the petroleum-producing states.

1. Semi-arid climates

The semi-arid lands are those parts of the world where the rain is insufficient or barely sufficient for satisfactory crop growth in most years. Such regions can be defined only in an arbitrary manner. A map which was prepared by Meigs (1953) for UNESCO has been widely accepted as a useful guide, for example by Hills (1966) in a book bringing together some of the results of UNESCO's Arid Zone Programme. McGinnies, Goldman & Paylore (1968) used maps of the continents, in *Deserts of the world*, depicting the arid zone in much the same way as Meigs had done, and similar maps appear in *Arid lands in transition* (Dregne 1970) and also in Dov Nir's *Semi-arid lands* (1974). Based on Thornethwaite's (1948) aridity coefficient, the UNESCO map is derived from the relation between precipitation, potential evapotranspiration, water surplus and water replenishment, calculated for individual months throughout the year. Indices distinguish the semi-arid from the arid lands, and extremely arid lands are defined as those where 12 successive months have been recorded without rain.

The extremely arid lands correspond roughly with those having mean annual rainfall totals of less than 25 mm. Arid lands between the tropics correspond with those receiving between about 25 and 200 mm; semi-arid lands approximate to those areas with mean annual rainfall totals of 200–500 mm. Towards the poles, mean annual precipitation figures corresponding to the limits of arid and semi-arid land diminish as evapotranspiration diminishes (figure 1).

Aridity in low latitudes is associated with the main tropical high pressure systems and with dry air descending on the poleward sides of Hadley cells. Rain falls in the summer season, when the high pressure cells lie poleward of their mean positions and humid equatorial air reaches higher latitudes. Rainfall is typically episodic with local storms a few kilometres in diameter moving across country. The main growing season starts with the soils thoroughly dry and

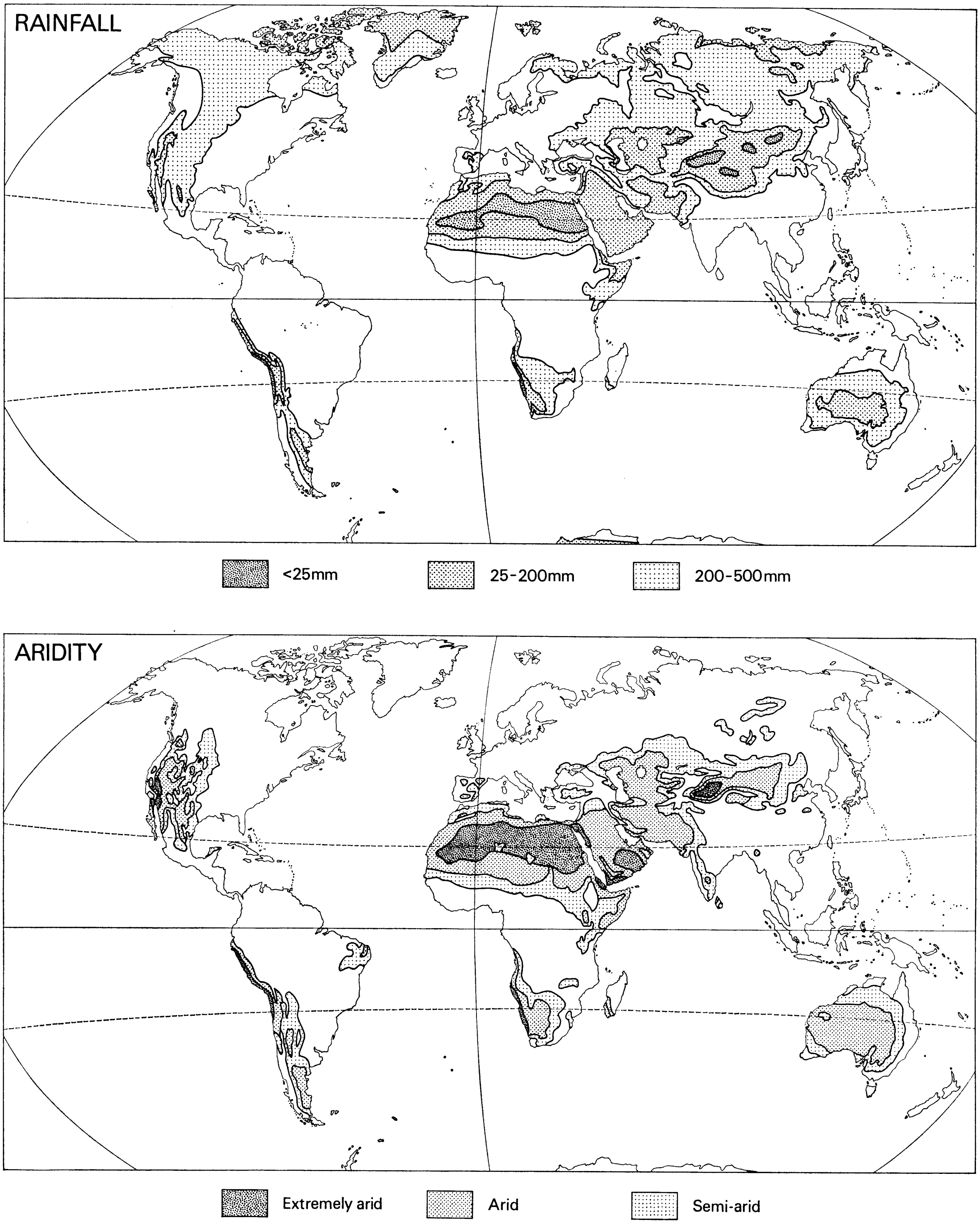

FIGURE 1. (*a*) Mean annual precipitation. (*b*) Extremely arid, arid and semi-arid regions (after Meigs 1953).

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consequently risks of crop failure are high if the early rains are interrupted by a dry spell. Such is the case if the poleward movement of the equatorial air is indecisive.

On the poleward sides of the tropical deserts, lands under the influence of the tropical high pressure systems and therefore dry during the summer season receive rain from mid-latitude depressions during the winter months. In the spring, soils are moist at depth and crop growth is, in this respect, less hazardous than in areas with similar mean annual rainfall totals lying between the tropics. In many such areas supplementary irrigation water is available from neighbouring mountain catchments and, in some places, from glaciers.

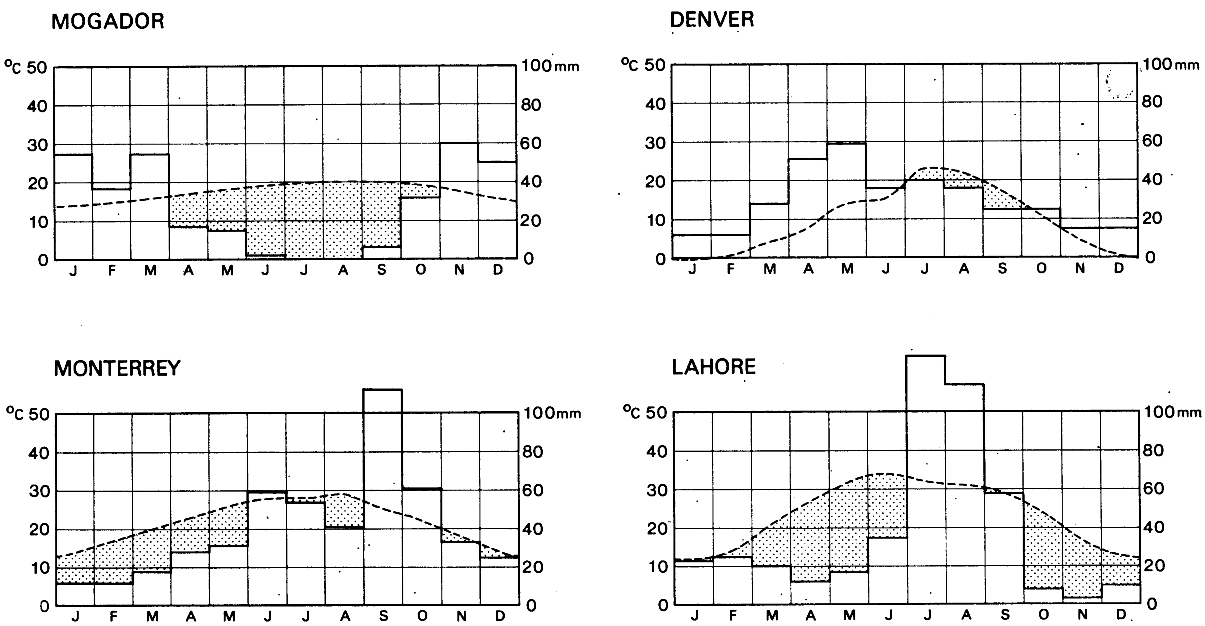

FIGURE 2. Mean monthly precipitation (solid lines) and mean monthly temperature (dashed lines) for Mogador, Morocco; sub-tropical west coast Denver, Colorado, USA; mid-latitude continental Monterrey, Nuevo Leon, Mexico; tropical highland Lahore, Pakistan, tropical continental semi-arid.

Mid-latitude aridity is more closely related to the global distribution of land and sea. The most extensive area of low rainfall extends from the tropical North Atlantic across the Sahara and Arabia into the heart of the Asian landmass. It is bordered to north and south by semi-arid country stretching from Asia Minor and the regions bordering the Caspian Sea, across central Asia into Mongolia and China. Other extensive semi-arid lands in middle latitudes lie on the leeward sides of mountain ranges running across the track of westerlies, in western North America from the Gulf of Mexico to the southwestern Canadian prairies, in Argentina and in eastern Europe (figure 2). Precipitation is more evenly distributed through the year than nearer the equator, but the growing season is limited by low temperatures persisting well into the spring and by autumn frost and snow. Winter snowfall is commonly an important source of moisture for agriculture and for river flow.

Maps showing the distribution of precipitation over the globe show steep gradients of raininess, not only across mountain ranges but over the oceans as well. Consequently quite small shifts in global circulation patterns in the atmosphere or oceans can produce marked changes in the rainfall received at particular stations, especially in the months at the beginning and end of the rainy season. Such variations from year to year and over longer periods of time are well marked over the oceans and at their margins as well as over the continents. Surface water temperatures, which are related to the vigour of upwelling and the strength of the Trade Winds, have a great effect on precipitation (Musk 1976). Records of annual rainfall from oceanic islands in the tropics exhibit persistence of high or low values over periods of several years (Aspin 1976). Continental margins may be involved in such variations and although their climate means may characterize them as semi-arid, conditions vary from intensely arid for years on end to disastrously wet for several months or years.

Individual years and sequences of years with rainfall totals well below median values also occur in continental interiors. In 1972, for example, the zone of semi-arid land south of the Sahara was displaced between 100 and 200 km south of its mean position; the rains in several of the preceding years had also been deficient and the following year was a dry one. The resulting sufferings of people and livestock living in the region attracted world attention. In that same year, 1972, a warm current of equatorial water, El Niño, spread down the west coast of South America (Caviedes 1975). In place of cold, upwelling water, with abundant nutrients and fishlife, warm water reached more than 12° S, and instead of aridity there were heavy rains on the coast. Catches of fish were reduced from about 9 million to about 4 million tonnes. That year rainfall was below median values in the semi-arid lands of Mexico, the U.S.S.R., and India. Some climatologists were inclined to see the decline in rainfall as being associated with a global climatic fluctuation that was likely to be long-lasting. Some suspected that man's activities were in part responsible, particularly the consumption of fossil fuel and pollution of the atmosphere with dust and other substances. However, rainfall records show that runs of years with rainfall below the median are to be expected, and it has not been shown that any long-term displacement of the semi-arid zones is in progress. It has been made clear to all that climate is of its nature variable and that the semi-arid lands with their high evapo-transpiration losses are particularly sensitive to rainfall deficiencies.

2. Effects of Late Quaternary climatic changes

The evidence for climatic fluctuations before the instrumental period, is difficult to interpret. There are indications from long Chinese historical records (Chu Ko Chen 1973) and from elsewhere that shifts in the climatic boundaries of the kind that occurred around 1972 have happened in the past and that increased aridity has persisted over much long periods of time. In general, however, it would seem that we may have experienced in the last century or two the full range of variations in climate that have affected the globe over the last three or four thousand years. Studies that have been made in a number of different fields, especially since 1960, have shown that the positions of the climatic boundaries shifted more violently over the longer time period of the Late Quaternary, in low latitudes as well as in high latitudes. It appears that the mean values of precipitation in tropical Africa moved through a wider range in the Late Quaternary than have extreme values for individual years in this century.

For the globe as a whole, three periods of different levels of biological activity can be distinguished in the last 20000 years. The first period might be called a state of low activity, the second a state of high activity, and the third a state of reduced activity.

At the height of the last glacial episode, from some time before 20000 to about 13000 years ago, global biological activity and terrestrial biomass were at low levels. Ice desert occupied

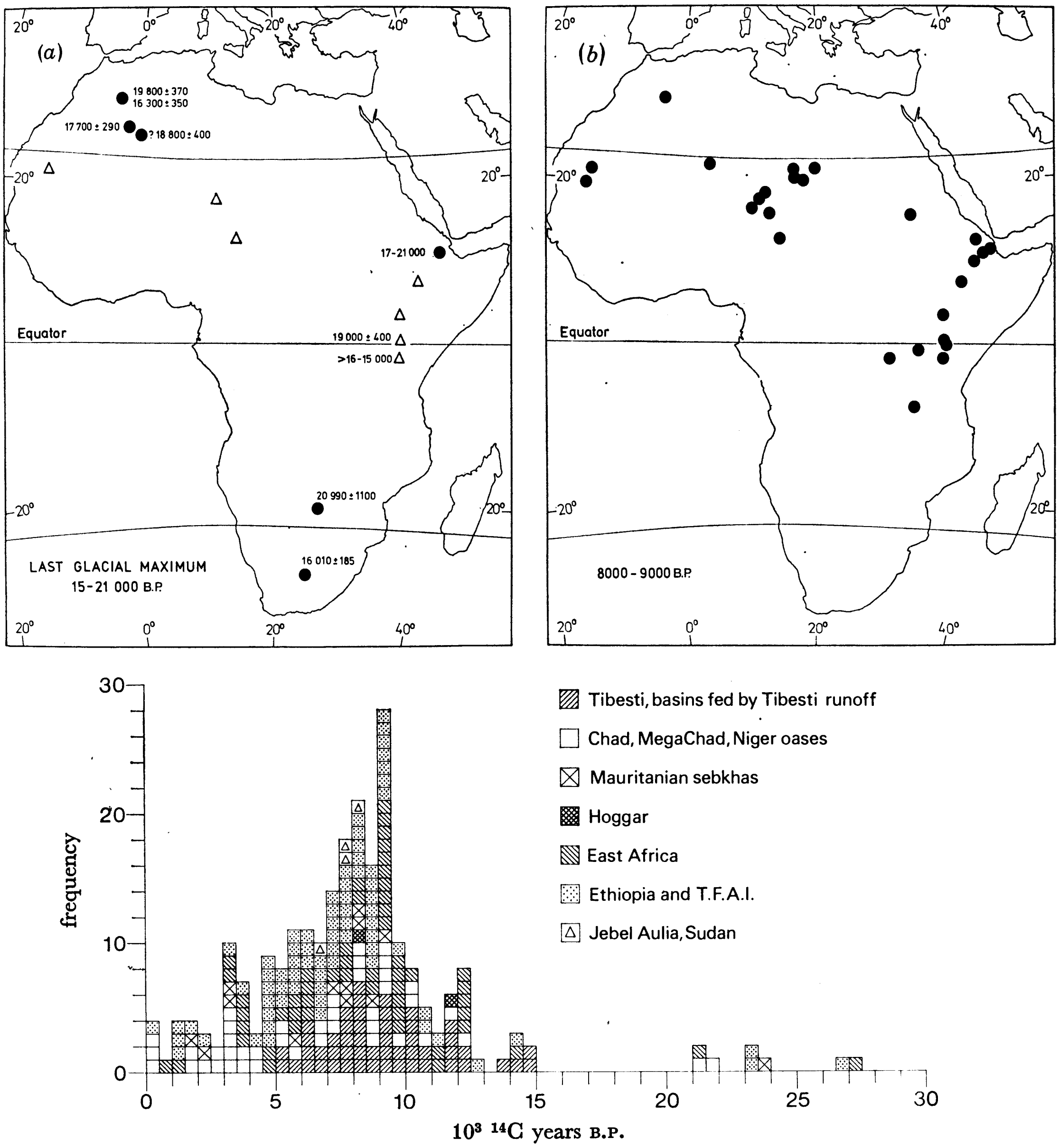

FIGURE 3. (*a*) Africa about 18000 B.P. Circles indicate dated lacustrine sediments, triangles that the lakes were dry at this time. (*b*) Africa 8000–9000 B.P. with dated lacustrine sediments, circles, indicating the presence of lakes in numerous tropical basins at this time. (*c*) Dated lacustrine sediments indicating that lakes stood at or above present levels (from Street & Grove 1976).

most of the surface within 40° of the Poles; loess formations were accumulating in middle latitude, semi-arid regions of the present day, and although there were extensive lakes in southwest United States of America and other mid-latitude regions now semi-arid, they were the result of lower temperatures and evaporation rather than increased precipitation (Flint 1971). In general, the inter-tropical regions were drier than at present (Williams 1975). Active dunes occupied much of the Sudan zone of Africa (Grove 1958), the semi-arid regions of north-west India (Goudie 1973), North-Central Australia (Bowler *et al.* 1975) and savannalands in the basin of the upper Orinoco and Sao Francisco rivers of South America (Tricart 1975). Arid conditions thus extended into regions now semi-arid.

After about 15000 years ago, global climatic conditions ameliorated, with precipitation increasing and temperatures rising, though not steadily. By 9500 years ago, basins in tropical Africa held very extensive lakes (Street & Grove 1976; figure 3). Temperatures, except in the vicinity of the Laurentide ice sheet, were similar to those of the present day, and in tropical Africa it would seem that annual rainfall was about 150 % of present day means. Semi-arid conditions in Africa and possibly over much of the globe were limited to certain west coastal strips in low latitudes and to regions that are now arid. The present semi-arid regions were much better watered than they are today. Lakes now confined to closed basins overflowed; Megachad into the Benue in West Africa (Pias 1970); the Galla lakes of Ethiopia into the Awash; Lakes Stefanie and Turkana to the White Nile (Grove, Street & Goudie 1975).

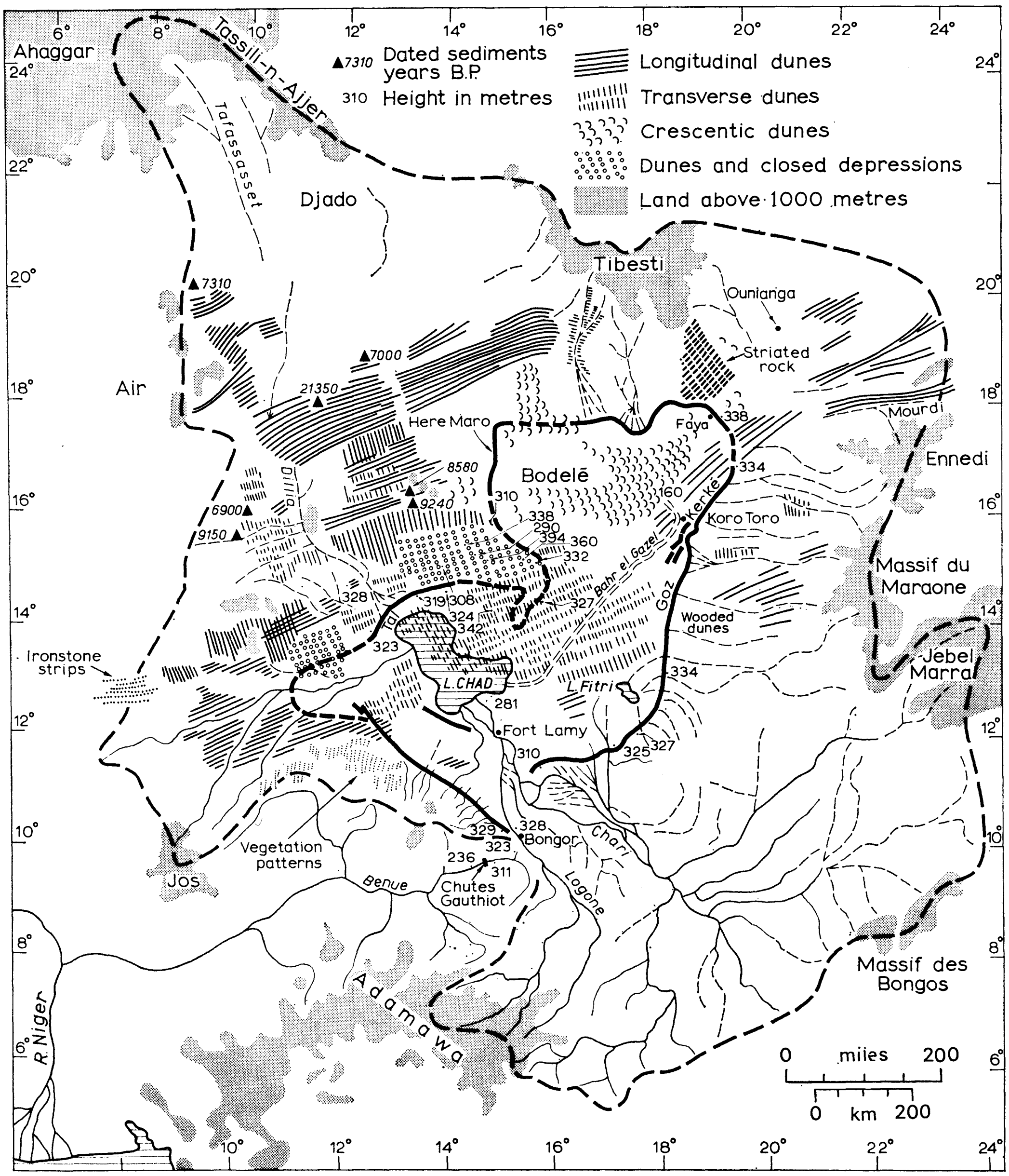

FIGURE 4 (*a*). For description see opposite.

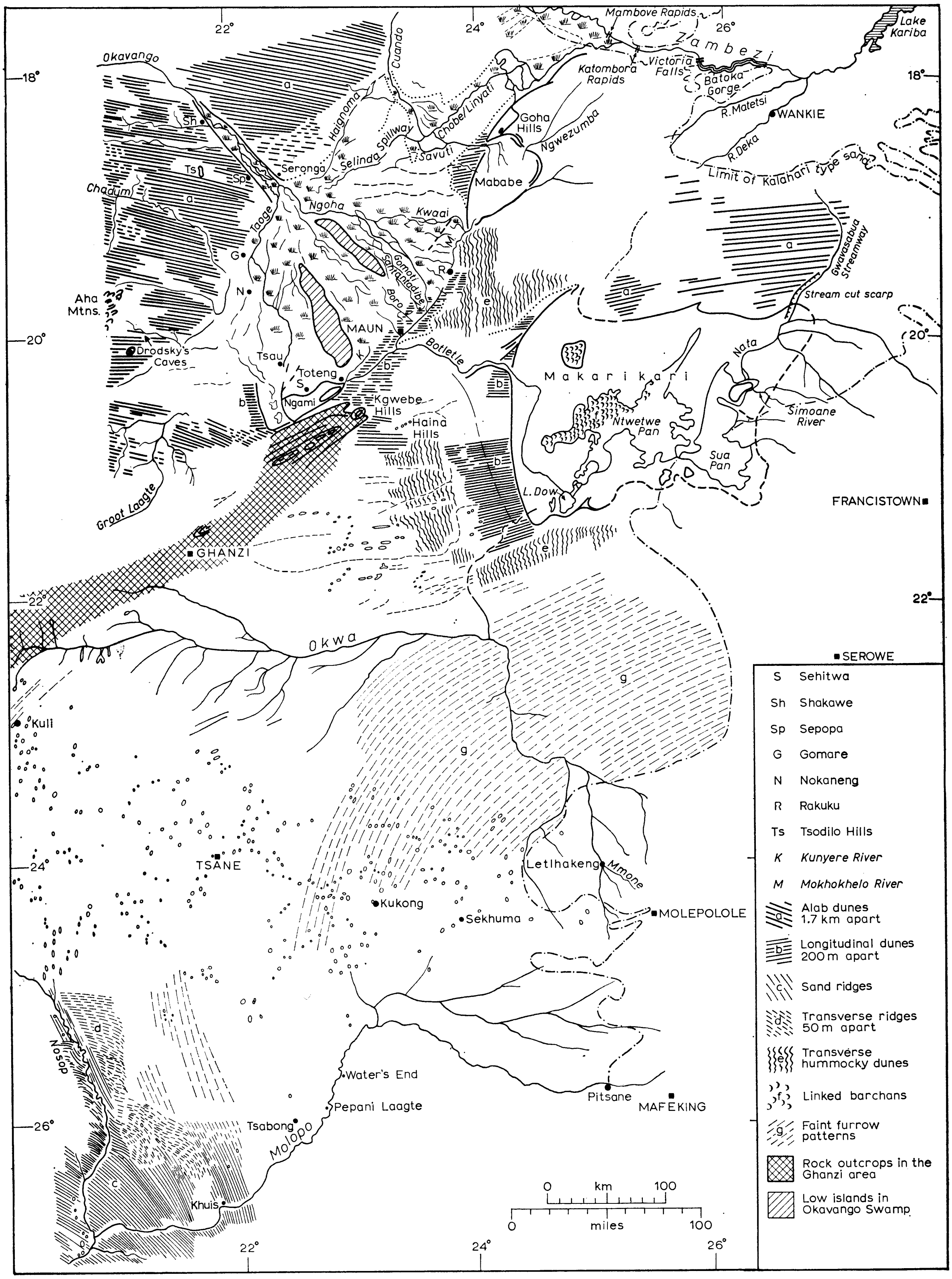

FIGURE 4 (*b*). (*a*) Late Quaternary dunes and lakes in the Chad basin (from Grove & Warren 1968). (*b*) Late Quaternary dunes and lakes in the Kalahari (from Grove 1969).

About 7000 years ago climates began to deteriorate, fluctuating from time to time, but after 5000 B.P. becoming somewhat cooler and, in tropical Africa at least, markedly drier. Since 4500 B.P. there have been fluctuations of climate but on a smaller scale than those of the preceding 15000 years.

The climatic changes of the last 20000 years, that have been briefly summarized above, are only the latest in a Quaternary history extending more than a million years into the past. From our point of view these latest changes are important because of the deep impression they have made on the semi-arid lands as we find them today. To an observer on the ground the traces left by them may not be immediately apparent, but from the air and from satellites they are readily recognizable. The land surfaces of semi-arid Australia, the Saharan borderlands, the Kalahari, northern Argentina, the southwest U.S.A. and central Asia preserve features derived from both the wetter and the drier episodes of the Late Quaternary (figures 4 *a*, *b* and 5, plate 1). Soils are closely related to the sedimentary landforms with soil properties varying greatly over short distances according to the sediments underlying them and the morphology of landforms resulting from past wind and water action. Various organizations concerned with mapping the resources and assessing the potential of extensive tracts of semi-arid country have used the morphology and patterns appearing on air photographs as aids to ground surveying. One might mention the publications of the C.S.I.R.O. in Australia, the French O.R.S.T.O.M. on the south side of the Sahara, the Land Resources Division of the United Kingdom Directorate of Overseas Surveys in Botswana and Nigeria, Huntings and other commercial organizations in Sudan and Iraq among other countries.

In tropical semi-arid regions, soils derived from dunes that were active in the last glacial period, though leached and even gullied in the succeeding period of high biological activity of Early Holocene times, are productive under cultivation; they are particularly suitable for crops like groundnuts and bullrush millet. In the basins of Chad and on the plains east of the White Nile in Sudan, heavy montmorillonitic clay soils, derived from riverine, lagoonal and lacustrine clays, are of increasing agricultural importance. They are difficult to cultivate with traditional tools, but deep cracking in the dry season reduces weed growth and certain varieties of sorghum have long been grown, being sown towards the end of the rains, drawing on water stored in the soil and harvested in the middle of the dry season. The clay soils of the Gezira are derived from sediments of the Blue Nile laid down at this time of high discharge in the Early Holocene. Both the dune and the lacustrine clay soils are more fertile than older soils in the same general regions, which have been strongly leached over a long period of time and commonly include lateritic ironstone.

On the poleward sides of the tropical deserts, in the Kalahari, on the northern margins of the Sahara, in the southwest U.S.A., and in parts of Australia, lime has accumulated in soil profiles and may exist as hard caliche and calcrete. Its development is also believed to be related to the climatic fluctuations of the Late Quaternary. In higher latitudes, towards the margins of the glaciated regions, the chernozems and other soils of the grasslands and steppes are commonly derived from loess and other wind-deposited or alluvial materials of Late Quaternary times. Among them are some of the world's most productive wheatlands.

The availability and reliability of subsurface water in the deeper aquifers of semi-arid lands, especially in low latitudes, is related to past climatic conditions. They were charged in the more humid periods of the past and may no longer be replenished. Use of such water is a form of mining, the consumption of a non-renewable resource.

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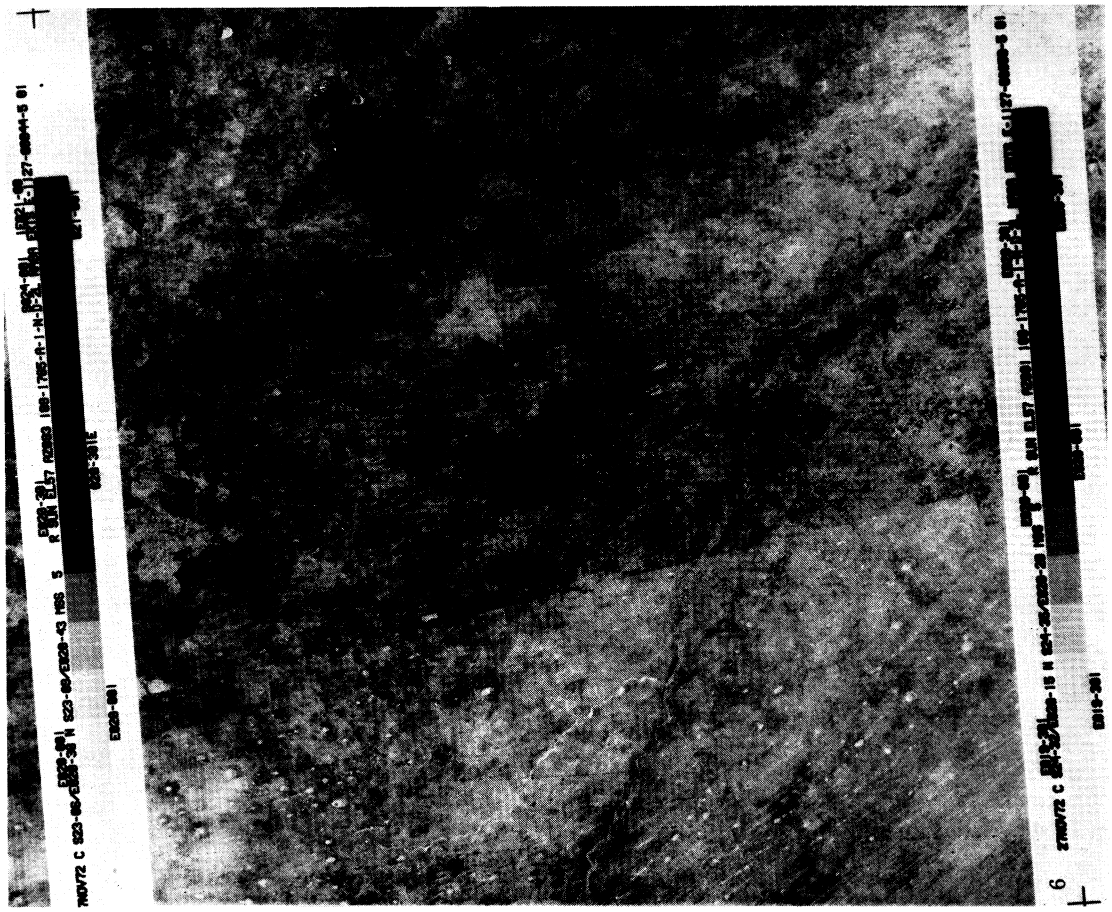

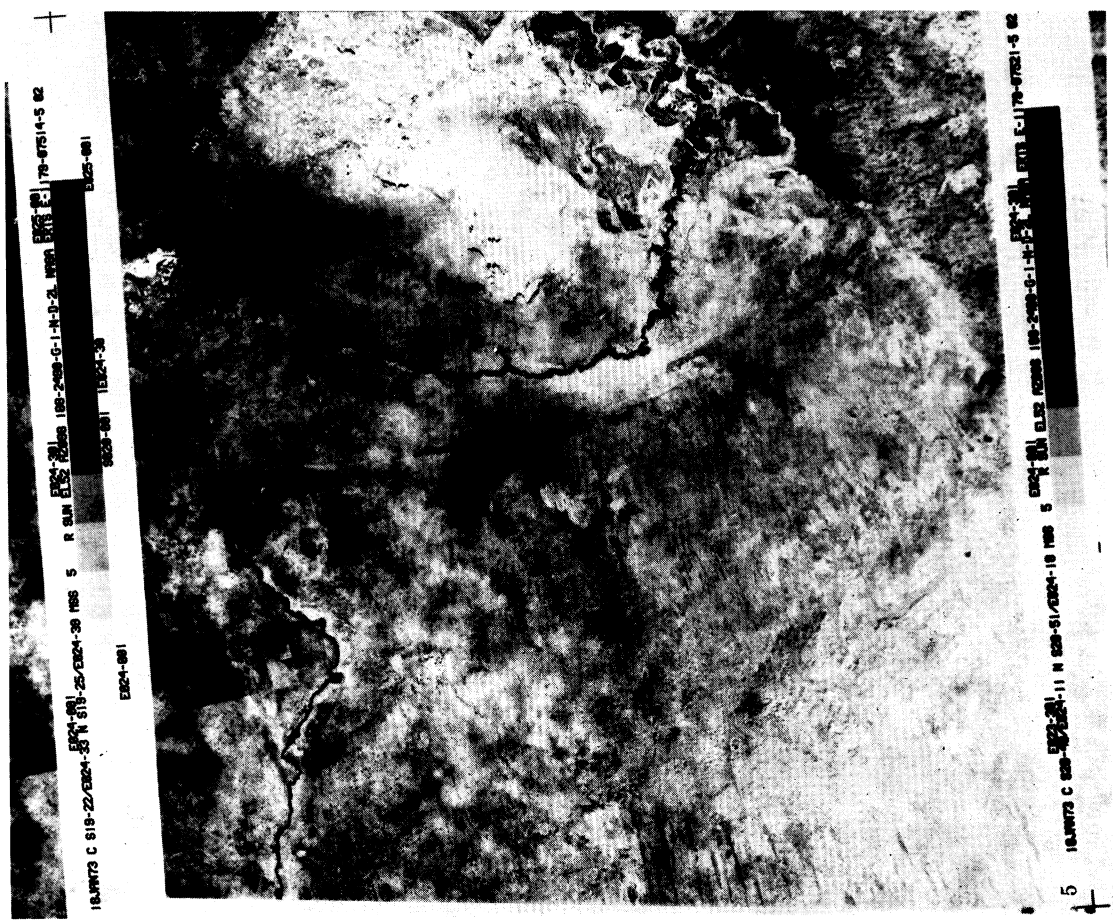

Figure 5. ERTS. The western margin of Pleistocene lake in the Makarikari depression, Botswana. 1179–07521.

Figure 6. ERTS. Vegetated dunes and pans on either side of the frontier between Botswana and Namibia. 1127–08050.

3. Modification of semi-arid ecosystems by man

The fauna and flora of semi-arid lands are adapted to water stress in various ways. In general, biological productivity is low as compared with temperate and low latitude forested regions on account of seasonal lack of water, and the frequency of disturbances such as floods and droughts. Much of the biomass is beneath the surface in the form of roots and bulbs. In low latitudes the number of species present is low, especially at heights above 1500 m. Generally, plant systems and communities are simple and robust, but life forms vary markedly over short distances according to the availability of water on sites differing in slope, soil depth and drainage.

The proportion of the surface of the ground covered by transpiring vegetation surface diminishes as aridity increases, but the amount of cover may vary greatly over short distances even on gently sloping plains with rather undifferentiated soils. Many such areas with mean annual rainfall totals of 250–750 mm are characterized by rhythmic banding of the vegetation; the *brousse tigrée* of southern Mali and Niger, vegetation arcs in Sudan, Somalia and Jordan, the groves and lanes north of Alice Springs in central Australia. These features have received a good deal of attention but the patterning is still not well understood. Its effect is to concentrate the available water in a small proportion of the total area, thereby allowing higher forms of life to persist than would otherwise be the case.

The density of the vegetation cover has everywhere in semi-arid lands been modified by man, in most places throughout the course of the Holocene. In recent decades the disturbance resulting from grazing, and general use by growing populations, has been greater than ever. Its severity has varied from one country to another and in certain regions the contrasts are so marked that international frontiers can be recognized on satellite imagery from the tonal differences (figure 6, plate 1).

It is possible that the increased albedo has strengthened subsidence of air over those regions where the vegetation has suffered most, thereby intensifying the aridity, but this is so far unproven (Charney 1975). There is no doubt that exclusion of people and their stock would allow regeneration of the vegetation, and it is possible to sow and plant indigenous and exotic species of grasses and trees, but such measures are difficult politically and generally too costly to undertake.

In recent years efforts to conserve and rehabilitate semi-arid land have been directed to those areas that have been irrigated in the past and where salt accumulation has damaged the soil. Now attention is turning to the vast areas threatened by the extension of desert conditions in the Sahel and Sudan zones and in other similar parts of the world. The problems here are immense, and solutions may involve attracting people from such areas into towns and into regions more able to sustain population pressure. Perhaps it would be more rewarding to concentrate attention on safe-guarding areas of special ecological significance such as the inland deltas. In Africa the Sudd, Okavango, inland Niger and Logone-Shari deltas are rich floristically and faunistically but liable to drastic modification as a result of development. It might also be argued that it is in such areas subject to flooding that responses to reliable climatic predictions might most usefully be developed.

The fauna of semi-arid lands was once remarkably rich in large species of herbivores and the creatures that preyed on them. The large grazing animals are walking energy stores, able to move long distances and make good use of primary production varying greatly with the season and from place to place. A century ago, the kinds of game numbers that still exist in Serengeti were encountered over much more extensive tracts of semi-arid Africa. Cloudesley-Thompson (1967) has collected together many accounts by travellers in earlier centuries, some of them responsible for introducing the precise firearms that have reduced numbers so drastically.

While the numbers of the larger animals have been drastically reduced, conditions for the survival of certain species of the smaller ones, especially the smaller social creatures, like quelea and locusts, have been improved in some respects, with irrigated land providing oases where they can rest and feed. Control of locusts appears to have been increasingly successful and in recent years the threat of quelea and rats has been more serious to countries in semi-arid Africa.

4. The history of development of semi-arid lands

Pastoralism probably evolved in semi-arid lands over the millennia as symbiotic relationships developed between people and certain species of animals. Now most semi-arid land is devoted to pastoralism, although its importance in terms of the numbers of people involved in pastoral production and its value in these regions is commonly exceeded by agriculture or other activities. Generally the seasonal variations in the availability of water and grass result in nomadism or, more commonly, regular seasonal migrations comparable to those of antelope and other wild animals. Traditional movements have been modified by international frontiers and by interference from governments mainly responsive to pressures from city-dwellers (Monod 1975; Leshnik & Sontheimer 1975).

The harvesting of grasses and the sowing of cereals originated in semi-arid lands, probably in the lands around the eastern Mediterranean in the Late Quaternary. Cereals like sorghum were probably domesticated on the south side of the Sahara about the end of the last humid period. The desert and its semi-arid margins continued to provide the setting for later civilizations, Persian and Harrapan, Greek and Roman in North Africa, the Islamic world extending from Morocco to India, the Empires of Ghana, Mali and Songhai in the western Sudan (Stamp 1961).

The environment was always defective and its costs therefore high because of the shortage of water, except near major rivers rising in wetter areas. Wood was scarce for constructional purposes, fuel and charcoal, and became scarcer as time went on. Forests in neighbouring areas with higher relief and rainfall were exploited with resultant damage to the vegetation, soils and rivers of the mountains and accelerated sedimentation on valley floors in the semi-arid lands. Desert extended into the lands along the south and eastern sides of the Mediterranean, and the winter rainfall zone was degraded. Shortage of wood in the region may help to explain why it fell so far behind Europe in the 17th and 18th centuries. Now, concrete and plastics, petroleum and natural gas help to offset the shortage of wood.

Much uncertainty exists as to the timing of the deterioration of the plant cover around the Mediterranean and elsewhere. But it is clear that the danger of desert conditions spreading into semi-arid lands has never been greater than in this century, with numbers of people and livestock increasing at unprecedented rates, and the individual's demands on environmental resources increasing still faster. Everywhere the vegetation cover of semi-arid lands has been degraded by burning, grazing, felling and cultivation, thereby setting in train soil deterioration.

Erosion losses are naturally high under semi-arid conditions because of the relatively poor protection afforded by the vegetation and the occasional occurrence of heavy storms. With biome changes, erosion by wind and water accelerate. Sediment yield per unit area, already high, increases still further, overloading rivers with coarse sediments, clogging channels, and transforming meandering rivers into braided waterways while headwater streams are entrenched. Commonly, road construction works and culverts, by concentrating runoff from wide areas, can initiate channel erosion and the formation of arroyos.

Reservoirs in semi-arid lands require extensive catchments; with high sediment yields per unit area they are liable to fill rapidly. Once they are rendered useless, alternative dam sites are difficult to find and costs of water storage mount as time goes on.

The solute load of rivers in semi-arid lands depends on conditions in the source regions. The Niger and Senegal rivers rising on the lateritized high plateaus of West Africa are so dilute that when their waters are used for irrigation, soils are liable to become increasingly leached and acid. The waters of the Blue Nile, rising on lava highlands in Ethopia, are much richer in nutrients and very suitable for irrigation (Grove 1972). Some other rivers rising in the mineral springs of tectonically active regions, or on rocks containing evaporites, have excessively high solute loads. Entering semi-arid country from more humid highlands, such rivers acquire increasingly high sodium/calcium ratios and, if such rivers are used for irrigation, risks of soil salinization are high (Gibbs 1970). Drainage water from irrigated land enhances the solute load of rivers already carrying much material in solution. Industrial and urban wastes may further overload the hydrological system.

Underground sources of water, some of them artesian or sub-artesian, have been heavily exploited for watering stock, irrigating crops and for industrial and domestic purposes. Almost invariably the large volumes required for irrigation lower water tables, necessitating the deepening of wells and boreholes and the installation of more powerful and expensive pumps. The needs of traditional pastoralists and villagers are usually met without too much difficulty, for the essential needs of a single person or livestock unit are only about 25 l per day and a single well yielding 5000 l an hour can supply the needs of a village or the cattle likely to be within daily walking distance of it. But such a well could provide enough water to irrigate only a hectare or two in the dry season. In western Texas, according to Dregne (1970), '63000 irrigation wells pump from 4900 to 9800×10^6 m^3 of water from the Ogallala formation from depths of 30 to 90 m, to irrigate 2.1 M hectares of land. Since 1949 the average pumping lift in Hale County, Texas, has increased from 12 to 30 metres.' People living in urban areas use several times as much water as villagers and the demands of industrial plants are enormous.

In spite of the obstacles to development in semi-arid lands, the costs resulting from water scarcity, and the hazards of drought, they have always been attractive to people. Stores of energy and nutrients have accumulated in the grassland soils; the vegetation cover is readily cleared for agriculture; abundant sunshine makes for pleasant living conditions. Particularly well-favoured are the coastal semi-arid lands of middle latitudes. With winter rain and then sunshine, a wide range of crops can be grown, both annuals like cereals and pulses, and perennial citrus, vines, olives, figs and dates. With water from underground sources or rivers from more humid neighbouring regions, such crops yield more heavily than anywhere else in the world.

Modern technology has done much to improve living conditions in semi-arid lands. Air conditioners temper the heat of summer, and refrigeration is a boon. The most attractive areas have been coastal semi-arid lands backed by mountains. Piedmont areas in the continental interiors are also booming, cities in such regions having very high growth rates. Manufacturing industry, using water from the mountains and underground, is expanding. People like to live in such environments so that labour is no problem and tourism is important. Additional economic resources may be associated with the climate, notably fisheries harvesting the product of upwelling ocean waters offshore. Other resources of a more incidental kind, notably phosphate and mineral oil, have stimulated economic growth in certain instances.

Human use has involved deterioration in the habitats of semi-arid lands especially in the last few decades. Stores of underground water and soils built up over long periods of time have been depleted in a few decades in the course of this century. The costs of restoring the situation, by pumping in water, by desalinization or by afforestation are inevitably high. Productivity can be restored and the semi-arid lands be made to yield more crops and livestock and support more people in a pleasanter environment, but only with heavy expenditure in skill and equipment.

5. Development of semi-arid lands

The future of semi-arid lands will vary according to the wealth of the countries in which they are situated. Some of the dry lands are remote, distant from the coast, from ocean transport and contacts with the rest of the world. Some are of only marginal value to the states of which they form a part, others are of vital importance to the nation. The states themselves vary in size and population, wealth and stage of modernization. All these influence the prospects for development and the availability of funds to finance it. The long-term effectiveness of such development depends heavily on the management skills of governments and other organizations involved in the process.

A useful indicator of the funds available locally for investment in semi-arid lands is the gross domestic product (g.d.p.) and g.d.p. per head of the population. Out of some 50 countries with sizeable areas of semi-arid land, some like Mali, Niger and Upper Volta, Sudan, Ethiopia and Somalia are among the poorest in the world, with g.d.ps per capita of less than \$200 per year. A small number are wealthy, with over \$2000. These last fall into two groups, industrial countries and those with infant industries but rich mineral resources, notably mineral oil and natural gas. There are other countries with extensive areas of semi-arid land, including China and India, which do not fall neatly into either group.

(a) *Development in industrial countries*

In the wealthy, industrialized countries, development of semi-arid land has usually involved, first, extensive pastoralism and ranching, then, more locally, mining, dry farming and irrigation. In Northern Australia, tourism now exceeds livestock production in value and both are far exceeded in importance by mining.

Oil prospecting and the development of oilfields and pipelines has led to the discovery and exploitation of underground water resources, notably in the borderlands of the northern Sahara. In South Africa, water pumped from the deep goldmines of the Witwatersrand adds significantly to local supplies. But industry and mining usually compete with agriculture for scarce supplies of water in semi-arid lands. For the production of a tonne of maize, 5000–10000 m^3 of water may be needed, enough to allow the production of, say, 20 tonne of steel. Where industry and agriculture compete for water, as in the Vaal river basin, it is the needs of industry that usually turn out to be the greater, in financial terms.

In Australia, South Africa, the U.S.A. and U.S.S.R., semi-arid lands are in close proximity to industrial heartlands. Especially in the U.S.A., urban expansion has been rapid, with towns attracting manufacturing industry, and also large numbers of retired people. Costs of development are high, and it has been argued that such urban growth is effectively a drain on the national economy rather than providing a net contribution to it. It could be replied that using the semi-arid lands in this way adds to the enjoyment of the nation even if it does not add materially to its economic benefits. Nevertheless, it is possible that only wealthy countries can afford to direct investment to the growth of industrial centres in semi-arid lands, very dependent on inputs of resources and finances from outside, and possibly contributing less than they receive to national economies.

Table 1. Industrial countries

	(a) area (10^6 km²)	(b) pop. (10^6)	(c) *d* pop. (% per year)	(d) g.d.p. (10^6 $)	(e) g.d.p./head ($/year)	(f) agric. g.d.p./head ($/year)	(g) oil (10^6 tonnes per year)	(h) dry area (%)
Africa								
South Africa	1.2	23.0	2.7	19928	843	–	–	55
N. America								
U.S.A.	9.3	209.8	1.1	1159318	5551	2285	467	35
Canada	10.0	21.9	1.6	104979	4805	1311	73	4
Mexico	2.0	52.6	3.5	41096	781	153	21	52
S. America								
Argentina	2.7	24.0	1.5	29706	1261	646	22	54
Asia								
Israel	0.02	3.1	2.9	7077	2298	785	6	75
U.S.S.R.	16.8	61.7	1.7	–	–	–	–	–
Australasia								
Australia	7.7	13.0	1.9	41098	3228	2092	16	82

The figures in all the tables are for 1972 unless otherwise indicated.
Sources: (*a–e, g*) *United Nations Statistical Yearbook*, 1973. (*f, h*) F.A.O. Committee on Agriculture: *Improving Productivity in Low Rainfall Areas* (COAG/74/4, Rev. 1, April 1974, pp. 9, 25).

The development of agriculture in the semi-arid lands of industrial countries presents hazards of two kinds for the future. Firstly there is the risk that water tables will be lowered to such an extent that supplies for irrigation will diminish. Such risks are predictable and therefore of less significance, certainly to the rest of the world, than the risks of failure of rain-fed crops as a result of drought. The importance of shortfalls in cereal production, notably in the U.S.S.R., are generally appreciated. They played a part in the increase in commodity prices in 1972 and deficits in 1975 are attracting attention currently. So long as North American harvests are satisfactory, global demands can be met, but if drought were to reduce production in America at the same time as in the U.S.S.R., and especially if drought recurred in successive years, the effects on world food stocks and the financial system would be severe. The rôle of these semi-arid lands in international economic affairs is clearly a very important one.

(*b*) *Development in oil-rich countries*

Of particular importance today are the semi-arid regions of those countries which have only recently begun to industrialize and where the extraction of minerals, especially petroleum, is attracting enormous sums of money from the oil-consuming countries; western Europe, the U.S.A. and Japan, with their great industries and wealthy populations. Part of the money is being invested in the oil-consuming countries, a part in purchasing consumer goods and armaments, a third part is being spent on capital goods with the aim of installing utilities of various kinds and manufacturing plants. Fourthly, a part is being directed towards the poorer countries, many of which are Islamic and semi-arid.

About 60% of the world's oil reserves and a half of present production are concentrated around the Persian/Arabian Gulf. Some of the states involved are small and entirely arid and do not therefore enter into our considerations directly. The larger ones include great tracts of semi-arid land. Much of Iran's $20000 million per year income is being directed into industry

Table 2. Oil rich countries

	(*a*) area 10^6 km²	(*b*) pop. 10^6	(*c*) *d* pop. (% per year)	(*d*) g.d.p. 10^6 $	(*e*) g.d.p./head $/year	(*f*) agric. g.d.p./head $/year	(*g*) oil 10^6 t/year	(*h*) dry area (%)
Africa								
Algeria	2.4	15.3	3.5	4156^{69}	299^{69}	52	51	96
Libya	1.8	2.1	3.7	4860	2337	79	106	100
Nigeria	0.9	58.0	2.5	5310^{69}	99^{69}	61	91	28
S. America								
Venezuela	0.9	11.0	3.4	14159	1291	224	168	9
Asia								
Iran	1.6	30.6	3.0	17001	556	130	248	85
Iraq	0.4	10.1	3.3	3141^{69}	343^{69}	106	71	97
Oman	0.2	0.7	3.0	—	—	—	14	100
Saudi Arabia	2.1	8.1	2.8	—	—	48	286	100

and agriculture in semi-arid land. With a population of 30 million growing at 3% annually, Iran can absorb such sums. Both Algeria and Iraq are in a similar position to Iran. Oil in Algeria brings in about $3700 million per year; it has a population of over 15 million growing at 3.5% annually and is investing mainly in its Mediterranean fringe, much of which is semi-arid. Iraq's population of more than 10 million is growing at 3.3% annually and its oil income of $6700 million can be invested locally. Nigeria's $8000 million are being spent widely through the country, the greater part of which is outside the arid zone, but considerable sums are being invested in irrigation schemes in the semi-arid northern districts, where pressure of population on land resources has for long been high.

In all these oil-producing countries, expenditure first by oil companies and latterly by national and regional governments on roads, urban facilities and the civil service is attracting the traditional pastoralists and the sedentary cultivators from the countryside. Lack of rain in individual years pushes more people into the towns, not only from oil-producing countries but also from neighbouring territories. Everywhere, g.d.p. per head in agriculture is well below the mean national figure and the discrepancies have been magnified greatly over the last three or four years. The exodus from the countryside to the towns will inevitably accelerate (Clarke 1973).

So far, investment in agriculture has not been outstandingly effective. Rising food prices have been associated with increased imports of foodstuffs from overseas. Eventually, one may suppose, incomes of cultivators and their ability to farm more profitably will improve, but they have not always been helped by governments subsidizing imported foods to keep down the costs of living for the townspeople.

The situation is different in the oil-producing states with small populations. Kuwait falls into this class as do a number of the other Gulf States. Some funds from these countries have moved in the direction of the Sudan Republic for agricultural development. Both Saudi Arabia and Libya have very large incomes from oil in relation to their populations and the land at their disposal that is not arid. Saudi Arabia's 8 million people, increasing at 2.8% annually, have $30000 million annually at their government's disposal; Libya, with 2 million people, has an oil income that varies but is of the order of $6000 million per year. In both countries nomadic pastoralism has declined and intensive stock-rearing using imported feeding stuffs is starting. In agriculture, much of the investment in land and irrigation is by townspeople and is in the semi-arid areas adjacent to urban areas. The spread of irrigation in the semi-arid northwest coastal regions of Tripolitania has resulted in a rapid fall in the level of groundwater.

In the short term it might be argued that the chief problems to be faced are social and political. In Saudi Arabia, much reliance is placed on Yemeni labourers to carry out the more menial tasks, Libya depends on Tunisians, and Kuwait on Lebanese and other nationalities. Where oil money can provide for all, and everyone is a lily of the field, will society survive unscathed? Fundamentally, the industrial west is concerned with the development of semi-arid lands because it is to them that a large part of the payments they make for oil are being directed, and this involves the product of their factories, farms and labour forces. Ineffective investment represents a waste of the world's resources and of human effort.

(*c*) *Development in the poor countries*

The problems of resource development in semi-arid lands are most severe where the countries concerned are entirely in the arid zone and where their mineral resources are on a modest scale or non-existent. The Sahelian countries typify this situation. Senegal, Mali, Upper Volta and Niger with a total population of about 20 million have per capita g.d.p.s of about $200 and in agriculture of about half that amount. Traditional systems of pastoralism persist, and the cycle of poverty, lack of investment and no improvement in living standards is hard to break. In the years from 1968 to 1974, gross production rose slowly but production per head of population fell. Wealth in the form of cattle was destroyed and the process of recovery will take several years without any guarantee that similar setbacks will not recur with increasing frequency as populations continue to increase. All four countries, except Senegal, are land-locked. Upper Volta has no navigable rivers; the other countries include stretches of the Niger and Senegal with their flood plains which provide opportunities for large scale irrigation schemes and power development. International river commissions have been in existence for some years and various schemes for developing the country bordering the southern parts of lake Chad have been prepared. It seems likely that Nigeria, with funds from oil and the need for land, will go ahead with its own agricultural schemes in that part of the Chad basin lying in Borno State without paying too much regard to the other countries concerned.

In southern Africa, both Botswana and Namibia are entirely in the arid zone. Both have larger mineral resources than the states of the western Sahel and their economies are associated with South African industry. Both have small populations, and prospects for the future are better than in the countries of the Sahel.

Sudan and Ethiopia include much country outside the arid zone. Vast areas of clay plains in the Sudan, east of the White Nile, have been brought under the plough in recent decades and fears have been expressed as to whether fertility can be maintained. Attention is now being directed to the rainlands of the Qoz, the fixed dune country west of the Nile and north of the Bahr-el-Arab where there are opportunities, in the savanna lands of southern Darfur, to work out schemes of sustained yield agriculture before the population reaches critical levels.

In Ethiopia, the most extensive areas of semi-arid land lie on the plateaus of the southeast, with soils derived in part from volcanic rocks. Wide stretches have been brought under cultivation in recent decades and opened up by new roads. The opportunities for increasing the productivity of these lands would seem to be good.

Table 3. Poorer countries. Mainly arid and semi-arid

	(*a*) area 10^6 km²	(*b*) pop. 10^6	(*c*) pop. (% per year)	(*d*) g.d.p. 10^6 $	(*e*) g.d.p./head $/year	(*f*) agric. g.d.p./head $/year	(*g*) oil 10^6 t/year	(*h*) dry area (%)
Asia								
Afghanistan	0.6	17.9	2.3	1496^{70}	88^{70}	44	0	81
Jordan	0.1	2.5	3.4	671	272	108	0	98
Pakistan	0.8	56.1	2.4	11186	204	60	0	90
Syria	0.2	6.7	3.4	2277	341	118	6	83
Yemen (Arab Rep.)	0.2	6.1	–	–	–	35	0	92
Yemen (Dem. Rep.)	–	–	–	–	–	–	0	100
Africa								
Ethiopia	1.2	25.9	1.9	–	–	38	0	74
Morocco	0.5	15.8	–	3872	245	95	0	85
Somalia	0.6	2.9	2.3	231^{69}	85^{69}	–	0	100
Sudan	2.5	16.5	2.7	1832	117^{70}	60	0	91
Tunisia	0.2	5.4	3.0	1609	304^{71}	76	4	92
Africa								
Botswana	0.6	0.6	2.8	140^{71}	209^{71}	–	0	91
Chad	1.3	3.2	2.0	270	74^{70}	33	0	92
Kenya	0.6	12.1	–	1992	165	47	0	75
Mali	1.2	5.3	2.0	262^{69}	54^{69}	39	0	95
Mauritania	1.0	1.2	2.2	182^{69}	160^{69}	50	0	100
Namibia	0.8	0.6	2.0	–	–	–	0	90
Niger	1.3	4.2	2.6	378^{69}	97^{69}	56	0	100
Senegal	0.2	4.1	2.4	1029	250	79	0	87
Upper Volta	0.3	5.6	2.1	–	–	26	0	94

Table 4. Poorer countries. Partly arid and semi-arid

	(*a*) area 10^6 km²	(*b*) pop. 10^6	(*c*) *d* pop. (% per year)	(*d*) g.d.p. 10^6 $	(*e*) g.d.p./head $/year	(*f*) agric. g.d.p./head $/year	(*g*) oil 10^6 t/year	(*h*) dry area (%)
Africa								
Angola	1.2	5.8	–	–	–	49	7	23
Cameroon	0.5	5.0	–	1091^{70}	187^{70}	84	0	9
Madagascar	0.6	6.2	–	973	141^{71}	–	0	15
Tanzania	0.9	14.0	2.6	1529	112	38	0	20
S. America								
Brazil	8.5	98.9	2.9	50717	513	98	8	5
Bolivia	1.1	5.2	2.6	1106	219	56	2	22
Chile	0.8	8.8	–	5684	574	166	2	47
Paraguay	0.4	2.6	3.4	769	298	141	0	8
Peru	1.3	14.4	3.1	5473	378	99	3	17
Asia								
India	3.3	563.5	2.2	49087^{69}	96^{69}	–	7	–
Turkey	0.8	37.0	2.5	16121	436	136	3	41

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Many other countries so far not mentioned by name have their own particular problems and possibilities for development. Some fall neatly into one or other of the categories that have been distinguished, others have the characteristics of more than one of the conditions affecting the development of their resources.

The conclusion of a working group that recently reported on the obstacles to development of arid and semi-arid lands was that 'the overarching need is for the refinement of integrated approaches to the planning and development programmes' and that 'most efforts have suffered from concentration on narrow sectors to the detriment of integrated approaches that take in the whole complex of the resources and human needs of a region and that look to practical use of the findings' (U.N. Economic and Social Council).

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Discussion

M. R. Miles (*Meteorological Office, Bracknell, Berkshire*). Is it possible that arid and semi-arid lands may get wetter. No one would deny the possibility but when he links it with the increase of CO_2 due to burning of fossil fuel and increased aerosol loading then it becomes a probability that can be the subject of comment. The latest estimates of these effects is a warming due to CO_2 of at most about 1 °C by the end of the century and a cooling of about the same amount due to the additional aerosol.

Now the wetter period in the Sahara to which Mr Grove has referred occurred at a time when the ice-limits were still at more southerly latitudes, than they are today and when temperature was recovering from a level some 5–10 °C below present-day values. It is still not known exactly what brought this large temperature change about. I think the view put forward by Prof. Newell that it was due to the release of heat gained by the deep oceanic waters during the thousands of years of glaciation is among the most likely. Thus the Saharan wetness 5–10000 years ago occurred against a very different set of conditions from those now prevailing. The effects of increasing CO_2 and aerosol loading appear unlikely to bring this kind of wetness about.

A. T. Grove. I understand that there is still some uncertainty as to the effects of increased aerosol loading on global temperatures. It would indeed be a happy coincidence if the effects were to balance those of increased CO_2 due to burning fossil fuel, but I would not think that one can be complacent about this. A global increase of temperature of only 1 °C is not negligible in importance; such an increase is unlikely to be uniform over the surface. I do not think we are in a good position to predict the consequences for precipitation of such a warming; it seems to me not unlikely that it could result in increased evaporation, especially from tropical oceans, and some associated increase in rainfall.

E. B. Worthington (*I.B.P., c/o The Linnean Society, Burlington House, Piccadilly, London W1V 0LQ*). Important new information has been presented concerning the changes of climate in Africa, and their dating since the last ice age. The former much greater extent of lakes, for instance in the southern Sahara, and in the Eastern Rift Valley, related closely to the present distribution and evolution of fishes. Conversely the fishes had contributed evidence of past climatic change – a nice example of the relation between two quite different disciplines.

H. Doggett (*Leader, Cereals Improvement, I.C.R.I.S.A.T.* 1–11–256, *Begumpet, Hyderabad* 500016, *India*). An area in which more reliable prediction of rainfall and drought years could be of value is in the determination of cropping patterns. Seed stocks of shorter term varieties, or even of different very short-term crops, could be stored, and issued to farmers, with appropriate advice, when such seasons are expected. This would help to reduce the logistical problems of moving in food supplies, and the size of the stocks needing to be stored against the risk of a succession of drought years. The 'mid-season correction' is being used in India, so that when the early weeks of the rains are poor, farmers are advised to grow short-term crops such as setaria millet and mung bean in the resultant enforced late plantings.

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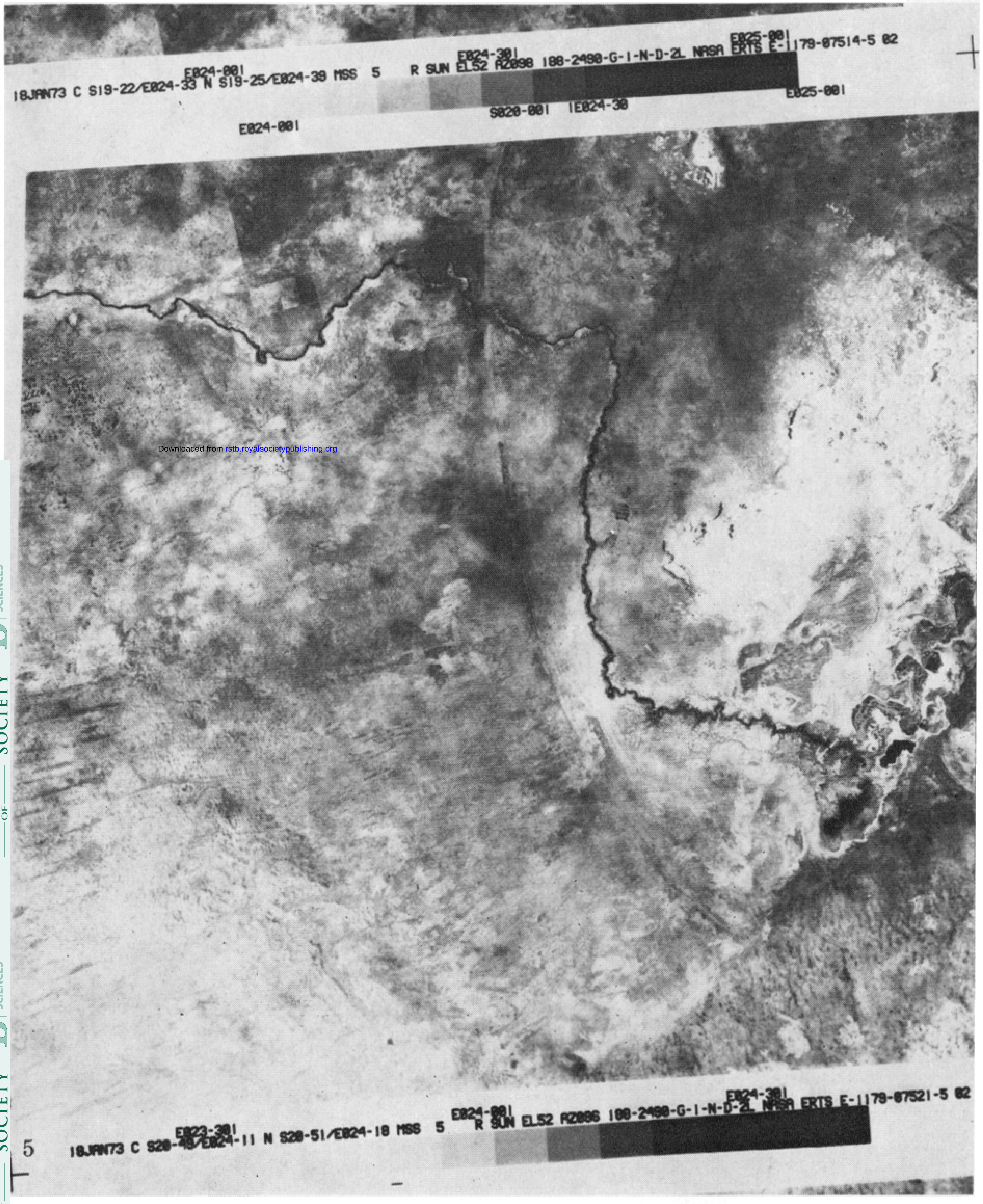
B. Dasgupta (*Institute of Development Studies, University of Sussex*). As one among the few social scientists present in this gathering, let me first thank the speakers for their valuable contribution. My point relates to the suggestion regarding the feasibility of switching the cropping pattern to drought-resistance crops in response to mid-season weather forecasting. This suggestion presupposes the unrestricted flow of information to the farmers, their understanding of the various cropping practices, and the availability of seed stocks of different varieties of crops at the village level. My contention is that, apart from the fact that very few villages possess the requisite seed storage capacity, the low level of literacy, the low development of mass media and given the highly stratified and hierarchically based character of many villages, particularly in South Asia, knowledge is a precious commodity which is least accessible to those who are most vulnerable to weather changes, that is the poor farmers.

B. H. Farmer (*Centre of South Asian Studies, University of Cambridge, Laundress Lane, Cambridge CB2 1SD*). I would like to pursue the point made by Mr Jain about mid-crop weather forecasts and, in particular, Dr Gupta's comment on the difficulty of getting cultivators in the villages to act on such forecasts. First, it cannot be too strongly or too often emphasized that to adjust cropping patterns on a government research station is one thing; but to get village farmers to adjust their patterns is quite another. This applies in general, and in particular to adjustments to mid-crop weather forecasts which indicate, let us say, that there will be an early withdrawal of the Monsoon. Secondly, I would suggest (on the experience of my Centre's research project on the so-called 'Green Revolution' in North Arcot District of Tamil Nadu, South India) that the problem may not so much be one of information: our cultivators were surprisingly well informed on a wide variety of agronomic matters. Much more, I would say, is it a problem of the perception of the cultivator (especially the small cultivator) of the relative risks and likely benefits of leaving his sown crop in the ground in the hope of sufficient rain (despite the forecast) and of ploughing it in and resowing with another crop (always assuming he can obtain the necessary inputs) because the forecast is that the rain will be inadequate for the crop already in the ground.



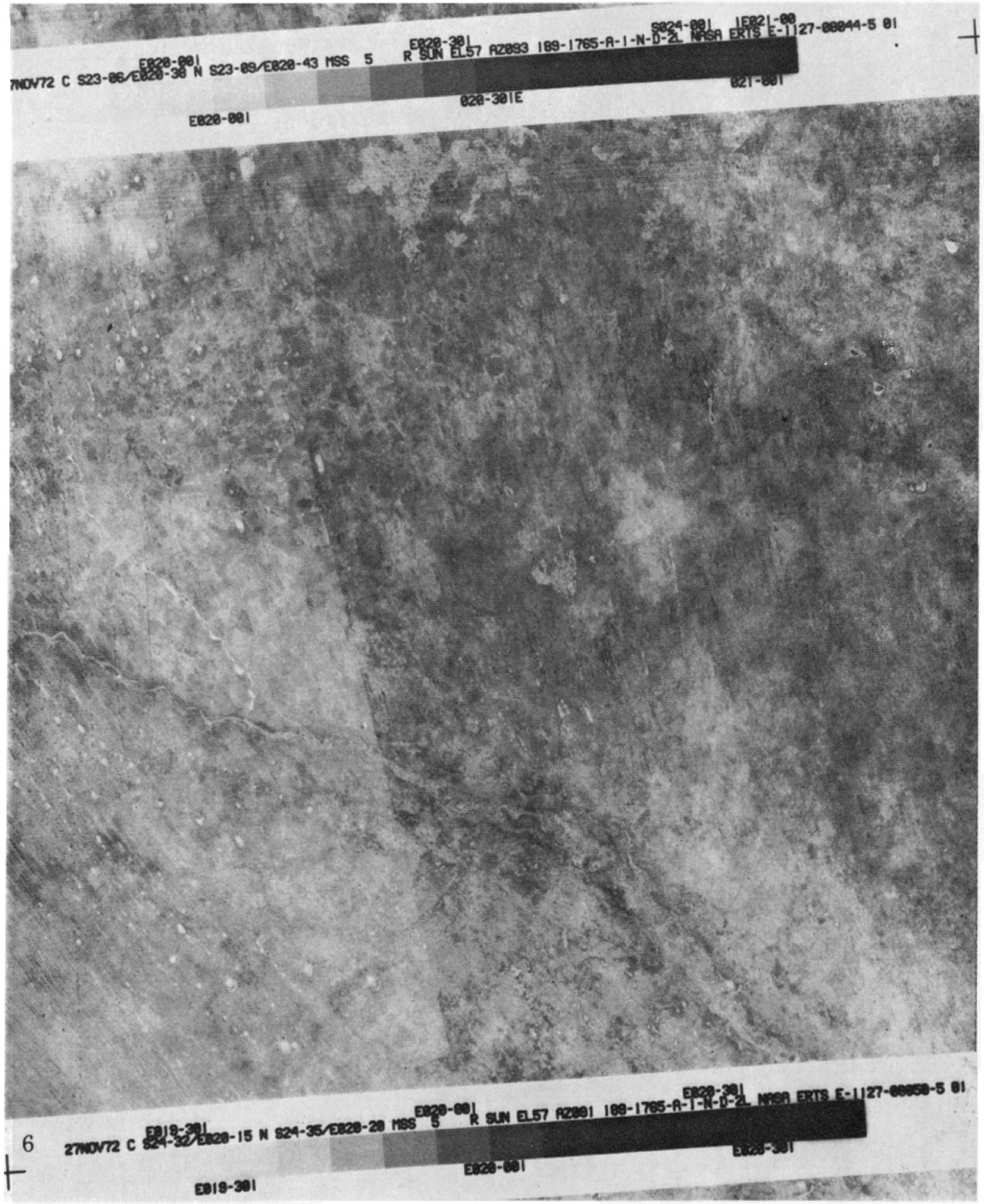


FIGURE 5. ERTS. The western margin of Pleistocene lake in the Makarikari depression, Botswana. 1179–07521.

FIGURE 6. ERTS. Vegetated dunes and pans on either side of the frontier between Botswana and Namibia. 1127–08050.