DRYLAND SOIL RESOURCES

Contract No. 53-319R-2-153
Foreign Agriculture Service
U.S. Department of Agriculture

September 1982

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Agency for International Development
Department of State
Washington, D.C. 20523

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DRYLAND SOIL RESOURCES

Summary

The climatic zones where water is a limiting factor for crop production during at least three months of the year cover about 4 billion hectares, or about 27 percent of the world's land area. As much as 75 percent (3 billion hectares) may have soils with physical properties that render them suitable for cropping if erosion can be controlled.

The principal soil problems facing dryland agriculture, apart from dryness, are low inherent fertility, water erosion, crusting and hardening, wind erosion, compaction by tillage, shallow and stony soils, poor drainage, and salinization. Control measures are available for all of the problems except that of shallow and stony soils. In dryland regions, controlling drainage and salinization is frequently too costly to be economic.

In Africa the dominant soil problem is low inherent fertility, due to coarse textures and acidic soils in the Sahel and to the low nutrient holding capacity and high phosphorus fixation capacity of soils in the wetter part of the dryland zone. A close second is surface soil hardening, which involves surface sealing as well as compaction and hardening to a depth of several centimeters.

The severity of all of the major controllable dryland soil problems could be eased by increasing soil organic matter content. How to bring about that increase in a practical and economic manner is perhaps the greatest challenge to applied research in the tropics and subtropics.

Introduction

Dryland agriculture is a rainfed crop production system in which the major limitation is a deficiency of water. At best, dryland farming is a risky enterprise. Drought is the principal hazard that dryland farmers face but locusts, hail, high winds, and intense rains are other hazards that can destroy crops in a matter of minutes. Little can be done to prevent most sudden disasters but there are soil and crop management practices that can reduce the impact of all but the most protracted droughts.

While low soil moisture levels commonly restrict crop yields in semiarid and subhumid lands, there are several other soil problems that can also influence dryland production. They are: surface soil hardening, compaction by tillage implements, water erosion, wind erosion, low fertility, shallow soils, stony soils, restricted soil drainage, and salinization. Surface hardening is a common characteristic of medium to coarse textured soils in dry tropical climates and is one of the more difficult problems to control. There is no practical way to improve shallow or stony soils and little can be done to overcome poor drainage, if that should be desired. The other problems can be controlled with presently available techniques. Whether or not it is economic to do so is another matter.

Dryland Agriculture Regions

For the purposes of this report, the dryland agriculture regions of the world are those shown in Figure 1 for the world and Figure 2 for Africa. The basis for the map is climate. The delineated areas are those having a growing period of 90 to 270 days, during which both moisture and temperature are favorable for crop growth. By and large, the areas have the type of climate that is usually referred to as semiarid or subhumid. All of the regions shown

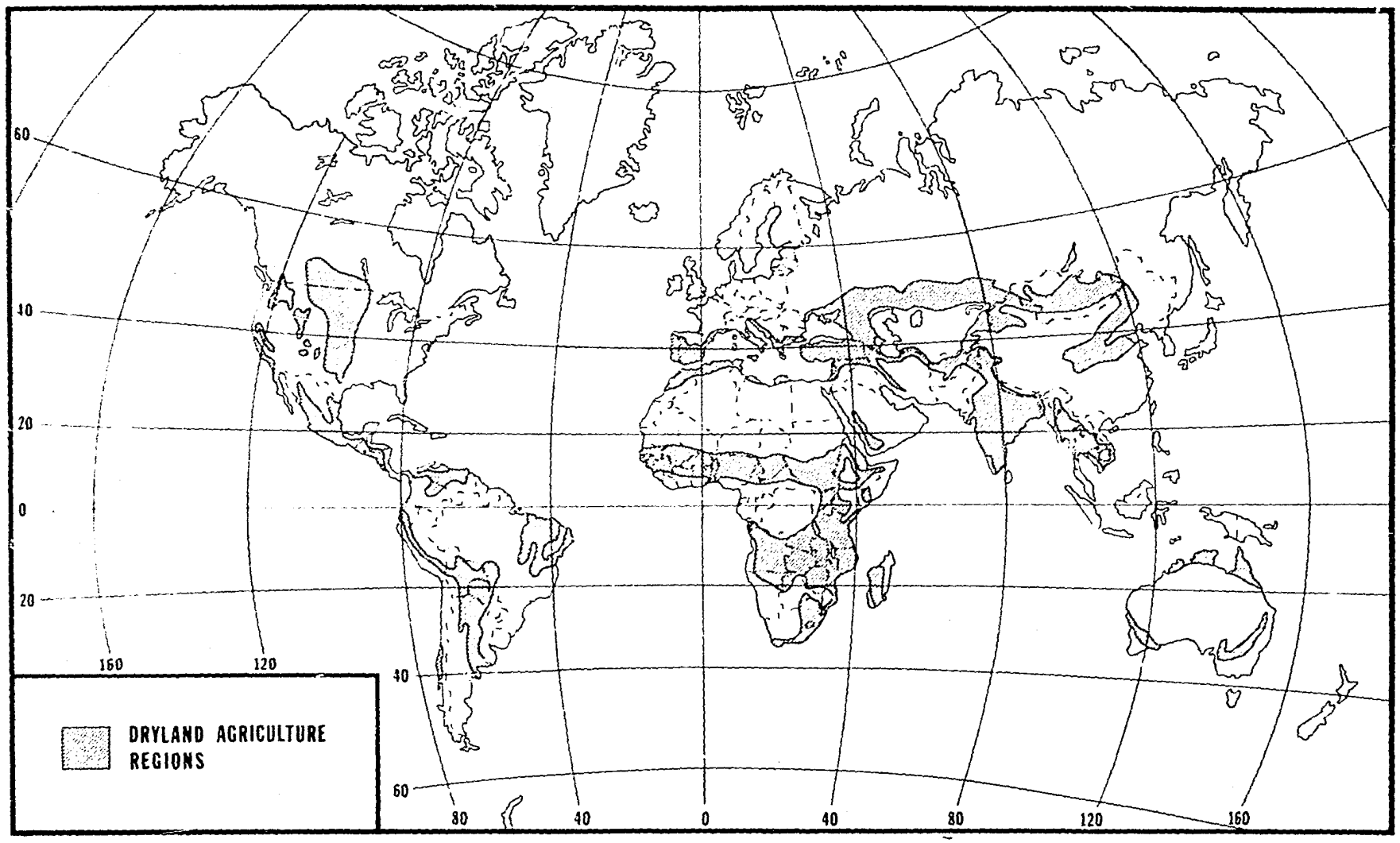

Figure 1. Dryland agriculture regions of the world.

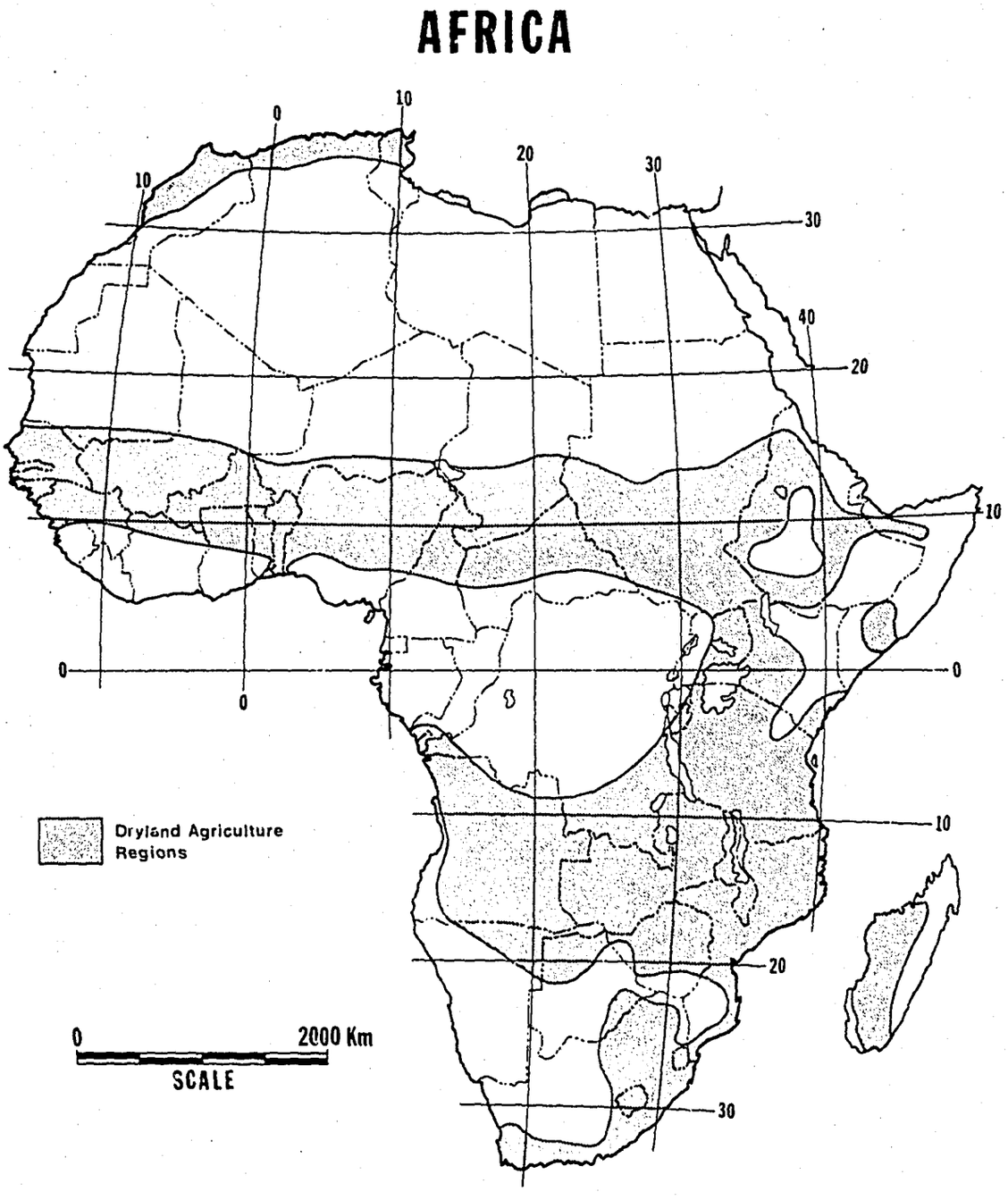

Figure 2. Dryland agriculture regions of Africa.

on the map will have dry periods of three months or more except in the northern part of the northern hemisphere and in mountainous regions, where frosts rather than moisture limit the length of the growing season. To a first approximation, the "growing period," insofar as precipitation is concerned, is the number of days when precipitation exceeds half of the potential evapotranspiration (see Appendix).

In the wetter parts of the dryland zone, moisture is not a limiting factor for most of the year. It is during the few months of the dry season that moisture deficiencies restrict crop growth even though temperatures are favorable. This situation occurs mainly in southeast Asia, India, central Africa, Brazil, and Central America.

Table 1 gives an estimate of the land area represented by the dryland zones in Figure 1. Of the 4 billion hectares, which is 27 percent of the world's land area, perhaps 75 percent (3 billion hectares) are suitable for crop production. The remainder are too shallow or too stony or too steep for growing crops, and some of it is too salty or too wet. Only about 10 percent of the land having a climate suitable for dryland agriculture was actually cropped in 1980. A much larger area is used in a long-time crop-fallow rotation, particularly in Africa, where as little as one-third of the land may be cropped in any one year.

The time during which rain falls is nearly as important -- and in some cases more so -- than the amount that falls. Widely spaced light rains may provide little available water to crops, whereas the same amount of water falling in one slow rain could be highly beneficial. Winter (cool season) rains are more efficient than summer (hot season) rains, due to the higher temperatures and greater evaporative losses in summer. Figure 3 shows the rainfall pattern during the year at seven locations in the dryland regions

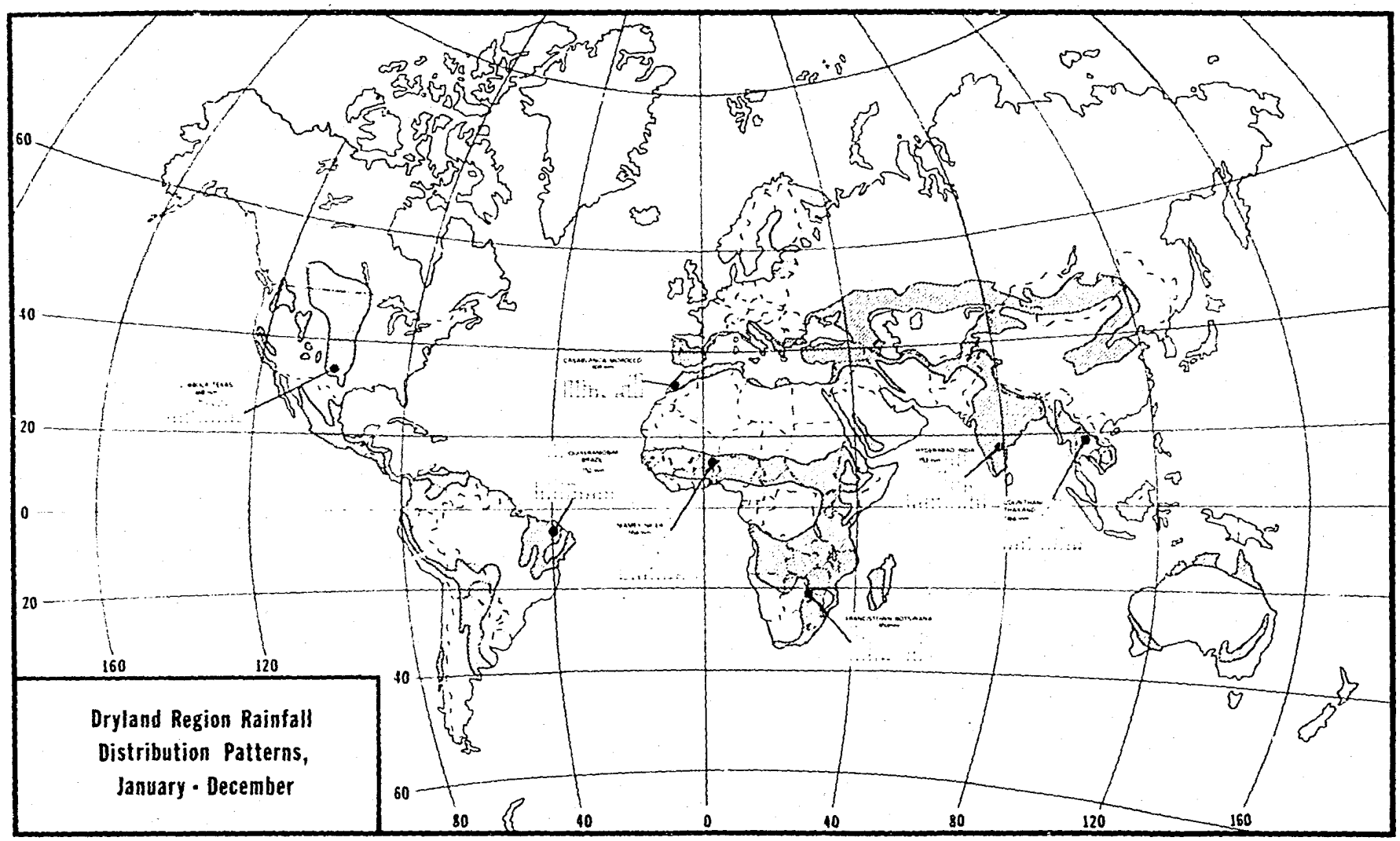

Figure 3. Rainfall distribution patterns in dryland agriculture regions.

Table 1. Dryland agriculture land area

Continent	Potential Dryland area*		1980 Cropped area
	percent of continent	hectares	hectares
Africa	40	1,190,000,000	110,000,000
Asia	34	1,490,000,000	180,000,000
Australia	20	150,000,000	11,500,000
Europe	18	170,000,000	8,100,000
North America	17	410,000,000	55,000,000
South America	35	620,000,000	15,000,000
Total		4,030,000,000	379,600,000

*Area having climate where dryland agriculture could be practiced.

of the world.

Four kinds of rainfall distribution patterns can be observed in dryland agriculture regions: winter, summer, continental, and multimodal. The winter rainfall type is also referred to as the Mediterranean type because it is typical of the rainfall pattern in countries bordering on the Mediterranean Sea. Practically all of the rain comes in eight or nine months, leaving three or four summer months completely or nearly rainless. This is the rainfall pattern along the west coast of North and South America, in southwest Australia, and along the southern tip of Africa, as well as around the Mediterranean Sea and east to Iran. Rains tend to be more reliable and less intense than in the summer rainfall areas and the rains are more effective in recharging the soil root zone. Wheat is the principal dryland crop. Casablanca, Morocco is an example of the winter rainfall type.

The second rainfall type has precipitation concentrated in three to five summer months, followed by seven to nine very dry months. Typically, rainfall in the Sahelian countries south of the Sahara follows this pattern, with the length of the rainy (growing) season becoming longer as one proceeds south from the Sahara. Botswana in southern Africa has a similar pattern, as does northeastern Brazil and northern Australia. There are no places in North America, Europe, or Asia where the Sahelian kind of extreme concentration of rain in the summer occurs. Rains tend to be intense and erratic both in when they come and how much rain falls in any one month. Drought years are frequent, and may persist for several consecutive years. The erratic character of the rains makes dryland cropping very unreliable in northeastern Brazil, especially, despite a high annual rainfall. Sorghum and millet are the principal crops in the African summer rainfall zones. Corn (maize), cassava, cotton, and dry beans are important crops in northeastern Brazil. Niamey,

Niger and Francistown, Botswana are representative of the summer-only rainfall zones. Udon Thani in Thailand, Hyderabad in India, and Quixerabomim in Brazil have three, four, and seven dry months, respectively, but none is completely rainless.

The third pattern is the continental type, with precipitation distributed throughout the year, sometimes in the form of snow. Rainfall effectiveness is intermediate between the winter and summer types. The continental pattern is dominant in the great dryland wheat producing regions of central North America, the Soviet Union, China, and Argentina. Lubbock, Texas, in the southern Great Plains of the United States, has a typically continental rainfall distribution pattern.

The fourth rainfall pattern is the multimodal type, with two or more periods of short rains and long rains interspersed with dry months. This is said to occur in some places in East Africa and southeast Asia.

Rainfall-Soil Relations

Soil characteristics are strongly influenced by the climate in which the soils are developed. Within the dryland agriculture regions of the world, the principal soil characteristics that vary widely from one climatic region to another are soil reaction, lime content, nutrient holding capacity, and fertility level. Upland soils in the winter and continental rainfall zones tend to have a neutral or basic reaction, with a lime (carbonate) concentration in the subsoil, a moderate nutrient holding capacity, and a moderate fertility level. In the summer rainfall and the multimodal rainfall zones of the tropics and subtropics, upland soils are usually moderately to strongly acid, there is no lime anywhere within the root zone, nutrient holding capacities are low, and phosphorus and nitrogen contents, particularly, are low. Sulfur and some microelements may also be present at levels too low to meet crop needs.

In all four climatic zones, upland soils usually are sandy to a greater or lesser degree, have low organic matter and nitrogen contents, and may also be gravelly or stony. Soils of lowland depressions, irrespective of the climatic zone in which they occur, are generally of a heavy clay texture, have a neutral or slightly acid reaction, are slowly permeable, have a high nutrient holding capacity, and are moderately to highly fertile. In the drier areas, salts may be a problem in depression soils.

The principal exception to the general statement that upland soils usually are sandy is in India where there is an extensive occurrence of upland clay soils. These clays are known as black cotton soils or regurs. They are classified as Vertisols, which develop deep and wide cracks when they dry. There also are large areas of Vertisols in the central Sudan, in Chad, and in eastern Australia.

For the most part, dryland soils lying north of about 30 degrees north latitude and south of about 30 degrees south latitude have properties similar to those described for soils of the winter and continental rainfall zones. Soils of the other upland group are found between the two 30 degree latitude lines. The latter soils are the ones exhibiting pronounced deficiencies in nitrogen and phosphorus and low nutrient holding capacities.

Dryland Soil Problems

The principal soil problems affecting dryland crop production -- aside from dryness, which is ubiquitous during the dry season -- are noted in Figure 4. Water erosion is the number one problem throughout the world. Low inherent fertility is a problem of tropical soils in southern Asia, Africa south of the Sahara, northeastern Brazil, and Venezuela. Wind erosion is most extensive in the Sahel and the Soviet Union but occurs to some extent throughout the drylands. Surface soil hardening is more widespread than the map indicates but it is

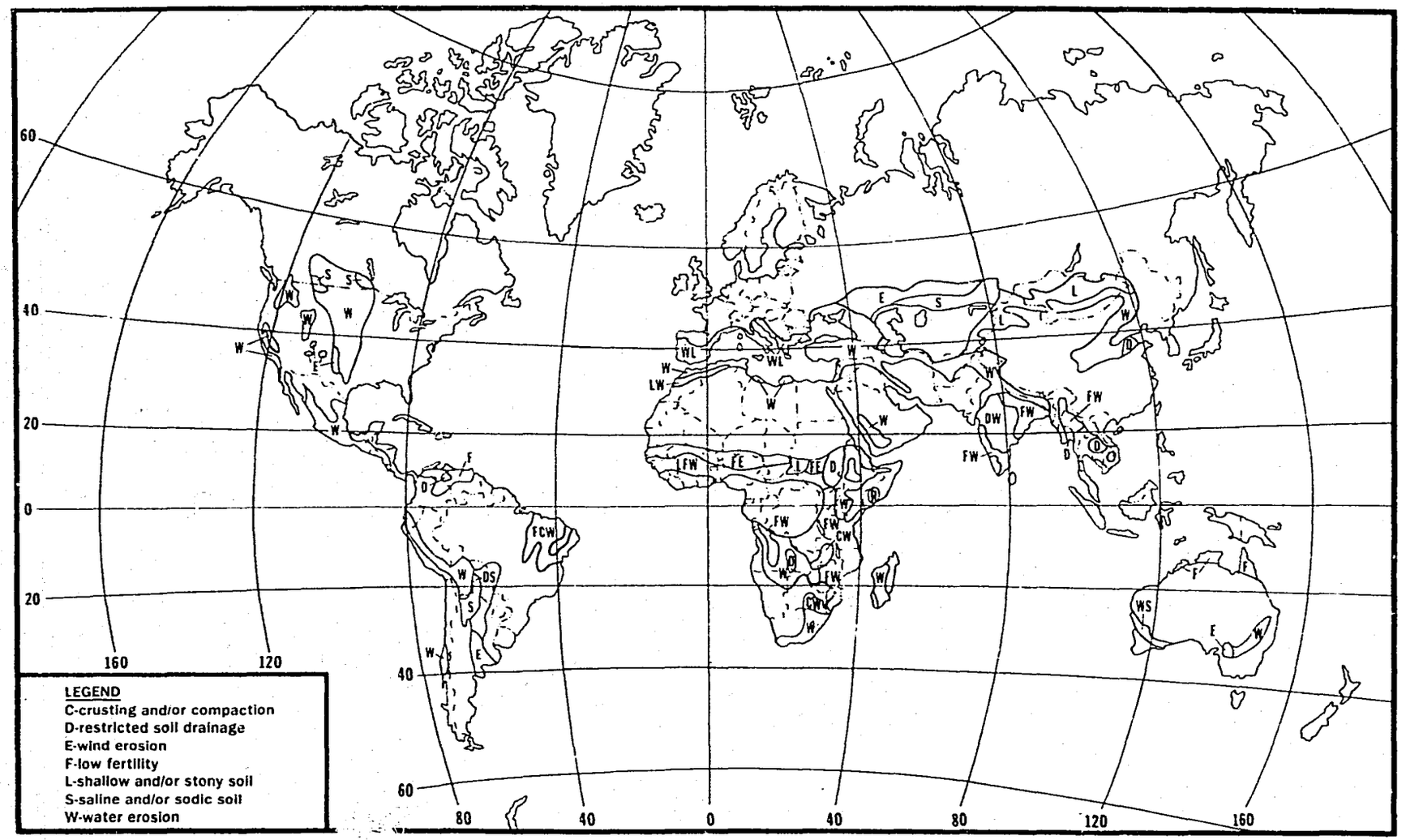

Figure 4. Soil management problems in dryland regions of the world.

especially important in the designated areas. The drainage problem is due either to seasonal flooding of lowlands or to the low permeability of clayey Vertisol soils. Large scale saline and sodic soil problems are confined to the wheat belt in Australia, Canada, the Soviet Union, and the United States and to the low-lying lands of the Chaco region of Argentina, Bolivia, and Paraguay.

Controlling Soil Problems

The most important practice in dryland soil management is water conservation. If water conservation is to be accomplished, then water erosion and the surface soil hardening that results in soil crusting and sealing must be controlled. In turn, conserving precipitation has a feedback effect in that the additional soil moisture usually increases crop growth and reduces susceptibility of the land to water and wind erosion and to surface soil sealing. In dryland regions, the principal cause of water erosion is the absence of plant cover to protect the soil surface from the pounding effect of raindrops. The splash erosion that results from the beating of raindrops not only moves soil downslope but -- more importantly -- disperses fine soil particles and causes the sealing (crusting) which encourages runoff and consequent erosion.

Water Conservation

Water conservation is accomplished in many ways. Terraces designed to capture and hold water, such as bench terraces, conservation bench terraces, level terraces, and mini bench terraces, can be employed. Furrow diking, which was called basin listing 40 years ago, is an effective way to hold rain water in a field by constructing dikes every few meters along furrows. The practice is also called "ridge tying", with the tied ridges forming ponds. Contour cultivation and tillage practices that leave crop residues on the surface

are other measures to hold water on the land. Vegetative and nonvegetative mulches reduce evaporation and runoff. Vegetative mulches usually consist of crop residues, whereas nonvegetative mulches may be stones or gravel or man-made stabilized soil aggregates.

Water harvesting is a special type of water conservation. The idea is to increase runoff from one area in order to concentrate it on a neighboring area. Water harvesting is usually thought of as a large scale practice where runoff from several hectares is captured on a lower lying field. However, a more practical procedure may be to increase runoff from a crop row and catch it in the adjoining furrow. Asphalt, plastic sheeting, water repellent chemicals, or even compacting the soil can be used to shed water, concentrate it in the furrow, and reduce evaporation while increasing deep percolation. Numerous water harvesting techniques are under study in different countries.

Tillage to improve surface soil permeability is another means of conserving water. Most dryland soils, when dry, form hard crusts that reduce infiltration. Commonly, the only practical way to increase infiltration in such soils is to cultivate them to break the crust.

Water Erosion

Steep slopes and intense rains account for much water erosion but the problem is the dominant soil hazard everywhere except on level permeable soils. Fine textured clays on 0.5 percent slopes can experience erosion that cuts rills and gullies and washes out seeds at the top of the slope while covering plants at the bottom of the slope. The less dramatic sheet erosion eats quietly away at the soil resource, going unnoticed until the unproductive subsoil is exposed or the soil becomes too shallow to support good crop growth. Water erosion tends to be less of a problem where fields are small and scattered, as in traditional agriculture, than where fields are large, as in mechanized farming.

Water erosion control methods are well known and used widely. The best control practice, without question, is to maintain a good vegetative cover on the land. In dryland areas, that is much easier said than done, whether the farming is done in the traditional method or by using mechanical power, because crop growth is less than maximum in most years. Consequently, reliance probably will have to be placed on structural devices to reduce erosion, which generally means terracing. Conventional bench terraces have the potential to absolutely control erosion but they are expensive to construct, are not desirable on shallow soils, and can lead to disastrous failures if they are not maintained properly. Broad-based terraces, with sloping land between terraces, are now the principal ones used on mechanically cultivated, moderately sloping land. Simpler terraces embodying the same principle as broad-based terraces can be constructed by hand or with animal draught. Terraces can be on the contour or, if well designed, in parallel to each other. Contour cultivation is another simple erosion control measure, as is furrow diking or tied ridges. For all terracing, safe disposal of excess runoff must be provided. The U.S. Department of Agriculture has developed the Universal Soil Loss Equation as a guide to the selection of control practices. The equation appears to be useful worldwide.

Low Inherent Soil Fertility

Low native fertility is a widespread problem on sandy soils and on the lateritic ferruginous (iron-rich) medium textured soils in Africa south of the Sahara, south and southeast Asia, northeastern and northern South America, and northern Australia.

Coupled with low inherent fertility in Africa, especially, is the drastic shortening in the fallow period that formerly provided 25 years or more for soils to recover from a few years of cultivation. As the population has

increased, pressure to produce more crops has increased. The response of the traditional farmer is to raise the cropping intensity by shortening or eliminating the fallow period, with no change in crop management practices.

Applications of mineral fertilizers to overcome nutrient deficiencies in West Africa soils that have been cultivated for a few years is not enough to raise crop yields to what they were immediately after the land was first cleared. The explanation seems to be that the reduction in organic matter that accompanies land clearing has an adverse impact on fertilizer effectiveness. This means that some provision must be made to increase soil organic matter content if long-time productivity is to be kept at a high level. The same constraint may well apply elsewhere in the tropical zone. If so, it emphasizes the value of crop rotations, which is the cornerstone of good soil management.

Among the fertilizer elements, nitrogen and phosphorus can be expected to be the major limiting nutrients in dryland agriculture. Sulfur deficiency is present on ferruginous soils in West Africa and northeastern Brazil and may be a problem on permeable ferruginous soils elsewhere. Potassium should become deficient on highly permeable soils of subhumid regions after several years of cultivation. Micronutrient deficiencies do occur but are associated with particular crops grown on particular soils.

In many cases, fertilizer responses have been poor for reasons having nothing to do with soil conditions. Poor responses have been attributed to the use of crop varieties that do not respond to fertilizer applications, inadequate weed, disease, and insect control, low plant populations, and deficient rainfall. Merely applying fertilizer is not enough.

Crusting and/or Compaction

Most medium and coarse textured dryland soils form a crust when they are wetted and dried. In addition, some medium to fine textured soils become hard

and compact to a depth of several centimeters when dried. The latter problem is important in southern Africa (Botswana, South Africa, Zambia, and Zimbabwe) and northeastern Brazil on soils that have considerable iron in the profile and are very low in organic matter. Hardening on drying is said to be a problem in Thailand, and very likely presents difficulties in many, if not most, soils where the content of iron is high and organic matter is low. Crust formation causes surface soil sealing which impedes seedling emergence, reduces infiltration, and increases runoff. Topsoil hardening also reduces infiltration and seedling emergence and, in addition, can severely restrict root development. Crust formation is associated with low soil organic matter and high silt contents. Mechanical tillage usually plow pans to form at the bottom of the plow layer in nearly all dryland soils.

Tillage to break the surface crust and to open up the soil is the short-term answer to the hardening and the plow pan problem. The long-term answer is to increase the soil organic matter content and the rooting depth by rotating soil-building crops with soil-depleting crops. Unfortunately, it is very difficult to maintain higher organic matter levels over periods of months and years in the hot regions. In most cases, the beneficial effects of a soil-building crop are dissipated shortly after the first plowing is done.

Mulching soils with crop residues is an effective way to reduce the rate of crust formation and soil hardening in moist soils. The mulch slows down the rate of soil drying and reduces the dispersing and compacting effect of raindrops.

A rough soil surface also helps decrease the rate of crusting and hardening by providing pockets where rainfall can collect. That serves to decrease runoff, increase soil water content, and delay drying.

Wind Erosion

Soils are subject to wind erosion wherever the wind velocity is high, soil particles are small, and the surface is bare. Sandy, silty, and clayey soils are all susceptible to wind erosion when conditions are right but sandy soils are the ones most affected.

Wind erosion removes the fine mineral and organic particles that are the most valuable part of the soil, covers roads, homes, and fences, and destroys crops by shredding leaves and stems. Dust and sand storms also create human and livestock health hazards, in addition to other kinds of non-agricultural damage. Agriculturally, the greatest damage is due to sand blasting of young crops.

Erosion control consists of preventing soil particles from being dislodged. As with water erosion, a good vegetative cover is the most effective wind erosion control measure. Asphalt sprays can protect the soil but their cost is high and their effect temporary unless exceptional circumstances exist. Wind barriers of fences, walls, oil drums, palm tree fronds, shrubs, and trees can all be used. The protected distance behind a wind barrier is equal to about 10 times the height of the barrier if the wind blows at right angles to the barrier. While shelterbelts are usually thought of as consisting of trees and shrubs, annual and perennial grasses are successfully used to control soil movement in fields of row crops. Windbreaks do not have to be several rows wide; two rows are effective if the plants are properly spaced.

Besides wind barriers and surface-applied soil stabilizers, stubble mulching, minimum tillage, deep plowing, cover crops, intercropping, strip cropping, and mulches are possible means of controlling wind erosion. When all else fails, emergency tillage to roughen the soil surface is a temporary control measure.

The U.S. Department of Agriculture has devised a Wind Erosion Equation for estimating soil losses. The equation needs to be improved considerably before it can be used outside the Great Plains of the United States.

Restricted Soil Drainage

Drainage problems in dryland soils are confined to slowly permeable clays, usually in depressions but also on upland sites. A drainage problem can turn into an asset if the soils become thoroughly wetted during the rainy season. After flood waters recede, crops can frequently be grown during the dry season on the residual water in the soil. Such "recession" farming is practiced in the Sudd region of the Sudan as well as elsewhere.

The dryland soils experiencing poor drainage belong to the Vertisol soil order of deep cracking clays. These soils are extensive in the Sudan, India, and Australia.

Control of drainage on Vertisols is very difficult because water movement, vertically or horizontally, is very slow. The best procedure is to protect them from flooding in the first place, if that is feasible. Removing ponded water is also difficult, ordinarily, but sometimes can be done by constructing a few surface drainage channels.

Saline and/or Sodic Soils

Salinization is not usually a problem in dryland soils. Upland soils tend to be permeable, with a deep water table. Salty soils are, however, found in dryland wheat areas of Australia, Canada, and the United States, where they are called "saline seeps". They also are found in the Chaco region of Argentina, Bolivia, and Paraguay, where saline ground waters are close to the surface. There are practically no salt problems in the dryland soils of Africa.

Sodic (black alkali) soils are restricted to a few small locations in the

Great Plains and to a large area in the wheat growing region of the Soviet Union.

Saline soils are called Solonchaks and sodic soils are called Solonetz. Controlling salinity consists of lowering ground water tables and of leaching the soil with water. Sodic soils usually require application of gypsum, followed by leaching.

Shallow and/or Stony Soils

There is no practical way to do anything to change shallow or stony soils. All one can do is live with the problem. Stony soils may be excellent for tree crops such as olives, but little can be done to make shallow soils productive under dryland conditions.

Africa Soil Problems

Figure 5 delineates the areas within the dryland agriculture climate zone where various soil problems occur. Low inherent soil fertility is the most significant and the most pervasive problem. It arises from the sandy and acidic character of the soils in the Sahel zone and from the low nutrient holding capacity and high phosphorus fixation capacity of the ferruginous soils in the wet part of the dryland agriculture zone. Nitrogen is the first limiting fertilizer element, with phosphorus a close second. Sulfur is deficient for some crops grown on the ferruginous soils, and some microelements probably are needed for certain crops on those same soils. Potassium deficiencies are likely only on porous soils that have been cultivated for several years.

Surface soil crusting is more or less of a problem everywhere. Hardening of the top several centimeters of soil is serious in southern Africa. Drainage is poor on the clay plains of the Sudan, Chad, and along the Angola-Zambia border. Poor drainage, however, is a problem during the dry season only if rains or floods have not saturated the soil earlier.

AFRICA

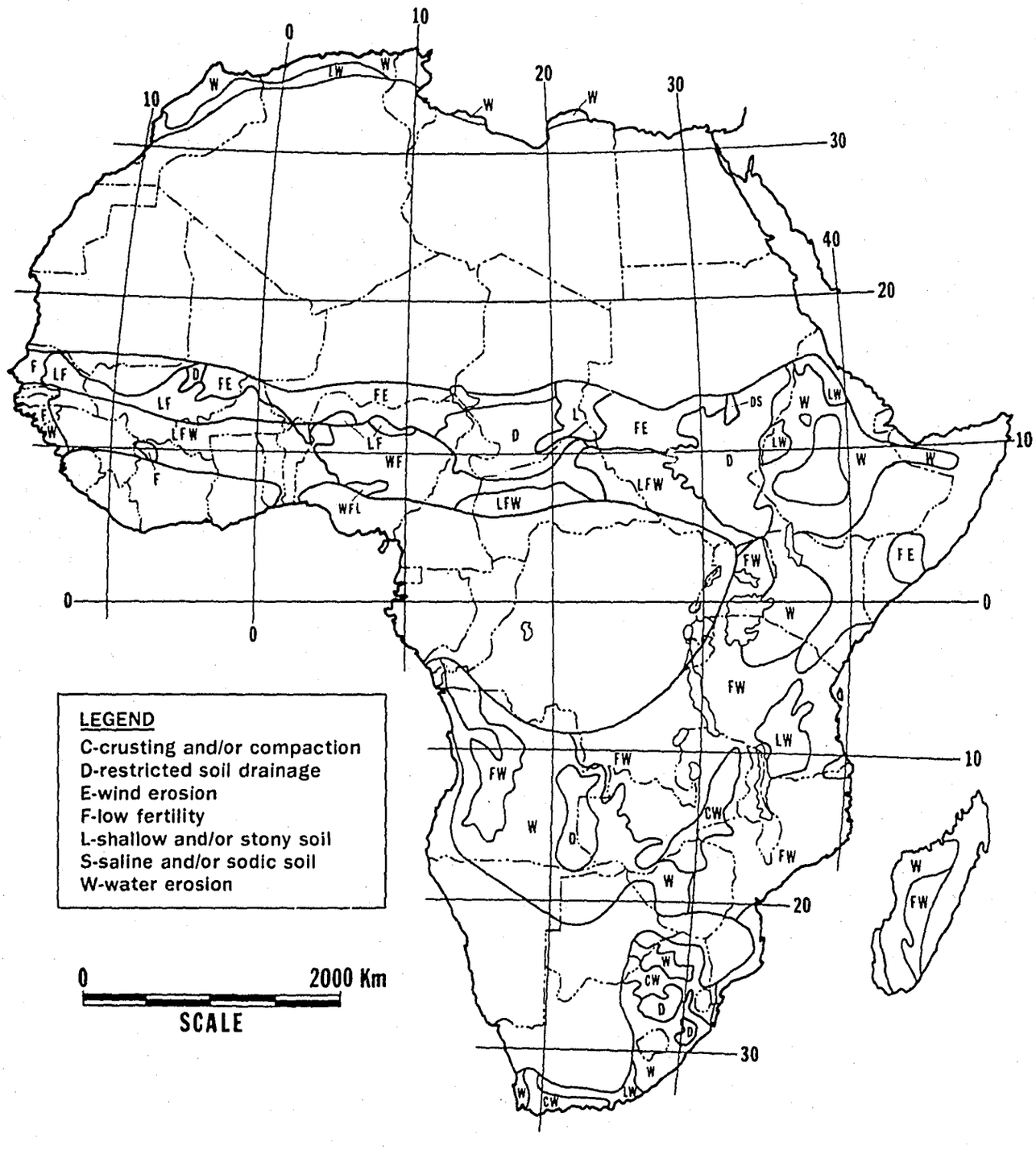

Figure 5. Soil management problems in dryland regions of Africa.

Appendix I

Climatic Zones

Delineation of the climatic zones for dryland agriculture was based on a combination of two criteria, plus a bit of personal judgement. The principal criterion for Africa, South America, southwest Asia, and southeast Asia was the maps published by the Agroecological Zones Project of FAO (FAO, 1978). For the remaining regions, the 1977 Unesco map of arid regions (Unesco, 1979) was consulted.

The FAO maps are drawn on the basis of length of the growing period, in days. The growing period is defined as the continuous period during the year, from the time when rainfall exceeds half the potential evaporation until the time when rainfall falls below full potential evapotranspiration, plus the number of days required to evaporate an assumed 100 mm of soil moisture reserve when available. Any growing period is likely to have a humid period when rainfall exceeds potential evapotranspiration. If low temperatures preclude crop growth, that period of low temperature is excluded from the growing period.

For the Unesco map, the various degrees of aridity (hyperarid, arid, semiarid, and subhumid) are defined by the ratio of precipitation to potential evapotranspiration. A subhumid region is one in which annual precipitation is 0.5 to 0.75 of annual potential evapotranspiration (P/ETp=0.5 to 0.75).

Both FAO and Unesco calculated potential evapotranspiration by the Penman method.

Working from the FAO and Unesco maps, the bounds of the regions where dryland agriculture practices were needed were set between 90 and 270 days in the places where the FAO maps were available and between the P/ETp of approximately 0.3 and 0.75 for the remaining areas. The dryland agriculture regions

thus include the subhumid and part of the semiarid zones, in Unesco terminology. Less than a 90 day growing period is too short to allow successful dryland cropping; more than a 270 day growing period means that the dry season probably is too short to warrant adapting soil and crop management techniques to cope with dryness.

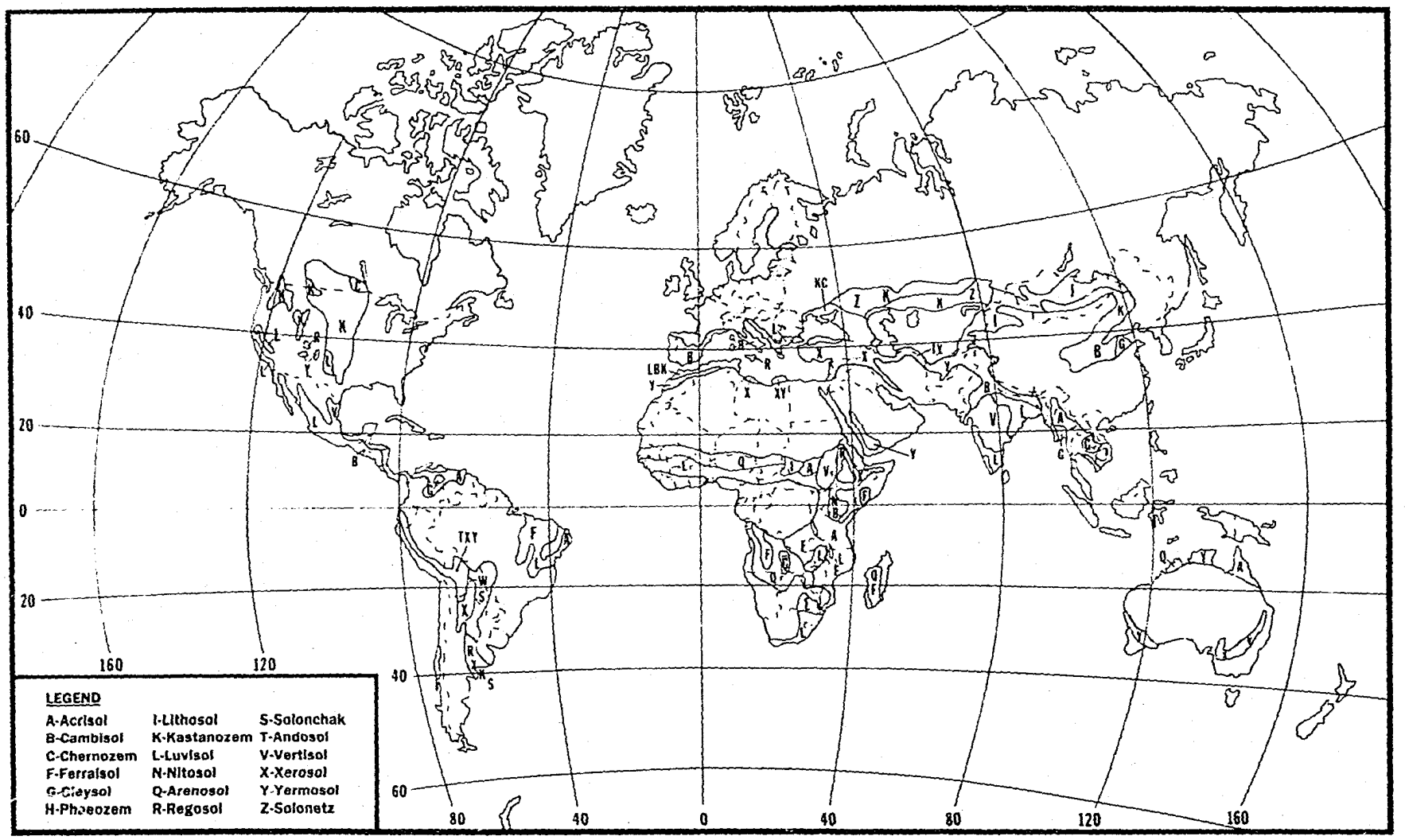

Figure 6. Principal soil orders of dryland regions of the world.

Appendix 2

Soil Characteristics

Soils of the dryland agriculture zone (Figure 6) are of three general kinds: 1) coarse to medium textured, moderately to strongly acidic, kaolinitic-montmorillonitic (smectite) mineralogy, low cation exchange capacity, low organic matter content, moderate to strong phosphorus fixation capacity, 2) coarse to medium textured, neutral to alkaline, calcareous in the surface and/or subsoil, montmorillonitic-illitic-kaolinitic mineralogy, moderate to low cation exchange capacity and organic matter content, and low phosphorus fixation capacity, and 3) fine textured Vertisols of uplands and depressions, neutral pH, very slowly permeable, montmorillonitic mineralogy, high cation exchange capacity, high to low organic matter content, low phosphorus fixation capacity.

Group 1 Soils

Soils of the first group are dominant in Africa south of the Sahara, India, southeast Asia, northern Australia, northeastern Brazil, Venezuela, and Central America (FAO/Unesco, 1971, 1975b, 1975c, 1977, 1978d, 1979). Cation exchange capacities are usually less than 10 m.e./100 g. and frequently are less than 5 m.e./100 g. Organic matter contents under native vegetation may be as much as 3 percent but the level drops to less than 1 percent soon after cultivation begins. The sandy soils occupy gently rolling plains, whereas the medium textured soils are found on a wide range of slopes. Most of the soils have good permeability and are deep except on steep slopes. Crusting is a problem everywhere and the ferruginous soils have a tendency to harden to a considerable depth. The heavy summer rains, even in the Sahel, are responsible for thorough leaching of the soils and their acidification.

The cause of crust formation in soils is not known with certainty. It seems to be due principally to the binding effect of amorphous silica and noncrystalline hydrated alumino-silica and to the net negative water pressure exerted during drying (Uehara and Jones, 1974; Gifford and Thran, 1974; Uehara and Gillman, 1981). The amorphous gels are reversible, in contrast to the irreversibility of the sesquioxide gels that probably are responsible for the hardness and permanence of laterite crusts. The compaction that aids in crust formation results from the beating force of raindrops, sodic soil dispersion, and the negative pressure pulling particles together when a soil dries.

Soil hardening to a depth of several centimeters is not the same as the surface soil sealing that is referred to here as crusting. Deep hardening appears to be somewhat analagous to the irreversible hardening of plinthite upon drying. In dryland soils, rarely does the hardening proceed to the brick-like stage of ironstone. Instead, the hardening process leads to a reduction in porosity and in the number of large pores and to greater impedence to root extension.

The principal soils of Group 1 occur in the tropics and belong to the Acrisol, Arenosol, Luvisol, and Ferralsol orders of the FAO/Unesco classification (FAO, 1974). In the U.S. comprehensive soil classification system (Soil Survey Staff, 1975), the equivalent orders are Alfisols (Acrisols, Arenosols, Luvisols) and Ultisols (Ferralsols). Alfisols have a Bt horizon; Ultisols usually do. Ferralsol clay minerals are a mixture of 1:1 minerals and hydrous oxides. Petroferric horizons are fairly common in Africa Ferralsols.

French soil scientists have done most of the soil classification in West Africa and North Africa. In the French system (Aubert, 1968), the dryland West Africa soils are classified in the subclasses of Sols Ferrugineux

Tropicaux (Alfisols) and Sols Fersiallitiques (Alfisols and Ultisols).

Group 2 Soils

Soils of the second group occupy most of the remainder of the dryland agriculture regions of the world (FAO/Unesco, 1971, 1975a, 1977, 1978c, 1978d, 1981). By and large, they occur in the temperate climatic regions of northern Asia, around the Mediterranean Sea, in North America, in the south of South America and in the Andes Mountains, and in southern Australia. Lack of deep leaching allows calcium carbonate to accumulate somewhere in the upper profile. Clays minerals are a mixture of montmorillonite, kaolinite, and illite. Cation exchange capacities are generally in the 10-20 m.e./100 g. range. Organic matter is 1 percent or less, in the main. Many of the soils are shallow or moderately deep over a calcic horizon, a petrocalcic layer, or bedrock. Phosphorus fixation is not a significant problem but phosphorus deficiencies for crops such as sorghum and corn are common.

A large number of soil orders of the FAO/Unesco classification are represented in this group of soils. They include Kastanozems, Cambisols, Xerosols Chernozems, Regosols, Andosols, Lithosols, Luvisols, Yermosols, and Solonetz. Kastanozems are most extensive. According to the U.S. system, the soils are Mollisols (Kastanozem, Chernozem), Inceptisols (Cambisol, Andosol), Aridisols (Xerosol, Yermosol), and Entisols (Regosol). Lithosol and Solonetz soils are found in more than one U.S. order.

The Soviet Union system classifies the soils as Chernozem, Kastanozem, and Solonetz.

In North Africa, the French assign the dryland agriculture soils to the Sols Isohumiques, Sols Calcomagnesimorphes, and Sols Mineraux Bruts classes (Aubert, 1968).

Group 3 Soils

Deep cracking clays (Vertisols) constitute the third group of soils. Permeability is low or very low, cation exchange capacities are in the range of 30 or more m.e./100 g., organic matter content is low in places such as the Sudan and high in Chad, the pH is in the slightly acid to alkaline range, and the dominant clay mineral is montmorillonite. Few of these soils are saline or sodic in the dryland agriculture climatic zone but some of them are borderline sodic soils. The high water holding capacities and low permeabilities of Vertisols is an asset most of the time but they cause waterlogging in wet years.

Vertisols are found in extensive plains in the Sudan, Chad, Australia, and Mexico. In India, they occur on undulating to hilly topography. For a soil to be a Vertisol the climate must be such that a dry season is long enough to dehydrate the soil to the extent that deep cracks develop. Soils similar in physical properties to Vertisols but having a wet moisture regime are shown in Figures 6 and 7 as Gleysols.

In the FAO/Unesco, U.S., and French classification systems, Vertisols are Vertisols. They are designated Gray, Brown, and Red Clays in Australia (Stace et al, 1968).

Africa Soils

Figure 7 shows the distribution of soil orders in Africa, using the FAO/Unesco classification. The map boundaries are the same as the soil problem boundaries in Figure 5.

North of the Sahara is where most of the calcareous dryland soils are found. In the older classification systems, they were called Rendzina, Terra Rossa, and Non-Calcic (Shantung) Brown soils. The FAO/Unesco terms are Calcic Cambisols, Calcic Xerosols, Calcic Kastanozems, Chromic Luvisols, and

AFRICA

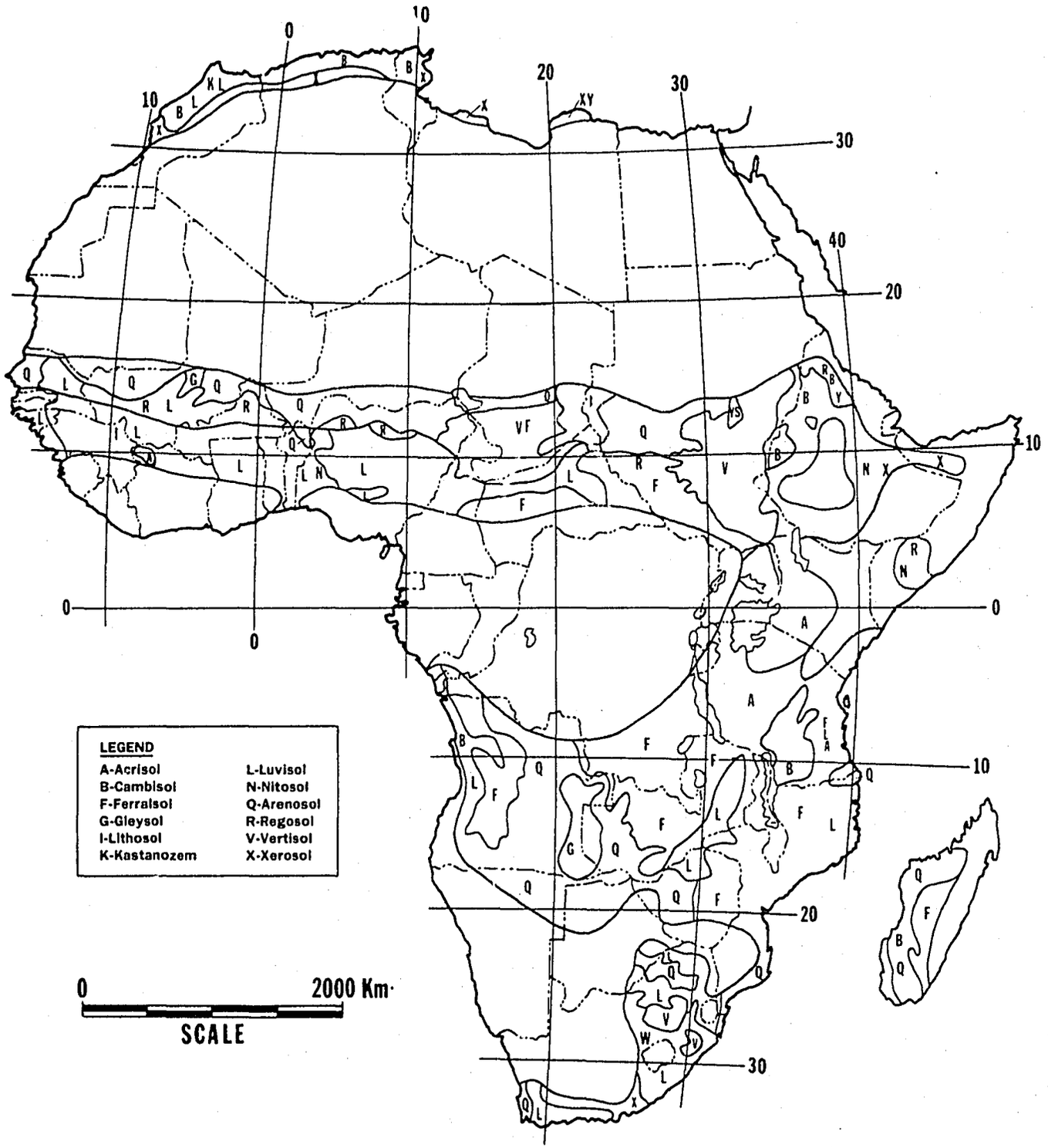

Figure 7. Principal soil orders of dryland regions of Africa.

Rendzinas. Many of the soils are shallow, stony, or gravelly and occupy moderate to steep slopes. The better soils are moderately productive and respond to nitrogen and phosphorus.

Similar soils occur in northern Ethiopia, Kenya, and Tanzania. The shallow and stony soils are even more prevalent in East Africa than in North Africa.

South of the Sahara -- except for Ethiopia, Kenya, and northern Tanzania -- leached acidic soils are the rule. Even in the dry, Sahel upland soils are acidic if the annual rainfall exceeds 400 mm. The reason is that the soils are sandy and permeable and virtually all of the rain falls in three months, during which time precipitation may exceed potential evapotranspiration. In a continental climate with annual precipitation of 400 mm, the upland soils usually are calcareous.

In the wet summer regions, Cambic Arenosols and Luvic Arenosols are found in the drier zones; Ferric Luvisols, Plinthic Luvisols, Eutric Regosols, and Ferralic Arenosols in the intermediate zones; and Ferric Acrisols and Orthic Ferralsols in the wetter dryland zones. All are deep soils, and all have weak to moderate argillic horizons except the Regosols.

The transition toward progressively wetter zones brings an increase in the content of 1:1 clay minerals and hydrous iron and aluminum oxides, greater phosphorus fixation capacity, and more petroferric and plinthite horizons in the subsoil. And more crusting and hardening problems.

Soil Surveys

The only comprehensive study of world soils that involved mapping and descriptions was the recently completed Soil Map of the World project. They have been published over a period of ten years (FAO/Unesco, 1971, 1974, 1975a, 1975b, 1975c, 1977, 1978a, 1978b, 1979, 1981). D'Hoore published an excellent

report -- with map -- on the soils of Africa in 1964 (D'Hoore, 1964). Map sheets showing the soils of Asia in the U.S.S.R. classification have been published but without an explanatory text (Kovda and Lobova, 1970).

The FAO/Unesco soil map publications mention sources of information that were utilized in the preparation of the reports. The Africa report lists soil survey maps and reports that have been prepared for each country. About seven percent of the continent has survey maps that are reasonably reliable, although the quality of the mapping varies considerably. Another 38 percent of Africa is covered by reconnaissance maps showing broad soil differences, usually based on climate and vegetation rather than on field studies. The remaining 55 percent is virtually unknown from the standpoint of field observations.

Among the many factors that reduce the usefulness of soil maps and reports is that the scale, the mapping system, the accuracy of the base maps, and the knowledge and experience of the mappers differs greatly from survey to survey. Bits and pieces of soils information can be found in ministry of agriculture offices and elsewhere in every country but their utility is minimal because of their mode of preparation. A tremendous amount of analytical data has accumulated that is virtually useless because the methods employed and the sampling location and conditions are not known.

The biggest single problem in soil classification is the multitude of classification and survey systems in use in the past and today. And the international situation will get worse in the future as national soil survey agencies develop new classification guides. Forty years ago, most national soil survey agencies used a version of the Russian classification system based on what Baldwin et al.(1938) called "great soil groups". Since 1965, the U.S. Soil Conservation Service has been using a radically different system

(Soil Survey Staff, 1975) based on a quantitative rather than a qualitative assessment of soil properties. Later, FAO introduced a new system for the FAO/Unesco Soil Map of the World, the Australians began the change to the very different profile form concept (Northcote, 1971), and the French have begun testing a major change in their system (ORSTOM, 1979). Other nations are involved in less dramatic changes. The result is a number of incompatible classifications of soils, where boundaries on one map are completely different from boundaries on other maps of the same area. Confusion reigns. The one reassuring factor is the approaching similarity in horizon terminology, and the use of diagnostic horizons for classification purposes.

Appendix 3

Dryland Soil Management

By definition, dryland soil management revolves around water conservation, in one form or another. Water conservation calls for 1) rain water to be held where it falls or to be collected from small or large watersheds (while avoiding waterlogging), 2) infiltration of the water into the soil, and 3) reduction in evaporative losses of stored soil water.

Nearly as important as water conservation -- and sometimes more important -- is the provision of fertilizer elements to deficient soils. Water use efficiency is a function of the nutrient status of the plant (Viets, 1962), among other things, and a low soil phosphorus level in the tropical drylands may be more of a crop production limitation than water.

Fallowing

Fallowing is a practice that arises from a need to conserve water or restore fertility or do both. Grass fallow or bush fallow is different from the clean fallow practiced in mechanized agriculture in that its purposes are to increase fertility, improve infiltration, and reduce erosion (FAO, 1960). Clean fallow is for water conservation, with fertility improvement a side benefit (USDA, 1974). Grass fallow can conserve deep soil moisture, under some circumstances (Charreau, 1974), and is the kind of fallow practiced in the Sahel. If grass fallow is left untouched for several years, bushes and trees appear.

In addition to the effects of grass fallow on fertility improvement, infiltration rates may also be improved. That improvement, however, occurs only if the fallow is allowed to continue for about six or more years. Even then, a single moldboard plowing can negate that effect (Charreau, 1974).

With the increase in population that is a fact of life everywhere in the developing world, fallow periods are becoming shorter and shorter, which means, in most cases, that they are becoming less and less effective in restoring soil fertility. Potential dryland crop yields in Botswana, for example, were considerably greater than actual yields even several years ago (Bawden and Stobbs, 1963). Mineral fertilizers appear to be essential to raise soil nutrient contents since manure is generally in short supply, long fallow periods are no longer practicable, and no suitable short season legumes have yet been identified for Africa south of the Sahara, although leucaena looks promising for some situations (AID, 1981).

Fertilizer

Nitrogen and phosphorus are the principal fertilizer nutrients likely to be deficient in African soils (Charreau, 1974; Aitchison et al, 1972; Sanchez, 1976). Ahn (1977) says sulfur deficiencies are common in the Sahel, Maignien (1965) described sulfur deficiency in Senegal, and Blair (1979) describes sulfur deficiencies elsewhere in the tropics. Numerous reports have been made of microelement deficiencies in the tropics but there is no easily identifiable pattern in their occurrence.

Despite well-documented nutrient deficiencies in dryland soils, poor responses to field fertilizer applications are frequent. Charreau (1974) notes some of the reasons: 1) unresponsive plant varieties, 2) inadequate or no weed, disease, and insect control, 3) low plant populations, and 4) inadequate rainfall. The latter reason is a common one that reduces the economic value of applying mineral fertilizers. Lal and Kang (1982) note the opportunities and the limitations associated with the use of organic materials to increase soil fertility while improving physical conditions.

Crusting and Hardening

Surface sealing and hardening contribute to poor seedling emergence and to restricted root development in West Africa (Charreau, 1974; Ahn, 1977), Thailand (Moorman and Rojanasoonthon, 1972), Botswana (Willcocks, 1980), and Nigeria (Aitchison et al, 1972), and elsewhere. Tillage to break the crust and increase soil porosity is essential for water infiltration. Poor or uneven plant stands due to unfavorable soil physical conditions is one of the major causes of low crop yields in the semi-arid tropics (ICRISAT, 1981). Another cause is the delay in planting occasioned by the inability of the cultivator to hoe his land before the rainy season is well under way (Ahn, 1977). Organic matter increases through crop rotations would help ease the problem but the economic advantage of doing so on a field scale has not been demonstrated. Lal and Kang (1982) contend that it is better to feed the green manure crop to cattle and add the resulting manure to the soil, using crop residue mulches to increase surface organic matter levels.

Water Erosion

Soil losses to water erosion in Africa were described by Jacks and Whyte (1939) several decades ago. More recently, Lal and Greenland (1979) have elaborated upon the severity of the problem. Some of the worst water erosion in the world has devastated Lesotho (Coates, 1966): land is overgrazed, soils are unstable, rains are hard, slopes are steep, no conservation practices are used, and gully erosion is terrible. The same listing of contributions to soil loss would apply to other countries of the tropics and subtropics. And the results would also be the same.

Damaging water erosion has led to the establishment of government soil conservation programs in the Mahgreb countries of North Africa, in East Africa, and in southern Africa. Erosion has been recognized as a problem in

West Africa and field experiments have been conducted on erosion control (Delwaulle, 1973) but little action seems to be taken by governments to cope with the problem. As a Britisher working in Africa said (Huxley, 1937), erosion is a problem designed for deferring because it is thorny, packed with political dynamite, and will always keep for another couple of years.

Swindale (1982) has noted the excessive water erosion occurring on Vertisols in India during the summer monsoon rains. He emphasizes the need to develop farming practices that not only will control erosion during that highly susceptible period but will also take advantage of the favorable moisture conditions at that time. Current common practice is to plant after the rainy season is well advanced and the soils are soft enough to plow more easily than when they are dry or to crop only in the post-monsoon period.

Prediction of soil losses due to water erosion has advanced considerably with the development and testing of the Universal Soil Loss Equation (Wischmeier and Smith, 1965). Application of the equation to Africa has been discussed in two recent books (SCSA, 1975; de Boodt and Gabriels, 1980). An adaptation of the equation to Zimbabwe conditions has been made by Elwell and Stocking (1982). The principal problems in applying the Universal Soil Loss Equation to tropical areas reside in determination of a suitable rainfall factor (R) and crop factor (C).

Wind Erosion

Wind erosion in Africa dryland agriculture areas is principally a problem in the sandy soils (Arenosols) of the Sahel from Senegal and Mauritania to Somalia. Studies on windbreaks and sand dune stabilization have been conducted for several years in the region (Delwaulle, 1977). Again, however, little has been accomplished to reduce erosion in farmer fields.

A wind erosion prediction equation has been developed (Woodruff and Siddoway, 1965) but it has, thus far, limited applicability, even in the United States. The status of wind erosion research is indicated by the fact that two major books on erosion (SCSA, 1977; de Boodt and Gabriels, 1980) do not even discuss wind erosion.

Bibliographies

Oregon State University published a Bibliography of Dryland Agriculture under its 211(d) AID grant titled, "Moisture Conservation and Utilization in Low Winter Rainfall Areas of LDCs" (OSU, 1980). The third edition has listings by author, subject, and title. There are 4700 entries.

An information network called "CIDNET" was established by the University of California at Riverside under its 211(d) AID grant titled, "Moisture Utilization in Semi-Arid Tropics: Summer Rainfall Agriculture". CIDNET is computerized, has 32,000 entries, and is searchable. A book titled, Proceedings of an International Symposium on Rainfed Agriculture in Semi-Arid Regions, was published under the AID grant in 1977 (Cannell, 1977).

Appendix 4

Characteristics of Soil Orders

The principal distinguishing characteristics of the important FAO/Unesco soil orders occurring in dryland regions are as follows:

ACRISOLS:	soils having a B horizon of illuvial clay accumulation, with a low base saturation.
ANDOSOLS:	soils derived from volcanic ash.
ARENOSOLS:	weakly developed sandy soils.
CAMBISOLS:	weakly developed soils showing changes in color, structure, and consistence in the subsoil resulting from weathering in place.
CHERNOZEMS:	black colored soils rich in organic matter.
FERRALSOLS:	soils high in sesquioxides.
GLEYSOLS:	wet soils.
KASTANOZEMS:	brown or chestnut colored soils rich in organic matter.
LITHOSOLS:	shallow and/or stony soils.
LUVISOLS:	soils having a B horizon of illuvial clay accumulation, with high base saturation.
NITOSOLS:	soils of humid regions with an argillic B horizon, with minimal clay difference in upper 150 cm.
PHAEOZEMS:	soils of subhumid regions having a mollic A horizon and a leached permeable profile.
REGOSOLS:	weakly developed upland soils on unconsolidated material other than clay and volcanic ash.
SOLONCHAKS:	saline soils.
SOLONETZ:	sodic soils.

VERTISOLS: deep cracking clays.

XEROSOLS: upland soils of arid regions.

YERMOSOLS: upland soils of extremely arid regions.

In addition to these 18 soil orders, there are many relatively small areas along rivers where Fluvisols (recent alluvium) are dominant. Those areas are too narrow to show on the maps.

The equivalence of FAO/Unesco and U.S. soil orders is approximately as follows:

Acrisol - Ultisol

Andosol - Inceptisol

Arenosol - Entisol

Cambisol - Inceptisol

Chernozem - Mollisol

Ferralsol - Ultisol and Oxisol

Gleysol - Inceptisol and Mollisol

Kastanozem - Mollisol

Lithosol - lithic subgroups

Luvisol - Alfisol

Nitosol - Alfisol and Ultisol

Phaeozem - Mollisol

Regosol - Entisol

Solonchak - salic groups and subgroups

Solonetz - natric groups and subgroups

Vertisol - Vertisol

Xerosol - Aridisol

Yermosol - Aridisol

Appendix 5

Sources of Research Information

Two recently established centers have primary responsibility for dryland soil management research among the international agricultural research institutes operating under the auspices of the Consultative Group on International Agricultural Research (CGIAR). They are the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), begun in 1972, and the International Center for Agricultural Research in Dry Areas (ICARDA), established in 1976. ICRISAT is headquartered in Hyderabad, India and ICARDA in Aleppo, Syria. Both centers have their programs focussed on particular dryland crops. ICRISAT concentrates its efforts on the dry tropics with summer (warm-season) rainfall and ICARDA on the semi-arid temperate zones winter (cool-season) rainfall. Each center has cooperative research programs with several developing countries.

Among the other CGIAR centers, the Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) in Mexico City, Mexico and the International Institute of Tropical Agriculture (IITA) in Ibadan, Nigeria have been most involved in coping with dryland soil problems in subhumid regions. ICRISAT and IITA have done much research on dryland farming systems, taking the holistic, farm management approach to increasing agricultural production.

All of the international centers produce annual reports as well as specialized reports and the proceedings of conferences. The publications are available from the individual centers.

The Food and Agriculture Organization of the United Nations (FAO) conducts applied research in developing countries around the world, with major emphasis on soil fertility and soil conservation. Its greatest contribution to dryland

soil management is its program of soil surveys, which provide the basic information on soil characteristics. Research and soil survey publications frequently are difficult to identify and obtain because there is no readily available and comprehensive publication list, even in FAO headquarters. Copies usually are easier to obtain in the country concerned, if they can be located. Few copies are made of the great majority of FAO-sponsored reports. Most are mimeographed.

FAO has two series of publications dealing with soils. Soil classification studies are reported in the World Soil Resources Reports. Reports on soil properties and management are found in FAO Soils Bulletins. Additionally, there are numerous reports on expert consultations and on specialized subjects such as the FAO soil conservation guide titled "Conservation in arid and semi-arid zones". The Soil Map of the World Project was a joint FAO/UNESCO project and copies are available through UNESCO sales offices.

For the Francophone countries of North Africa and West Africa, the principal source of published information on soil properties is the Office de la Recherche Scientifique et Technique d'Outre-Mer (ORSTOM) in Paris, France. Whereas O.R.S.T.O.M. is primarily concerned with basic soil resource data, the Institut de Recherches Agronomiques Tropicales (IRAT) headquartered in Nogent, France conducts research on crop and soil management. IRAT has operated a number of research stations in West Africa, for many years. The Centre Technique Forestier Tropical in Nogent-sur-Marne, France has conducted considerable research on water erosion control in the Sahel countries. The Centre publishes a journal Bois et Forêts des Tropiques. Aside from the forestry center journal, publications of the French research organizations are not readily available outside headquarters offices in France and research centers in individual countries.

In former British colonies, the Ministry of Overseas Development of the United Kingdom conducts research and carries out land resource surveys. Nigeria and Botswana have received most attention in Africa. A long-time dryland farming research project was completed in 1979 in Botswana, for which reports are available from the Land Resources Development Center of the Ministry of Overseas Development in Surbiton, Surrey, England.

Nearly all developing countries will have had land resource surveys of varying quality made at some time - and probably several times - by FAO, UNESCO, the United Nations Development Programme, the World Bank, the Arab League, or technical assistance agencies of Germany, France, the United Kingdom, the United States, Canada, etc. Obtaining copies of such reports is very difficult. It usually is necessary to probe around in offices of government ministries of agriculture, rural development, planning, and finance, plus other offices to learn what has been done and to find copies. Information on what soil and other natural resource surveys have been carried out can usually be found in country environmental reports and in area handbooks of the U.S. State Department.

The Instituto Interamericano de Ciencias Agricolas (IICA) in San Jose, Costa Rica, sponsored by the Organization of American States, is a specialized agency for the agricultural sector of Latin America. It maintains a library dealing with natural resources and rural development and contains many documents with very limited circulation. IICA administers a research and training center for tropical agriculture, the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) at Turrialba, Costa Rica.

Three publications are or will be the principal sources of research information on dryland soil management in the United States. One is Summer Fallow in the Western United States (USDA, 1977). The second is Dryland Farming

by K. G. Brengle, published by the Colorado Associated University Press of Boulder, Colorado. The third one, Dryland Agriculture, edited by H. E. Dregne and W. O. Willis, is in press and will be published by the American Society of Agronomy, Madison, Wisconsin. Together, these three publications cover the significant research on dryland soil management in North America. It should be remembered, however, that the climates are of the continental and winter rainfall types. Similar climates in developing countries are limited to the Mediterranean Sea region, the Middle East, China, and southern South America.

It is fair to say that there is a wealth of information available on dryland soil resources throughout the world but it is difficult to obtain. Data on dryland soil management are scarce, primarily because little emphasis has been put on that subject in developing countries. Most research resources have gone into humid region and irrigation agriculture studies. Computerized information retrieval systems and abstract services have helped increase the effectiveness of literature searches but the majority of reports are not on anyone's computer list or are not available.

Addresses of some national and international organizations having publications dealing with dryland soils resources are listed below.

A. International Agriculture Research Centers

1. International Crops Research Institute for the Semi-Arid Tropics ICRISAT)
   ICRISAT Patancheru P.O., A.P. 502324
   India

2. International Centre for Agricultural Research in Dry Areas (ICARDA)
   P.O. Box 5466
   Aleppo
   Syria

3. International Institute for Tropical Agriculture (IITA)
   PMB 5320
   Ibadan
   Nigeria

4. Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT)
   Apartado 6-641
   Mexico 5, D.F.
   Mexico

5. Centro Internacional de Agricultura Tropical (CIAT)
   Apartado Aereo 67-13
   Cali
   Colombia

B. France

1. Office de la Recherche Scientifique et Technique d'Outre-Mer (ORSTOM)
   24, rue Bayard
   75008 Paris
   France

2. Institut de Recherches Agronomiques Tropicales et des Cultures Vivrieres (IRAT)
   110, rue de l'Université
   75340 Paris Cedex 07
   France

3. Centre Technique Forestier Tropical
   45 bis, avenue de la Belle-Gabrielle
   94130 Nogent-sur-Marne
   France

C. Latin America

1. Instituto Interamericano de Ciencias Agricolas (IICA)
   Apartado 10281
   San Jose
   Costa Rica

2. Centro Agronomico Tropical de Investigacion y Enseñanza (CATIE)
   Turrialba
   Costa Rica

D. Middle East and North Africa

1. Arab Center for Studies of Arid Zones and Dry Lands (ACSAD)
   P.O. Box 2440
   Damascus
   Syria

E. United Kingdom

1. Land Resources Development Center
   Ministry of Overseas Development
   Surbiton, Surrey
   England

F. United Nations

1. Food and Agriculture Organization (FAO)
   via delle Terme di Caracalla
   00100 Rome
   Italy

2. United Nations Educational, Scientific, and Cultural Organization (UNESCO)
   7, place de Fontenoy
   75007 Paris
   France

Appendix 6

Dryland Soil Research Needs

Four dryland soil problems are particularly important worldwide: 1) low soil fertility, 2) water conservation, 3) water erosion, and 4) crusting and compaction. In areas where deep cracking Vertisols on uplands are extensive, such as in India, safe water disposal during the rainy season is also a problem.

Low Soil Fertility

Answers are needed for several questions concerning fertility improvement. One of them is the matter of what are the best times, rates, and placements of mineral fertilizers for farming operations where the power comes from hand labor, or animal draught. Another is to identify the conditions under which rock phosphate is a suitable phosphorus source. Still another is the possibility of utilizing a short-season legume to provide nitrogen. And how to make the best use of livestock dung remains an unanswered question.

If success is to be achieved in increasing soil fertility, the research approach will need to consider why the farmer does what he does now, what the realistic potential for yield increases are, what changes must be made to achieve that potential, and how the changes can be introduced gradually.

The greatest challenge, at first, seems to be that of learning how to make the most effective use of minimal amounts of mineral fertilizers. The solution may be to fertilize only the most profitable and most responsive crops. Nitrogen and phosphorus are the key elements now. At some time in the future, potassium, sulfur, and microelements can be expected to become important limiting elements, at least under certain conditions. Studies are needed now to identify where these deficiencies will arise.

Water Conservation

Much of the research conducted in the developed countries can be expected to be transferable, in principle, to developing countries. Probably nearly all of what is known about water conservation in winter-rainfall areas of the United States, for example, is transferable to winter-rainfall areas elsewhere. The same would be true for continental climates. However, the big unanswered question is what water conservation practices can be used successfully in the summer-rainfall zones having permeable soils with low water-holding capacities. A second question, of importance on Vertisols of India, is how much good it does to even try to hold rain on slowly permeable soils where soil aeration may be restricted.

Water conservation on heavy clays in subhumid regions can be a means of thoroughly wetting the soil profile before the onset of an extended dry season. Research is needed on the effectiveness of that practice as contrasted with the need to allow the soil to dry at harvest time for the wet season crops.

In the drier regions, water conservation and water erosion control are mutually supportive practices, for the most part. However, that becomes less true when rains are hard, as they typically are in the tropical summer-rainfall climatic zones. Under those conditions trying to control erosion while conserving water must be balanced by avoiding drowning of crops in ponded water. Little research has been done on that problem.

Water Erosion

Erosion control practices and structures have been developed to the point where guides to soil conservation are widely available. One of these guides is FAO Soils Bulletin 30, Soil Conservation for Developing Countries.

While testing of erosion control practices in the local setting is essential before broad-scale application is undertaken, most of the basic

research needed for soil conservation appears to have been done. The problem of erosion control is in acceptance and application by farmers of recommended practices.

Crusting and Compaction

Coping with the widespread problem in dryland tropical soils, especially, of surface soil sealing and reduced porosity and hardening of the A horizon is a major research challenge. This is another area where little research has been done.

Tillage equipment is used to break crusts and to increase porosity but that is only a temporary solution that must be repeated after another wetting and drying cycle. Furthermore, draught requirements for loosening a soil may exceed oxen power. The obvious solution is to change the soil, and increasing organic matter is the way to do that. But raising organic matter levels in tropical soils is very difficult. Mulching with crop residues may reduce surface soil sealing and delay soil hardening, but residues frequently are not available at planting time or cannot be manipulated satisfactorily using hand labor or oxen.

The hardening phenomenon is one of the greatest impediments to early planting of crops in summer-rainfall zones. Until that problem is solved, maximum beneficial use of rain is impossible.

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