Improving and Sustaining Productivity in Dryland Regions of Developing Countries*

J.L. Steiner, J.C. Day, R.I. Papendick, R.E. Meyer, and A.R. Bertrand

I. Introduction

Interest in dryland and rain-fed farming systems has increased significantly in recent years in many regions of the world because of rapidly increasing human populations coupled with low productivity gains, escalating water development costs for new irrigation projects, and high operation and maintenance costs associated with irrigated agriculture.

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The terms "rain-fed" and "dryland" are often used synonymously, but in fact, they refer to vastly different physical and biological systems. Both rain-fed and dryland systems exclude irrigation, but beyond that, they can differ significantly. Stewart and Burnett (1987) characterized dryland agricultural systems as those that emphasize water conservation, sustainable crop yields, limited inputs for soil fertility maintenance, and wind and water erosion constraints, whereas rain-fed systems in more humid zones often emphasize disposal of excess water, maximum crop yields, and substantial inputs of fertilizer. Oram (1980) also distinguished between rain-fed farming and dryland agriculture stating that dryland agriculture—as opposed to rain-fed farming—is defined as husbandry under conditions of moderate to severe moisture stress during a substantial portion of the year, which require special cultural techniques and adapted crops and systems for successful and stable agricultural production. Such conditions generally occur in regions classified as semiarid or arid. Pastoral systems are an important part of dryland agriculture, because in some areas, particularly arid areas, they constitute the sole form of agricultural use. However, the purpose of this paper is to discuss dryland crop production in developing areas, including a description of dryland areas, major constraints to dryland productivity, and measures required to alleviate these constraints.

A. Definition of Dryland Areas

Although dryland regions can be described in general terms, specific delineations of dryland areas are difficult. Two contrasting and influential definitions are those based on an aridity index and on length of the growing period.

1. Aridity Index

The United Nations Conference on Desertification (UNESCO, 1977) defined bioclimatic zones based on the climatic aridity index: P/ETP, where P = precipitation and ETP = potential evapotranspiration calculated by the method of Penman (Doorenbos and Pruitt, 1977), taking into account atmospheric humidity, wind, and solar radiation. The zones established by the conference (UNESCO, 1977) were as follows: (1) the *hyperarid zone* ($P/ETP < 0.03$), consisting of areas largely void of vegetation except for ephemerals and shrubs in river beds and which are virtually unsettled; (2) the *arid zone* ($0.03 < P/ETP < 0.20$), comprising dryland areas with sparse perennial and annual vegetation utilized mainly by pastoral systems; (3) the *semiarid zone* ($0.20 < P/ETP < 0.50$), including steppe or tropical shrubland with a discontinuous herbaceous layer and increased frequency of perennials where dryland farming is widely practiced; and (4) the *subhumid zone* ($0.50 < P/ETP < 0.75$), characterized by more dense vegetation where rain-fed farming is widely practiced with crops adapted to seasonal drought.

2. Growing Period

The Food and Agriculture Organization (FAO) of the United Nations (FAO, 1978a) used the growing period as the basis for assessing climatic resources in developing countries. The growing period is the number of days during a year when precipitation exceeds half the potential evapotranspiration, plus a period required to use an assumed 100 mm of water from excess precipitation (or less, if not available) stored in the soil profile. A normal growing period by their classification must exhibit a humid period, having an excess of precipitation over potential evapotranspiration. Growing periods that did not include a humid period were classified as intermediate periods. Finally, areas where precipitation never exceeded half the potential evapotranspiration were classified as dry with no growing period. Additionally, any time interval during the period when water is available is excluded if the temperature is too low for crop growth (mean temperature below 6.5°C). Calculation of the growing period is based on a simple water balance model, comparing precipitation (P) with potential evapotranspiration (ETP).

Areas having a growing period between 1 and 74 days are classified as arid, and areas with growing periods between 75 and 119 are considered semiarid. The regions of Africa (FAO, 1978a), southwest Asia (FAO, 1978b), southeast Asia (FAO, 1980), and South and Central America (FAO, 1981) have been characterized by this classification system.

3. Example Locations

The average monthly precipitation, potential evapotranspiration, and half-potential evapotranspiration for three locations are presented in Figure 1. All three locations are classified as semiarid by the aridity index ($0.2 < P/ETP < 0.5$). However, by the FAO growing period classification, only the Rajkot, India, location is classified as semiarid. This location has a growing period of 96 days, which is within the 75-to-119-day range classified as semiarid. The Amman, Jordan, location has a growing period ($P > 0.5$ ETP) in excess of 120 days, so this location would not be considered semiarid. Bushland, Texas, located in a major dryland farming region in the United States, would be classified as dry, with a 0-day growing period, because the average monthly precipitation never exceeds 0.5 ETP.

These examples point out that there is still a lot of imprecision in defining and classifying climatic zones. Each classification scheme presented, as well as many others in the literature, has advantages for specific purposes and locations, but subjective judgment is required for their interpretation.

Although it is difficult to clearly delineate dryland areas, they do have certain common climatic characteristics. Oram (1980) lists these as (1) low total rainfall with at least one pronounced dry season (and sometimes two) so that lack of moisture puts a ceiling on year-round cropping even though

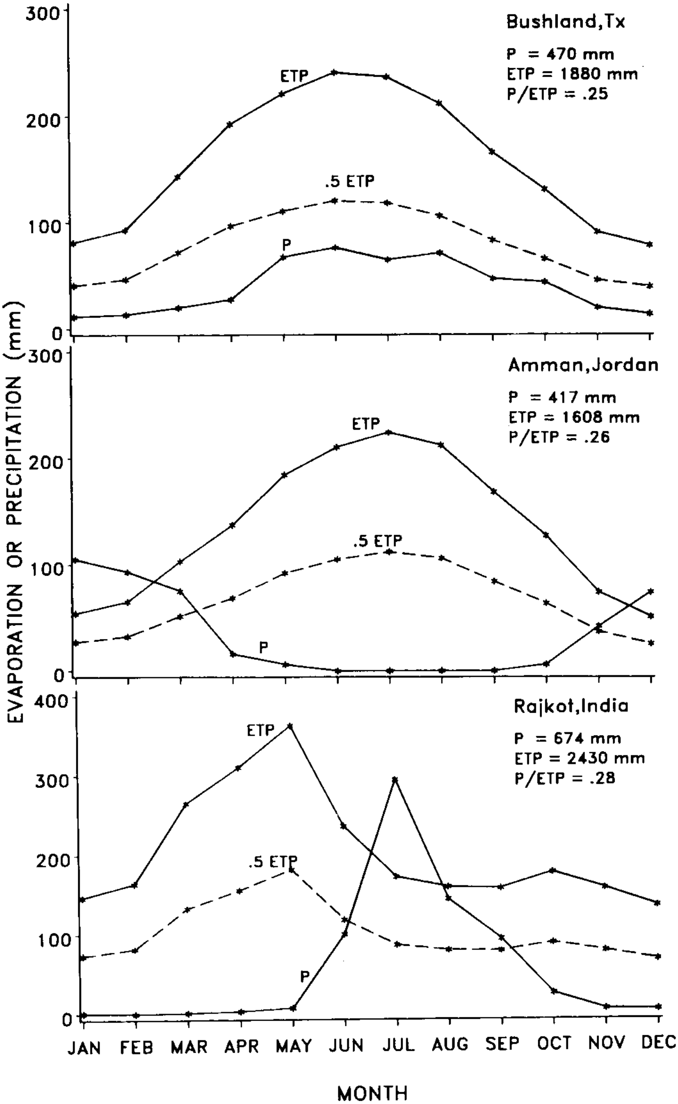

Figure 1. Agroclimatic characteristics of three representative dryland locations.

it may be adequate for one crop; (2) highly variable and unreliable precipitation during the rainy season, with large year-to-year differences in total rainfall and its distribution, and from month to month within seasons; (3) increasing unreliability and variability with decreasing annual rainfall; (4) potential evapotranspiration exceeding precipitation for at least 7 months of the year; and (5) very high-intensity rainstorms leading to high runoff and erosion.

B. Geographic Distribution

The dryland agricultural regions of the world, as characterized by Dregne (1982), are shown in Figure 2. Dregne included areas having a growing period of 90–270 days. These areas are essentially those commonly referred to as semiarid and subhumid. In the wetter parts of these areas, 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.

A more conservative, and perhaps a more accurate, representation of dryland areas is presented in Figure 3 for the developing countries of the world. This map is based on the FAO (1978a) growing period classification described earlier and represents arid and semiarid regions. The arid regions are used mostly for pastoral systems, and crop production is largely restricted to the semiarid regions.

The extent of the dryland areas can be more clearly shown by the data presented in Table 1. Very large portions of Africa and southwest Asia are in the low-rainfall regions. The 1975 human population numbers for the respective areas are shown in Table 2. Southwest Asia has about 30% of its total population in the dryland regions, and Africa and southeast Asia have larger absolute numbers of people in the dryland areas than southwest Asia, although they have lower percentages of their population in dryland areas. The population numbers reported are 1975 figures and would be substantially higher now, because the rate of population growth in many of the dryland regions is in excess of 2.5% annually (World Bank, 1986).

C. Precipitation Patterns

Four kinds of rainfall distribution patterns occur in dryland regions—winter, summer, continental, and multimodal (Dregne, 1982). The winter rainfall type, also known as Mediterranean, is characterized by most of the precipitation occurring in 8 or 9 cool months, with the other months completely or nearly dry. This pattern is found along the west coast of South and North America, in southern and western Australia, and around the Mediterranean Sea as far east as Iran. The data for Amman, Jordan, in Figure 1 represents this pattern. The summer rainfall type has precipitation concentrated in 3–5 summer months, with the remainder of the year being dry. Rainfall in the Sahelian countries south of the Sahara follows this pattern, with the rainy season becoming longer with increasing distance south from the Sahara. Botswana, northeastern Brazil, and northern Australia have similar patterns. The pattern shown in Figure 1 for Rajkot, India, is fairly typical of this summer rainfall type. "Continental" rainfall patterns have precipitation distributed throughout the year, with pronounced summer peaks and with lesser amounts during the winter, often occurring as snow. This pattern is dominant in regions of central North America, the Soviet Union, China, and Argentina and is represented in

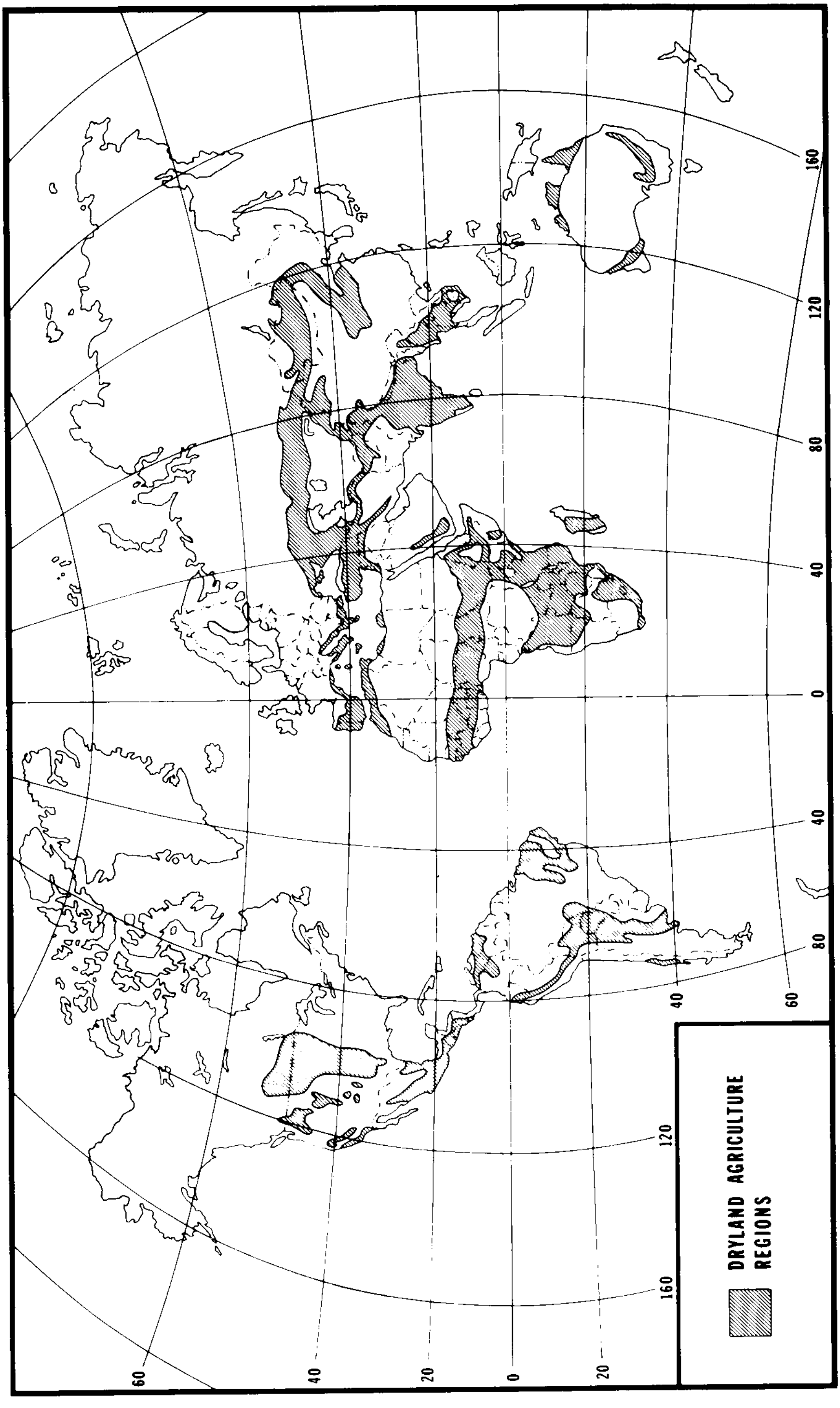

Figure 2. Dryland areas of the world (Dregne, 1982).

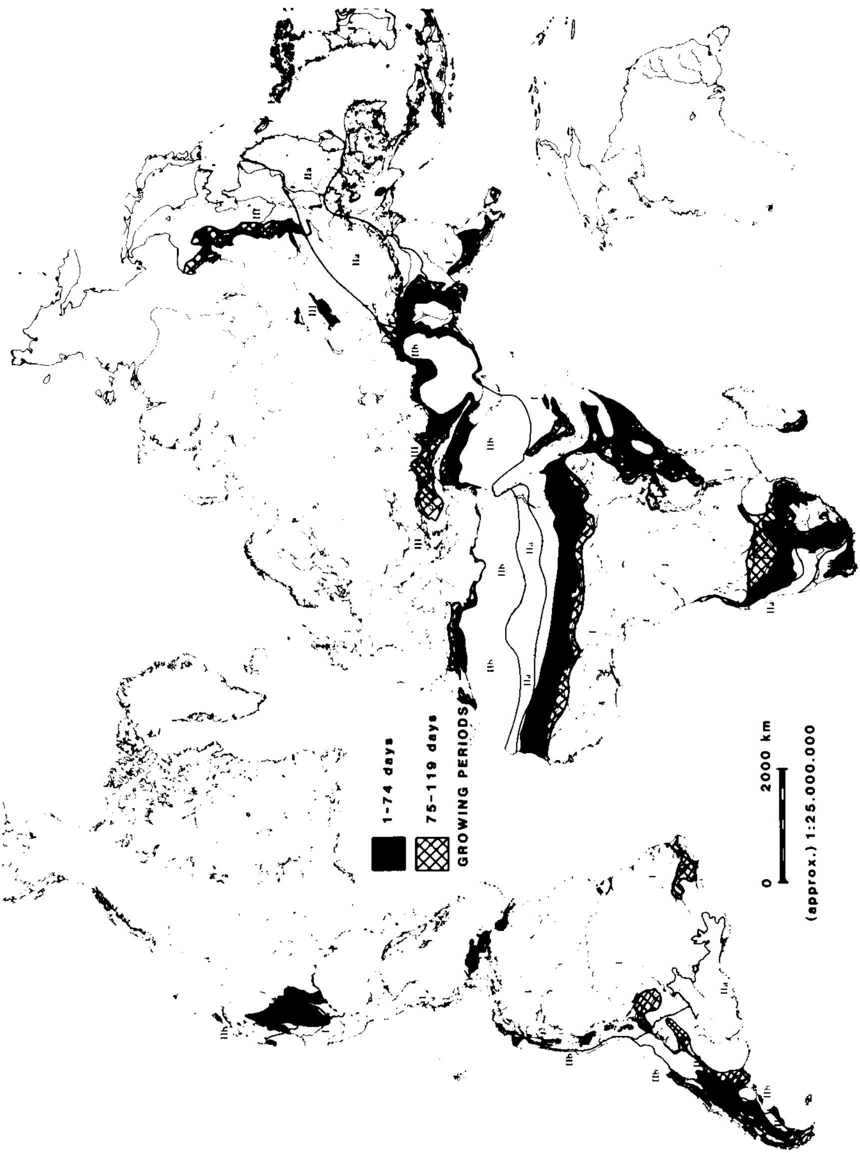

Figure 3. Dryland areas of developing regions (adapted from FAO, 1974).

Table 1. Land area of different growing season zones in developing countries within major geographic regions (in millions of hectares)

Growing days (number)	Africa[a]	Southwest Asia[a]	Southeast Asia[a]	Central America[a]	South America[a]	East Asia[b]
0—Cold	9.1	113.7	47.7	0.8	60.8	NA
0—Dry	846.7	369.7	39.2	35.9	81.2	NA
1–74[c]	*487.9*	*72.6*	*54.6*	*62.2*	*114.6*	*27.7*
75–119	*230.7*	*61.9*	*55.0*	*12.1*	*116.7*	*70.4*
120–179	314.7	37.0	146.9	50.7	113.7	NA
180–269	548.1	20.2	249.7	66.9	293.6	NA
270–365	440.9	2.3	304.5	43.0	989.6	NA
Total	2878.1	677.4	897.6	271.6	1770.2	954.6

Consolidated from data in [a]FAO, 1982; [b]FAO, 1987.

[c]Figures in italics represent arid and semiarid regions.

Table 2. Human population in millions in 1975 in developing countries within major geographic regions living in different growing season zones[a]

Growing days (number)	Africa	Southwest Asia	Southeast Asia	Central America	South America	East Asia
0—Cold	3.7	36.3	11.5	4.2	8.0	NA
0—Dry	48.8	20.2	27.4	3.0	8.1	NA
1–74[b]	*31.0*	*16.1*	*46.2*	*8.5*	*9.4*	*NA*
75–119	*32.7*	*24.4*	*101.1*	*3.8*	*21.1*	*NA*
120–179	98.3	17.9	286.0	25.5	25.2	NA
180–269	113.6	19.6	385.5	45.2	41.0	NA
270–365	78.8	1.8	260.0	16.4	103.0	NA
Total	406.9	136.3	1117.7	106.6	215.8	NA

[a]Consolidated from data in FAO, 1982.

[b]Figures in italics represent arid and semiarid regions.

Figure 1 by the data for Bushland, Texas. The multimodal type, with two or more short rainy periods interspersed with dry months, occurs in parts of eastern Africa and southeast Asia.

D. Present Situation

Land degradation is common in many dryland regions and can lead to desertification. Degradation processes can be arrested and even reversed, but desertification is a continuously degrading process going through several stages before reaching an irreversible stage. Desertification is the impoverishment of terrestrial ecosystems under the impact of human pressure. It results in deterioration of ecosystems that can be detected by reduced productivity of desirable plants, undesirable alteration in the biomass and diversity of the micro and macro fauna and flora, accelerated soil erosion, and increased hazards for human occupancy (UNESCO, 1977).

Although there is a substantial base of scientific and technological information on how to control land degradation, the problem is accelerating in many arid and semiarid regions of the world. In the African Sahel, extensive land areas that were once productive have been added to the territories of the Sahara. In the past two decades, deserts have expanded southward in the Sudan by 90–100 km. Large areas of agricultural lands are being degraded in Brazil, Iran, Pakistan, Afghanistan, and the Middle East. Morocco, Algeria, Tunisia, and Libya are also affected (Mageed, 1986).

The FAO (1974) Report on Improving Productivity in Low Rainfall Areas to the Committee on Agriculture identified 64 countries with low-rainfall problems (Table 3). Their report focused on the 21 countries with most of their land (92% average) in low-rainfall areas and with little or no irrigation (category II). A recent study by the U.S. Department of Agriculture (1985) identified 43 developing countries with declining grain production per person, 1950–52 to 1982–84. Of the 21 category II countries mentioned above, 14 showed declines in per capita food production ranging from 2% to 68%, with an average decline of 28% (Table 4).

A recent study (FAO, 1982) of the developing world (excluding east Asia) concluded that with all regions taken as a whole, the total land and water resources were capable of producing sufficient food to sustain twice their 1975 population and one and a half times their projected year 2000 population, even with a low level of agricultural inputs. However, when individual countries were assessed, 15 of 16 countries in southwest Asia were not capable of feeding their present or expected populations from their own lands with low level of inputs, and in Africa, population levels in 30 of 51 countries would exceed the potential supporting capacity of their land resources with low level of inputs by the year 2000. The study further projected that 19 countries will be unable to meet their food needs from national land resources, even with high levels of inputs. These countries, without exception, are dominated by drylands. This study clearly shows the importance of the drylands in many countries and the urgent need for improving the productivity of these areas.

Water resources are very limited in dryland areas, but the principal causes of desertification result from overuse and inadequate management of physical and biological resources. Sung-Chiao (1981) identified resource degradation as a major limitation to productivity in many arid and semiarid regions of China. Conservation of physical resources was identified as the

Table 3. Countries affected by low-rainfall problems[a]

Country	Low-rainfall area (%)	Country	Low-rainfall area (%)	Country	Low-rainfall area (%)	Country	Low-rainfall area (%)
Developing Countries							
Category I[b]:		Category II:		Cateogry III:		Category IV:	
Egypt	100	Botswana	91	Nigeria	28	Angola	23
Iran	85	Chad	92	Argentina	54	Cameroon	9
Iraq	97	Ethiopia	74	Chile	47	Central Afr. Rep.	4
Saudi Arabia	100	Djibouti	100	Mexico	52	Dahomey	24
Yemen (Arab Rep.)	92	Kenya	75	Turkey	41	Ghana	11
Yemen (Dem. Rep.)	100	Mali	95	India	42	Lesotho	20
Pakistan	90	Mauritania	100			Madagascar	15
		Namibia	90			Tanzania	20
		Niger	100			Togo	20
		Senegal	87			Uganda	2
		Somalia	100			Zambia	5
		Spanish Sahara	100			Bolivia	22
		Burkina Faso	94			Brazil	5
		Algeria	96			Columbia	2
		Afghanistan	81			Ecuador	6
		Jordan	98			Paraguay	8
		Libya	100			Peru	17
		Morocco	85			Venezuela	9
		Sudan	91			Lebanon	20[c]
		Syria	83			Sri Lanka	25
		Tunisia	92				

Table 3. Continued

Country	Low-rainfall area (%)	Country	Low-rainfall area (%)	Country	Low-rainfall area (%)	Country	Low-rainfall area (%)
Developed Countries							
Market economies:		Centrally planned economies:					
Australia	82	China	33				
Canada	4	Mongolia	62				
Greece	15	USSR	22				
Israel	75						
South Africa	55						
Spain	33						
USA	35						

Source: FAO (1974).

[a] Some very small countries (Malta, Kuwait, Qatar, Oman, Bahrain) were not included in this list.

[b] Category I: Countries almost entirely dry. Largely dependent on irrigation. Category II: Countries with most of their land in dry areas. Little irrigation. Category III: Countries with appreciable proportion of their land dry. Moderate amount of irrigation. Category IV: Countries with little of their land dry. Little irrigation.

[c] Estimated only. Areas too small to measure with planimeter.

Table 4. Developing countries with declining grain production per person, 1950–52 to 1982–84 (in kilograms per year)

Country	1950–52	1982–84	Decrease (%)
North Africa			
Algeria	219	79	64
Libya	106	69	35
Morocco	258	177	31
Tunisia	196	154	21
Sub-Saharan Africa			
Mozambique	97	36	63
Mali	242	134	45
Angola	81	45	44
Kenya	226	139	38
Nigeria	171	111	35
Ghana	66	44	33
Uganda	155	107	31
Guinea	131	95	27
Rwanda	58	43	26
Zaire	39	32	18
Benin	124	103	17
Senegal	139	118	15
Cameroon	112	97	13
Togo	121	108	11
Liberia	153	139	9
Niger	186	260	9
Sudan	114	104	9
Sierra Leona	155	143	8
Ethiopia	202	189	6
Burkina Faso	181	177	2
Middle East			
Lebanon	54	8	85
Jordan	138	44	68
Iraq	269	105	61
Syria	315	215	32
Iran	193	176	9
Turkey	472	446	5
Latin America			
Haiti	135	75	44
Honduras	194	133	31
Nicaragua	188	136	28
Panama	174	136	22
Chile	192	153	20
Peru	105	85	19
El Salvador	142	129	9
Cuba	55	52	5
Costa Rica	142	141	1

Table 4. Continued

Country	1950–52	1982–84	Decrease (%)
Asia			
Kampuchea	401	267	33
Afghanistan	417	324	22
Nepal	296	243	18
Bangladesh	240	235	2

Source: USDA (1985).

single most important factor for developing sustainable economies in Africa (FAO, 1986).

In a paper prepared for the World Bank, Newcombe (1984) described the stages of land degradation that occur when natural forests are cleared and plowed as people seek new agricultural land. Nutrient cycling is drastically altered, and soil fertility declines following clearing. In the first stage, wood supplies remain plentiful, and gradual erosion is largely unnoticed. As population increases, demand for wood increases for both construction and fuel, initiating a self-feeding cycle of degradation involving cutting wood from remnant forests to generate income, burning crop residues and dung for household fuel, reduced soil fertility, degraded soil structure due to residue and dung removal, and increased vulnerability to wind and water erosion. Eventually, dung and crop residues turn up in markets where only wood was previously sold. As a result of declining organic matter, the cropland becomes less productive, and crop yields prove barely sufficient even for subsistence. Eventually, dung becomes the main fuel source in villages, and rural families use crop residues for cooking and for feeding livestock, which can no longer be supported by grazing land. In the final stage of degradation, crop failures become common even in normal seasons, because topsoil and organic matter depletion have lowered the soil water-holding capacity. As a result, both food and fuel prices rise rapidly. Newcombe (1984) believes a critical point occurs in subsistence economies when more trees are cut for fuel than to make way for farmland.

There is evidence that many regions or countries have entered this cycle of degradation in Africa, Asia, Central America, and South America (Postel, 1984; Brown and Wolf, 1986). A 1980 World Bank study of western Africa showed that fuel wood demand exceeded estimated sustainable yields in 11 of the 13 countries surveyed (Schramm and Jhirad, 1984). India is also facing a fuel wood shortage. Delhi now imports fuel wood from sources 1000 km away (Centre for Science and Environment, 1985), and prices increased at a rate of 4.9% per year from 1977 to 1984 in constant currency (Brown and Jacobson, 1987). A survey in Madhya Pradesh, India, indicated that dung and crop residue exceeded wood as a household fuel by the late 1970s (Centre for Science and Environment, 1985). In western Africa and Central America, as much as 25% of a family's income may go for fuel wood and charcoal (Postel, 1984). It is estimated that at least 400 million tons of manure are burned annually for fuel worldwide (FAO, 1987).

E. Development Objectives

A decrease in land degradation and an increase in the productivity of developing low-rainfall areas can be achieved by improved management of land and water resources. In many locations, improvements can be achieved by more widespread application of known principles of soil and water management to crop and livestock production. In other situations, new concepts and methodologies appropriate to unique aspects of developing areas are required. Lal (1987) presented an excellent review of available low-input technologies that can improve the productivity of dryland regions and protect soil resources from erosion processes. Chase and Boudouresque (1987) described simple use of woodcutters' residues to protect the soil surface, coupled with protection from grazing during the seedling phase, to prevent or arrest degradation of lands following harvest of fuel wood trees from a savanna region in Niger.

Government policies, land tenure arrangements, and social, cultural, and economic factors influence the way in which dryland resources are utilized. When exploring ways to improve natural resource use, the important role played by socioeconomic institutions, in combination with technological advancements, must be recognized. Achieving long-term sustained growth in the productive capacity of low-rainfall areas requires sound decisions based on accurate assessments of resource problems and potentials and on careful analysis of alternative policies, programs, and projects. Hence, the capacity of governments and donor agencies to make technical evaluations and conduct rigorous analyses must be improved if the necessary changes are to occur. A recent study by FAO (1986) outlined specific practices and policies needed to improve African agricultural productivity which focused on provision of incentives, inputs, institutions, and infrastructure.

A critical factor in improving productivity of dryland areas involves implementing improved technology in the field. Policy actions that stimulate the widespread adoption of better soil and water conservation practices, create effective marketing distribution systems for farm commodities, and lead to improved education and information dissemination networks are badly needed for dryland regions. Policies and programs to reduce the rate of population growth must also be developed. Unless current rates of population growth are drastically and immediately curtailed, then all the social and economic goals that governments set for themselves, from higher incomes to food self-sufficiency, will be unattainable or seriously jeopardized in many developing countries.

Overall development goals for improving and sustaining productivity of dryland areas are (1) improve the lives of people who live in dryland areas; (2) improve the contribution that dryland regions make to the growth and development of national economies; (3) sustain the productive life of drylands by arresting the processes of land degradation; (4) rehabilitate land that has already undergone serious degradation; (5) develop systems for dryland management that are economically and sociologically viable and physically sustainable; and (6) improve decision-making ability of national planners.

Technological objectives required to achieve the overall development goals are (1) collect and organize agroclimatic information to form a database sufficient for probabilistic analysis; (2) collect and organize basic soils information required for development of optimal soil and water management practices; (3) collect and organize economic information required to evaluate management practices at the farm, community, region, and national levels; (4) develop sound soil and crop management practices based on proven principles; (5) strengthen multidisciplinary approaches that integrate agroclimatic, soils, agronomic, and economic data for assessment of dryland systems and related policy and program planning; (6) develop demographic and sociological information required for national planning; (7) develop and put in place the infrastructure, such as markets and roads, required for accomplishing the overall goals; and (8) design and put in place social and economic programs to relieve pressure on dryland areas, to foster changes in existing systems, and to restore productivity of degraded resources.

II. Identifying and Alleviating Constraints to Productivity

Dryland farming is a risky enterprise at best. Although a major constraint to dryland agriculture is deficient water, hazards such as insects, diseases, hail, high winds, and intensive rains can destroy crops in a matter of minutes or days. Making matters even more hazardous, farmers in dryland regions are often resource-poor, and these regions are usually of low priority when national resources are allocated. Improving the productivity of dryland regions requires that constraints be clearly identified. Programs then need to be developed that will remove, or at least allow farmers to cope with, these constraints.

Even when there is a knowledge base available for planning and managing crop and livestock systems in dryland regions, the most difficult task is to develop strategies that package technology, necessary infrastructure, and social and economic components together. Perhaps the toughest challenge for both farmers and governments will be to separate measures that are important from those that are expedient. Choosing expedient solutions in dryland areas is always tempting but almost surely leads to failure in the long term. At the same time, the destruction that results from expedient solutions often prevents implementation of the important measures that should have been used initially. An example of an expedient solution is the development of fragile lands for cropland where evidence is clear that cropping cannot be sustained. However, it will become increasingly difficult to avoid misuse of land resources in areas where population pressures are rapidly increasing. Some measures for alleviating known constraints in dryland areas are presented in the following sections.

A. Physical Constraints

1. Agroclimatic Conditions

Crop productivity is a function of the genetic potential of the crop and of the total environment in which the crop is grown. In dryland areas, the environment is often more yield-limiting than the genetic potential of crops. The aerial environment is usually defined in terms of solar radiation, temperature, precipitation, cloudiness, wind, and relative humidity, all of which have a direct effect on the plant. The combination of these factors at a given time and place defines the weather, and the synthesis of weather over long periods of time is climate.

Dominant features of rainfall in dryland regions are its limited amount, temporal and spatial variability, and unpredictibility. With mean annual rainfalls of 200–300 mm, the amount received in a given year ranges from 40% to 200% of the mean, and for areas where the mean is 100 mm per year, the range is from 30% to 350% of the mean (Mageed, 1986). High-rainfall years raise the long-term mean more than low-rainfall years lower it. Consequently, there are more years below the mean than above the mean, with the degree of skewness inversely related to amount of rainfall. This fact makes it imperative that more emphasis be placed on probabilistic analysis, with less attention given to mean values for designing crop calendars. To match a crop to an area, the length of the growing season required for the crop must be matched to periods with favorable temperature for crop growth and a "reasonable" probability of adequate rainfall to produce a yield. Rainfall distribution in space is also very irregular; and, as a result, neighbouring localities can have very different fortunes in the same year. Finally, rainfall intensity is extremely variable, and high-intensity events, even when the amount is relatively low, can result in substantial runoff and soil erosion, so a crop management system must protect the soil resource.

Because of climatic and yield extremes, individuals and governments cannot count on a given production figure for the coming season. Consequently, managing dryland agriculture is, in reality, adopting procedures to cope with the dry, variable climate, including dealing with the economic risks of possible crop failure one year and bumper harvests the next. In either case, farm income may be devastatingly low.

In winter and summer rainfall areas, where there are definite rainy seasons, farmers often respond to a late start in the rainy season by reducing the amount of land sowed or the amounts of seed and fertilizer used. They do this because it is likely that seasonal rainfall will be low if the start of the rainy season is late. On the other hand, they seldom increase inputs significantly in years that the rainy season begins early. Recent studies have shown that seasonal rainfall increases predictably with early onset of the rainy period in areas such as north Africa (Stewart, 1986a), the Near East (Stewart, 1986b), India (Stewart, 1986c), and the Sahelian region (Stewart, 1987). In practical terms, this means that farmers face very different sets of seasonal rainfall probabilities depending on when the rainy season begins. Decisions on crop, plant populations, mineral fertilizers, and other inputs should be based on the beginning of the rainy season. Early onset indicates an increased probability of above-average rainfall, so longer-season crops, higher plant populations, and higher rates of mineral fertilizers should be used. Conversely, the probability of high seasonal rainfall is very low when the rainy season begins very late, and a different set of decisions should be made, often the opposite of those above.

Climatic records of 15–20 years or more, available in many areas, can be used to calculate rainfall probability levels. Rainfall probability analysis should have a very high priority in developing strategies for improving the productivity of drylands. Future emphasis will move toward flexible cropping systems where cropping decisions are based on the availability of stored soil water at certain times and on the probability of growing season rainfall. Computers will become an increasingly important tool in planning and managing successful dryland systems.

Temperature extremes also limit productivity in many dryland areas. Plants are either killed or permanently injured when critical temperatures are exceeded; however, most often the excess heat or cold slows growth rather than being lethal. High temperatures are a growth constraint in the low-altitude tropical and subtropical regions, where the cool season is short or nonexistent. On the other hand, either excessively high or excessively low temperatures can damage crops or limit growth in the higher latitudes, especially in the continental regions. For example, in the northern Great Plains of the United States, loss or damage of fall-sown wheat can occur from extreme cold in the winter, extreme heat (usually combined with dryness) in the summer, or both. In warmer climates, effects of prolonged exposure of crop plants to high soil and air temperatures are not well understood but need to be considered in the development of cropping systems for improved production and water use efficiency.

Soil temperature extremes can often be reduced through simple management practices that alter the properties of the surface layer or the shallow subsoil. For example, mulching the surface with materials such as straw, peat, wood chips, stones, or gravel can markedly reduce soil temperature variations in the shallow layers. A loose soil layer formed by tillage also acts as a thermal blanket and dampens temperature variations in the layers below, compared with unworked soil. These methods can improve moisture conservation and result in more favorable soil temperatures for crop growth and need to be adapted for local situations (Geiger, 1965; Papendick *et al.*, 1973).

Adjusting the crop calendar is another effective method for reducing the risk of damage to crops from either extreme heat or extreme cold. For example, farmers in some areas can delay planting second crops until temperatures moderate after the summer as a means to protect plants against heat injury. In other cases, crop varieties are selected that mature ahead of the hot season, which otherwise would stress plants and reduce crop yields.

Many dryland areas are also subject to winds that adversely affect the water economy of plants, increase soil water evaporation, and cause soil erosion. Wind often accentuates the effect of temperature extremes on plant growth. For example, wind increases heat and cold stress of plants by enhancing desiccation, especially under conditions of low humidity. Gale-force winds that physically damage crops may occur but are, for the most part, isolated weather phenomena and are not a general problem in dryland agriculture. Physical damage to plants caused by blowing sand can be a serious problem in localized areas.

Artificial wind protection has been shown to increase the growth of vegetation and agricultural yields as well as to protect the soil against erosion (Geiger, 1965). Practical methods in dryland areas include planting tree shelterbelts, hedgerows of shrubs, or rows of tall grass or other plants perpendicular to the main wind direction. Alternative windbreaks may also be constructed of materials such as wooden slats, reeds, stones, or combinations of stones and shrubs. The effectiveness of wind barriers depends on the width, height, and density of the belt; crop grown; wind characteristics; and the soil and other local conditions (Geiger, 1965). Other methods to specifically reduce wind erosion include mulching, manipulating field size, soil ridging, interplanting or strip cropping, and tillage to roughen the soil surface after rains (Fryrear and Skidmore, 1985). Keeping the land covered with living or dead vegetation has proved to be among the most effective methods known to control wind erosion (Woodruff *et al.*, 1972).

When forest or grassland areas are being brought into cropland, it is extremely important that attention be given to the relationship of the current weather to the historical range of weather for the area. Catastrophic failures have resulted from converting large areas into cropland during very favorable periods, only to realize later that the years were abnormally wet. Dryland areas are particularly vulnerable, because the soil organic matter declines rapidly after cultivation begins; when droughts occur, the hazard of soil erosion by wind and water becomes severe. A well-known example of such a development is the so-called Dust Bowl of the Great Plains of North America that occurred in the 1930s following an over-optimistic expansion of dryland farming in the 1920s when rainfall was unusually plentiful. The drought of the 1930s led to crop failures and some of the most severe wind erosion ever documented.

2. Soil Characteristics

Soils in the dryland regions of the world range from sandy, shallow, low-fertility soils to highly productive, medium- to fine-textured, deep soils, but the majority of dryland soils have serious problems (Dregne, 1982). Soil characteristics are strongly influenced by the climate in which soils develop, and the interactions of these characteristics with current climatic conditions are a major consideration in understanding the productivity of dryland soils.

Although low soil water levels commonly restrict crop yields in dryland regions, other soil problems such as surface soil hardening, compaction by tillage implements, susceptibility to water and wind erosion, low fertility, shallowness, stoniness, restricted drainage, and salinization also affect crop production. Dregne (1982) developed a generalized map showing principle soil problems in dryland regions of the world (Figure 4).

Increased soil organic matter could alleviate the severity of all the major controllable soil problems, but most practices used in dryland areas tend to reduce organic matter levels. Devising practical and economic means to protect or improve soil resources is a great challenge for researchers, farmers, and policy makers in dryland areas (Dregne, 1982).

The first priority for easing constraints caused by soil problems is to develop a soil capability database and technical and policy plans for sustaining crop production. The most difficult, but also the most vital, part of the strategy will be to withstand the pressure to overdevelop and overuse the resource base, which can make the soil problems more serious through destruction of the resource base.

a. Physical

Poor physical properties of soil are major constraints in dryland regions. Many of the upland soils in the tropical dryland areas are sandy, often gravelly, and generally shallow. These factors contribute to a low water-holding capacity, which makes it more difficult to deal with the detrimental effects of erratic and limited precipitation. Erosion, both wind and water, has intensified these constraints.

There are also large expanses of soils with high clay content. Vertisols are major land resource areas in India, Sudan, Chad, and Australia. While these soils have high water-holding capacities, they have a very limited range of water content and, therefore, of time when they can be tilled. They also require a lot of power for tillage. Management of these soils is particularly difficult when only human or animal power is available.

Soil hardening and crusting are very common in dryland soils and result in large amounts of runoff. When water runs off, there is less water avail-

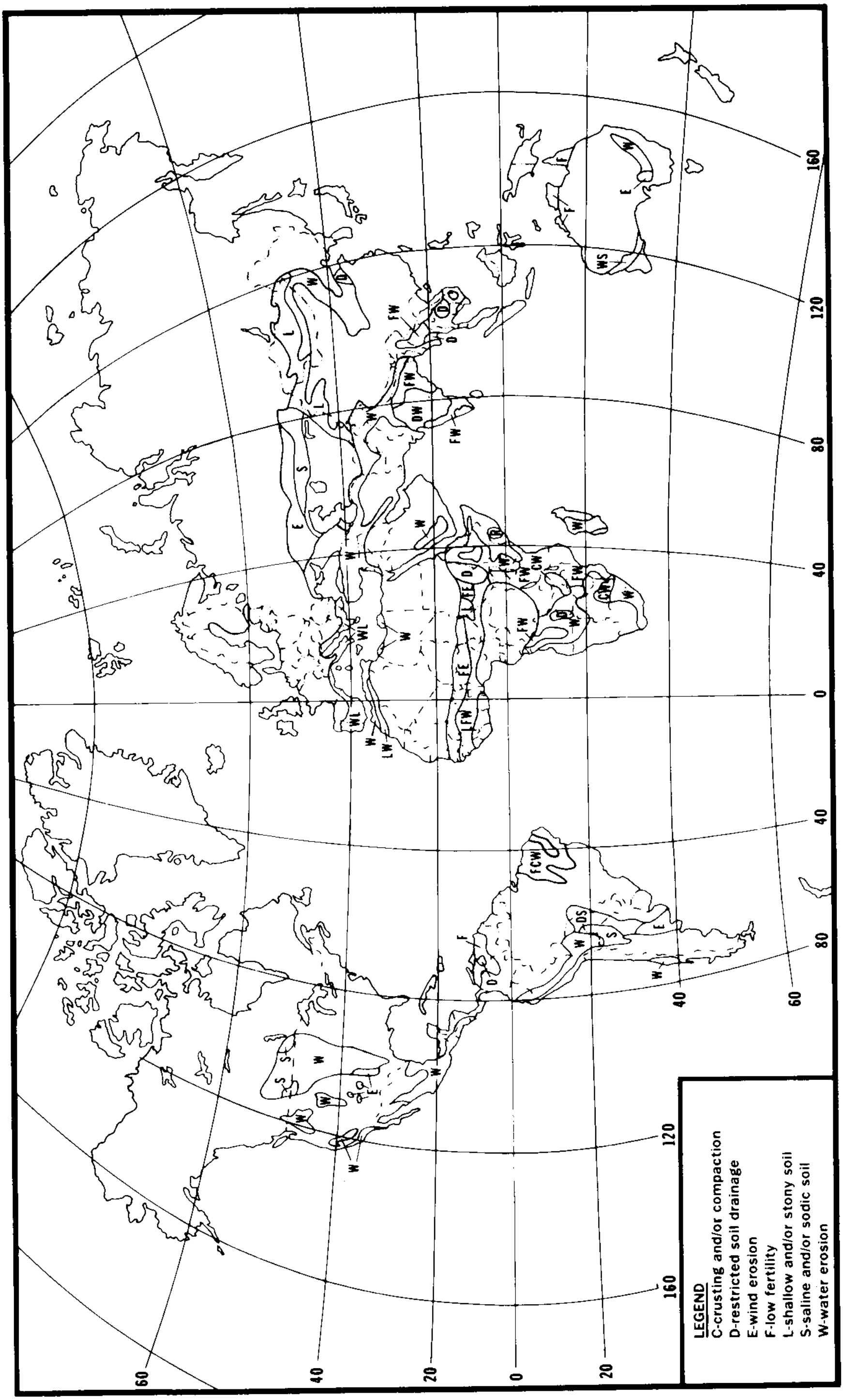

Figure 4. Major soil problems in dryland regions of the world (Dregne, 1982).

able for producing biomass and less input of organic material into the soil, which makes maintenance of good soil physical conditions even more difficult. Tillage is often essential for increasing infiltration (Lal, 1987), but it must be emphasized that tillage should be used as sparingly as possible, because tillage increases the rate of organic matter decomposition. Subsurface tillage, which results in most of the surface residues remaining on the surface, increases infiltration, reduces erosion significantly and results in less organic matter decomposition.

Sweep tillage, often called stubble mulching, was the single most important practice developed to control erosion in the United States Great Plains following the Dust Bowl of the 1930s (McCalla and Army, 1961; Allen and Fenster, 1986). Willcocks (1984), however, cautioned that sweep or chisel tillage would not be satisfactory on very dense soils unless it resulted in adequate loosening of the soil to allow for normal root development of the crop.

Many traditional farming practices exist for rainwater harvesting that could be incorporated into dryland management systems. Use of these techniques helps to minimize the erosive effects of water runoff and increases the water available for crop production (Boers and Ben-Asher, 1982).

b. Chemical

Many dryland soils have serious chemical constraints. Problems include low inherent fertility, acidity, toxic levels of aluminum or other elements, and low nutrient-holding capacity (Dregne, 1982). Extreme spatial variability can make it difficult to obtain research results valid for describing the soil system and developing solutions to relieve constraints (Chase *et al.*, 1987).

Essential plant nutrients can be lost through surface runoff, erosion, leaching, and removal of plant materials. Low inherent levels of phosphate appear to be the major constraint in many Sahelian soils, which greatly reduces the efficiency of use of the limited water available and thus exacerbates the climatic limitation. Results of the Malian-Dutch "Primary Production in the Sahel" project indicate that low fertility is at least as great a limitation to production as water in many of the Sahelian soils (Breman and Uithol, 1987). Soil acidity resulting in aluminum toxicity is a common chemical problem in dryland soils.

Soil testing capabilities should be improved in many developing countries for delineating and addressing these constraints. Strategies should be developed that use combinations of selected crops and cultivars, fertilizers, legumes, and cropping practices to deal with these constraints.

c. Biological

Biological activity in soils is generally much lower in dryland than in more humid zones. The reasons are apparent—lower organic matter levels and periods of extreme dryness. There is also evidence that the organic matter present in dryland soils is chemically and biologically less stable, because there is less biological turnover of organic matter (Anderson, 1987). The net result is that the inherent low level of organic matter in dryland soils decreases more rapidly and to a lower percentage level than in soils of humid zones. The effect is a rapid downward spiral, where the decline in organic matter causes a collapse of the soil structure, a drop in water and nutrient retention, an increase in acidity, and a decrease in plant growth that, in turn, reduces the supply of organic residues (FAO/UNEP, 1983). Forest land, as compared to grassland, has an even more rapid decline rate, because most of the organic matter is at the surface, where decomposition is the most rapid when the land is cultivated. The very rapid and high percentage loss of an already low level of organic matter is the most serious soil problem in dryland regions.

A new equilibrium level of soil organic matter will be reached after new lands are brought into crop production, but that level will be greatly affected by the number and intensity of tillage operations. Any practice that stirs the soil exposes more surface area and increases organic-matter decomposition. Subsurface tillage, which leaves more organic matter on the surface and exposes fewer soil surfaces than most other forms of tillage, results in a higher level of organic matter (USDA, 1974). This improves the overall biological condition of the soil and the chemical and physical characteristics of the soil.

Increasing and maintaining soil organic matter becomes almost impossible when populations of both people and animals require that all the crop residues be utilized for use as fuel or feed. Under extreme conditions, the soil organic matter content drops to the point where the soil becomes useless and soil erosion becomes rampant. This is the final stage in land degradation discussed earlier (Newcombe, 1984).

B. Technological Constraints

1. 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, southern and southeastern Asia, northeastern and northern South America, and northern Australia. Aluminum toxicity, the result of extreme soil acidity, is also a major problem in certain locales.

In North Africa, the Middle East, and Africa south of the Sahara, nitrogen and phosphorus deficiencies limit crop production. The lack of some micronutrients is apparent in specific areas, and these deficiencies will intensify and spread as cropping systems intensify. The interactions between nutrients and water are very pronounced, resulting in inadequate response to additional water at low fertility levels and poor response to nutrient additions if water is not available for plant growth. Consequently, nutrient additions must be considered as a component of an improved technology package. A major problem in dryland areas is that single technological improvements may not increase yield, and although total package improvement may be economically beneficial over a period of years, it may not be in low-rainfall years.

The use of soil testing should become more widespread. This technology can be extremely useful in developing countries, because data and experience are not sufficient for making sound fertilizer recommendations. Soil tests can be very helpful in delineating problem areas that suffer phosphorus deficiency and aluminum toxicity. ICARDA (International Center for Agricultural Research in Dryland Areas, Aleppo, Syria) and ICRISAT (International Crops Research Institute in Semi-Arid Tropics, Patancheru, India) have conducted and coordinated studies in recent years, and a database is emerging. Providing plant nutrients in the proper balance is important. Otherwise, farmers may alleviate the limitation of one nutrient only to have other elements become limiting to plant growth.

Biological fixation of nitrogen should be used whenever feasible as a means of improving soil fertility and reducing the need for chemical fertilizers. Incorporation of legume crops into cropping systems is a common way of utilizing biological fixation. It is very important that the legumes be inoculated with the proper *Rhizobium*, especially when a legume is introduced into an area where it was not previously grown, and that adequate phosphorus be available. Gibson *et al.* (1986) reported that the activity of the common diazotroph, *Azotobacter*, could be stimulated by incorporation of wheat straw into the soil to increase the carbon supply available to the bacteria. They believed that up to 50 kg N/ha/year might be added to a soil through enhanced biological fixation under favorable conditions.

Even with the maximization of biological fixation, some fertilizer nitrogen will be required in many situations. Phosphorus, sulfur, and micronutrient deficiencies may have to be overcome by manure or mineral fertilizer additions. Aluminum toxicity problems can be corrected by lime additions, but the best approach will likely be through crop selection and plant breeding for aluminum-tolerant cultivars. Some phosphorus-deficient regions have native rock phosphate resources that may have potential for development which could limit the currency resources required to increase phosphatic fertilization (Kounkandji, 1987).

Mycorrhizal infections can greatly enhance the nutrient-absorbing capacity of root systems in many herbaceous, graminaceous, and tree species, particularly for phosphorus (Read *et al.*, 1985) but also for micronutrients (Killham, 1985). Sieverding (1986) reported that mycorrhiza-infected sorghum plants developed greater root length and were less sensitive to drought stress than noinfected plants because of enhanced phosphorus uptake. Sorghum is a major grain crop in many dryland regions of the world. However, Wang *et al.* (1985) reported that mycorrhizal infection was inhibited at pH below 5.5. Some soils on which plants most need the enhanced nutrient uptake, such as the nutrient-poor, acid Sahelien soils, may be least likely to benefit from use of these organisms. A better understanding of the potential for and limitations to mycorrhizal activity for enhanced nutrient uptake has great potential to improve crop productivity through management of the soil biosphere.

Broadcasting of fertilizer, which is the most common method of application in many regions, may lead to inefficient use of expensive fertilizer inputs. The applicability of new technologies such as improved timing or fertilizer placement between paired rows is unknown. The effect of this technology in "hiding" the fertilizer from access by weeds and decreasing the nutrient immobilization could have significant effects on increasing fertilizer application efficiency, decreasing weed competition, controlling costs, and improving the crop response function (Papendick, 1984).

2. Crop Germplasm

Improved crop varieties and hybrids have resulted in large yield increases in many parts of the world. This factor was a major component of the "green revolution" in Asia, as was an assured moisture supply which reduced risk levels sufficiently to make investments in increased fertilizer and management inputs feasible. The interaction of increased inputs with high-yielding varieties resulted in large payoffs in the classic green revolution wheats and rices. Assured moisture supply is generally lacking in dryland regions, and farmers therefore cannot risk increasing the capital inputs in their crop management systems. Under dryland conditions, the emphasis should be on soil management, especially water-conserving practices, because lack of water is the limiting factor in crop production. More emphasis should also be given to legumes, oilseed crops, and the quality of forage and residue.

In dryland areas where livestock is an important part of the production system, the straw portion of the crops is, in many cases, as important to the farmer as the grain (Cooper *et al.*, 1987). In these regions, increases in grain production due to changing the harvest index are not always desirable. The emphasis under these situations must be to increase biomass. At least in the short run, this will largely be done by improved soil water storage and other soil management practices.

Some attention for long-term plant-breeding programs for improved drought resistance is warranted, but this effort should be a relatively small part of the overall effort, particularly for developing near-term strategies. Improving germplasm for disease and insect resistance is another matter, and this activity and the development of cultivars that are tolerant to aluminum toxicity resulting from soil acidity are extremely important in dryland regions (Wright, 1976). Plants growing in tropical and subtropical areas are subject to a wide variety of disease and insect problems. Major advances have been made in developing improved varieties of major grain crops such as sorghum (House, 1987). Breeding of improved lines of many pulse and root crops merits increased emphasis. Booth *et al.* (1987) describe a climatic analysis technique that can expedite the transfer of plant materials from one region to another, which is especially important when crops are introduced into new areas.

3. Production Practices

Low crop and animal production in dryland farming is not necessarily the result of a lack of scientific knowledge. The principles of dryland farming are fairly well established, and proven practices have been developed for some areas. Although the principles apply worldwide, technologies must be adapted to the local environment as well as to the prevailing social, economic, and institutional conditions. Lal (1987) describes soil management practices that can be incorporated to improve productivity at all levels of agricultural development.

The first priority should be to identify existing technologies and adapt them to specific environments and economic and social conditions. Indigenous technologies should not be overlooked. Where conditions are unique and existing technologies cannot be identified for adaptation, the emphasis should be on developing applied agronomic practices that focus on water conservation and water-fertility interactions, essential steps in increasing biomass production.

a. Agronomic

The most immediate and significant improvements in dryland crop production will result from improved agronomic practices focusing on soil and water conservation, increased biomass production, and cropping systems to maintain soil cover and organic matter levels. In many countries, forage-livestock systems should be given as high a priority as grain production systems.

Agronomic practices are often more effective when two or more are used in concert because of the positive interactions. For example, added fertilizers will not be wholly effective without improved water conservation, and even then they will usually not be beneficial without weed control or if proper nutrient balances are not maintained (Ohm *et al.*, 1985).

Despite its potential, "package" adoption is not evident in the typical sequential adoption pattern of subsistence farmers (Eicher and Baker, 1982). A farmer with limited resources will find it difficult and risky to simultaneously adopt several new techniques that require a shifting of household resources. Moreover, learning a new practice thoroughly may extend over several seasons and have uncertain future payoffs. For these reasons, technology adoption often proceeds slowly despite the potential benefits demonstrated at a research level.

Examples of technologies that could improve the productivity of dryland agriculture include contour ridging, tied ridges, water harvesting, organic and chemical fertilizers, green manures, mulching, weed control, disease and insect control, erosion control practices, and agroforestry/alley cropping.

b. Mechanization and Power

The lack of adequate animal and mechanical traction constrains crop production in many dryland regions. Soil water conditions often change rapidly, and the timing of tillage or other practices can be extremely critical. Improved equipment, ranging from better hand tools to animal-pulled machines to tractor-powered equipment, will be required to make meaningful improvements in production. The size and complexity of equipment must be economically and socially acceptable to the farmers.

Improved tillage systems are urgently needed, because tillage is often desirable to improve infiltration and necessary for weed control (Unger, 1984). However, as already discussed, tillage can be very destructive, because organic matter levels decrease with increased tillage, and this is particularly true in areas of high temperatures (Tate, 1987). As organic matter declines, the soil structure deteriorates, soils become very hard upon drying, and more tillage is necessary to increase water infiltration (FAO/UNEP, 1983). The organic matter/soil structure/infiltration relationship must be studied, documented, and demonstrated to farmers in these critical soil areas. Tillage, which turns and mixes the surface soil layers, results in rapid degradation of surface residues and soil organic matter. Emphasis should be given to use of implements that undercut the surface without turning the soil. Weed control and improved infiltration will be accomplished by such implements, but erosion will be significantly reduced, and organic matter decomposition will not be as rapid as with surface mixing.

Without question, the most important development in North American dryland agriculture has been maintaining crop residue on the soil surface. The residues control erosion and enhance soil water storage, both of which tend to increase yields. Residue management practices started in Canada in the 1930s with the introduction of V-shaped undercutting implements and has spread throughout the North American drylands. In recent years, chemicals have been widely used for weed control, and tillage is being reduced even more.

Broadcasting is still the dominant practice in many areas for seeding and fertilizing crops. Generally, much more seed and fertilizer are required than for more precise placement. An observed advantage of broadcast seeding, however, is that seeds are often broadcast on ridged land and then the ridges are dragged, resulting in seeds placed from very shallow to fairly deep. If a heavy seeding rate is used, a crop stand is generally assured regardless of the rainfall distribution. A uniform seeding depth sometimes results in failure, because sufficient rain occurs for seed germination, but the crop may be lost before additional rains occur.

Skip cropping, alternating fallow strips with cropped strips, has been used extensively as a means of controlling wind erosion. In some cases, a single row of a tall crop is planted every few meters in a field for wind erosion control. The tall strip crops have the additional advantage of trapping snow and enhancing water storage in colder dryland regions.

c. Fallowing

Fallowing has been used in many agricultural systems to increase the supply of nutrients or water in a soil for production in a subsequent crop. In nutrient-poor soils, fallow has been used primarily to maintain the productivity of the soil over time. In many regions of the world, traditional agriculture has relied on shifting cultivation which allowed long fallow periods for restoration of depleted soils. Areola *et al.* (1982) reported that soil organic matter, water-holding capacity, and fertility were strongly correlated with the number of years a field had been in fallow, particularly under forest vegetation. However, as lands have come under greater human and animal pressure, fallow periods have been eliminated or shortened, causing severe land degradation (FAO/UNEP, 1983).

In North America, summer fallowing is widely used as a means to increase the water available for succeeding crop growth (USDA, 1974). This practice has been very successful in increasing and stabilizing yields. However, summer fallow has increased wind and water erosion and the decline of organic matter levels.

The basis for summer fallowing can be seen clearly in Figures 5 and 6, showing the effect of increased soil-water storage on grain yield. Substantial amounts of water are required for growing season evapotranspiration before initial grain development, and beyond that, grain yields increase rapidly. Research data and experience in North America suggest that four practices improve water conservation and erosion control in dryland systems: (1) control weeds; (2) leave residues on the surface to reduce evaporation and control erosion and to trap snowfall in some locales; (3) retain hard soil clods 1–8 cm in diameter on soil surface to resist wind erosion, slow runoff water, anchor mulches, provide shade, and physically protect small plants; and (4) manage soil to retain enough water in the seedbed to germinate seeds (Greb, 1979). These conditions are required for both fallow and nonfallow systems.

Conservation tillage systems that leave crop residues on the soil surface are being studied and applied as a means to minimize the adverse effects of summer fallow and to increase the efficiency of soil-water storage. In the early 1900s, when 7–10 tillage operations were common during the fallow period, the percentage of precipitation retained in the soil profile ranged from 18% to 23% in the central Great Plains. Today, with limited tillage

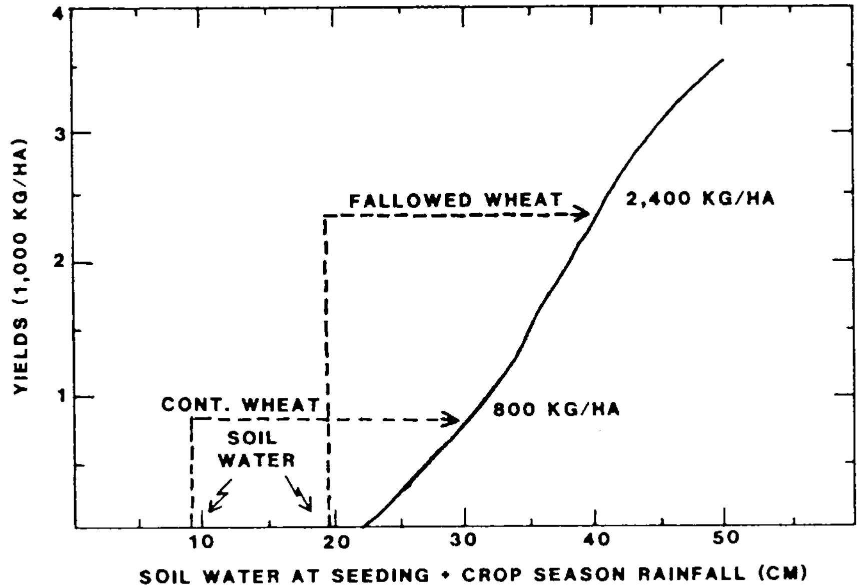

Figure 5. Wheat yield expectancy at North Platte, Nebraska, 1921–1967 (from Greb, 1983, as adapted from Greb *et al.* 1974, and Smika, 1970; reprinted with permission).

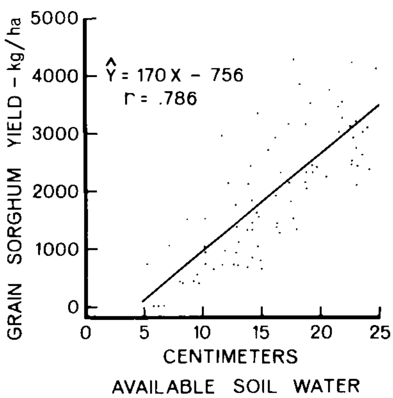

Figure 6. Effect of soil water at seeding (0 to 1.8 m depth) on dryland grain sorghum yield (Jones and Hauser, 1975).

systems, 45–55% efficiencies are achieved. This and other technologies have led to more than a twofold increase in yields.

Greb *et al.* (1979) suggested the following percentage credits: 45% from improved stored water during fallow; 30% to improved wheat varieties with increased harvest index, better tillering, more winterhardiness, earlier ripening to escape heat and hail damage, and more resistance to disease and insect pests; 8% to improved planting equipment; 12% to improved harvesting equipment; and 5% to improved fertilization practices (many soils in the Great Plains have high inherent fertility, particularly under fallow). Of course, the rise in production is due not to any one factor but to the interaction of factors. Elliott and Lynch (1984) reported that straw residues enhance soil aggregation. Lynch (1985) reported that the patterns of N immobilization during straw decomposition could have beneficial effects in that the nitrogen would be immobilized and protected from leaching during the fall and winter months and released in an available form during the spring growth of the crop.

The extent to which fallow is used, or should be used, depends on its effect on quantity, economy, and stability of production and on other factors. These are in turn affected by other considerations, such as soil-water storage capacity, the kind of crops grown, the competition afforded by replacement crops, the type of farming practiced, the weed control needed and afforded, erosion hazards, and the ultimate effect on soil productivity.

The Bushland, Texas, example shown in Figures 1 and 6 illustrates the importance of stored soil water at time of crop seeding in the southern Great Plains of the United States. Since rainfall is significantly less than potential evapotranspiration throughout the year, successful crop production depends on the use of stored soil water in addition to rainfall. Fallowing in other regions, particularly in the winter rainfall regions of the Middle East and north Africa, has not been very successful in increasing stored soil water and subsequent yields (Cooper *et al.*, 1987). Using Amman, Jordan, as an example (Figure 1), a long, dry, hot period follows the rainy season, and very little soil water storage can be maintained through this period. Also, soil water storage prior to seeding is not so important, because the soil profile will be fully recharged in most seasons during the humid portion of the year that occurs soon after seeding crops in the fall. Similar situations occur in summer rainfall regions illustrated by the Rajkot, India, data in Figure 1. Soil water storage is extremely important in these latter two cases for extending the growing season, but they differ greatly from the Bushland, Texas, example in that the soil profiles in those cases are generally fully recharged during the growing season.

Summer fallow was also practiced in Australia in the early 1900s, but some regions experienced yield declines due to low soil fertility associated with the rapid loss of organic matter in the less productive soils. To cope with this problem, Australians incorporated annual self-regenerating species of clovers and medics into cereal crop rotations and integrated cereal and animal production into very successful dryland systems (Puckridge and Carter, 1980). For other regions of the Australian wheat belt where bare fallow systems are still used, Ridge (1986) has shown that fallow enhances the stability of production without reducing the overall productivity of the system.

C. Institutional and Infrastructure Constraints

Dryland farming occupies 97% of the area under cultivation in the Sahel. It also occupies the major land area in northern Africa and the Middle East. Increases in total food production in these areas the past several years have primarily come from expanding the cropland area and reducing the length of fallow. However, per-capita food production is falling, land pressures are becoming more severe, and continued reliance on such extensive means for increasing food production is not realistic. The other option is to implement the institutional and infrastructure changes necessary to become more intensive and raise the level of production.

1. Credit

A move toward more intensive farming systems significantly raises the cost of production and, in dryland areas where moisture supplies are not assured, greatly elevates the risk level of making a profit. In years of severe moisture shortages, the more intensive methods will not increase yields. Since most farmers in these areas have very limited resources, institutional programs must be established to assist the farmer. International donors and governments of developing countries have emphasized subsidized credit to help small farmers adopt novel or risky technologies including natural resource conservation practices. These policies usually did not help small farmers but benefited large, better-off farmers who also had access to these resources (Shaffer *et al.*, 1983). Better institutions in rural areas are needed to ensure that all segments of the communities have access to credit at affordable terms. Local input is essential in the allocation of credit.

Affordable credit must be available to the low-resource farmer if widespread adoption of practices that require expenditures "up front" are to occur. Credit can help the farmer deal with risk associated with changing from traditional practices. Credit must be available in many cases for more than 1 year, because intensive farming systems in dryland areas must have the staying power necessary to take advantage of the favorable years, even though they will often be unprofitable during the less favorable years. At the same time, the systems must provide for family subsistence even in the bad years.

2. Marketing and Distribution

Annual production in dryland regions ranges from very low during years of poor weather conditions to abundant output during years of good rainfall. As discussed above, crop and livestock production systems must take advantage of the favorable years as well as maintain some production and sustain families in the poor years. Effective marketing and distribution systems are essential in this effort. The inability to effectively market produce limits farmers' ability to dispose of surplus output and reduces their income-earning potential. This, in turn, restricts their ability to purchase inputs needed to be fully productive. External inputs are often not available to farmers when they need them at prices they can afford to pay. Moreover, the difficulties farmers face obtaining parts and maintaining equipment create further disincentives for adoption of new technology. As farm incomes remain low, community, regional, and national growth are restricted.

Farm income must rise through marketing before low-resource farmers can invest in the technologies that can enhance the long-term productivity of their land. Farmer cooperatives and trade associations can strengthen small farmers' access to input and output markets.

Most developing regions need improved physical infrastructure. Storage facilities (on-farm and regional) can provide an incentive to produce more than could be consumed by the farm family. All-weather roads, vehicles, and rail systems provide the means to maintain the flow of surplus output to market centers and urban outlets, thus increasing economic activity and opportunity.

Transportation systems also improve access to production inputs, to research and technology transfer services, and to emergency food and fuel during critically bad years. Consequently, infrastructural improvements can lead to substantial productivity gains in dryland areas.

3. Research and Technology Transfer

In dryland regions, especially in many developing countries, research institutions are woefully inadequate. Too often, the resources allocated to drylands have been minimal, because primary attention has been focused on irrigated agriculture or on favorable rainfall areas. Although this past allocation of resources can be easily understood and perhaps even justified, successful development of dryland regions occurs only after research institutions have developed technologies adapted to particular conditions in each area. Data are often inadequate for analyzing agroclimatology and soil resources and management practices. Good databases are essential for the development of dryland regions.

In developing countries, the first priority should be to improve indigenous practices by adapting practices from other regions where such practices have proved successful. The practices from other regions cannot be directly transferred, but the principles will apply, and the specific practices can be altered to fit the local environment and social and economic conditions. The research component should be applied research, focusing on agronomic and cultural practices to increase water conservation and maintain the soil resource.

Economic costs and returns associated with innovative practices must be evaluated. Adaptive research, coupled closely with technology-transfer demonstration plots on the farmers' fields, is essential. Farmers will accept information from other farmers quicker and with more confidence than from technicians. The research must be conducted with equipment appropriate for the region. Research for developing regions must focus on resilient species, minimum effective input rates, low risk of failure, adequate minimum production in poor years, and diverse cropping patterns (Bay-Petersen, 1986). Research and technology transfer programs must be long-term commitments.

4. Fertilizers and Pesticides

Increasing water conservation must be the focal point of improved crop production systems in dryland areas, but water conservation is only the first of several necessary steps. The productivity of many dryland soils cannot be increased without raising the fertility level and controlling pests. The lack of phosphorus is particularly serious in much of Africa and the Middle East. Soil fertility can quickly become the limiting factor in crop production, and the infrastructure (foreign exchange, transportation, and distribution systems) is inadequate in many dryland regions to assure the availability of fertilizers and pesticides. In addition, monitoring and reporting of climatic conditions are often not fed into planning agencies so that limited fertilizer and pesticide inputs can be concentrated in the areas having the most favorable rainfall.

As research results become available regarding the need for fertilizers and pest control, institutional structures must be in place to assure that the information reaches farmers. It is important to ensure that the chemicals are available in areas where they are most needed. Unwise or misguided use of chemical inputs can be very costly and can lead to low efficiency and disenchanted farmers.

5. Farm-Level Knowledge Base

A critical element in technology transfer is the ability of the intended end user to absorb new ideas and effectively utilize new technology over the long run. If dryland farmers are to fulfill their role in the development process, they must become better informed about technical and economic matters that affect them. Traditional land and water management practices generally represent reasonably efficient use of the limited resources available. In the past, these practices were adequate for producing the food and fiber requirements of economies that were either largely self-sufficient or engaged in limited trade with nearby countries. However, traditional methods cannot serve current and future needs to support increased numbers of people.

Despite inherent conservatism and an understandable reluctance to take on risks, typical dryland farmers are receptive to new ideas and interested in technologies that can improve their situation. However, dryland farmers must have a better base of technical knowledge and an understanding of interactions between their farming practices and current and future physical resources. They must also improve their ability to assess new technologies and to keep abreast of economic conditions that affect profitability. In short, the general level of technical and economic knowledge found among dryland farmers must be upgraded if the productivity of the dryland areas of the world is to be raised.

Fundamental needs are better systems of rural education, agricultural production training, and dissemination of information in rural areas. To meet these needs, more and better schools, technology transfer services, producer training programs, field demonstrations, and weather, crop, and marketing reporting services are required.

D. Socioeconomic Constraints

1. Population Growth

During the past few decades, the world has witnessed an unprecedented growth in human population. This has forced equally unprecedented attention to meeting the food, fiber, fuel, and other needs of an expanding population without permitting degradation of soils and other natural resources. Population pressure affects the resource base extensively and intensively. Extensive pressure leads to conversion of grasslands and forests to cropland, with expansion normally progressing into less and less favorable areas. Adequate databases and policies are not available in many cases for making sound decisions regarding expansion of agricultural lands, so land is being destroyed when people indiscriminately cut and burn forests, burn and overgraze grasslands, and cultivate soils that should have remained in native vegetation. The dynamic processes that are being affected on such a massive scale are poorly understood (FAO/UNEP, 1983). This is particularly true in some of the dryland regions of the world where population rates are rapidly rising. Although average population growth in all developing countries peaked at 2.4% a year in 1965 and has since fallen to about 2.1%, the rate of increase is 3% or more and still rising in much of Africa (FAO, 1986). Since many countries in this region depend almost entirely on dryland crop production, enormous pressure is being placed on fragile land resources. With increasing population, millions will settle in drought-prone areas shunned by farmers throughout history. Generally speaking, the drought, in many cases, has not moved to the people; rather, the people have moved and continue to move to drought-prone areas.

Intensive pressure from increased population in dryland regions requires an increase in cropping intensity. The problem now facing many developing countries is that traditional methods of coping with the risks and hazards of dryland agriculture, such as long fallow and nomadism, are breaking down under population pressure, and modern technology has not yet produced acceptable alternatives. The rapid deterioration of soil structure and sharp decline in soil organic matter along with increased weed problems are serious problems in intensive systems that were previously managed by long fallow periods in which bushes or grasses were allowed to grow and decay to restore the productive capacity of the soil.

Dryland areas, as elaborated throughout this chapter, are fragile and very limited in their productive capability even under the best of management. When mismanaged and overused, they become even less productive, resulting in a rapid downward spiral, because less production means fewer root and residue materials for maintaining organic matter. As organic matter declines, the soil becomes very erodible, and severe degradation can occur which renders the land completely useless for plant production. Therefore, the relationship between population levels and productivity in dryland areas is a critical issue that is perhaps the largest of many challenges. Social and economic programs must be developed that address this problem over the long term; otherwise, the resource base in many countries will be damaged beyond repair.

2. Land Tenure and Fragmentation

Land ownership patterns in many parts of the world are based on cultural inheritance traditions and often provide for equal division of agricultural land among heirs. This often results in dividing land into long strips or in small blocks. With small land parcels, use of modern machinery is much more difficult. Weed, insect, and disease control with chemical pesticides is often difficult on small, noncontiguous blocks of land separated by inconvenient distances. Often the land division occurs up and down slope, making it difficult to use sound soil and water conservation practices such as terracing, contouring, and other methods of cross-slope farming. Thus, land fragmentation is a major constraint to improving the productivity of many dryland areas.

Economically sized farms are essential for improvement of land productivity and profitability to farmers. The actual size of an economically viable unit will vary according to availability of water resources, soil characteristics, slope of the land, and climatic features. In developed countries, land holdings have progressively increased in size, whereas in developing countries, farm sizes have become smaller and smaller as they are subdivided among a growing population (FAO, 1987). Potential solutions for land aggregation are to develop national strategies that would encourage combining small parcels into large blocks and greater use of advanced technologies for increasing crop production and conserving soil and water resources. A possibility for land consolidation where family ties are strong is to encourage a system where a single member manages combined family land ownership. Also, in some areas with small landholdings, it may be possible to organize cooperatives and persuade farmers to sow common crops in large blocks to make cultural practices such as water management and pest control possible through cooperative efforts. This has already proved workable in India for some cash crops such as cotton and sugarcane (Papendick *et al.*, 1988). In most situations, aggregating land holdings will be a complex process, because it requires combining technological and social factors to develop solutions.

The first step in dealing with the problem of land fragmentation is to demonstrate clearly that aggregating land parcels increases productivity. Secondly, the constraints to land aggregation must be identified, and potential methods for their removal must be evaluated.

3. Role of Women

Women's role in agriculture has not received adequate attention in agricultural development. Women do more than half the work involved in food production in much of India and Nepal and up to 80% in Africa (Sicoli, 1980). Equipment and related crop production improvements have not been developed to increase the efficiency of women's work because in much of the developing world, women are not typically included in formal and informal training programs or in information networks that lead to better ways of doing things. As a result, technology transfer services, production loans, fertilizer subsidies, and most other support activities are frequently denied to an important human segment of rural areas. Since dryland regions tend to be less advanced than areas where large-scale irrigation programs are in place, it is likely that women in these locations are even more removed from the mainstream of development. It has already been pointed out that lack of land ownership and lack of financing are major constraints to adoption of improved management practices. Women seldom hold title to land or other items of sufficient worth to use as collateral.

Women also have many other labor-intensive tasks necessary for the existence of their families that reduce the time they can spend in agricultural production jobs. As technology packages are developed and strategies are designed for implementing these packages, the role of women will be affected; the success of such programs may very well depend on how successfully their roles are analyzed and addressed.

4. Pastoral Grazing

Livestock play an important role in dryland agriculture and can contribute to more stable income for farm families (Sanford, 1987). However, the numbers of animals frequently exceed the carrying capacity of the land resource. Livestock numbers have grown steadily in recent years, though generally not quite as rapidly as the human population. Dryland areas of developing countries support about 59% of the world's cattle, 82% of buffalo, 41% of sheep, 78% of goats, and 93% of camels (FAO, 1987). A high percentage of these animals are raised in conjunction with farming and are fed on hay, sown forages, and crop residues. Range grazing supports a dwindling share of livestock in industrial and developing countries alike.

Millions of hectares of the world's most fertile grazing lands have been plowed and planted to crops in tandem with accelerating growth of the world's population.

In many parts of the world, nomadic or transhumant grazing is widely practiced in the same manner as it has been for centuries. After crop harvest, fields are grazed by livestock owned or managed by pastoralists. In many cases, the farmers do not have the authority or means to prevent this grazing. Therefore, they do not control this vital portion of the farming system. The removal of both grain and residue from the land results in a rapid decrease in organic matter, soil fertility, and soil structure. With loss in productivity, there is a rapid increase in the likelihood of soil erosion. Before farmers in such areas can institute cropping systems that maintain soil organic-matter levels, cultural and legal factors related to livestock ownership and land utilization must be changed. Policies and programs to deal with this situation will be required before efficient dryland systems can be developed in many regions.

5. Lack of Labor

It is ironic, but true, that in spite of the enormous population growth in many dryland areas, there are often shortages of labor for agricultural production. Shortage of labor at the time of sowing or weeding constrains both the amount of land that can be cultivated by a family and the types of new technologies that can be used effectively. New technologies, if they are to make significant impacts, often must be used as packages of two or more practices such as tied ridges and fertilizer placement. Labor shortages often impede their adoption. A great deal of labor is required from family members (particularly women and children) to meet nonagricultural needs of existence. Two major tasks are often obtaining household water and fuel for cooking. Community development of domestic water supplies and agroforestry projects can reduce the workload of meeting these needs and increase the availability of family labor for farming operations.

The timing of operations in dryland farming systems is critical. Proper timing is essential for water conservation, seeding, weed control, and erosion control. A matter of a few days, and in some cases hours, can mean the difference between success and failure. Seeding operations are particularly critical in a summer or winter rainfall area with a limited growing period, such as the season shown in Figure 1 for Rajkot, India. Delays of even a few days will limit the yield of the crop, because the rains stop very abruptly, and crop growth cannot be extended beyond the length of time it takes to deplete the soil water reserve. In continental climates, such as represented by Bushland, Texas (Figure 1), there is the possibility of precipitation at any time of the year, so a delay in planting is not necessarily associated with a reduced yield in any given year.

Since labor shortages during crop production and harvest periods play important roles in determining what crops are produced and in what quantities, policy measures must be developed that target this important issue. Actions to remove rural/urban wage rate disparities, improve seasonal labor mobility from region to region (including the urban unemployed and imported labor), and improve rural living conditions for migratory workers are universally needed to help solve labor shortages in remote dryland areas.

6. Macroeconomic Policy Constraints

To a great extent, the macroeconomic policies of a country can either augment or diminish programs designed to stimulate agricultural production and reduce rural poverty. In general, the economic policies of developing countries in past years have had negative effects on development in the dryland regions. Development strategies have shifted resources away from dryland to irrigated production and from rural to urban areas. Since dryland farmers are poorer and politically less influential, the effects of adverse macroeconomic policies fall disproportionately on them, in spite of the fact that they are often the primary producers of food crops.

Examples of macroeconomic policies that have hindered development of stable dryland agricultural systems include (1) disparity in urban-rural wage rates, which draws labor from agricultural areas; (2) government reliance on food imports and food aid, leading to depressed domestic food prices and reduced farmer income (OTA, 1986); (3) an overvalued exchange rate, which reduces export potential and encourages imports (Timmer *et al.*, 1983); (4) export taxes on agricultural commodities, which further exacerbates the income-earning problem faced by farmers; (5) cheap food policies that benefit urban consumers, creating severe problems for food producers; (6) unchecked inflation, which together with commodity price ceilings further erodes the incentive to invest in improved technology; and (7) taxation and subsidy policies, which lead to distorted prices for inputs. Subsidies are often designed to offset a tax or to adjust for commodity price manipulations, but these subsidies are generally ineffective in reaching the low-resource farmer. Subsidies usually lead to shortages and possibly rationing, with the result that the relatively well-off farmers benefit most. Good examples of these problems are government-subsidized credit and fertilizer.

When governments place too much emphasis on developing irrigation schemes, generally to increase production of export crops, limited public resources are diverted to the costly dams, canals, infrastructure, and farm production systems necessary to make irrigation possible. This means that fewer resources are available to help solve dryland problems (Lele, 1984). Since irrigated farming tends to be highly subsidized and supported, it also means that the dryland farmer is at an economic disadvantage in competing for markets, inputs, and new technology. Alleviating these constraints means modifying policies that have negative impacts on dryland agriculture or implementing new ones effective in bringing about needed changes.

Policies should bring input-output price ratios more in line with market supply and demand, including trade in international markets. At the same time, greater effort is needed to find ways in which society at large can share with dryland producers the risks of climatic variability and the ups and downs of domestic and international trade through appropriate government policies and programs. This kind of support is particularly important in the early stages of development of dryland agriculture as it becomes more dependent on the marketing of inputs and outputs. Price stability programs, therefore, should be given high priority.

Government and donor agencies should also strengthen effects to encourage more widespread adoption of improved soil and water management practices in dryland areas. For example, tax advantages tied to conservation investments can provide incentives for farmers to carry out costly, long-term land improvements that might not otherwise occur. Underwriting part of the cost of inputs and specialized equipment—e.g., tied ridgers—can do the same. Improving agricultural extension and soil and water conservation technical support services is a policy decision that must be taken.

In summary, the macroeconomic policies developing countries follow have far-reaching impacts on dryland agricultural productivity and on the overall growth and development of dryland regions. The macropolicy climate must be conducive to change and technological advancement. Macropolicies do this by creating an environment in which the appropriate incentives are allowed to operate and where government efforts are directed to all sectors of the agricultural economy, dryland and irrigated alike.

III. Conclusions

As an increasing number of people live and support themselves in dryland regions of the world, the stress placed on fragile dryland systems is becoming more and more evident. Inadequate and erratic crop production in these regions leads to tremendous hardship for the people dependent on dryland agriculture. Governments of many developing countries are being asked to deal simultaneously with food relief, the need for rapid and sustained agricultural production increases, protection of physical and biological resources from degradation, and reclamation of degraded lands. Achieving developmental objectives, which often seem conflicting, requires sound planning and large investments of time and money. However, the urgent need for rapid development of dryland regions, which are essential to the food and fiber production of so many countries in the world, can no longer be overlooked.

Soil and water management practices that can result in increased productivity over a relatively short term with few purchased inputs include contour terracing, tied ridges, water harvesting, and improved weed control. To do this, on-farm demonstrations and adaptive research need to be strengthened, and policies to relieve labor bottlenecks must be implemented. Over the medium term, it will be essential to identify, adapt, develop, and package practices that can further increase agricultural productivity through the use of purchased inputs, such as fertilizers, improved tools and implements, and improved seed varieties with disease and insect resistance. Technological recommendations must allow farmers flexibility in choosing production practices that best fit their particular environment. To identify reasonable technologies to meet the needs of specific regions, detailed databases for agroclimate, soil, and other resources must be developed for planning purposes.

The fragility and importance of the soil and water resource base must receive greater recognition, at both the national and on-farm levels. Productivity cannot be sustained if the resources that support productivity are degraded. Governments must develop criteria to detect the rate of land degradation, to evaluate the impact of degradation on productivity, and to determine the population-supporting capacity of their land. Implementation of policies that will ensure that lands are not expected to produce beyond their capacity is a major long-term challenge.

National policies must recognize that contributions of dryland agriculture are vital to the national economy and to the well-being of the people living in the dryland regions. National tax, currency, and wage/price policies must treat the dryland agricultural regions fairly. Dryland farmers cannot assume all of the risks of production in extremely risky environments if access to stable markets, credit, storage, and purchase of food are not assured.

Improved cropping systems must evolve from the agricultural and social systems currently in place, but the importance of resource protection and maintenance must be recognized. Development and maintenance of improved agricultural productivity will require governments to strengthen rural area infrastructure and improve national economic policies. Development will also require institutions at the local and community level that can interact directly with farmers to bring about better land and resource management. Without effort at all levels, the situation of the people in many dryland areas will continue to deteriorate.

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