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Challenges Confronting Soil Management for Dryland Agriculture

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Abstract: Dryland cropping regions are present on every continent except Antarctica and represent major small grain producing regions as well as major food grain producing regions. As the human population continues to grow there will be greater demand for food, fiber, and biofuel production. Society is emphasizing the quality of production in addition to the quantity produced. Increased production will be needed at the same time land is being lost to urban encroachment and degradation resulting from wind and water erosion, physical and chemical degradation, and other competing uses (e.g., natural areas). Increased productivity will require efficient capture, storage, and use of precipitation and efficient utilization of all available nutrient resources. Tools for quantifying the spatial variability in soil properties affecting water dynamics, tools for sensing crop stresses that can be alleviated through management, and methods for quantifying the spatial variability in nutrient availability are needed. As efforts are undertaken to increase productivity under dryland conditions, practices that are sustainable and preserve biotic and abiotic natural resources will need to be developed and adopted by producers.

Key words: Sustainable agriculture, land degradation, soil conservation, nutrient management, cropping systems.

Dryland agriculture is that practiced under conditions of moderate to severe moisture stress during a substantial part of the year (Oram, 1980). Under such conditions soil management emphasizes water conservation, sustainable crop yields, limited inputs for soil fertility, and protection against wind and water erosion (Stewart and Barnett, 1987). Dryland cropping regions are present on every continent except Antarctica. Regions under dryland cropping represent major small grain producing areas of many developed countries and major food grain producing areas of developing countries. In addition, these regions produce many pulse and oilseed crops.

Irrigation is a management practice that can be used to overcome moisture stress. From 1950 to 1990 the area under irrigation tripled to over 240 million hectares. The high cost of constructing irrigation projects and competing uses for limited water resources has greatly slowed the rate of increase in irrigation. In contrast the human population continues to grow and with it the demand for food and fiber. Since the potential for expansion of irrigation appears limited (Postel, 1998) and the demand for food, fiber, and biofuels is increasing, improving productivity and sustainability in dryland cropping is critical. Such improvements will require improved soil management practices that make efficient use of available water and nutrients while protecting the soil against degradation.

Farming practices in dryland areas vary greatly among regions. In much of the America's central Asia, and Australia, large land holdings and mechanized agriculture predominate. In south central Asia, east Asia, parts of Central and South America, and much of Africa, land holdings tend to be smaller and agricultural practices are more labor intensive. Regardless of the scale at which farming practices are implemented, water and nutrient availability most often limit crop yields and soil degradation is a serious threat to long-term productivity in many regions. These conditions result in crop production being below the potential yield in most cases, suggesting the need for continued improvements in management. As efforts are made to develop improved management practices, there are a number of impending challenges facing agriculture worldwide that will strongly influence how food and fiber is produced in the future.

Impending Challenges

Population

In 1900 the world had a human population of 1.63 billion with one-third of those people living in developed countries (Table 1). By 2020 our population is expected to exceed 8 billion people with more than 80% living in developing countries (Haub and Farnsworth-Riche, 1994). The largest absolute increase in population will occur in Asia while the largest relative increase in population will occur in Africa (Fischer and Heilig, 1998). Not only will there be more people, those in developing countries will be striving to improve their standard of living. These trends will greatly increase the demand for food, fiber, and biofuels of both high quantity and quality. There are a number of emerging constraints confronting agriculture that will likely intensify. Producers will have to address these constraints as they strive to meet the food and fiber demands of society. These constraints include: loss of arable land through urban encroachment, and degradation; competition for water resources; and environmental quality issues.

Given current population trends, grain yields will have to increase 1.2% (for wheat and rice) to 1.5% (for corn) per year to meet future demands (Rosegrant *et al.*, 1998). Prior to 1950, increases in food production were accomplished almost solely by bringing additional land into crop production. The rapidly increasing yields during the 1950's, 1960's, and 1970's

Table 1. Trends and distribution of the human population[a]

Years	Developing	Developed	World
	billions		
1900	1.070	0.560	1.630
1950	1.682	0.835	2.516
1990	4.079	1.213	5.292
2020	6.739	1.353	8.092

[a] Haub and Farnsworth-Riche, 1994.

resulted from the rapid expansion in the use of irrigation; development of crop varieties that better tolerate biotic and abiotic stresses; the availability of pesticides to control pathogens, weeds, and insects; and the development of management practices that meet the nutrient needs of the crop and make more efficient use of soil and water resources. Meeting future food, fiber, and biofuel demands will require continued advances in plant breeding and the development of management practices that continue improvements in soil and water conservation and nutrient management. Evans (1998) suggests that there is potential for continued yield increases through breeding to select for improved harvest index and environmental adaptation, but that it is unlikely these efforts will achieve the rate of yield increases needed to meet future demands. Major increases in crop yield will likely require that the efficiency of the photosynthetic process be improved. Traditional plant breeding has not been as successful in improving the photosynthetic efficiency of crops as have management practices (N and other fertilizer management practices). Genetic engineering may be a tool that plant breeders can use to affect the photosynthetic efficiency of crops. In addition, genetic engineering may play a key role in improving the quality of crops. Continued cooperation between plant breeders and agronomists is essential to achieving the rates of increase in crop yield that will be required in the relatively near future.

Consumers, especially in developed countries, are placing greater emphasis on food quality. Producers are often paid for producing goods meeting quality criteria (wheat, barley, sugar beets, potato). Genetic engineering may play a role in improving the quality of crops or in giving crops traits that currently do not exist. Most genetically enhanced crops in the market today possess traits that aid the producer (e.g., herbicide resistance, Bt trait). The next generation of genetically enhanced crops will likely possess traits that meet nutritional needs of the consumer that are currently not being met (Ye *et al.*, 2000) or improve feed use efficiency (Ertl *et al.*, 1998).

Loss of arable land

In addition to the population increases given above, there is a trend for increasing urbanization. In the United States the percentage of the population classified as living in rural areas decreased from 29.6% in 1961 to 23.4% in 1997 (http://apps.fao.org/). An increasing population combined with a greater percentage of those people living in urban areas has resulted in the amount of land in urban use doubling from 11 million ha in 1959 to 24 million hectares in 1992 (http://usda.mannlib.cornell.edu/datasets/land/89003/). This situation is not atypical with similar changes being observed in China, Brazil, and many other regions of the world. In many cases the observed urbanization is affecting arable land.

Soil degradation results in the loss of productivity on about 10 Mha of land each year (Pimentel *et al.* 1995). Oldeman (1994) placed soil degradation into four categories: water erosion, wind erosion, chemical degradation, and physical degradation (Table 2). The total land area of the world is 13013 Mha of which 1475 Mha is agricultural land (Oldeman, 1994). Human-induced degradation due to agricultural mis-

Table 2. Area of potential crop land lost to degradation as a function of various types of degradation[1]

Type of degradation	Dryland[2]	Total
	----------Area (Mha)-------	
Water erosion	478	1094
Wind erosion	513	548
Chemical (salinization, acidification, pollution, nutrient depletion, loss of organic matter)	111	240
Physical (compaction, crusting and sealing)	35	83

[1] Oldeman (1994), [2] Climatic region with an annual precipitation/evapotranspiration ratio ≤0.65.

management has affected 552 Mha. Degradation impacts a larger percentage of agricultural land in some regions than in others. In Central America and Africa over half of the agricultural land is classified as degraded.

In dryland areas water erosion results during the short-duration, high-intensity rain events common to many of these regions. Wind erosion affects a greater percentage of dryland area than does water erosion (Table 2). Loss of soil to wind erosion at rates faster than soil formation reduces crop yields (Tanaka and Aase, 1989). Chemical degradation includes: depletion of organic matter and nutrients, salinization, acidification, and pollution (Oldeman, 1994). Excessive tillage and fallow have resulted in loss of organic matter in many dryland soils (Reeves, 1997). Erosion and failure to replace nutrients removed by the crop or lost to erosion results in nutrient depletion. Salinization is usually associated with poor irrigation water management. Under certain hydrologic conditions, poor water management in dryland cropping can cause saline seep development. For example, salinization resulting from saline seep development has affected nearly 80000 ha in the Northern Great Plains of North America (Black *et al.*, 1981). Acidification of soil is largely a leaching process. In dryland areas extensive leaching is not expected, but soil acidification can result from the inefficient use of ammonical fertilizer. Soil degradation due to pollution is the result of human activity. Physical degradation includes compaction, crusting, and sealing (Oldeman, 1994). Use of heavy equipment, repeated passes over the field, and travelling over a field under high soil moisture conditions all result in soil compaction. Surface compaction can be overcome using tillage. Subsurface compaction is a much more serious problem with few efficient solutions at the present time (Håkansson and Reeder, 1994). Deep compaction restricts root penetration, reduces water-use efficiency, and may facilitate leaching. Crusting and sealing result from the alteration of soil structure at the surface layer often the result of rain falling on unprotected soil (e.g., no crop residue or plant canopy). Crusting can severely impede seedling emergence. Sealing greatly reduces infiltration rates increasing the potential for runoff losses and erosion. Reduced infiltration rates and subsequent runoff losses reduce water harvesting efficiency.

Several countries have undertaken programs to remove agricultural land that is susceptible to wind and water erosion out of production. In China, 6 million ha (~5% of total arable land) is being returned to forest and grass to reduce wind and water erosion. In the United States the Conservation Reserve Program was created in 1985 to place highly erodible land (14.7 million hectares) into perennial vegetation for 10 years. Hence, soil conservation programs compete with crop production for land area but for much of this land crop production was not a sustainable practice.

Competition for limited water resources

Urbanization in arid and semi-arid areas are increasing demands on limited water supplies. In the western United States, in China, and in India, urban pressures have shifted water out of agriculture and into urban uses. In some regions, public pressure to preserve natural ecosystems has reduced the allocation of water to agriculture. In other regions utilization of below ground water sources has occurred at rates exceeding the recharge rate bringing into question the sustainability of these practices. While many of the water issues affect irrigated agriculture to a greater degree than dryland agriculture they underscore the fact that large increases in irrigation are unlikely and dryland agriculture will continue to play an important role in meeting food and fiber demands.

After assessing land and water resources Penning de Vries *et al*. (1997) estimated sufficient food could be produced to meet food and fiber demands to the year 2040. When such an assessment was conducted on a country by country basis they found that China would need to use all land resources and India all water resources to meet future food needs. Socio-economic conditions will continue to influence food production and distribution. Poverty will prevent large segments of the population from obtaining sufficient food and fiber. In addition, other uses (e.g., bio-fuels, non-food crops, and nature) will prevent crop production on some potentially arable land making it unlikely that producing sufficient food will be accomplished smoothly.

Environmental issues

Public awareness of environmental quality began increasing in the early 1960's. Even in areas where dryland agriculture is practiced, highly variable precipitation patterns create the potential for leaching and runoff to contribute to contamination of surface and ground water resources. Water erosion contributes to environmental contamination through siltation of reservoirs and river channels and through the addition of chemicals adsorbed to transported sediment. During the drought years of the 1930's dust clouds generated in the Great Plains of the United States were visible on the east coast providing a lasting reminder of the impact wind erosion can have on air quality. While our understanding of fate and transport of agricultural chemicals has improved greatly, recent reports of pesticides on produce, contamination of surface and ground water by agricultural chemicals, fish kills resulting from manure spills, hypoxia, pfisteria outbreaks, and other incidences are evidence that much remains to be done. Residue management and development of erosion control practices has done much to reduce erosion rates. Modest levels of adoption and, in some settings, reduced yields under conservation tillage suggest that better practices need to be developed.

Loss of arable land and competition for limited resources will require that agricultural practices be developed that provide the food and fiber for the current population and maintain the soil and water resources for future generations. Maintaining soil and water resources for future generations will require development and implementation of management practices that prevent degradation of these resources. In addition, reclamation practices will be needed to restore the productivity of degraded lands.

Sustainable Soil Management

Agronomic sustainability is a difficult term to define. The difficulty arises from the need for a definition that has utility for the various disciplines (e.g., agronomic, economic, environmental, and social) using the term and yet addresses the interrelatedness of the disciplines. In addition to being multi-disciplinary, there are hierarchical aspects to sustainability with issues present at the field-, farm-, region-, national-, and world-scales (Lowrance *et al.* 1986). Parr *et al.* (1990) offered the following definition: sustainable agriculture utilizes farming systems that are productive and profitable, conserve the natural resource base, protect the environment, and enhance health and safety, and do so over the long-term.

Agronomically sustainability suggests that the capacity for production of food and fiber must be maintained or improved over a long period of time. To accomplish this the resource base must be conserved and efficient use made of nutrient and water resources. In addition, crops and livestock adopted to local conditions should be used while maintaining as much diversity in the system as possible (Lockeretz, 1988).

Economically sustainability suggests that food and fiber are produced that is affordable for the consumer and yet provides the producer with sufficient income to cover costs. In addition, the income generated should allow producers a standard of living that makes agriculture an attractive vocation.

Environmentally sustainability suggests that biotic and abiotic resources are maintained to perform the myriad of functions necessary to support life. Soil serves as a substrate supporting plant growth, as a reservoir for many nutrients, as a filter maintaining air quality through interactions with the atmosphere, as a storage and purification medium for water as it passes through the soil, and as a biological reactor completing the cycle of life through decomposition and recycling of animal and plant products. Water is essential to all life.

Socially sustainability suggests that agriculture produces the goods and services needed by society in the proper quantity and quality. Included in the goods and services provided by agriculture are natural areas that allow native plants and animals to persist and provide recreational opportunities for people. Hence, land use and ownership issues become intricately involved in sustainability. Societal needs will vary from region to region in the world.

The various aspects of agricultural sustainability described above are not independent of one another. For example, if the resource base degrades and agronomic productivity is maintained only through increased inputs, off-site impacts are likely (resulting both from degradation of the resource and inefficient use of inputs) and the profitability of the operation will likely decrease. Similarly, if a crop is grown and there is no market available it is unlikely that the producer will make a profit or that the operation will be socially acceptable.

Also if the price a producer received for a crop is too low or input costs are too high for the operator to make an acceptable profit the operation will not be economically viable. If this situation persists ownership patterns may change to something less desired by society.

There have been major advances in improving productivity and efficiency in agriculture. Mechanization, improved cultivars, development of pesticides, development of water management tools, and increased use of fertilizers has improved the efficiency so that in many regions a small percentage of the population is able to produce the food and fiber needed by society. In spite of these advances, a dependence on fossil fuels, contamination of air and water by agricultural chemicals, and poor fertilizer and water-use efficiency by the crop suggest that further advances will be required to achieve sustainability in agriculture.

Current Limitations

Duvick and Cassman (1999) recently suggested that 50% of the yield increase obtained during the green revolution was the result of genetic improvement in varieties developed by plant breeders and 50% the result of improvements in management. At present actual yields of major cereal crops are 60 to 70% of potential yields suggesting that new management practices will continue to result in improved yields (Cassman, 1999).

Water-use efficiency

Under dryland conditions water is the factor most commonly limiting crop production. While long-term average precipitation values suggest that many of these areas are able to support crop production, the high temporal and spatial variability exhibit by precipitation makes dryland cropping a high risk enterprise. One objective of management practices designed for dryland areas must be to minimize risk.

Crop-fallow is a traditional system whereby water is stored in the soil profile during the fallow year for use by the subsequent crop. As fallow systems evolved from dust mulch (maximum tillage using plow or deep disk) to stubble mulch (minimum tillage using rod-weeder or sweeps) to no-tillage (herbicides) fallow efficiency (amount of fallow precipitation stored as soil water) improved from 20% in the 1920's to 35 to 40% in the 1970's (Peterson *et al.*, 1996). Fallow efficiency has not improved since the 1970's with further improvements being limited by the amount of residue that is produced and maintained on the soil surface in these systems (Unger, 1978). In areas where crop residues are removed for other uses the fallow efficiency would be very low.

While crop-fallow systems are successful in stabilizing yields they have negative aspects as well. When tillage is used to control weeds, incorporation of crop residue exposes the soil to wind and water erosion and creates a more oxidative soil environment (Doran, 1980) resulting in the loss of soil organic matter. Also a large fraction of available land does not produce a crop during a given year when crop-fallow systems are used. As demands for food and fiber increase, it is unlikely that leaving land idle for a growing season will be an acceptable option. To overcome these

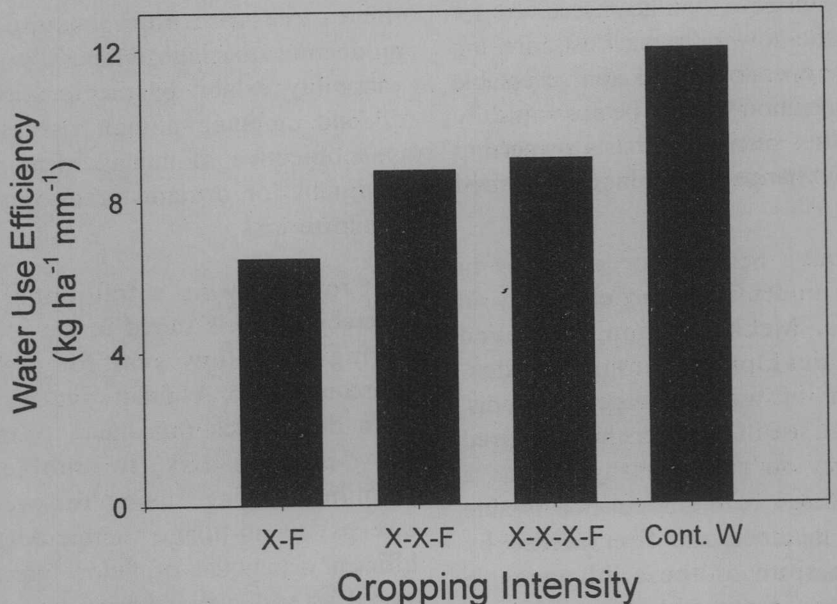

Fig. 1. water-use efficiency as a function of cropping intensity for several locations in the Central Great Plains of North America. All systems are wheat based with corn, sorghum, and millet used in the multi-year rotations (from Peterson et al. 1996).

negative aspects, systems utilizing conservation tillage and more intensive cropping have been developed. These more intensive systems exhibit improved water-use efficiency (Peterson *et al.*, 1996) and are economical when compared to crop-fallow systems (Dhuyvetter *et al.*, 1996). Peterson *et al.* (1996) summarized results from a number of cropping systems studied in the Central Great Plains of North America and found that water-use efficiency was 80% greater under continuous cropping when compared to crop-fallow (Fig. 1). Even under continuous cropping a large percentage of precipitation falling in dryland areas is still lost through evaporation suggesting that there is continued potential for improving water conservation and water-use efficiency in these areas.

In China, crops grown on 60% of the arable land depend solely on precipitation and development of management practices for improving precipitation capture, storage, and utilization by the crop are being actively pursued. One common practice is to deep plow the soil (30 to 40 cm) to increase pore space. After precipitation is received the soil surface (2 to 5 cm) is loosened using special hand tools. This practice breaks crusts that may have formed and creates a rough surface that reduces evaporation losses, but is labor intensive.

Cropping and tillage systems

As cropping intensity increases there is greater need to use diverse crops in the rotation to avoid pest problems. Use of a single crop for a number of growing season allows pests (weeds with similar life histories, insects that prefer that crop, diseases specific to that crop, etc.) to increase above threshold levels. As pest pressure increases yield losses will result, or control of the pest will increase input costs. In addition, it is commonly observed that a crop grown in a rotation will exhibit greater yields than the same crop grown continuously. The cause for this rotation effect has been elusive and likely has multiple components (e.g., increased nutrient availability, improved water-use efficiency, decreased pest pressure). A better understanding of the rotation effect will allow us to design better crop rotations.

Increasing diversity in a cropping system requires that crops adapted to the region be available, that producers have the proper equipment for planting and harvesting the alternate crop, and that there are markets for the alternate crop. In addition, management skills required for diverse cropping systems are greater than those used in mono-crop systems. Lack of alternate crops adapted to various regions, poor or cyclic markets for many alternate crops, need for additional equipment to plant and harvest alternate crops, and lack of management tools for designing efficient cropping systems all limit productivity in dryland agriculture.

As noted earlier wind and water erosion have degraded extensive areas of soil (Table 2). A number of conservation tillage practices (tillage practices that allow >30% of the soil surface to remain covered by residue at planting) have been developed for dryland areas. Conservation tillage under dryland conditions protects the soil from wind erosion and the impact of rain, reduces evaporation by maintaining cooler soil temperature and serving as a layer through which water vapor must diffuse, and saves energy by reducing the number of passes a producer must make across each field. It is difficult to determine how extensive adoption of conservation tillage has been on a global basis. Using available estimates for one particular conservation tillage practice (no-tillage), it appears adoption of conservation tillage practices varies greatly across regions being higher in North and South America than in other parts of the world (Table 3). While conservation tillage practices other than no-tillage are available, this summary gives a rough idea of the level of adoption. In South America no-tillage accounts for more that 95% of the area in conservation tillage so the values in Table 3 provide a reasonable estimate for that region. In the United States conservation tillage is used on 37% of the cropped land (CTIC, 1998) and in Canada conservation tillage is used on 31% of the seeded land (Dumanski *et al.*, 1994). For both countries these percentages are much larger than those given in Table 3 since no-tillage is not the dominant form of conservation tillage used in these countries. Available data suggest that there is great potential for increasing the use of conservation tillage. Much work remains to be done identifying and finding solutions for impediments to implementing conservation tillage practices.

Nutrient management

Nutrient availability often limits dryland crop production. Nutrient deficiencies reduce yield and prevent the crop from fully utilizing available soil water. Fertilizer management is an essential component to sustainable agriculture and proper inputs of fertilizer nutrients are essential to optimizing crop production. Nitrogen is the nutrient most

Table 3. Arable land and percentage of total arable land under no-tillage in different countries

Country	Area under no-tillage (ha)	Percentage of arable area (%)[1]
United States	19,347,000	10.9
Brazil	11,200,000	21.1
Argentina	7,270,000	29.1
Canada	4,080,000	9.0
Australia	1,000,000	1.9
Paraguay	790,000	35.9
Mexico	500,000	2.0
Bolivia	200,000	10.1
Chile	96,000	4.9
Uruguay	50,000	4.0
Others	1,000,000	
Total	45,533,000	3.3

[1] Calculated by dividing the area under no-tillage by the total arable area

often limiting crop yield and the nutrient added in largest amounts by producers (Table 4). Phosphorus and potassium (potash) are also added in large amount by producers (Table 4). For some crops sulphur additions are necessary (e.g., canola, oilseed rape, and legumes) and a umber of micronutrients may be locally important. Research suggests that chlorine may play a role in disease resistance in wheat although the response varies among varieties (Lamond *et al*., 2000).

Specialization in agriculture has created regional discontinuities in nutrient use and supply. Many regions with large confined livestock operations generate byproducts containing nutrients in excess of what is required by crops in the local area. This results in export of nutrient from grain production areas and an accumulation of nutrient in animal production areas. There is great potential for conserving and utilizing nutrients contained in animal byproducts more efficiently.

There are many consequences to improper nutrient management. Under-fertilization results in sub-optimum crop performance and soil nutrient depletion. Over-fertilization results in poor fertilizer use efficiency by the crop and in the accumulation of nutrients in the soil profile. For mobile elements, accumulation in the soil profile increases the potential for environmental contamination of surface- and ground-waters, and for nitrogen the emission of greenhouse gases to the atmosphere. Inefficient use of ammonical fertilizer leads to soil

Table 4. Worldwide fertilizer use in 1998

Fertilizer type	Mass (metric tonne)
Nitrogenous fertilizer	82,421,368
Phosphate fertilizer	32,911,510
Potash fertilizer	22,022,165
Total fertilizer consumption	137,355,043

acidification. In addition, inefficient fertilization has an economic penalty as under-fertilization results in yield loss and over-fertilization represents an unnecessary expense.

Nutrient management is very complex having economic, agronomic, and environmental aspects. Economically the producer must determine which nutrients will elicit a crop response and which fertilizer form is the most cost effective. Agronomically the producer must have knowledge of crop demand throughout the growing season and the total amount of nutrients needed to meet potential yield. Potential yield is dependent on growing season conditions, which are very dynamic in most dryland regions, and is therefore difficult to estimate with certainty early in the growing season when nutrient additions are usually made. The producer must also understand nutrient availability for their soil conditions. Soil pH, clay mineralogy, organic matter content, and other soil properties effect fertilizer availability. Environmentally producers need to minimize negative offsite impacts. Nutrients added in amounts that cause offsite impacts increase production costs and offsite impacts are not socially acceptable. Given this complexity there is great potential for improving nutrient management for dryland cropping.

Research Needs

Since water is the factor most limiting production in dryland systems, a major research need will continue to be the development of management practices that capture and store precipitation for use by the growing crop. In addition, management practices for ameliorating soil conditions that impede root penetration (e.g., aluminum toxicity, compaction) are needed. Improving the rooting environment will allow crops to more efficiently utilize nutrient and water present throughout the root zone. Quantifying the spatial variability at the field scale in soil properties that affect water dynamics (e.g., texture, slope) could be used to adjust seeding rates or to plant crops or varieties best adapted to site specific conditions thereby improving water-use efficiency across the field (Shanahan *et al.*, in press).

Nutrient management represents a complex aspect of dryland agriculture with numerous opportunities for improvement. Improving our ability to estimate potential yield (based on current growing season conditions) and knowledge about nutrient uptake patterns would facilitate development of management practices that synchronize nutrient availability and crop demand. There is a need for methods of rapidly quantifying spatial variability associated with nutrient availability. Use of variable rate applicators to apply nutrients based on the spatial patterns present in a field have potential for improving nutrient management. A major challenge to applying such technology will be the development of tools and approaches for delineating management zones within a field (Luchiari *et al.*, in press). Nutrients from agricultural fields are a major non-point source of contamination for surface- and ground-water. Better use must be made of all nutrient sources (fertilizers, animal byproducts, municipal sludge, biological N fixation) to maximize utilization of nutrients by the crop and minimize losses. Controlled release technology and inhibitors are current technologies that reduce losses of N and improve availability to the crop. Additional efforts are needed to improve delivery systems for fertilizer inputs.

Dryland agriculture soils have tremendous potential for C-sequestration (Janzen *et al.* 1998). Continued improvements in residue production and management will increase the rate of C accumulation. Carbon sequestration will not only reduce the accumulation of greenhouse gases in the atmosphere, but will also improve a number of soil properties. A better understanding of the interaction between management practices and emission of other greenhouse gases is needed.

Remote sensing offers potential for rapidly determining crop stresses. In addition to the satellite and aircraft based platforms being developed there are a number of hand held technologies that can be used to assess crop stress. The Minolta SPAD 502 chlorophyll meter is a commercially available tool that has been used to assess the N status of a number of crops (e.g., Wienhold and Krupinsky, 1999; Schepers *et al.*, 1992; Peng *et al.*, 1996). The chlorophyll fluorescence meter has potential for identifying multiple stresses in plants (Mohammed *et al.*, 1995) and efforts are underway to scale up this methodology from single plant measures to canopy measures (Buschmann and Lichtenthaler, 1998). Research needs include tools for determining the causes for a particular stress and identifying stresses early enough in the life cycle of the plant so that management practices can be altered to alleviate the stress before yield is negatively affected. To accomplish this it will be necessary to identify critical growth stages where stress must be minimized to optimize crop yield. Also, a better understanding of how stresses (type and magnitude) at different growth stages effect crop yield and the plasticity of this effect (e.g., if a stress is identified and corrected will crop yield recover?) is needed.

As researchers strive to meet these needs there must be a continuous effort to transfer the acquired information to the producers. It is only through the adoption of new practices by producers that problems will be solved and improved sustainability in the production of food, fiber, and biofuel will be achieved.

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