ARRESTING SOIL DEGRADATION AND INCREASING CROP YIELDS IN SEMIARID REGIONS

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Abstract
Twenty percent of the world's land area occurs in semiarid regions where dryland agriculture is widespread. Soil degradation processes such as wind and water erosion, organic matter decline, soil compaction, and soil fertility loss occur rapidly in these areas because of high temperatures and low and highly erratic precipitation. In contrast, soil restoration practices are difficult because climatic conditions limit the choice of crops, legumes in particular, that can be grown successfully. Crop residues that can be returned to the soil are limited because of low yields. This is exacerbated in many developing countries by the demand of crop residues for animal feed and household fuel. Consequently, soils in dryland areas have been significantly degraded making the limited water even more limiting because of poor soil physical properties. The infamous Dust Bowl of the 1930s in the U.S. Great Plains is a classic example of the devastation that can occur from soil degradation in semiarid regions. This disaster demanded major changes in tillage practices and cropping systems. While dryland farming in this region remains a risky enterprise, conservation agriculture principles — avoiding mechanical soil disturbance, maintaining soil cover, and crop rotation — have increased crop yields and enhanced soil quality.

Additional Keywords: organic matter, wind erosion, tillage, dryland, soil quality

Introduction
Semiarid lands make up 20 percent of the world land area (FAO, 2000) but only 11 percent of the wheat and 8 percent of the maize are produced in semiarid regions in developing countries excluding China, and much of this is produced under irrigation (FAO, 1996). An estimated 60 percent of the wheat produced in developing countries is irrigated. The need to enhance cereal production in semiarid regions is clear as population pressures increase rapidly. Because water for irrigation in these regions is limited, dryland farming systems must be developed that can help meet the food and fiber needs of an increasing population while sustaining the soil resource base. The 1994 United Nations Convention to Combat Desertification stated that desertification is caused by climate variability and human activities (UNCCD, 2000). In the past, drylands often recovered following long droughts. Under current conditions, however, they tend to lose their biological and economic productivity quickly. Drylands on every continent are being degraded by exposure of soils to raindrop impact or wind erosion due to over-cultivation, overgrazing, deforestation and poor irrigation practices. Economic and social pressures, price and input subsidies, over-dependence on export crops; recurrent droughts, ignorance and conflicts generally cause such over-exploitation. Stewart et al. (1991) also expressed concern about soil degradation in semiarid regions and developed a simplified conceptual model of the potential for soil degradation in dryland regions. The objective of this paper is to present soil and water conservation approaches for increasing crop yields in semiarid regions while sustaining the soil resource base. The U.S. Southern Great Plains, where the infamous Dust Bowl of the 1930s ravished the area, is used as a case history.

Historical Perspective
The Great Plains of North America is a vast region east of the Rocky Mountains beginning at about 1600 m elevation and annual precipitation of about 400 mm and extending east to about 700 mm annual precipitation and an elevation of about 700 m above sea level. The region extends north to the 40th parallel and south to the 32nd parallel. In all, the Great Plains occupies parts of 10 U.S. states and 3 Canadian provinces. Agriculture in the region began in the late 1800s and early 1900s as land in the more favourable humid regions became limited and farmers began to expand westward to the more marginal lands in the semiarid Great Plains. The plains were almost entirely covered with grass and the only trees that existed were along the very few streams and rivers.
The dominant soils of the region were medium to fine textured and early cultivation was done primarily with the mouldboard plow. Later, disk plows became common. Early-day conservationists warned of the erosion that would take place in many parts of the Great Plains if the land were cultivated. As long as those soils most susceptible to erosion remained primarily in grass, erosion by wind and water was not serious. As agriculture expanded, however, the semiarid Plains region was opened to homesteading, land was broken from sod, and erosion problems—particularly wind erosion—became increasingly serious. Following World War I, high wheat prices, coupled with the development of power machinery, led to the rapid expansion in cultivated land and the large-scale

production of wheat and other crops. Even marginal soils that should have been left in grass were plowed and seeded to wheat. This expansion in cultivated land peaked in the decade of 1915 to 1925. While drought was experienced in some areas even during the early days of cultivation, the Plains as a whole received average or above-average precipitation before 1930. This coupled with the generally good physical and chemical properties of the newly tilled grassland soils resulted in favourable wheat yields. The highest yields occurred when wheat was grown on land that had been fallowed for several months to store water in the soil that would be available to supplement the growing season precipitation. Therefore, many farmers grew only one wheat crop every two years, so the land was mostly bare for about 16 of 24 months in the southern plains where winter wheat was grown to as long as 21 months in the northern plains where spring wheat was grown. Beginning in about 1930 and lasting until about 1940, the Great Plains suffered recurring droughts and the resulting wind erosion focused national attention on the Great Plains. Severe wind erosion in much of the Great Plains, particularly in southeast Colorado, southwest Kansas, western Oklahoma, and northwest Texas, resulted in the infamous Dust Bowl. Figures 1 and 2 illustrate the severity of soil degradation that occurred during that period.

Figure 1. Wind erosion during the Dust Bowl of the 1930s in the U.S. Great Plains.

Figure 2. Severe land degradation by wind erosion during the U.S. Dust Bowl.

The future of the Great Plains, particularly the southern portion where the Dust Bowl was the worst, was in doubt. Irrigation from the Ogallala aquifer became widespread following World War II that ended in 1945 and more 50 percent of the cropland became irrigated. However, the aquifer in parts of the southern Great Plains is being rapidly depleted so irrigation cannot be sustained for the long-term in much of the area. Therefore, dryland farming will again become the dominant system and care must be taken to insure that another Dust Bowl does not occur.
Stewart et al. (1991) developed a simple conceptual model to describe the difficulty of developing sustainable cropping systems when moving form wet and cool areas to hot and dry areas (Figures 3 and 4). Figure 3 shows the

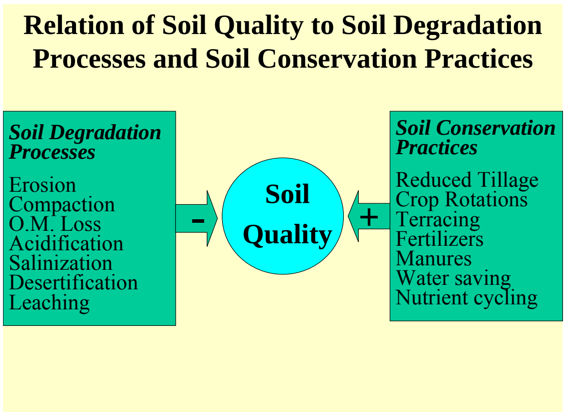

Figure 3. Relation of soil quality to soil degradation processes and soil conservation practices (modified from Hornick and Parr, 1987).

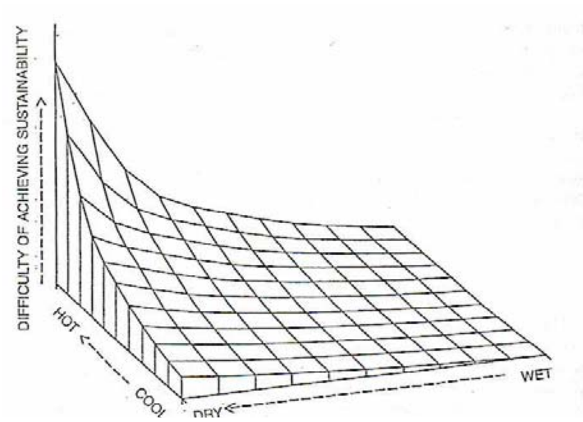

Figure 4. Conceptual model of temperature and precipitation effects on difficulty of developing sustainable agroecosystems in semiarid regions (from Stewart et al., 1991).

relationships between soil quality and soil degradation processes and soil conservation practices. Whenever an ecosystem like a grassland prairie in a semiarid region is transformed into cropland for the purpose of food and fiber production, there are several soil degradation processes set into motion. This is particularly true if raindrops fall directly onto the soil surface uncovered by vegetation, crop residues, mulches, etc. Some examples are soil organic matter decline, wind and water erosion, deterioration of soil structure, salinization, and acidification. In an ideal situation, soil conservation practices such as minimum or zero-tillage, crop rotations including legume crops, application of chemical and organic fertilizers, crop residue management, terracing, and other that reduce degradation processes and maintain soil productivity are used to offset the degradation processes. These negative and positive processes occur simultaneously as illustrated in Figure 3 and determine soil quality and crop productivity. Stewart et al. (1991) suggested that it becomes much more difficult to balance soil degradation processes with soil conservation practices as the climate becomes either drier or hotter, and much more difficult when both of these climatic factors increase simultaneously (Figure 4). This is because the rates of soil degradation processes increase in hot, dry areas especially when there is soil compaction due to intensive cultivation. Intensive cultivation also leads to a rapid decline in soil organic matter that affects all of the physical, chemical, and biological soil processes. Perhaps even more important than the increased rate of degradation processes in hot, dry areas is that the soil conservation practices needed to offset soil degradation processes become more difficult to implement and manage in hot, dry areas. Consequently, the resilience of soils in semiarid regions can be rapidly changed and can lead to desertification that has both physical and socio-economic consequences. It should also not be overlooked that one of the primary reasons that farmers till the soil intensively is to purposely promote the decomposition of soil organic matter because this supplies nutrients required for crop production. Unfortunately, this also degrades the soil physical properties and makes the already limited water resources even more limited.

Enhanced Water Conservation

Although the main function of summer fallowing is to store water in the soil, its inefficiency in doing so is well known. Mathews and Army (1960) reported that less than 15 percent of the precipitation was stored by summer fallowing for 15 months between wheat crops in the southern Great Plains. For annual wheat production where there was only a 3-month preparatory period between crops, approximately 22 percent of the precipitation during this period was stored in the soil. Even these relatively low storage efficiencies were somewhat higher than those prior to and during the Dust Bowl era. One of the most pronounced changes resulting from the Dust Bowl was a change in tillage practices. As a means of controlling wind erosion, sub-surface tillage was introduced and soon became the dominant tillage practice. Sometimes called stubble mulch tillage, the basic principle was to pull a blade or V-shaped sweep about 10 cm below the soil surface. This would cut the roots of vegetation growing during the fallow period but would leave as much as 80 percent of the crop residues on the soil surface to control wind erosion. Even after three or four tillage operations during the fallow period, there would still usually be enough crop residues on the soil to greatly minimize or control wind erosion. Even though the shift in tillage was for wind erosion control, it soon became apparent that the amount of water stored during the fallow period was increased. Johnson et al. (1974) reported results from a wheat study conducted from 1942 to 1969 in the southern Great Plains. When wheat was grown annually with about three months between crops, the amount of stored soil water at time of seeding was 103 mm for the sub-tilled treatment compared to 91 mm for the disk tillage treatment. For the wheat-fallow system that produced one crop every 2 years with a 15-month fallow period between crops, the amount of stored water at seeding averaged 154 mm for the sub-tilled treatment compared to 128 for the disk tilled treatment. Although these differences were relatively small, the average wheat yields were increased by sub-tillage when compared to disk tillage from 600 to 700 kg ha^{-1} for the continuous wheat treatment and from 950 to 1070 kg ha^{-1} for the wheat following fallow treatment. These results clearly showed that small increases in stored soil water significantly increased grain yields so the sub-tillage technology was not only controlling wind erosion but increasing water storage and grain yield as well. Another noted benefit of sub-tillage was that it did not result in as much loss of soil organic matter. From an initial organic matter content of 2.44 percent in the 0 to 15 cm layer in 1941, the average organic matter content of the sub-tilled plots dropped to 1.62 and 1.79 percent for the wheat–fallow and continuous wheat, respectively, by 1966. Disk tillage resulted in an even larger loss. Thus, for this study, results showed that the longer the fallow period and the more intense the tillage, the greater the loss of soil organic matter. These results reinforce the concepts illustrated in Figures 3 and 4.

The next major change in tillage in the southern Great Plains began to occur in the early 1970s. The Organization of Petroleum Exporting Countries was formed in 1960 but the influence of this group was not widely felt until the 1970s. There were two oil-pricing crises. The first and most pronounced was triggered by the Arab oil embargo in 1973 and the second was the outbreak of the Iranian Revolution in 1979. These crises caused fundamental imbalances in the market and resulted in oil prices rising steeply. The sharp rise in oil prices had a dramatic effect on agriculture, particularly in developed countries, where modern agriculture technologies were highly dependent on energy inputs. The cost of oil, and energy in general, increased much more rapid than agricultural products, particularly grain. This is illustrated in Figure 5 that shows from 1950 to 1973 a bushel of wheat (27.3 kg) would buy a barrel (167 liters) of oil, but following 1973, it has taken as many as 10 bushels of wheat to purchase one barrel of oil. On a positive note, the sharp increase in energy prices in 1973 resulted in a tremendous interest in reduced tillage and no-tillage cropping systems. Researchers, change agents, industry representatives, and policy makers began in earnest to develop cropping systems that largely used herbicides for weed control rather than tillage. In many cases, the emphasis was on erosion control but in dryland areas it once again became apparent that less tillage that left more residues on the soil surface, soil water storage increased. An example for the southern Great Plains is Figure 6 showing a summary of many years of research prior to and following 1973. The average soil water content at the time of seeding grain sorghum following an 11-month fallow period after harvesting wheat for study years prior to 1973 was 102 mm compared to an average of 173 mm for years following 1973. This increase is even more impressive because the data prior to 1973 were primarily from sub-tillage plots that had already shown an increase over disk tillage.

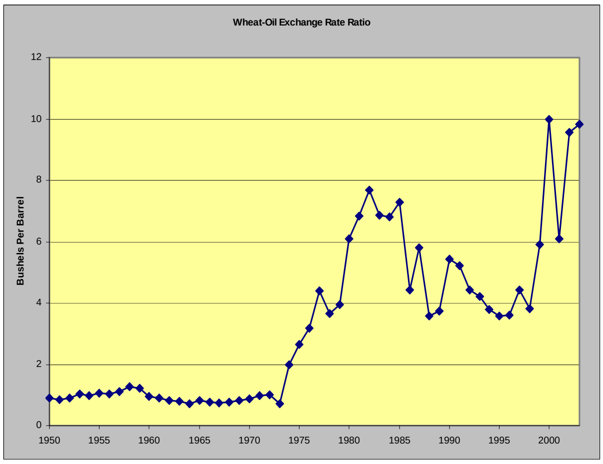

Figure 5. The ratio of the value of one bushel (27.3 kg) of wheat and one barrel (167 liters) of oil from 1950 to 2003.

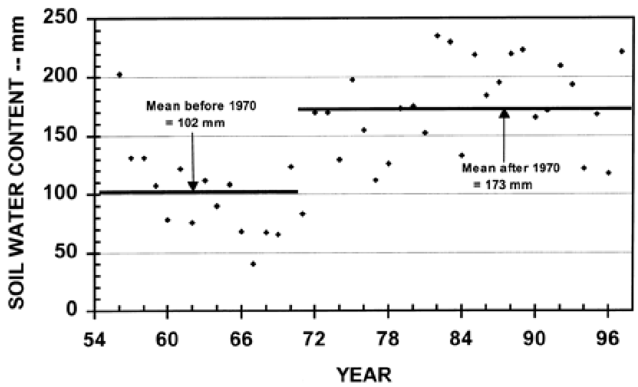

Figure 6. Average annual volumetric soil water content at planting time for grain sorghum in Texas (Unger and Baumhardt, 1999).

The change in soil water storage and its subsequent influence on crop yields is also reflected in farmer yields. Figure 7 shows dryland farmer yields of wheat grain from 1949 to 1999 for Deaf Smith County, Texas. The average annual precipitation for the county is about 450 mm and the annual potential evapotranspiration is about 1800 mm. Therefore, drought is a very common occurrence and severe water stress occurs every year. The yearly precipitation amounts show a range from less than 200 mm to more than 800 mm. A 10-year moving average (each yearly point is the average precipitation amount for the year shown plus the nine previous years) line of annual precipitation is also shown and although there is some variation, the average annual amount has remained relatively stable. The county average wheat yields for each year are also shown in Figure 7 and there is also a line showing the 10-year moving averages. It is noteworthy that the moving yield average and moving precipitation average closely paralleled each other until about 1973. Since that time, the moving average grain yield increased essentially every year and the average yield has more than doubled. No single factor is responsible but it clearly shows that the water use efficiency dramatically increased. Water management is the first factor that must be addressed in semiarid regions because other improved technologies such as improved cultivars and fertilizers are usually not beneficial without improved water management. Again, many factors contributed to the increased yields shown in Figure 7 because these values represent the average yield of all farmers in the county. There were effects of government programs, better seeding and harvesting methods, and as already mentioned, improved cultivars and fertilizers. However, it is more than happenstance that the increasing yields beginning in 1973 coincides with the time of sharp increases in energy prices that began a movement toward reduced tillage and no-tillage. There has been a gradual increase in farmer adoption of reduced tillage and no-tillage systems and this trend continues. However, there are still many farmers that have not adopted these new technologies even though the advantages appear great. Reasons for not adopting no-till systems are several but some of the more important ones include higher management skills and a need for different kinds of equipment, particularly seeding equipment.

Also, many farmers in the southern Great Plains use cattle to graze wheat in the late fall and winter and in some years producers grow wheat only for grazing and this results in enough compaction that they feel that some tillage such as chiselling is necessary.

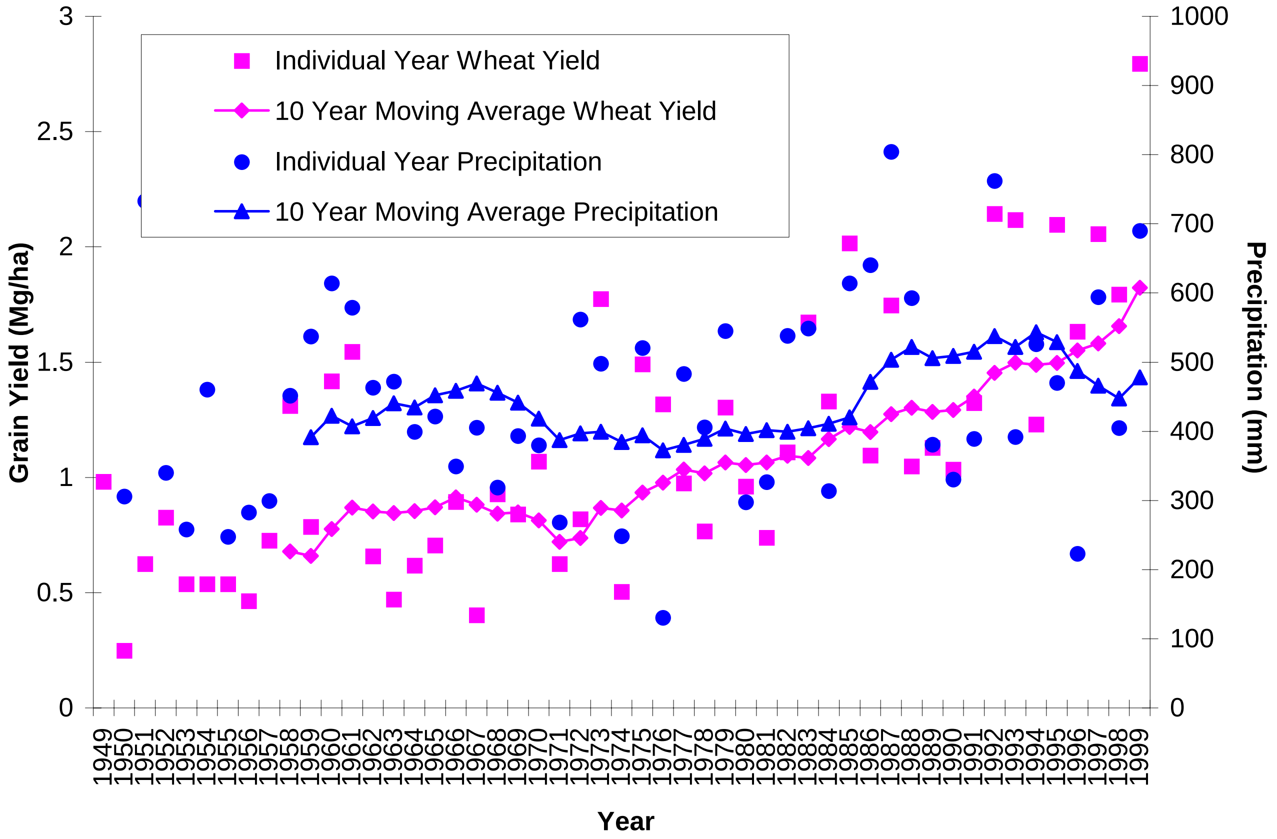

Figure 7. Average dryland wheat yields of farmers in Deaf Smith County, Texas, and precipitation (unpublished data, Zhen Wu, W.A. Colette and B.A. Stewart, West Texas A&M University).

Conservation Agriculture Principles

FAO (2002) states that the most successful sustainable agroecosystems are those that use some form of conservation agriculture. The goal of conservation agriculture is to conserve, improve and make more efficient use of natural resources through integrated management of available soil water and biological resources combined with external inputs. Conservation agriculture contributes to environmental conservation as well as to enhanced and sustained agricultural production. It can also be referred to as resource-efficient agriculture. Conservation agriculture as defined by FAO (2002) is based on three principles: 1) avoiding mechanical soil disturbance; 2) maintaining a permanent soil cover, by crop residues and crops; and 3) crop rotation. Conservation agriculture is practiced on 45 million ha, mostly in South and North America. However, this accounts for only about 3 percent of the 15 billion ha of arable land worldwide (FAO, 2002). Conservation agriculture has been most successful in South America, particularly Brazil, where economic and environmental pressures are great. Conservation agriculture is practiced from the humid tropics almost to the arctic circle and on all kinds of soils. However, FAO (2002) stated “So far the only area where the concept has not been successfully adapted is the arid areas with extreme water shortage and low production of organic matter. In these areas both humans and animals compete with the soil for crop residues.” Again, the difficulty of using conservation agriculture in dryland regions agrees with the earlier discussion of Figures 3 and 4. Maintaining a permanent soil cover and utilizing crop rotations are the principles of conservation agriculture that are the most difficult to practice under dryland conditions. However, the fact that it is difficult to carry out all the principles of conservation agriculture in dryland regions must not deter efforts to adapt the concepts as far as feasible in these regions. The dryland regions are where the benefits of conservation agriculture are critically needed and where soil degradation can be disastrous without the application of some of the concepts of conservation agriculture. Also, the example of the southern Great Plains presented earlier clearly shows that these principles can be partially applied to dryland areas resulting in both increased yields and improved soil conditions.

Conclusions

Conservation agriculture is based on the principles of avoiding mechanical soil disturbance, maintaining a permanent soil cover by crop residues or growing crops, and crop rotation. Conservation agriculture was largely developed in humid regions with the focus on controlling water erosion. More recently, it has been widely promoted for carbon sequestration. The application of conservation agriculture in dryland regions has been questioned because of the low production of crop residues and also because crop residues in many dryland regions are often used for animal feed or household fuels. Results presented in this paper and others, however, have shown that conservation agriculture principles can be instituted into dryland areas. Even relatively low amounts of crop residues left on the soil surface can significantly reduce wind and water erosion, enhance soil water storage, and improve soil quality in semiarid regions. Even more important, small increases in stored soil water can significantly increase grain yields. Therefore, even though significant progress in dryland regions will take years, or even decades, the principles of conservation agriculture should be applied in these regions as quickly and completely as feasible.

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