Soil Management Research for Water Conservation and Quality

Paul W. Unger, Andrew N. Sharpley, Jean L. Steiner, Robert I. Papendick, and William M. Edwards

Introduction

Remains of ancient aqueducts and other water-diversion systems show that early civilizations recognized the need for adequate water to obtain favorable crop yields. Even in our country, Native Americans often diverted water from streams to their crops.

Early immigrants to North America settled mainly near the eastern coast where precipitation generally was favorable for crop production. However, farther west, plant water stress occurred frequently and droughts that lasted several years occurred occasionally. A major drought in the U.S. Great Plains and the adjacent Canadian provinces in the 1930s led to widespread soil erosion by wind. To control the erosion, stubble mulch tillage was developed, which retained crop residues on the soil surface. The residues also aided soil water conservation, which improved crop yields. Subsequently, extensive research has been conducted to further improve water conservation, which is highly important for crop production. Also, agriculture must use available water resources efficiently because of increasing competition for water from other sectors of society (municipal, industrial, recreational). Efficient and responsible water use by all sectors of society is needed to help assure availability of adequate water in the future for all users.

Whereas much water conservation research has been conducted since the 1930s and 1940s, strong emphasis on water quality began more recently. When land is farmed, chemicals such as fertilizers and pesticides often are applied to obtain optimum crop yields. While tillage helps conserve water and maximize benefits of chemical inputs, it was clear in early farming systems that more tillage and chemical inputs increased the potential for degradation of water quality. Recent public concern has led to increased agricultural research regarding the effect of land management on water quality.

Ground and surface water quality is important because leachate and runoff water from agricultural land often is the primary source of water for municipal, industrial, and recreational users. High-quality water is extremely important for many purposes, including drinking, food preparation, and industrial food processing. Good-quality water is important for power generation, fishing industries, and recreational use.

Besides soil and pesticide losses from agricultural lands, many water quality concerns center on nonpoint transport of nitrogen (N) and phosphorus (P). Due to their differing mobility in soil, N concerns revolve around nitrate leaching to groundwater, whereas P concerns focus on P transport in surface runoff.

Nitrate in water has been linked to methemoglobinemia in infants, toxicities in livestock, and water eutrophication (Amdur et al., 1991). If reduced to nitrite, it can cause methemoglobinemia that causes abortions in cattle. Phosphorus in water is not considered directly toxic to humans and animals (Amdur et al., 1991). However, free air-water exchange of N and fixation of atmospheric N by blue-green algae means that P most often limits freshwater eutrophication (Sharpley et al., 1994).

It is impractical to discuss in detail the vast literature regarding water conservation and quality. Hence, we will identify practices affecting water conservation and quality and indicate the principles involved, but give only selected examples of results that can be expected from using the different practices.

Function of Soil Management Techniques for Conserving Water

Overall goals of soil management regarding water conservation are to promote water entry into soil, reduce evaporation, and use the water to grow crops. Sometimes, excess water must be removed for successful crop production. These goals can be achieved by using appropriate tillage systems, structural and support practices, surface mulch, and cropping systems and rotations. Stewart et al. (1975) showed the relative effectiveness of various practices for reducing runoff (Table 1). Ranges in reduction given in Table 1 are shown in Figure 1.

Tillage Systems

Many tillage systems are available. We grouped them into clean, conservation, and deep tillage types to discuss effects on water conservation. Tillage influences water conservation through its effects on soil conditions that retard runoff, enhance infiltration, suppress evaporation, and control weeds. Runoff is retarded and infiltration is enhanced when water flow into soil is unrestricted by surface conditions, water is temporarily stored on the surface to provide more time for infiltration, and water movement within the soil profile is not impeded. Evaporation is suppressed by insulating and cooling the soil surface, reflecting solar energy, decreasing wind speed at or near the soil surface, and providing a barrier against water vapor movement. Timely weed control is highly important because weeds may deplete soil water supplies.

Table 1. Practices for Controlling Direct Runoff and Their Highlights[a]

Runoff Control Practice	Effect on Runoff[b]
No-tillage planting in prior crop residues	Variable effect on direct runoff — from substantial reductions to increases on soils subject to compaction
Conservation tillage	Slight to substantial reduction
Sod-based rotations	Substantial reduction in sod year; slight to moderate reduction in row-crop year
Meadowless rotations	None to slight reduction
Winter cover crop	Slight increase to moderate reduction
Improved soil fertility	Slight to substantial reduction, depending on existing fertility level
Timing of field operations	Slight reduction
Plow-plant systems	Moderate reduction
Contouring	Slight to moderate reduction
Graded rows	Slight to moderate reduction
Contour strip cropping	Moderate to substantial reduction
Terraces	Slight increase to substantial reduction
Grassed outlets	Slight reduction
Ridge planting	Slight to substantial reduction
Contour listing	Moderate to substantial reduction
Change in land use	Moderate to substantial reduction
Other practices	
Contour furrows	Moderate to substantial reduction
Diversions	No reduction
Drainage	Increase to substantial decrease of surface runoff
Landforming	Increase to slight decrease
Construction of ponds	None to substantial reduction

[a]From Stewart et al., 1975.
[b]Ranges in percent reduction of potential direct growing season runoff for the descriptive terms, "slight," "moderate," and "substantial," are shown in Figure 1.

Where excess water must be removed, installation of drainage systems may be necessary.

Clean tillage is the process of plowing and cultivating to incorporate crop residues and control weeds (SSSA, 1987). Water conservation with clean tillage results primarily from disrupting soil crusts, providing for temporary water storage, and controlling weeds. Under some conditions, clean tillage also suppresses evaporation.

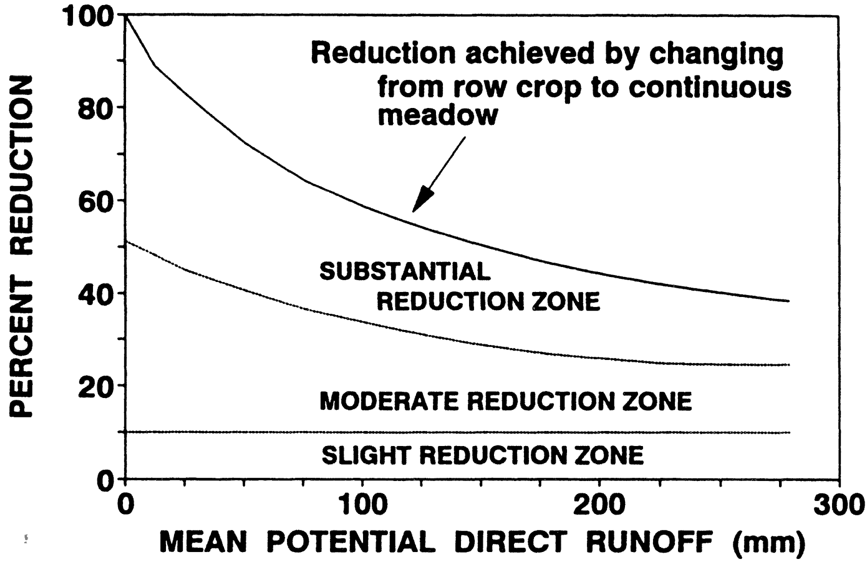

Figure 1. Ranges in percent reduction of potential direct mean growing season runoff resulting from practices shown in Table 1. (Adapted from Stewart et al., 1975).

When raindrops strike a bare soil, a surface seal often develops, resulting in reduced infiltration. When the soil dries, a crust develops that can hinder infiltration of the next rain. The residue-free surface condition produced by clean tillage often aggravates the crusting problem.

Tillage-induced surface roughness and cloddishness can reduce runoff velocity and create depressions for temporary water storage, thereby providing more time for infiltration. Tillage-induced soil loosening can increase water storage in the tillage layer (Burwell et al., 1966).

After wetting a bare soil, evaporation initially occurs at the potential rate, then becomes slower, depending on the rate of soil water movement to the surface. Disrupting water movement to the surface is one way to reduce evaporation. Shallow tillage for creating a "dust" mulch to reduce evaporation generally is ineffective where precipitation occurs mainly during the summer when the potential for evaporation is greatest and tillage is needed after each rain to control weeds (Jacks et al., 1955). Such mulch, however, reduces evaporation where a distinct dry season follows a wet period that has recharged the soil profile with water (Hammel et al., 1981; Papendick et al., 1973).

Weeds compete with crops for water, nutrients, and light, with competition for water generally being most important under dryland conditions. Therefore, effective weed control is essential if crops are to produce at their potential under the prevailing conditions.

Conservation tillage is any tillage sequence that provides at least 30% cover of crop residues on the soil surface after crop planting to control water erosion. Crop residues equivalent to at least 1.1 Mg ha^{-1} of straw must be present during the major wind erosion period to control wind erosion (CTIC, 1990). This definition emphasizes crop residue management, which is the term being used in some cases (Stewart and Moldenhauer, 1994). However, we will use conservation tillage, examples of which are stubble-mulch tillage, reduced tillage, and no-tillage.

Stubble-mulch tillage (SMT) was developed to combat wind erosion in the U.S. Great Plains and Canada in the 1930s. With SMT, sweeps or blades undercut the soil surface to sever weed roots and prepare a seedbed. Because SMT does not invert soil, most crop residues remain on the surface to enhance erosion control and provide water conservation benefits. Based on crop yields, SMT is better adapted to drier than to more humid regions, possibly because of an improved crop water-nutrient balance (Zingg and Whitfield, 1957) and better weed control in drier regions.

Since controlling weeds is a major reason for tillage, then the need for tillage is reduced if weeds are controlled by other means, as with herbicides. Reduced tillage systems that usually meet the requirements for conservation tillage include fall (autumn) chisel-field cultivate, disk-plant, till-plant, strip tillage, and tillage-herbicide combinations. Tillage-herbicide systems have received much attention where residue production is low, erosion potential is high, water conservation is important, and persistent weeds cannot be effectively controlled by tillage or herbicides alone. These systems have improved erosion control, water conservation, and crop yields, especially where precipitation is limited (Papendick and Miller, 1977; Smika and Wicks, 1968; Unger, 1984).

With no-tillage (NT), crops are planted with no preparatory tillage since harvest of the previous crop. Herbicides are used to control weeds. While NT is widely promoted to control erosion because it retains nearly all crop residues on the surface, it also provides water conservation benefits. Surface residues dissipate energy of falling raindrops, thus reducing aggregate dispersion and surface sealing and maintaining favorable water infiltration rates (Bruce et al., 1995; Unger, 1992); retard the rate of water flow across the surface, thus providing more time for infiltration; promote biological and fauna activity in soils, thus improving soil conditions for more rapid water infiltration and distribution within the soil profile (Edwards et al., 1988a, b); and reduce evaporation (Steiner, 1989). No-tillage generally is well-suited for use on well-drained and moderately well-drained soils, provided adequate residues are available and the soil is not severely degraded (Charreau, 1977). Results with NT often are poor on poorly-drained soils (Triplett and Van Doren, 1977) because reduced runoff and evaporation aggravate the poorly-drained condition.

Ridge tillage (RT) for which the seedbed level is raised above that of the surrounding soil, has become popular for producing some row crops. Use of RT aids soil drainage, improves residue management, provides for residue cycling in the plant root system, and generally is better than NT on poorly-drained soils. Other advantages include earlier soil warming, good erosion control, more timely planting because intensive tillage is not needed, and potentially less soil compaction because traffic can be confined to certain furrows. All these factors can improve soil water conservation.

Deep tillage generally means plowing 0.40 to 0.90 m deep (Burnett and Hauser, 1967). Profile modification to even greater depths is done with special equipment (Eck and Taylor, 1969). These operations improve water conservation primarily by disrupting naturally-dense or compacted soil layers that impede water movement, thus improving infiltration and increasing the depth to which plant-available water can be stored; and from mixing soil layers (for example, clayey and sandy layers), thus increasing the soil's water-holding capacity.

Structural and Support Practices

Use of appropriate tillage methods can improve water conservation on lands that have few limitations. However, as severity of limitations increases, tillage alone may become ineffective, and structural and support practices that complement tillage may be needed for effective water conservation.

For many U.S. locations, use of contour tillage reduced annual runoff by up to 20% and growing-season runoff by up to 33% (Stewart et al., 1975). Although used primarily for water erosion control, contour tillage helps conserve water because the contour ridges hold water on the entire field and provide more time for infiltration. Whereas contour tillage helps hold water on the land, graded furrows help remove water from land at nonerosive rates. Water conservation benefits may result when furrow gradients are low because runoff is slow and the potential runoff water is more uniformly distributed over the entire field (Richardson, 1973).

With basin listing, small earthen dams in furrows hold precipitation where it falls, which often prevents runoff and provides more time for infiltration (Jones and Clark, 1987). In some years, basin listing improved water storage and crop yields. Lack of response in other years resulted from inadequate rain to cause runoff, water loss by evaporation, and abundant rainfall that provided adequate water, even with unblocked furrows. Although used primarily to conserve water for dryland crops, basin listing also is an integral component of the low energy precision application (LEPA) irrigation system developed by Lyle and Bordovsky (1981). Irrigation application efficiencies above 95% have been achieved with the LEPA system.

Although used mainly to control erosion, strip cropping improves water conservation by causing water to flow through the strip of protective crops at a reduced rate, thus causing sediments to settle from the water and providing more time for infiltration. Water conservation due to strip cropping per se generally is variable, with wind speed, soil type, strip (barrier) type, climate, and crops grown affecting the results (Black and Aase, 1988; Rosenberg, 1966). In contrast, strip cropping conserves water from windblown snow by trapping snow in crop residues (often small grain stubble) or in specially-planted barrier strips (Black and Siddoway, 1977; Staple et al., 1960).

Terraces may have level or graded channels. Level terraces retain water on land whereas graded terraces remove excess water from land at a nonerosive velocity, but graded terraces have some water conservation benefits. Level terraces often have blocked outlets to prevent runoff. When blocked, they should be large enough to retain all storm water on land until it infiltrates. A disadvantage of level terraces, especially those with blocked ends, is that ponded water in channels may delay field operations or damage crops, unless the water is drained (Harper, 1941). Conservation bench terraces (CBTs) are special level terraces for which the adjacent upslope portion of the terrace interval is leveled. Runoff from the remaining nonleveled part of the terrace interval is captured and spread over the leveled area (Zingg and Hauser, 1959). A major constraint to using CBTs is the high cost of terrace construction and land leveling. To reduce these costs, Jones (1981) developed narrow CBTs (about 10 m wide), which provided water conservation benefits similar to those with larger systems (about 60 m wide).

Although designed primarily to control erosion by conveying water from land at nonerosive flow rates, use of graded terraces improves water infiltration because of the low flow rates within the terrace channel. However, most water is stored in or near the terrace channel and is of limited value for the crop on much of the field. Greater water conservation is achieved by using graded terraces along with graded furrows (discussed earlier) because increased water storage occurs on a larger part of the field (Richardson, 1973).

In contrast to CBTs for which only part of the land is leveled, the entire interval is leveled for a level bench terrace system. This system is widely used in some countries on steep slopes where cropland is limited and precipitation is relatively high, but generally is not practical for mechanized farming. Jones (1981), however, developed a level bench terrace system for conserving water for dryland crops on gently-sloping land (about 1%). By using a 5-m terrace interval, only a small amount of soil had to be moved, which greatly reduced the land-leveling cost.

Mulch

Water conservation by using mulch results from reduced evaporation, surface protection that results in more favorable infiltration, and reduced runoff rates that provide more time for infiltration. Various materials are used as mulch, but crop residues are used most commonly. Crop-residue mulch characteristics affecting evaporation include residue amount, orientation, uniformity, rainfall interception, reflectivity, and dynamic roughness (Van Doren and Allmaras, 1978).

Mulch effects on evaporation are readily apparent under laboratory conditions, but long-term effects of mulch on evaporation are difficult to show, especially under field conditions, because of its interacting effect on water infiltration, distribution in the profile, deep percolation, and subsequent evaporation.

Soil Surface Amendments

Surface sealing due to raindrop impact or flowing water on bare soils having low-stability surface aggregates can result in major losses of water as runoff. Therefore, if aggregates could be made more stable, runoff could be reduced, which could improve water conservation. By applying phosphogypsum at 10 Mg ha^{-1} to a ridged sandy soil, runoff was sixfold less than where it was not applied (Agassi et al., 1989).

Aggregate breakdown in furrows results in low infiltration and high sediment losses during furrow irrigations of crops under some conditions. When a polyacrylamide or starch copolymer solution was injected into irrigation water at different rates, net infiltration increased 15% and sediment loss decreased 94% (Lentz and Sojka, 1994). Injection of polyacrylamide at 10 g m^{-3} was one of the most effective treatments. The injection also improved lateral infiltration, which can improve water and nutrient use efficiency by row crops (Lentz et al., 1992).

Cropping Systems and Rotations

Besides effects of tillage systems, support practices, mulch, and surface amendments, water conservation is affected by the overall crop management systems in which the above practices are used. Crop management embraces such topics as management of planting materials, land use before planting, seedbed preparation, planting, plant pests, and plant products (Sprague, 1979). Subtopics related to several of the above are cropping systems and rotations, which often have a major effect on water conservation. Crop selection for a given locale generally is based on the probability of precipitation and amount of stored soil water being available to produce a satisfactory yield (Stewart and Steiner, 1990), but crops grown also influence water storage. In general, water storage should be greater for large-seeded crops that can be planted in a residue-covered or rough and cloddy seedbed than for those requiring a smooth, residue-free seedbed consisting of fine soil materials (small-seeded crops). The latter seedbeds often seal and crust severely when rain occurs, thus reducing infiltration and water conservation.

Crop growth habit and canopy influence water conservation through their effect on interception of raindrops, resistance to water flow across the soil surface, and evaporation. Upright-growing plants provide little surface protection early in the growing season, but may fully protect the surface when the canopy is complete. Low-growing vines or stoloniferous plants may provide relatively little surface cover, but retard water flow and, thereby, enhance water conservation. Fibrous-rooted plants generally provide greater stability to soil and, therefore, greater water conservation than tap-rooted plants. Densely planted crops generally provide ground cover more quickly than sparsely planted crops, which can improve water conservation due to greater infiltration and lower evaporation. Closely spaced plants also retard runoff, which provides more time for infiltration, than widely spaced plants.

Since soil water storage is influenced by the storage capacity, water remaining in soil from a previous storage event reduces additional storage. As rooting depth and intensity of water extraction increase, the potential for storing more water increases. Growing a deep-rooted crop after a shallow-rooted crop can improve water conservation (Stewart and Steiner, 1990).

Timing and duration of a crop's growing season relative to the time of most-probable precipitation can greatly influence soil water storage. For the dryland winter wheat-grain sorghum crop rotation for which a fallow period of 10 to 11 months precedes each crop in a 3-year period in the southern Great Plains, runoff is low after wheat harvest in June or July, although most rainfall occurs during the summer months (Jones and Hauser, 1975). Runoff is low because wheat usually extracts most available water, which results in a "dry" soil with a relatively large water storage capacity. In contrast, runoff during the same period is greater from land planted to grain sorghum because the soil contains water stored during the previous fallow period, and there is little opportunity for additional storage. Although antecedent soil water contents influenced the above results, differences in surface residue amounts and type also influenced the results (Jones et al., 1994).

For an irrigated crop, timing of the last irrigation greatly affects the soil water content at harvest. If the last irrigation is applied so that relatively little water remains at harvest, potentially more water can be stored during the ensuing interval between crops (Musick, 1970).

Legume or grass cover crops influence water conservation mainly through their effect on surface cover during their growth period, residues remaining after growth is stopped, use of soil water, and soil conditions resulting from their use. Although their use generally improves water conservation in more humid areas, their use in drier regions often is detrimental to water conservation because they use water that could be used by a subsequent crop.

Water conservation benefits from using legumes and cover crops may be realized also from improved soil conditions (Langdale et al., 1985; Stewart et al., 1975). These benefits result mainly from greater soil aggregate stability, which reduces aggregate dispersion and surface sealing due to raindrop impact.

Continuous cropping usually is practiced where precipitation recharges the soil profile with water between crops or supports a crop during its growing season, and generally refers to growing the same crop on the same land during successive growing seasons. We expand the meaning to include growing various crops on the same land in successive growing seasons, for example, summer crops such as corn (*Zea mays* L.), soybean (*Glycine max* L. Merr.), or sugar beet (*Beta vulgaris* L.), but without a fallow period. In contrast, crop-fallow systems are those for which land remains idle during all or the greater part of a typical growing season (SCSA, 1976; now SWCS).

A major reason for including a fallow period is to increase the soil water content at planting and, thereby, to reduce the risk of crop failure. Where precipitation is adequate, soil management usually has relatively little effect on soil profile water content at planting. As a result, a fallow period is seldom used in humid or subhumid regions. In contrast, systems involving fallow often are used in drier regions, which increases the potential for achieving favorable yields (Black, 1985).

Soil water storage generally increases as fallow period length increases. However, fallow storage efficiency, namely, unit of water stored per unit of precipitation during the fallow period, generally decreases as length of fallow increases. These trends occur because greater storage usually occurs when the antecedent soil water content is low early in the fallow period. Later, the antecedent water content is greater, which makes storing additional water more difficult.

Function of Soil Management Techniques for Protecting Water Quality

Generally, as the degree or intensity of agricultural management increases, loss of N through leaching to groundwater and P in surface runoff increases (OECD, 1982; Sharpley et al., 1994). As a result, more emphasis recently has been placed on reducing N and P losses via improved soil management. This has focused on managing soil water, residues, and cropping systems to enhance water- and nutrient-use efficiency. Soil management also influences the amount of sediments transported by runoff to surface waters.

Soil Water Management

Tillage influences surface hydrology and, thereby, soil-water budgets (Follett et al., 1987). As a result, tillage also affects transport of N and P in ground- and surface water, but effects of tillage on nitrate leaching are variable. Nitrate loss from Maury silt loam (Typic Paleudalf) in Kentucky was greater with no-tillage than with conventional tillage (Tyler and Thomas, 1977), but less nitrate leached from Clarion-Nicollet loam (Typic Hapludoll-Aquic Hapludoll) in a corn-soybean rotation in Iowa with no-tillage than with moldboard plowing (Kanwar et al., 1985).

Smith et al. (1987) and Sharpley and Smith (1993) measured nitrate concentrations in wells on watersheds from 1983 to 1994 at El Reno, Oklahoma. Annual rainfall averaged 740 mm and the water table was at depths between 3

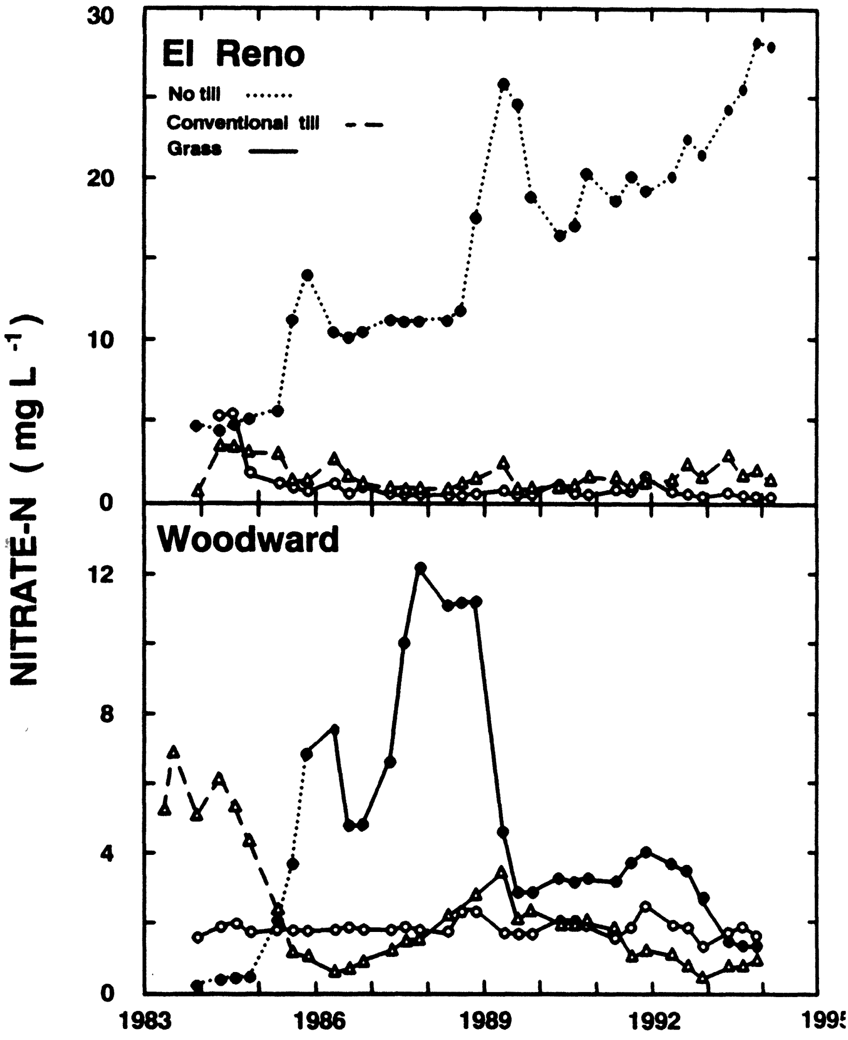

Figure 2. Nitrate-N concentrations of groundwater as a function of agricultural management at El Reno and Woodward, Oklahoma, from 1983 to 1994.

and 25 m. After converting a watershed from conventional tillage to no-tillage in 1984, nitrates gradually increased (Figure 2). Nitrate levels on the conventional and native grass watersheds were similar and consistently lower than on the no-tillage watershed.

At Woodward, Oklahoma, wells were installed in 1983 and one watershed was converted from conventional tillage wheat to no-tillage wheat the next year. Between 1983 and 1994, annual rainfall averaged 600 mm and the water table was at depths between 3 and 25 m. Early in 1984, nitrate levels in groundwater were greater on the conventional tillage than on the no-tillage watershed (Figure 2). During the next three years, nitrates increased on the no-tillage and decreased on the conventional-tillage watershed. In 1986, both watersheds were returned to grass. Nitrates in groundwater on the no-tillage watershed continued to increase for two years, but started to decrease by 1989 as residual N and potential sources of nitrates in the soil profile were depleted. By 1994, prior tillage management had no effect on groundwater nitrate level.

Conversion from conventional to no-tillage practices generally favors development of undisturbed soil pores and burrows (Edwards et al., 1988a, b; Shipitalo et al., 1990), which results in more rapid water flow into soil and enhances soil water storage. For example, plant-available water stored in the root zone of the El Reno, Oklahoma, wheat watersheds during 1991 was: native grass (100 mm), conventional tillage (150 mm), and no-tillage (190 mm). Less evaporation from no-tillage soil will also limit nitrate movement to the surface. As a result, no-tillage provides a wetter, cooler soil environment that may enhance nitrate leaching potential compared to conventional tillage. Preferential water flow in soil pores may contribute to greater leaching of nitrates and other chemicals with no-tillage.

At the Oklahoma locations, similar N fertilizer management for conventional and no-tillage wheat may have led to the different nitrate leaching potentials. Through optimum management of N fertilizer with respect to rate, time, and form of N application, it should be possible to reduce the potential for nitrate leaching under no-tillage conditions.

In terms of water quality standards, nitrate-N concentrations up to 10 and 100 mg L^{-1} are considered acceptable for human and livestock consumption, respectively. At two years after implementing no-tillage at El Reno and under introduced grass at Woodward, NO_3-N exceeded 10 mg L^{-1}.

Transport of N and P in surface runoff can be appreciably lower with conservation than with conventional tillage. This decrease results from less erosion and associated N and P loss with no-tillage due to crop residues protecting the surface soil from the erosive impact of rainfall and runoff. Over 12 yr, runoff and erosion were lower from conservation than from conventional tillage grain sorghum and wheat watersheds in the Southern Plains (Table 2). Soil-water management through use of no- and reduced-tillage practices also decreased total N and P losses in runoff (Table 2).

Although total N and P losses in runoff are lower with no-tillage than with conventional tillage, the bioavailability of P transported from no-tillage areas can be larger (Table 2). For example, bioavailable P was 82% of total P loss from wheat plots with no-tillage, but only 19% with conventional tillage at similar rates of P fertilization at El Reno, Oklahoma (Sharpley et al., 1992b), with the increased bioavailability attributed to leaching of P from crop residues and preferential transport of clay-sized particles in runoff (Andraski et al., 1985; Sharpley, 1981). Therefore, an increase in bioavailability of P transported due to using certain management practices may not reduce the

Table 2. Effect of Tillage Practice on Soil, N, and P Loss in Runoff from Sorghum and Wheat in the Southern Plains[a]

Crop and Tillage System	Runoff mm	Soil Loss kg ha^{-1} yr^{-1}	N Loss Nitrate	N Loss Total kg ha^{-1} yr^{-1}	P Loss Dissolved	P Loss Total kg ha^{-1} yr^{-1}
Sorghum						
No-	31	280	0.35	1.11	0.08	0.28
Reduced	21	520	0.41	1.40	0.04	0.37
Conventional	121	16150	0.62	1.34	0.24	4.03
Wheat						
No-	77	540	1.52	5.12	0.53	0.98
Reduced	61	800	1.92	4.59	0.10	0.59
Conventional	101	8470	1.74	20.19	0.21	3.96
Native grass	92	43	0.38	1.11	0.12	0.20

[a]Adapted from Sharpley et al., 1991; Smith et al., 1991.

trophic state of a water body as much as may be expected from inspection of total P loads only.

In terms of production, wheat grain yields were lower following implementation of no-tillage in 1983 than with conventional tillage (Sharpley and Smith, 1993). The lower yield is attributed in part to stratification of broadcast fertilizer, particularly P, in the surface 5 cm of soil. No-tillage wheat may respond to subsurface P applications and light tillage that incorporates surface-bound nutrients. Increased competition from weeds also has occurred since conversion to no-tillage. Although yields are not reduced by using no-tillage in most of the country, this Oklahoma example demonstrates the potential economic and environmental conflicts involved in soil-water management. Therefore, recommendations to farmers regarding soil-management techniques must be flexible and site-specific, addressing not only crop production goals but also the vulnerability of local water resources to either ground- or surface water impacts.

Residue Management

Crop residue management affects soil nutrient cycling and sediment transport, and potentially can influence water quality. Factors involved include quantity, type, and placement of crop residues. The quantity of residues involved will affect the amounts of nutrients being cycled and, after going through the mineralization-immobilization process, the amounts potentially available for uptake or movement with surface water. Increasing residue amounts can also reduce evaporation and keep the surface soil moist, particularly if residues are left on the surface. Thus, microbial transformation of N may increase, resulting in greater mineralization, availability, and uptake of indigenous soil N (Table 3). Greater residue P mineralization has been observed also for surface-incorporated residues (Sharpley and Smith, 1989).

The chemical composition of crop residues is particularly important in establishing the balance between mineralization and immobilization processes. Generally, if the C:N ratio is >30, net immobilization of N in residues occurs; with ratios <25, net mineralization occurs. Similarly, C:P ratios >300 favor immobilization and those <200 favor mineralization. Power et al. (1986) demonstrated that little N in corn residues (wide C:N ratio) was mineralized and used by the next crop, whereas a large part of the N in soybean residues (narrow C:N ratio) was available to the next crop (Table 3).

Different tillage implements result in crop residue placement at different depths (Staricka et al., 1991). When residues are incorporated, N and P are concentrated where the residues are placed by the given operation. In contrast, use of no-tillage concentrates nutrients near the soil surface. Due to the sorption and subsequent immobility of P in soil, P can rapidly accumulate and stratify at the surface of no-tillage soils (Griffith et al., 1977; Guertal et al., 1991).

Table 3. Uptake of N from Various Sources and Total Uptake at 1981 Harvest of Maize and Soybean (Whole Plant) as Affected by Crop Residue Rate on the Soil Surface[a]

	Source of N				
Crop and Residue Rate (%)[b]	Crop Residue	Residual Fertilizer kg ha^{-1}	Current Fertilizer kg ha^{-1}	Native Soil N[c] kg ha^{-1}	Total Uptake kg ha^{-1}
Maize					
0	0	5	4	73	82
50	0	6	7	97	110
100	2	6	7	114	129
150	1	6	11	124	142
Soybean					
0	0	2	14	84	100
50	1	2	21	124	148
100	38	7	16	116	177
150	63	6	20	106	195

[a]Adapted from Power et al., 1986.
[b]Based on the amounts of residue produced the previous year. For 100% treatment, amounts on a dry weight basis were 4.97 Mg ha^{-1} for maize and 4.58 Mg ha^{-1} for soybean.
[c]For soybean, native soil N includes biologically fixed N.

Clearly, residue management can affect N and P movement in ground- and surface water. Mostaghimi et al. (1988, 1992) found both tillage and amount of rye residues present affected N and P in runoff from a Groseclose silt loam (Typic Hapludult) in Virginia (Table 4). For both conventional and no-tillage, increasing residue levels decreased runoff and erosion. Also, N and P losses were consistently less with no-tillage than with conventional tillage. However, an increase in residues from 750 to 1500 kg ha^{-1} resulted in greater N and P losses in runoff, which were attributed to greater leaching of nitrates and dissolved P from the residues and less sorption of P by eroding soil at the higher residue level. Differences in amounts of P leached from various crop residues also affected seasonal and spatial variability in P losses among watersheds (Burwell et al., 1975; Sharpley, 1981).

Land application of materials such as manures and organic wastes can also affect ground- and surface-water quality. Factors such as composition and rate, placement, and timing of application of these materials influence N and P cycling. They also affect availability of N and P from these sources. Other organic residues important in localized areas include sewage sludge from municipalities, wastes from livestock slaughtering facilities, and wastes from food processing and other industries. If properly handled, they often serve as major N and P sources (Sharpley et al., 1995). If organic residues are added continually in amounts that provide more N and P than those removed by

Table 4. Effect of Tillage Method and Residue Amount on Soil, N, and P Loss in Runoff from Sorghum and Wheat in the Southern Plains

Tillage Method and Residue Amount (kg ha^{-1})	Runoff mm	Soil Loss kg ha^{-1} yr^{-1}	N Loss: Nitrate kg ha^{-1} yr^{-1}	N Loss: Total	P Loss: Dissolved kg ha^{-1} yr^{-1}	P Loss: Total
Conventional tillage						
0	36	2812	0.285	4.562	0.506	5.235
750	33	1001	0.283	1.665	0.265	0.982
1500	18	513	1.326	4.382	0.412	1.425
No-tillage						
0	5	72	0.210	0.608	0.073	0.101
750	3	11	0.003	0.009	0.002	0.057
1500	1	7	0.106	0.313	0.027	0.097
Reduction with no-tillage (%)						
0	87	97	26	87	86	98
750	92	99	99	99	99	94
1500	99	99	92	93	93	98

[a]Adapted from Mostaghimi et al., 1988, 1992.

crops, N and P may accumulate in soil profiles and lead to enrichment of P in runoff and nitrates in groundwater (Sharpley et al., 1995). Management of organic residues by incorporation with tillage redistributes N and P throughout the plow layer, which enhances uptake by crops. Also, timing of organic residue application to coincide with maximum crop uptake and low rainfall-runoff incidence reduces the potential for ground- and surface water contamination (Edwards et al., 1992).

Cropping System Management

Management of cropping systems can influence water quality through selection of species that maximize uptake of soil N and P, thereby reducing residual nutrients available for movement in ground- and surface water. This is most commonly accomplished through crop rotation and cover crop management.

The sequence of crops in a rotation influences available water and N movement through the soil profile and ultimately into groundwater (Carter et al., 1991). For example, legumes can effectively use or "scavenge" N remaining in soil from previous crops (Olson et al., 1970). To illustrate this, Sharpley et al. (1992a) overlaid hypothetical root development patterns for a corn-winter wheat-alfalfa (*Medicago sativa* L.) cropping system on typical N leaching patterns (Figure 3).

Olson et al. (1970) found nitrate concentrations at a depth of 1.2 to 1.5 m in a silt loam soil to be lower for an oat (*Avena sativa* L.)-meadow-alfalfa-corn rotation than for continuous corn when ammonium nitrate was applied to both systems. Nitrate reduction was directly proportional to the years oat, meadow, or alfalfa were in the rotation with corn, which was attributed to the combined recovery of nitrate by shallow-rooted oat followed by deep-rooted alfalfa.

Much information documents the benefits for N-use efficiency and reduced nitrate leaching potential with careful selection and sequencing of crops in a rotation, but less information is available for P. However, it is possible that selecting and using crops with a high affinity for P may reduce soil P stratification and increase P-use efficiency, particularly if the nonharvested part of crops is returned to the soil.

Including cover crops in management systems can affect ground- and surface water quality by reducing runoff and erosion, improving soil structure and tilth, fixing atmospheric N, and reducing nitrate leaching. Cover crops affect nitrate leaching and groundwater quality by modifying soil-water budgets and N uptake (Meisinger et al., 1991; Sharpley and Smith, 1991). Through evapotranspiration, cover crops reduce the amount of water available for leaching. However, as for crop rotations, cover crops must be carefully managed to avoid reducing soil-water reserves for the next crop. Both nonlegume and legume cover crops extract and incorporate mobile soil nitrate into immobile biomass N, thereby reducing the amount available for leaching.

Due to the above factors, inclusion of cover crops in management systems

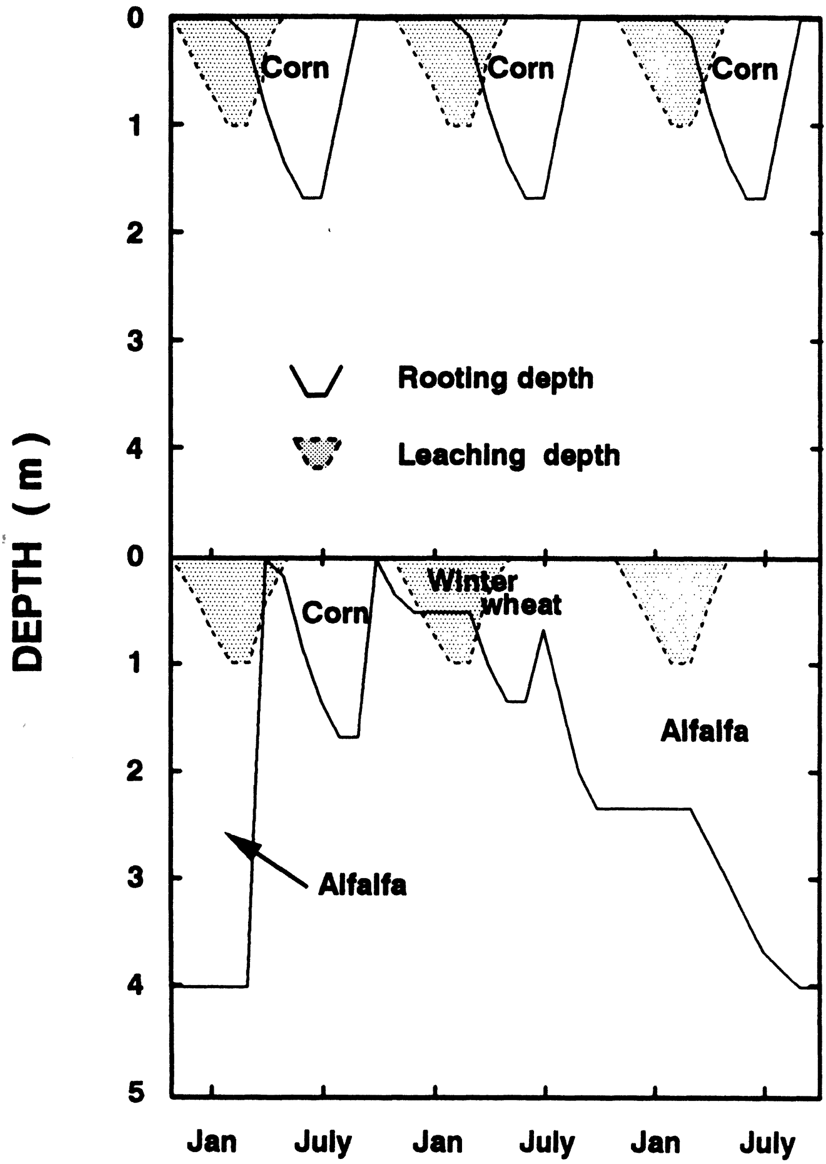

Figure 3. Typical root development of continuous corn and corn-winter wheat-alfalfa rotation in relation to soil drainage over a 3-yr period.

has consistently decreased nitrate leaching (Table 5), sometimes as much as 83%. Smaller reductions often result from winter kill and incorporation by tillage before planting the next crop and lower N uptake, if the crop is a legume.

Nonlegume cover crops can reduce soil nitrates, while legumes can provide N for the next crop. Therefore, legumes may not reduce nitrate leaching as ef-

Table 5. Effect of Cover Crops on N Leaching for Several Management Systems[a]

Crop	Cover Crop	Soil Texture	Location[b]	Added N kg ha^{-1} yr^{-1}	N Leached: Total kg ha^{-1} yr^{-1}	N Leached: Nitrate kg ha^{-1} yr^{-1}	Reduction[c]: Total %	Reduction[c]: Nitrate %
Fallow	None	Loamy sand	CT[1]	112	127	36		
	Turnips				16	6	87	83
Fallow	None	Sand & clay	Sweden[2]	375	197	41		
	Rape				69	16	65	61
Lespedeza	None	Silt loam	KY[3]	224	65	18		
	Rye				17	5	74	72
Sudangrass	None	Loam	CA[4]	112	84	52		
	Mustard				17	10	80	81
	Purple vetch				75	36	11	31
	Sweet clover				83	43	1	17
Tobacco	None	Sandy loam	CT[5]	224	83	24		
	Oats				36	12	57	50
	Rye				28	9	66	62
	Timothy				57	16	31	33
Winter wheat	None	Silt	France[6]	200	110	54		
	Ryegrass				40	28	64	48

[a]Adapted from Meisinger et al., 1991.
[b]Reference for each study location is: 1, Volk and Bell, 1945; 2, Bertilsson, 1988; 3, Karraker et al., 1950; 4, Chapman et al., 1949; 5, Morgan et al., 1942; and 6, Martinez and Guirard, 1990.
[c]Percent reduction in N leached due to cover crops.

fectively as nonlegumes (Table 5). Cover crops can reduce nitrate leaching by 20 to 80% (Meisinger et al., 1991), with nonlegumes being about two to three times more effective than legumes for reducing leaching.

For studies summarized in Table 6, inclusion of cover crops reduced runoff 50% due to increased infiltration. It also reduced erosion 85%, total N loss 80%, and total P loss 71% due to vegetative protection of the surface soil. However, cover crops less effectively reduced nitrate and dissolved P losses (average 61 and 37%, respectively), mainly due to increased nitrate and dissolved P concentrations in runoff because the cover crops decreased runoff volume.

Research on Soil Management Techniques

Water Conservation

Past Needs

Although the need for water by plants has long been recognized, strong emphasis on storing (conserving) water in soil for later use by plants began mainly in the first half of this century. Research to conserve water and, therefore, to improve crop growth under dryland conditions was initiated at many locations after the major drought and associated dust storms that plagued the U.S. Great Plains states, Canadian prairie provinces, and surrounding regions during the 1930s. Early research showed that the same practices that provided protection against erosion by wind or water also were important for soil water conservation. Crop residue maintenance on the soil surface was found to be highly effective for these purposes. Consequently, soil and water conservation often have been investigated simultaneously. Through effective water conservation along with soil conservation, the vast USA Great Plains region now is an important agricultural region. Early water conservation efforts also helped improve crop production in more humid regions where short-term droughts can greatly reduce yields.

Current Status

Whereas much of the past research focused on practices that conserve water, current research often is focused on obtaining an understanding on the mechanisms through which the water conservation is achieved. Through such understanding, it should be possible to improve previously developed practices and to develop even more effective practices for conserving water.

Besides conserving water for crop production, it is highly important that the agricultural community act responsibly by using water available to it efficiently because the amount available often is limited and other users often compete for the same water. Therefore, besides research on water conserva-

Table 6. Effect of Cover Crops on Soil, N, and P Loss for Several Management Systems

			Fertilizer			Soil	N Loss		P Loss	
			N	P	Runoff,	Loss	Nitrate	Total	Dissolved	Total
Crop	Cover	Loc.[a]	kg ha^{-1} yr^{-1}		mm	kg ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}
Corn	None	MD[1]	67	47	4	262	0.36	0.95	0.02	0.14
	Barley		67	47	1	33	0.05	0.12	0.01	0.01
Corn	None	GA[2]	—	20	159	3663	—	—	0.28	4.08
	Winter rye		—	50	97	938	—	—	0.30	1.39
Cotton	None	AL[3]	101	0	91	1067	1.40	3.13	0.31	0.44
	Winter wheat		101	0	35	260	0.56	0.88	0.16	0.20
Soybean	None	MO[4]	15	12	231	1439	3.36	—	0.46	—
	Common chickweed		15	12	133	233	0.77	—	0.17	—
	Canada bluegrass		15	12	142	93	0.88	—	0.43	—
	Downy brome		15	12	116	118	0.84	—	0.27	—
Wheat	None	NY[5]	241	64	173	—	1.14	—	0.32	—
	Ryegrass-alfalfa		241	64	74	—	0.93	—	0.17	—

[a]Reference for each study location is: 1, Angle et al., 1984; 2, Langdale et al., 1985; 3, Yoo et al., 1988; 4, Zhu et al., 1989; and 5, Klausner et al., 1974.

tion per se, the research often is aimed at improving water-use efficiency for crop production. Lysimeter facilities such as those at Coshocton, Ohio, and Bushland, Texas (Schneider et al., 1993), and waterflow models (Bristow et al., 1986; Hammel et al., 1981; Steiner et al., 1991) are being used increasingly to improve our understanding regarding the complex interrelationships among soil, plant, air, and climatic factors or conditions.

Future Challenges

Competition for available water resources undoubtedly will increase among the different sectors of society. Within agriculture, water conservation will remain important, and efficient water use will become increasingly important. Research to accomplish water conservation and efficient use of water will involve traditional field studies, models, lysimeters, and other equipment and facilities.

Besides conducting the research, results of the research must be conveyed to farmers through an effective technology transfer system. Even now, effective practices often are not used by farmers because of limited or ineffective technology transfer activities. While agencies other than research generally are responsible for technology transfer, a closer relationship between research and other groups may be required to achieve wider acceptance of effective water conservation and use practices.

Water Quality

Past Needs

Soil-management research for water quality has focused on developing practices that reduce N, P, and pesticide losses in ground- and surface waters, while maintaining optimum crop yield goals. This research was driven by the need to define the role of agriculture in nonpoint source pollution of water resources. In the 1970s, industrial, municipal, and urban sources of pollution were identified as major contributors to degrading water quality. Since passage of the Clean Water Act in 1972, much progress has been made in controlling pollution from point sources. As further control of pollution from remaining point sources becomes increasingly less cost-effective, and as significant water quality problems remain unresolved, more attention is being directed toward controlling pollution from agricultural nonpoint sources.

Current Status

Past research showed that general soil-management modifications over broad areas sometimes have not achieved expected water quality improvements. In fact, control measures are much more effective if concentrated on specific source areas rather than on entire watersheds (Heatwole et al., 1987; Prato and Wu, 1991). Therefore, current soil-management research directed at water quality is focusing on developing techniques that will allow us to identify areas that are major contributors of N or P to water resources, especially for watersheds with intensive confined animal operations, which often produce more N and P in manure than local crop requirements.

Future Challenges

With current technologies, chemical amendments are essential to maintain optimum crop yields that meet both local and world needs. However, if nutrient input rates are greater than crop removal rates, accumulations can occur in soil, which can increase the potential for chemical losses. Present water quality research often deals with one chemical. Future research should emphasize integrated programs involving C, N, and P. It should also consider holistic watershed management by balancing inputs and outputs on a large scale rather than at a field level. We must look beyond pure soil science and agronomic research and involve scientists from other disciplines. Most importantly, we must consider the economic impact of any changes in soil management on agricultural or rural communities.

Realistic water quality criteria. Water quality criteria for N and P have been established by the USEPA (1976). However, there is ongoing debate on whether to use maximum daily loadings or concentrations as the basis for management recommendations. Much of this debate centers on P due to a major difference between critical P values in water for eutrophication (0.01 to 0.02 mg L^{-1}) and in soil for crop growth (0.20 to 0.30 mg L^{-1}) as illustrated in Figure 4. This disparity emphasizes the sensitivity of many waters to inputs of P from agriculture.

Water quality criteria should not be used as the sole criteria to guide soil management where N and P losses are of concern. A more flexible approach considers relationships among N and P loadings, watershed characteristics, and use of the affected water. Such approach should encompass more than just N and P concentrations in runoff from impacted fields because unrealistic or unattainable criteria will not be adopted unless regulated. Phasing in of environmentally-sound management policies may receive wider acceptance and compliance by farmers without creating severe economic hardships within rural communities.

Economic and environmental sustainability. Sustainable soil management must involve agronomic, economic, and environmental compromises. For example, it may be necessary to apply P below the soil surface to reduce P in runoff and to periodically plow no-tillage soils to redistribute N and P throughout the plow layer. Both practices may indirectly reduce P loss by increasing crop uptake of P and yield, which affords more vegetative protection

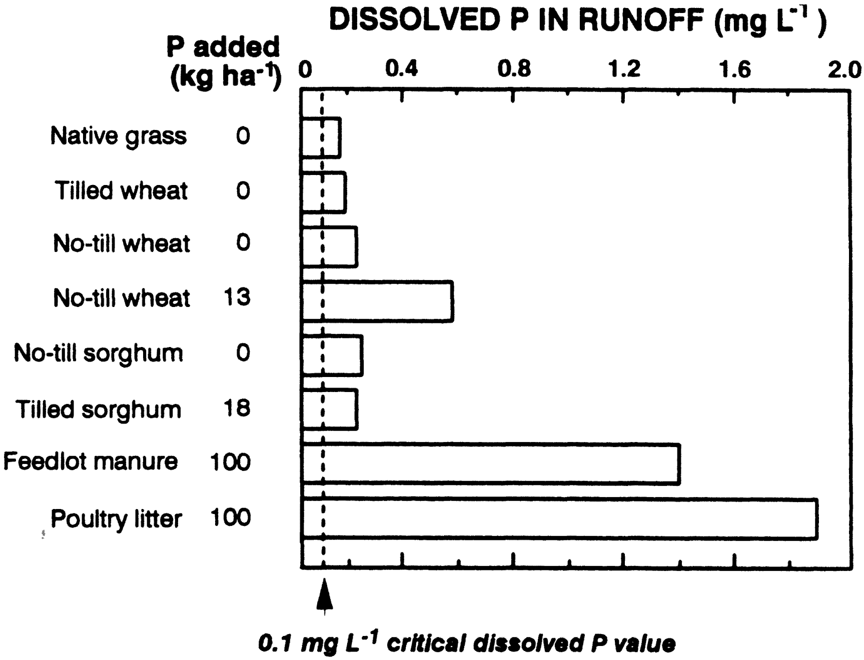

Figure 4. The mean flow-weighted concentration of dissolved P in runoff during one year as a function of watershed and manure management in the Southern Plains relative to critical values associated with accelerated eutrophication (adapted from Jones et al., 1995; Heathman et al., 1995).

of surface soil from erosion. However, conflicts may exist among best management practices (BMPs), residue management guidelines, and recommended subsurface applications. Thus, BMPs should be flexible enough to enable modified residue and nutrient management plans to be compatible.

Technology transfer and education programs. Although we have reduced water pollution due to point sources of N and P, less has been done regarding pollution due to nonpoint agricultural sources. To achieve this, we must identify critical sources in a watershed to target cost-effective remedial strategies. Perhaps most crucial to any water quality improvement strategy is efficient transfer of technology to the farmer. This will involve education programs to overcome the perception by water users that it is often cheaper to treat the symptoms of degradation than to control the nonpoint sources. Unfortunately, benefits of such programs often are not immediately visible to a concerned public. Future research and education programs should emphasize the long-term economic and environmental benefits of these measures.

References

Agassi, M., I. Shainberg, D. Warrington, and M. Ben-Hur. 1989. Runoff and erosion control in potato fields. Soil Sci. 148:149–154.

Amdur, M.O., J. Dull, and E.D. Klassen (eds.). 1991. Casarett and Doull's Toxicology. Fourth Ed., Pergamon Press, New York, NY.

Andraski, B.J., D.H. Mueller, and T.C. Daniel. 1985. Phosphorus losses in runoff as affected by tillage. Soil Sci. Soc. Am. J. 49:1523–1527.

Angle, J.S., G. McClung, M.C. McIntosh, P.M. Thomas, and D.C. Wolf. 1984. Nutrient losses in runoff from conventional and no-till corn watersheds. J. Environ. Qual.13:431–435.

Bertilsson, G. 1988. Lysimeter studies of nitrogen leaching and nitrogen balances as affected by agricultural practices. Acta Agric. Scand. 38:3–11.

Black, A.L. 1985. Resources and problems in the northern Great Plains area. pp. 25-38. In: Proceedings of a Workshop on Planning and Management of Water Conservation Systems in the Great Plains States, Lincoln, NE, October 1985. U.S. Department of Agriculture-Soil Conservation Service, Lincoln, NE.

Black, A.L., and J.K. Aase. 1988. The use of perennial herbaceous barriers for water conservation and the protection of soils and crops. Agric., Ecosystems, Environ. 22/23:135–148.

Black, A.L., and F.H. Siddoway. 1977. Winter wheat recropping on dryland as affected by stubble height and nitrogen fertilization. Soil Sci. Soc. Am. J. 41:1186–1190.

Bristow, K.L., G.S. Campbell, R.I. Papendick, and L.F. Elliott. 1986. Simulation of heat and moisture transfer through a surface residue-soil system. Agric. Forest Meteorol. 36:193–214.

Bruce, R.R., G.W. Langdale, L.T. West., and W.P. Miller. 1995. Surface soil degradation and soil productivity restoration and maintenance. Soil Sci. Soc. Am. J. 59:654–660.

Burnett, E., and V.L. Hauser. 1967. Deep tillage and soil-plant-water relationships. pp. 47–52. In: Proceedings of Tillage for Greater Crop Production Conference, December 1967. American Society of Agricultural Engineers, St. Joseph, MI.

Burwell, R.E., R.R. Allmaras, and L.L. Sloneker. 1966. Structural alteration of soil surfaces by tillage and rainfall. J. Soil Water Conserv. 21:61–63.

Burwell, R.E., D.R. Timmons, and R.F. Holt. 1975. Nutrient transport in surface runoff as influenced by soil cover and seasonal periods. Soil Sci. Soc. Am. Proc. 39:523–528.

Carter, D.L., R.D. Berg, and B.J. Sanders. 1991. Producing no-till cereal or corn following alfalfa on furrow irrigated land. J. Prod. Agric. 4:174–179.

Chapman, H.D., G.F. Liebig, and D.S. Rayner. 1949. A lysimeter investigation of nitrogen gains and losses under various systems of covercropping and fertilization and a discussion of error sources. Hilgardia 19:57–95.

Charreau, C. 1977. Some controversial technical aspects of farming systems in semi-arid west Africa. pp. 313-360. In: G.H. Cannell (ed.) Proceedings of International Symposium on Rainfed Agriculture in Semi-Arid Regions, Riverside, CA, April 1977. University of California, Riverside.

CTIC (Conservation Technology Information Center). 1990. Tillage definitions. Conserv. Impact 8(10):7.

Eck, H.V., and H.M. Taylor. 1969. Profile modification of a slowly permeable soil. Soil Sci. Soc. Am. Proc. 33:779–783.

Edwards, D.R., T.C. Daniels, and O. Marbun. 1992. Determination of best timing for poultry waste disposal: A modeling approach. Water Resour. Bull. 28:487–494.

Edwards, W.M., L.D. Norton, and C.E. Redmond. 1988a. Characterizing macropores that affect infiltration into nontilled soil. Soil Sci. Soc. Am. J. 52:483–487.

Edwards, W.M., M.J. Shipitalo, and L.D. Norton. 1988b. Contribution of macroporosity to infiltration into a continuous corn no-tilled watershed: Implications for contaminant movement. J. Contam. Hydrol. 3:193–205.

Follett, R.F., S.C. Gupta, and P.G. Hunt. 1987. Conservation practices: Relation to the management of plant nutrients for crop production. pp. 19-51. In: R.F. Follett et al. (ed.), Soil fertility and organic matter as critical components of production systems. SSSA Special Publication Number 19, Soil Science Society of America, Madison, WI.

Griffith, D.R., J.V. Mannering, and W.C. Moldenhauer. 1977. Conservation tillage in the eastern Corn Belt. J. Soil Water Conserv. 32:20–28.

Guertal, E.A., D.J. Eckert, S.J. Traina, and T.J. Logan. 1991. Differential phosphorus retention in soil profiles under no-till crop production. Soil Sci. Soc. Am. J. 55:410–413.

Hammel, J.E., R.I. Papendick, and G.S. Campbell. 1981. Fallow tillage effects on evaporation and seedzone water content in a dry summer climate. Soil Sci. Soc. Am. J. 45:1016–1022.

Harper, H.J. 1941. The effect of terrace ridges on the production of winter wheat. Soil Sci. Soc. Am. Proc. 6:474–479.

Heathman, G.C., A.N. Sharpley, S.J. Smith, and J.S. Robinson. 1995. Poultry litter application and water quality in Oklahoma. Fert. Res. 40:165–173.

Heatwole, C.D., A.B. Bottcher, and L.B. Baldwin. 1987. Modeling cost-effectiveness of agricultural nonpoint pollution abatement programs on two Florida basins. Water Resour. Bull. 23:127–131.

Jacks, G.V., W.D. Brind, and R. Smith. 1955. Mulching. Technical Communication Number 49, Commonwealth Bureau of Soil Science (England).

Jones, O.R. 1981. Land forming effects on dryland sorghum production in the Southern Great Plains. Soil Sci. Soc. Am. J. 45:606–611.

Jones, O.R., and R.N. Clark. 1987. Effects of furrow dikes on water conservation and dryland crop yields. Soil Sci. Soc. Am. J. 51:1307–1314.

Jones, O.R., and V.L. Hauser. 1975. Runoff utilization for grain production. pp. 277-283. In: Proceedings of a Water Harvesting Symposium, Phoenix, AZ, March 1974. USDA-ARS-W-22. U.S. Government Printing Office, Washington, D.C.

Jones, O.R., V.L. Hauser, and T.W. Popham. 1994. No-tillage effects on infiltration, runoff, and water conservation on dryland. Trans. Am. Soc. Agric. Eng. 37:473–479.

Jones, O.R., W.M. Willis, S.J. Smith, and B.A. Stewart. 1995. Nutrient cycling of cattle feedlot manure and composted manure applied to Southern High Plains drylands. pp. 265-272. In: K. Steele (ed.) Impact of Animal Manure and the Land-Water Interface. Lewis Publishers, Boca Raton, FL.

Kanwar, R.S., J.L. Baker, and J.M. Laflen. 1985. Nitrate movement through the soil profile in relation to tillage systems and fertilizer application methods. Trans. Am. Soc. Agric. Eng. 28:1802–1807.

Karraker, P.E., C.E. Bortner, and N.E. Fergus. 1950. Nitrogen balance in lysimeters as affected by growing Kentucky bluegrass and certain legumes separately and together. Bulletin Number 557, Kentucky Agricultural Experiment Station, Lexington.

Klausner, S.D., P.J. Zwerman, and D.F. Ellis. 1974. Surface runoff losses of soluble nitrogen and phosphorus under two systems of soil management. J. Environ. Qual. 3:42–46.

Langdale, G.W., R.A. Leonard, and A.W. Thomas. 1985. Conservation practice effects on phosphorus losses from Southern Piedmont watersheds. J.Soil Water Conserv. 40:157–160.

Lentz, R.D., I. Shainberg, R.E. Sojka, and D.L. Carter. 1992. Preventing irrigation furrow erosion with small applications of polymers. Soil Sci. Soc. Am. J. 56:1926–1932.

Lentz, R.D., and R.E. Sojka. 1994. Field results using polyacrylamide to manage furrow erosion and infiltration. Soil Sci. 158:274–282.

Lyle, W.M., and J.P. Bordovsky. 1981. Low energy precision application (LEPA) irrigation system. Trans. Am. Soc. Agric. Eng. 24:1241–1245.

Martinez, J., and G. Guirard. 1990. A lysimeter study of the effects of a ryegrass catch crop, during a winter wheat/maize rotation, on nitrate leaching and on the following crop. J. Soil Sci. 41:5–16.

Meisinger, J.J., W.L. Hargrove, R.L. Mikkelsen, J.R. Williams, and V.W. Benson. 1991. Effects of cover crops on groundwater quality. pp. 57–68. In: W.L. Hargrove (ed.) Cover crops for clean water. Soil and Water Conservation Society, Ankeny, IA.

Morgan, M.F., H.G.M. Jacobson, and S.B. LeCompte, Jr. 1942. Drainage water losses from a sandy soil as affected by cropping and cover crops. Bulletin 466, Connecticut Agricultural Experiment Station, New Haven.

Mostaghimi, S., T.A. Dillaha, and V.O. Shanholtz. 1988. Influence of tillage systems and residue level on runoff, sediment, and phosphorus losses. Trans. Am. Soc. Agric. Eng. 31:128–132.

Mostaghimi, S., T.M. Younos, and U.S. Tim. 1992. Crop residue effects on nitrogen yield in water and sediment runoff from two tillage systems. Agric., Ecosystems, Environ. 39:187–196.

Musick, J.T. 1970. Effect of antecedent soil water on preseason rainfall storage in a slowly permeable irrigated soil. J. Soil Water Conserv. 25:99–101.

OECD (Organization for Economic Cooperation and Development). 1982. Eutrophication of Waters: Monitoring, Assessment, and Control. OECD, Paris, France.

Olson, R.J., R.F. Hensler, O.J. Attoe, S.A. Witzel, and L.A. Peterson. 1970. Fertilizer nitrogen and crop rotation in relation to movement of nitrate nitrogen through soil profiles. Soil Sci. Soc. Am. Proc. 34:448–452.

Papendick, R.I., M.J. Lindstrom, and V.L. Cochran. 1973. Soil mulch effects on seedbed temperature and water during fallow in Eastern Washington. Soil Sci. Soc. Am. Proc. 37:307–313.

Papendick, R.I., and D.E. Miller. 1977. Conservation tillage in the Pacific Northwest. J. Soil Water Conserv. 32:49–56.

Power, J.F., W.W. Wilhelm, and J.W. Doran. 1986. Crop residue effects on soil environment and dryland maize and soybean production. Soil Tillage Res. 8:101–111.

Prato, T., and S. Wu. 1991. Erosion, sediment and economic effects of conservation compliance in an agricultural watershed. J. Soil Water Conserv. 46:211–214.

Richardson, C.W. 1973. Runoff, erosion, and tillage efficiency on graded-furrow and terraced watersheds. J. Soil Water Conserv. 28:162–164.

Rosenberg, N.J. 1966. Microclimate, air mixing and physiological regulation of transpiration as influenced by wind shelter in an irrigated bean field. Agric. Meteorol. 3:197–224.

Schneider, A.D., T.A. Howell, and J.L. Steiner. 1993. An evapotranspiration research facility using monolithic lysimeters from three soils. Appl. Eng. Agric. 9:227–235.

SCSA [Soil Conservation Society of America (now SWCS, Soil and Water Conservation Society)]. 1976. Resource conservation glossary. Soil and Water Conservation Society, Ankeny, IA.

Sharpley, A.N. 1981. The contribution of phosphorus leached from crop canopy to losses in surface runoff. J. Environ. Qual. 10:160–165.

Sharpley, A.N., S.C. Chapra, R. Wedepohl, J.T. Sims, T.C. Daniel, and K.R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. J. Environ. Qual. 23:437–451.

Sharpley, A.N., J.J. Meisinger, A. Breeuwsma, J.T. Sims, T.C. Daniel, and J.S. Schepers. 1995. Impacts of animal manure management on ground and surface water quality. In: J. Hatfield (ed.) Effective management of animal waste as a soil resource. John Wiley, New York (in press).

Sharpley, A.N., J.J. Meisinger, J. Power, and D.L. Suarez. 1992a. Root extraction of nutrients associated with long-term soil management. Adv. Soil Sci. 19:151–217.

Sharpley, A.N., and S.J. Smith. 1989. Mineralization and leaching of phosphorus from soil incubated with surface-applied and incorporated crop residues. J. Environ.Qual. 18:101–105.

Sharpley, A.N., and S.J. Smith. 1991. Effects of cover crops on surface water quality. pp. 41–49. In: W.L. Hargrove (ed.) Cover crops for clean water. Soil and Water Conservation Society, Ankeny, IA.

Sharpley, A.N., and S.J. Smith. 1993. Wheat tillage and water quality in the Southern Plains. Soil Tillage Res. 30:33–48.

Sharpley, A.N., S.J. Smith, O.R. Jones, W.A. Berg, and G.A. Coleman. 1992b. The transport of bioavailable phosphorus in agricultural runoff. J. Environ. Qual. 21:30–35.

Sharpley, A.N., S.J. Smith, J.R. Williams, O.R. Jones, and G.A. Coleman. 1991. Water quality impacts associated with sorghum culture in the Southern Plains. J. Environ. Qual. 20:239–244.

Shipitalo, M.J., W.M. Edwards, W.A. Dick, and L.B. Owens. 1990. Initial storm effects on macropore transport of surface-applied chemicals in no-till soil. Soil Sci. Soc. Am. J. 54:1530–1536.

Smika, D.E., and G.A. Wicks. 1968. Soil water storage during fallow in the Central Great Plains as influenced by tillage and herbicide treatments. Soil Sci. Soc. Am. Proc. 32:591–595.

Smith, S.J., J.W. Naney, and W.A. Berg. 1987. Nitrogen and ground water protection. pp. 367-374. In: D.M. Fairchild (ed.) Ground Water Quality and Agricultural Practices. Lewis Publishers, Chelsea, MI.

Smith, S.J., A.N. Sharpley, J.W. Naney, W.A. Berg, and O.R. Jones. 1991. Water quality impacts associated with wheat culture in the Southern Plains. J. Environ. Qual. 20:244–249.

Sprague, M.A. 1979. Agronomy. pp. 27-29. In: R.W. Fairbridge and C.W. Finkl, Jr. (eds.) The Encyclopedia of Soil Science, Part I, Physics, Chemistry, Biology, Fertility and Technology. Dowden, Hutchinson & Ross, Stroudsburg, PA.

SSSA (Soil Science Society of America). 1987. Glossary of Soil Science Terms. Soil Science Society of America, Madison, WI.

Staple, W.J., J.J. Lehane, and A. Wenhardt. 1960. Conservation of soil moisture from fall and winter precipitation. Can. J. Soil Sci. 40:80–88.

Staricka, J.A., R.R. Allmaras, and W.W. Nelson. 1991. Spatial variation of crop residue incorporated by tillage. Soil Sci. Soc. Am. J. 55:1668–1674.

Steiner, J.L. 1989. Tillage and surface residue effects on evaporation from soils. Soil Sci. Soc. Am. J. 53:911–916.

Steiner, J.L., T.A. Howell, J.A. Tolk, and A.D. Schneider. 1991. Evapotranspiration and growth predictions of CERES-maize, -sorghum, and -wheat for water management in the southern High Plains. pp. 297–303. In: Proceedings American Society of Civil Engineers National Conference on Irrigation and Drainage Research, Honolulu, HI, July 1991.

Stewart, B.A., and W.C. Moldenhauer (eds.). 1994. Crop residue management to reduce erosion and improve soil quality: Southern Great Plains. Conservation Research Report Number 37, U.S. Department of Agriculture-Agricultural Research Service.

Stewart, B.A., and J.L. Steiner. 1990. Water-use efficiency. Adv. Soil Sci. 13:151–173.

Stewart, B.A., D.A. Woolhiser, W.H. Wischmeier, J.H. Caro, and M.H. Frere. 1975. Control of water pollution from cropland. Volume 1. A manual for guideline development. U.S. Department of Agriculture Report Number ARS-H-5-1. U.S. Government Printing Office, Washington, D.C.

Triplett, Jr., G.B., and D.M. Van Doren, Jr. 1977. Agriculture without tillage. Sci. Am. 236(1):28–33.

Tyler, D.D., and G.W. Thomas. 1977. Lysimeter measurements of nitrate and chloride losses from conventional and no-tillage corn. J. Environ.Qual. 6:63–66.

Unger, P.W. 1984. Tillage and residue effects on wheat, sorghum, and sunflower grown in rotation. Soil Sci. Soc. Am. J. 48:885–891.

Unger, P.W. 1992. Infiltration of simulated rainfall: Tillage system and crop residue effects. Soil Sci. Soc. Am. J. 56:283–289.

USEPA (U.S. Environmental Protection Agency). 1976. Quality criteria for water. U.S. Government Printing Office, Washington, D.C.

Van Doren, Jr., D.M., and R.R. Allmaras. 1978. Effect of residue management practices on the soil physical environment, microclimate, and plant growth. pp. 49-83. In: W.R. Oschwald (ed.) Crop residue management systems. ASA Special Publication Number 31, American Society of Agronomy, Madison, WI.

Volk, G.M., and C.E. Bell. 1945. Some major factors in the leaching of calcium, potassium, sulfur and nitrogen from sandy soils: A lysimeter study. Bulletin Number 416, University of Florida, Gainesville.

Yoo, K.H., J.T. Touchton, and R.H. Walker. 1988. Runoff, sediment and nutrient losses from various tillage systems of cotton. Soil Tillage Res. 12:13–24.

Zhu, J.C., C.J. Gantzer, S.H. Anderson, E.E. Alberts, and P.R. Beuselinck. 1989. Runoff, soil, and dissolved nutrient losses from no-till soybean with winter cover crops. Soil Sci. Soc. Am. J. 53:1210–1214.

Zingg, A.W., and V.L. Hauser. 1959. Terrace benching to save potential runoff for semiarid land. Agron. J. 51:289–292.

Zingg, A.W., and C.J. Whitfield. 1957. A summary of research experience with stubble-mulch farming in the Western States. U.S. Department of Agriculture Technical Bulletin Number 1166. U.S. Government Printing Office, Washington, D.C.