DRAINAGE AND WATER QUALITY IN GREAT LAKES AND CORNBELT STATES[a]

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ABSTRACT: The soils and the climate of the Great Lakes and Cornbelt states dictate that drainage is required to carry out economically viable farming activities. When drained, the soils are very productive and this eight-state region accounts for nearly 80% of the agricultural production of the United States. Drainage played an important role in the development of the region and a historical perspective is included to indicate the impetus for drainage and the amount of drainage application. Research results of agricultural drainage effects on water quality indicate that agricultural subsurface drainage has both positive and negative impacts; i.e., reduction in sediment and phosphorous, and increase in nitrate-nitrogen delivery to receiving waters. Research is needed to evaluate the full potential of controlled drainage and water-table management systems for managing agricultural effects on water quality. This information is needed by state and federal agencies to help landowners meet existing and impending water-quality requirements. Drainage is an important management practice for improving water quality while sustaining agricultural viability.

HISTORY AND NEED

Drainage in the Midwest United States began after 1850 when the Swamp Land Acts of 1849 and 1850 released large amounts of swamp and wetlands still owned by the federal government. These lands were released for private development with the funds from their sale to be used to build drains and levees. Drainage districts began to be organized in the early 1900s. The Reclamation Act of 1902 established the Bureau of Agricultural Engineering within the U.S. Department of Agriculture (USDA), which was responsible for the design and construction of many of the major drainage ditches that were installed to create surface water outlets. In terms of hectares of land drained, the eight states that make up the Great Lakes and Cornbelt states (Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, Wisconsin) include the top four states plus the 7th, 11th, 13th, and 16th. All together these eight states account for over 20.6 million hectares of land (see Table 1) drained by surface and subsurface drainage. The drained cropland represents 37% of the total cropland. Without drainage, the U.S. Midwest would not be the most productive agricultural area in the world.

Society's concerns about the quality of our nation's surface and ground waters have intensified during the past 25 years. Agriculture is perceived to be an important non-point source of pollution. Agricultural drainage water contributes to the quality of the water in the receiving streams, and the quality of water discharged from subsurface drainage systems also indicates the quality of the water moving to recharge groundwater supplies. It is important to document and understand the effect of agricultural drainage on water quality. At present, the water-quality impacts of agricultural drainage cannot be simply and clearly stated. The interactions with tillage, cropping sequence, fertility management, site conditions, soil, and climate are complex and not well documented. In this paper we present a review of research conducted under Midwest soil and climate conditions that indicate the effect of agricultural drainage on water quality.

RESEARCH RESULTS

According to a recent review of literature (Fogiel and Belcher 1991a) on the role of water-table management on water quality, the study of water quality associated with subsurface drainage in the Midwest was not reported before 1970. During the 20 years that followed, a number of reports were published that document the quality of the water discharged through subsurface drains, but there is scant information about the impact of drainage, i.e., compared to no drainage or a presumed natural condition.

Skaggs et al. (1994) also recently completed a comprehensive review of research on the hydrologic and water-quality effects of agricultural drainage. Based on their survey of studies in the U.S., Canada, Europe and elsewhere, when compared to uncleared land under natural conditions, improved drainage and agricultural production usually increases peak runoff rates, sediment losses, and pollutant loads on surface-water resources. However, for conditions where land has been converted to agricultural production, and where drainage outlets are in place, improved subsurface drainage has been found to reduce runoff, peak outflow rates, and sediment losses. In addition, improved subsurface drainage may increase the loss of some pollutants and decrease the loss of others.

Within the Great Lakes and Cornbelt geographic region (including the southern portion of Ontario bounded by Lakes Huron and Erie), many of the early research reports focused on characterization of the soluble and suspended constituents in subsurface drainage discharge water. Some reported only on plant nutrient content while others also included sediment and pesticides.

The earliest substantive report was that by Willrich (1969) on the properties of tile drainage water in Iowa. In Willrich (1969), water samples were collected twice a month from 10 subsurface drainage outlets draining 2.4 to 148 ha. The median values for chemical properties of the drainage water ranged as follows: total N = 12 to 27 mg/L; P = 0.1 to 0.3 mg/L; K = 0.2 to 0.8 mg/L; hardness = 350 to 440 mg/L as $CaCO_3$, alkalinity = 260 to 330 mg/L; and pH from 7.4 to 7.8. The nitrogen was mostly in the nitrate form.

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TABLE 1. Drainage Statistics for North Central Region of the United States (USDA 1987)

State (1)	Rank (2)	Hectares drained (3)	Cropland Drainage: Percent of all drainage (4)	Cropland Drainage: Percent of all cropland (5)
Illinois	1	3,965,600	90	35
Indiana	2	3,273,300	85	50
Iowa	3	3,153,800	90	25
Ohio	4	2,996,000	80	50
Minnesota	7	2,579,000	75	20
Michigan	11	2,232,800	70	30
Missouri	13	1,716,600	70	25
Wisconsin	16	908,900	45	10

Bolton et al (1970) measured N, P, K, Ca, and Mg concentrations in subsurface drainage effluent from 1961 through 1967 at Woodslee, Ontario, Canada, and found that both crop system and fertility-management practice affected the nutrient content of drainage water. Baker et al. (1975) reported about nutrient (N, P, and S) content of subsurface drainage water and water taken from piezometers at depths deeper than the subsurface drain conduits. The nitrate content of the drain water was less or similar to that in water from the deeper depths. This finding along with data presented by Gambrell et al. (1975a, b) that drainage reduced the soluble carbon content of the soil and thus reduced denitrification, means that more nitrate is available to move toward ground water and baseflow to streams. Maier et al. (1976) presented evidence that the soluble carbon content of water from subsurface drains is low, and has minimal effect on the organic carbon content of stream water.

Baker and Johnson (1977) summarized the results of several studies (within and outside the Great Lakes and Cornbelt states) on the quality of agricultural drainage water for runoff, subsurface drainage discharge, and base flow. They concluded that concentrations of nitrate in subsurface drainage water were greater than in runoff; concentrations of ammonia in runoff usually were greater than in subsurface drainage water; phosphorus concentrations in subsurface drainage water were usually less than in runoff; dissolved organic carbon concentrations were greater in runoff than in subsurface drainage water; runoff rather than subsurface drainage was the mode of pesticide transport; and sediment loss was much greater by runoff than by subsurface drainage discharge. These conclusions were not based on side-by-side comparisons of drained versus nondrained agricultural lands, but represent general conditions that exist for runoff and subsurface drainage water quality.

Logan and Schwab (1976) monitored the quality of subsurface drainage water discharged from field-size areas on glacial till soils in Union County, in central Ohio. The fields were either continuous corn or established alfalfa. They reported N, P, and sediment content of the drainage water. Bottcher et al. (1981) detailed the sediment, pesticide and nutrients measured in the outflow water from a subsurface drainage system in Hoytville silty clay soil near Woodburn in northeast Indiana. Fausey (1983) reported N, P, and sediment content of subsurface drainage water from Clermont silt loam soil near Martinsville in southwestern Ohio. The results from these studies are in agreement with those summarized by Baker and Johnson (1977).

Many experiments have been conducted to study the effects of cropping systems, tillage, and fertility management on subsurface drainage water quality. Baker and Johnson (1981); Kanwar et al. (1983); Kanwar (1988); Kanwar et al. (1988); and Kanwar and Baker (1991, 1993) have presented results from such field research experiments in Iowa. Gast et al. (1978); Randall and Nelson (1985); Buhler et al. (1993); and Randall et al. (1993) presented results from research in Minnesota. Gold and Loudon (1989) reported about tillage effects on subsurface water quality on a clay loam soil southeast of Saginaw Bay in Michigan. Logan et al. (1989, 1994) reported the effects of tillage on nutrient and pesticide content of subsurface drainage water under drought and wet climatic conditions on a lakebed silty clay soil in northwest Ohio. Gaynor et al. (1992) reported pesticide content in subsurface drainage water as affected by tillage on a Brookston clay loam soil near Woodslee, Ontario, Canada. These studies generally indicate that tillage, cropping system, and fertility management greatly influence the amount and timing of nitrate and total nitrogen in subsurface drainage water, but have little or no effect on other water-quality parameters. These studies do not quantify the effects of drained versus undrained land and the subsequent impact of drainage on water quality.

Few research studies report the quality of water being delivered offsite from a specific agricultural management system with and without subsurface drainage. In Ohio, Schwab et al. (1980) reported the quality of water being delivered offsite by surface-drained-only and subsurface-drained-only plots. Their results confirm that, except for total nitrogen content, the subsurface drainage water was of better quality than the runoff water. Another feature of this experiment was the monitoring of subsurface drains at two depths, 0.9 m and 0.4 m. Table 2, taken from Schwab et al. (1985), presents data that show the water from the shallow drains contained less sediment and nutrients than water from the deeper drains. Shallow placement of drains is not a common practice (except in Ontario), but hydrologic and water quality benefits could result from shallow placement.

In Indiana, Kladivko et al. (1991) evaluated the effect of drain spacing on subsurface drainage water quality and reported that the amount of water, nutrients, and pesticides moved offsite was greater with narrow (6 m) compared to wider (12 m and 24 m) drain spacing. This research also illustrated that most (usually more than 90%) of the nitrate-nitrogen removed with subsurface drainage water occurred in the noncropping season (October to May), while most pesticide removal occurred within 2 months after application.

These last two cited studies (Schwab et al. 1980; Kladivko et al. 1991) provide evidence that the intensity of drainage influences subsurface drainage water quality. With somewhat less intense drainage (i.e., wider spacing and shallower depth), the subsurface drainage discharge water is of better quality.

Research focus in the Great Lakes and Cornbelt states has moved to water-table management (WTM). Recent studies describe effects of water-table management on the quality of water delivered to receiving streams and aquifiers. Water-table management combines conventional subsurface drainage with structural improvements that allow farmer control of drainage (controlled drainage) and capability to irrigate through the underground pipe system (subirrigation). Most

TABLE 2. Water Quality by Drainage System (Schwab et al. 1985)

Drainage treatment (1)	Years of record (2)	Average annual drain flow (mm) (3)	Average Annual Losses in kg/ha: Sediment (4)	NO_3-N (5)	Total P (6)	Soluble K (7)
Tile (deep)	1974–79	18.0	414	13.0	1.1	11.4
Tile (shallow)	1974–79	16.0	196	10.3	0.8	8.7
Surface	1969–79	17.8	2,347	11.0	2.1	31.2
Tile (deep)	1969–79	19.3	1,427	17.2	1.2	22.3

Note: Crops varied, but were the same for each treatment for years shown.

often, existing conventional subsurface drainage systems are modified for water-table management capability. As yet, definitive conclusions have not been reported and the results, as expected, are very site- and management-specific. However, early indications are that properly designed and operated water-table management systems provide both water-quality and economic benefit.

Michigan researchers have been monitoring the dissolved nutrient concentrations in subsurface drainage water at two locations. In 1987 the impact of subirrigation on water quality was made a part of the research effort at the Bannister site in central lower Michigan (Belcher 1990). In August 1989, a subirrigation water-quality research product was initiated in Tuscola County at Unionville (Fogiel and Belcher 1991b).

So far, water-table control by subirrigation/drainage reduced non-point-source pollution from the levels found with both wet cropland and cropland with subsurface drainage systems used only for drainage. For 20 months of monitoring (1987, 1988, and 1989) at the Bannister site, the total dissolved nitrate-nitrogen delivered from the field to the outlet ditch by the underground pipe system was reduced 64% by subirrigating (see Fig. 1). Subirrigation had little effect on the dissolved phosphate-phosphorus delivered by the subirrigation/drainage system (see Fig. 2). The average nitrate-nitrogen concentration in the subsurface drainage discharge water was 5.7 ppm with subirrigation/drainage compared to 9.0 ppm from subsurface drainage only. The average phosphate-phosphorus concentration was 0.12 ppm with subirrigation/drainage and 0.08 ppm with subsurface drainage only.

At the Unionville site, for the 1990 and 1991 growing seasons (12 months of monitoring), a 58% reduction in nitrate-nitrogen and a 16% reduction in dissolved phosphate-phosphorous was observed from WTM by subirrigation compared to conventional subsurface drainage (Figs. 1 and 2). For the months of May through October, the subirrigation treatment reduced the average nitrate-nitrogen concentration in the subsurface drainage water from 41.1 to 13.3 ppm in 1990, and 18.2 to 9.9 ppm in 1991. The average dissolved phosphate-phosphorus concentration was nearly equal for each growing season.

The results, all for corn production, indicate that controlling the water table by subirrigation offers agricultural producers the ability to reduce the offsite delivery of nitrate-nitrogen without increasing dissolved phosphate-phosphorus delivery.

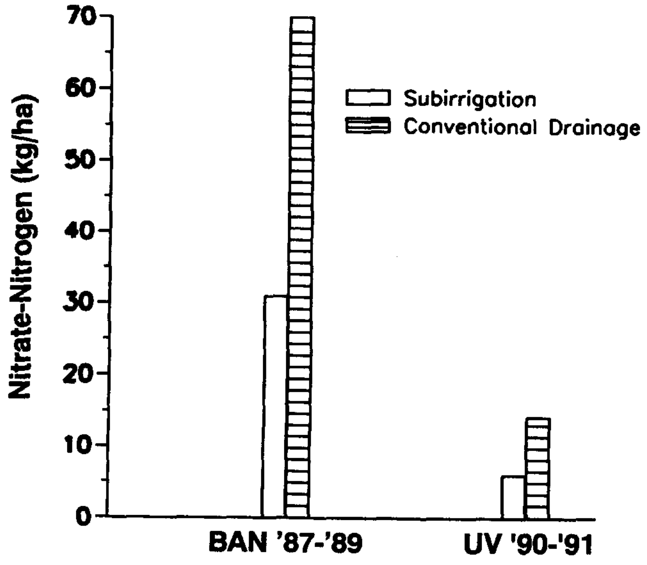

FIG. 1. Bannister (BAN) and Unionville (UV), Mich., Nitrate-Nitrogen Loadings (Pipe Flow at Bannister and Pipe Flow plus Overland Flow at Unionville)

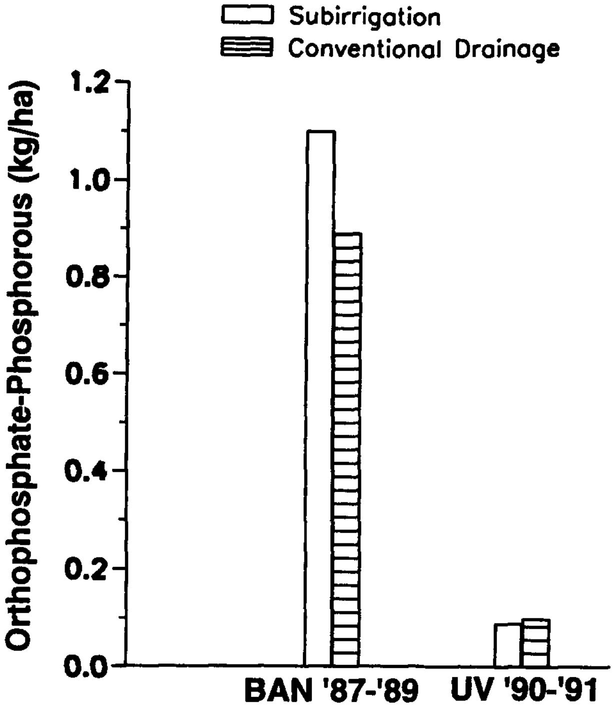

FIG. 2. Bannister (BAN) and Unionville (UV), Mich., Dissolved Phosphate-Phosphorus Loadings (Pipe Flow at Bannister and Pipe Flow plus Runoff at Unionville)

In Iowa, a study was conducted to evaluate the effect of WTM practices on water quality and crop yields. Corn yields and other corn growth parameters as affected by WTM practices in Iowa have been reported earlier (Kalita and Kanwar 1992). Water-table depths of 0.3, 0.6, and 0.9 m were maintained in field lysimeters at the Ames, Iowa site, and variable water-table depths were maintained in a subirrigation field at the Ankeny, Iowa site. Water samples were collected from various soil depths to analyze nitrate-nitrogen concentrations in the near-surface ground water. Concentration of nitrate-nitrogen in ground water changed with WTM practices. The lowest nitrate-nitrogen concentrations were observed under the shallow water-table depths. The nitrate-nitrogen concentrations in ground water generally decreased with increased depth and time during the growing season under all WTM practices. Results of the study indicated that WTM practices can be used to substantially reduce the concentrations of nitrate-nitrogen in the near-surface ground-water region (Kalita et al. 1992; Kanwar and Kalita 1990; Kanwar et al. 1993).

In Ohio, research on water-table management using a subirrigation/drainage system began in 1985 as reported in Cooper et al. (1991). Water-quality monitoring began in 1987, and additional field facilities have been added giving a total of three sites for research: Wooster, Hoytville, and Piketon, Ohio. Results from the Hoytville site for 1992 and 1993, showing the comparison of water quality in the near-surface ground water as affected by conventional drainage versus WTM using subirrigation during the growing season, are given in Figs. 3 and 4. The drains were installed in early 1991. The area was not cropped in 1991. Six plots were planted to corn and six were planted to soybeans in 1992. In 1993, the crop changed in all plots to establish a corn-soybean rotation. 1992 was a very wet year and 1993 was very dry. In general, the near-surface ground water beneath the conventional drainage plots had greater nitrate-nitrogen concentrations compared to that beneath the subirrigated plots.

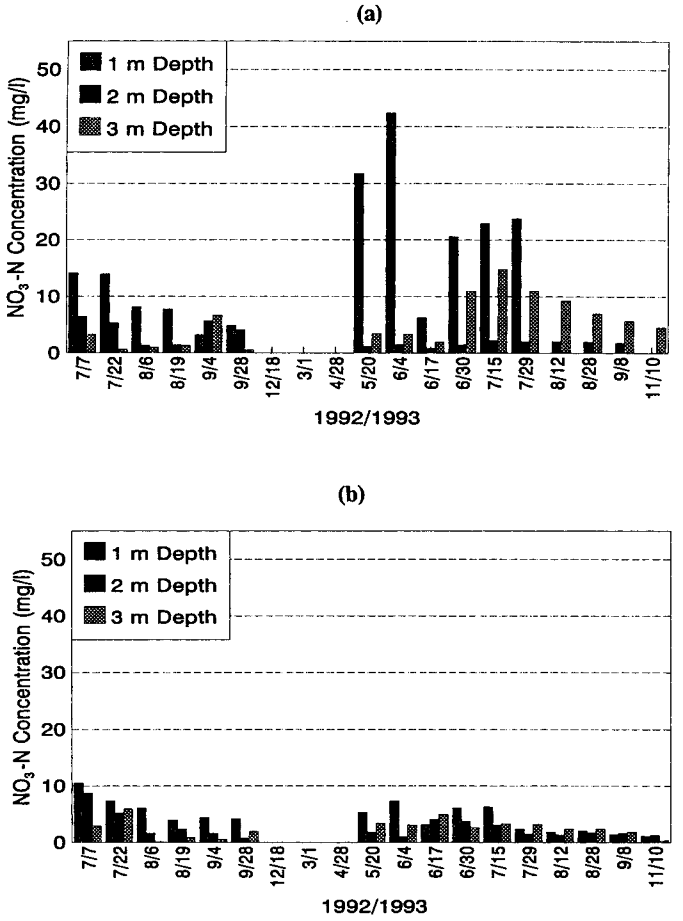

FIG. 3. NO$_3$-N Concentration in Water Samples Taken from Piezometer Wells 1, 2, and 3 m below Ground Surface with Soybean Crop at Hoytville, Ohio: (a) in Drainage only; and (b) in Subirrigated Water-Table Management Treatments

CONSTRAINTS AND OPPORTUNITIES

As the U.S. has evolved from an agrarian society to an urban society, resource perspectives have changed. There is efficient, abundant production with less than 2% of the population involved in production agriculture on a national basis. Ecological and environmental issues have come to the forefront of societal concerns. The impact of these concerns in relation to drainage was first framed by the 1977 Executive Order (E.O. 11990) that established a national policy of no (further) net loss of wetlands. Coupled with the downturn in the farm economy, which made capital unavailable for investment in drainage improvements, the progress of drainage slowed dramatically during the 1980s.

The 1985 Farm Bill specified that to continue to qualify for cost sharing and subsidy benefits from federal government programs, farmers were required to adopt what have been called the "Swampbuster" provisions of the bill. These provisions prohibit the conversion of wetlands by drainage improvements. The 1990 Farm Bill put even more stringent limits on conversion of existing wetlands.

Several factors contribute to excess water problems in many agricultural soils throughout the midwestern states: fine soil texture, massive soil structure, low soil permeability, topography, soil compaction, restrictive geologic layers underlying the soil profile, and excess precipitation. Texture affects soil water-holding capacity and permeability. Fine-textured soils (relatively large percentage of clay- and silt-sized particles) generally hold water well, but drain poorly compared to coarse-textured soils (large percentage of sand-sized particles), which drain well, but have poor water-holding ability. Granular soil structure helps promote the movement of water, but a massive structure usually limits the movement of water. Permeability is affected by both soil texture and structure, by human activities and other factors.

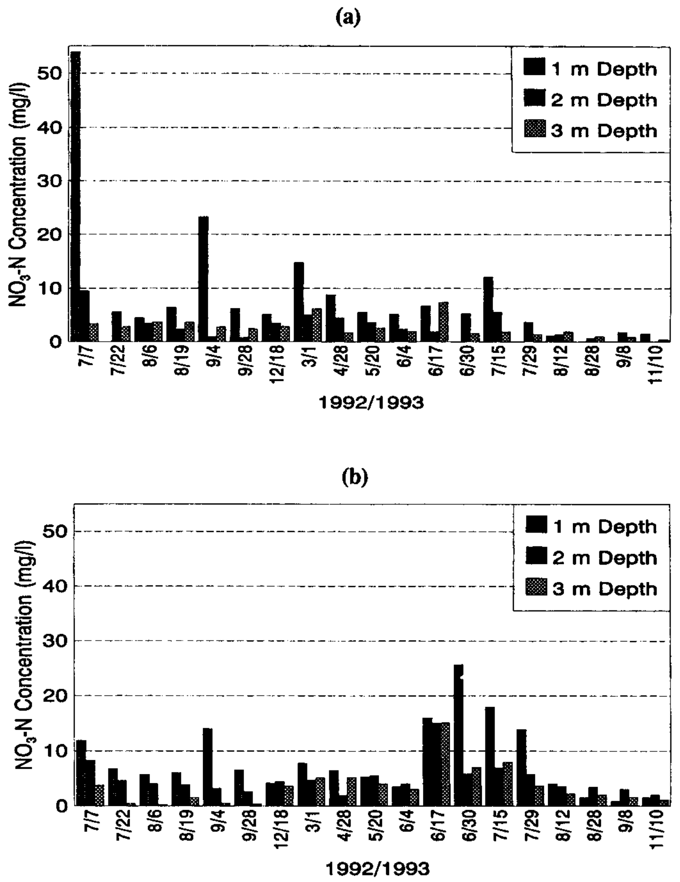

FIG. 4. NO$_3$-N Concentration in Water Samples Taken from Piezometer Wells 1, 2, and 3 m below Ground Surface with Corn Crop at Hoytville, Ohio: (a) in Drainage only; and (b) in Subirrigated Water-Table Management Treatments

Wise management of our water resources on agricultural lands is one of the most important concerns in developing sustainable agricultural systems. Both quantity and quality of water must be considered when assessing water-management practices, but recently only water quality has received public attention and concern. Many soils in the midwestern U.S. and other regions have problems with excess soil water in the spring and fall, which leads to excessive runoff and subsequent soil erosion, which can impair surface-water quality. Excess soil water in the soil profile (regionally high groundwater table, or locally perched water table) also poses a problem for the timely planting and harvesting of crops, and other cultural operations.

Historically there may have been significant, albeit not well documented, effects of drainage on water quality. Data presented by Keeney and DeLuca (1993) show that the average annual nitrate concentrations in the Des Moines river have not changed between 1945 and 1990. During this time, large increases occurred in agrichemical use, prevailing farming practices, and the amount of drainage installed on crop and pasture land. They conclude that reducing the levels of nitrate-nitrogen in the river requires changing the overall farming system approach, not by eliminating or changing one component of the farming system.

The idea that natural processes are intrinsically better, or to be preferred, is not fundamentally sound. There is tremendous natural erosion. Land surfaces are eroded, and lakes and streams are filled in with this sediment over time. Agriculture as practiced in the past has created conditions for accelerated erosion. Drainage has been a management tool that has lessened the potential for accelerated erosion from agricultural activities.

Well-planned and well-managed drainage systems change the hydrologic relationships on the land where applied. Surface drainage systems can reduce erosion through the reduction of slope length and overland flow, and the control of the velocity of discharge in channels with designed adequate capacity, proper slope, and vegetative protection where needed. Subsurface drainage can reduce the amount of runoff and reduce the peak rate of discharge through surface channels, thereby further reducing erosion and the associated off-site impacts of erosion.

Clearly not all cropland in the Midwest is wetland, and some drainage improvements for wet soils continue to be implemented by farmers, especially as land ownership changes. Typically, one of the first improvements that should be made on newly acquired cropland is the updating or upgrading of the drainage system. This is commensurate with the increasing average size of farms and the benefits of early seeding of crops. Drainage does increase the number of days available for planting and harvesting crops, and is an effective management tool for controlling runoff and erosion and associated pollutants.

Documenting and understanding the various impacts and benefits of agricultural water-management improvements, especially those associated with the drainage of excess water from existing cropland, is important for modern agricultural production in the United States. Subsurface drains were not designed or installed as water-quality management tools, but they do have an impact on agricultural chemical transport and fate. Very little attention has been given to the potential for management of existing subsurface drainage systems and the subsequent impact on ground-water quality. Subsurface drainage systems drain near-surface perched water tables or the "top" of aquifers. These drainage systems actually provide the opportunity to detect some water-quality problems, and then possibly control or eliminate these problems by: (1) diverting contaminated excess subsurface water to a treatment system (treating near-surface ground water should be cheaper than renovating an aquifer); (2) controlling the water table to promote biological and chemical degradation of contaminants; and/or (3) controlling the timing of release of drainage water to surface- and ground-water bodies.

RESEARCH NEEDS

More research clearly needs to be carried out to determine the full potential of water-table management for controlling or managing water quality effects of agricultural management systems. Water-table management practices that need to be considered are controlled drainage and subirrigation. Data by Cooper et al. (1991) clearly show the yield benefits of subirrigation for soybeans. Data by Fogiel and Belcher (1991b) and Belcher (1992) show the yield benefit of corn and sugar beet subirrigation. Water-table management research needs also to evaluate the short- and long-term effects on: fate and transport of agricultural chemicals; soil properties, soil productivity and trafficability parameters; surface and subsurface water and sediment movement; biological dynamics of the soil system within the root zone; and above- and below-ground plant development for a variety of agricultural crops.

Controlled drainage should be investigated for use with animal-waste disposal on cropland. The potential for denitrifying unused nitrogen remaining in the soil by controlled drainage during the winter months also needs investigation.

It is unclear how the presence of subsurface drains, and the subsequent manipulation of the water table, may affect the subsurface microbial ecology, or how these effects are translated to degradation of agricultural chemicals. This lack of information is a reflection of the fact that interest in this area has only recently developed, and as a result, a general lack of information on subsurface ecology exists. Also, the interfacing of agricultural drainage systems with constructed or enhanced wetland ecosystems needs to be evaluated.

Reducing nitrate concentrations in drainage waters may be possible by enhancing denitrification (Burford and Bremner 1975; Davenport et al. 1975; Meek et al 1969), and water-table management in the southeastern U.S. has shown potential for reducing nitrate concentrations in subsurface drainage water (Gilliam 1987; Gilliam and Skaggs 1986; Gilliam et al. 1979; Skaggs and Gilliam 1981). These studies clearly establish a precedent for reducing contamination through manipulating biological functions via water-table management. Insufficient attention, however, has been given to water-table management and pesticide fate. Preliminary data from several studies across the midwest and elsewhere indicate a potential positive benefit to using improved water-table management techniques (controlled drainage, subirrigation, etc) with existing or new subsurface drainage systems in regards to reducing pesticides losses to ground and surface waters. However, the management of agricultural drainage systems and the subsequent impact on pesticide movement to water resources is a complex problem, even more complex than that for nitrogen.

A comprehensive model of water-table management that incorporates solute transport is a significant, high priority research need. Such a model will be useful to study and describe cause and effect in water-quality issues. The model should be tested with case studies and would then be useful in the design of new water-table management systems.

Although some research on WTM is in progress in the Midwest, there are numerous research needs as indicated previously. Lastly, a more important need is the incorporation of current and future research results into comprehensive agricultural water management guides, with emphasis on the design and management of water-table management systems.

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