Herbicide and Nitrate in Surface and Ground Water: Results from the Iowa Management Systems Evaluation Area

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Abstract
Herbicides are transported through subsurface drainage to surface waters from corn-growing areas of the USA and Canada. Herbicide losses are highly variable, ranging between 0.01 to 10 g/ha. The magnitude of herbicide loss results from precipitation patterns, herbicide-soil interactions, and farming practices. This report reviews existing literature and presents new research concerning effects of farming practices on herbicide losses in drainage water. Conservation tillage practices which increase infiltration tend to increase herbicide losses. Increasing intensity of drainage and increased frequency and rate of herbicide use also increase herbicide losses. Banding lowers the application rate and reduces annual losses and average concentrations of atrazine compared to broadcast applications. Metolachlor losses were reduced by banding, but the effect was only statistically significant in continuous corn systems.

Disciplines
Agriculture | Bioresource and Agricultural Engineering | Water Resource Management

Comments

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Chapter 17

Herbicide and Nitrate in Surface and Ground Water: Results from the Iowa Management Systems Evaluation Area

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The Management System Evaluation Area (MSEA) program sponsored multidisciplinary research at plot, field and watershed scales. Like the Mississippi Delta MSEA, water quality research in the Iowa MSEA targeted herbicide and nitrate transport and fate in different hydrogeologic settings. In central and northeast Iowa, herbicides were transported from fields in runoff and in subsurface drainage water. Herbicides leached to groundwater, but concentrations generally remained below the maximum contamination level (MCL). Relative losses of different herbicides were related to their persistence patterns in soil and soil permeability. In contrast to herbicides, nitrate concentrations in stream water often exceeded the MCL and losses were controlled by subsurface drainage. Nitrate losses are affected by fertilization, mineralization of soil nitrogen, and timing of spring rainfall. Tillage affects nitrate loss indirectly, though changes in water infiltration. The MSEA program established knowledge about the routes of contaminant entry into surface waters, contaminant sources and effects of selected practices.

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Farming systems in the upper portion of the Mississippi River drainage basin have a significant influence on water quality in small and large stream systems. The sediment, nitrate, phosphorus and pesticides leaving agricultural lands impact local streams and lakes, groundwater, and large bodies of water, such as the Great Lakes and the Gulf of Mexico. The purpose of this chapter are to review other research conducted under the auspices of the USDA Water Quality Initiative, the Iowa MSEA program in particular, to provide a comparative reference for findings of the Mississippi Delta MSEA (MDMSEA). These results illustrate the soil, hydrology and management factors that influence movement of herbicides and nitrate into water resources.

The Management Systems Research Areas were initially established in the states of Iowa, Minnesota, Missouri, Nebraska and Ohio to determine the effects of production systems on water quality. The MSEA program was initiated in response to previous studies indicating that pesticides were widespread in both surface water and groundwater at levels that possibly were significant to public health (2, 3). Several MSEA programs included multiple sites and the Minnesota MSEA included sites in South Dakota, North Dakota and Wisconsin. The experiments performed at the sites were not standardized, but did share the common focus of evaluating the patterns and quantities of nutrient and pesticide movement into surface waters and groundwater under existing farming systems (7). The scale of experimentation ranged from the plot scale to the watershed scale. The Mississippi Delta MSEA was established later with the same general purpose. This paper reviews and summarizes the findings of the Iowa MSEA program, compares some water quality responses found in the Iowa MSEA to those found in the Mississippi Delta MSEA, and examines the impact of the Iowa MSEA on post-MSEA water quality research.

The Iowa MSEA program was carried out at three principal sites by a combination of researchers from the USDA-ARS, Iowa State University, and the US Geological Survey starting in 1991. The sites included:

1. small field-scale watersheds in loess hills area of southwest Iowa, near Treynor, IA
2. plot, field and watershed-scale studies conducted on the glaciated, rolling topography of central Iowa near Ames; and
3. the large plot-scale studies on the glaciated topography near Nashua in northeast Iowa.

Farming Practices

The farming practices in the area represented by the Iowa MSEA, and to a large extent by the other MSEA programs in Midwestern states, revolve around a fairly limited number of cropping systems that are practiced by the majority of farmers in the region. These systems tend to utilize corn and soybeans as the principal crops, with forage crops and small grains present in smaller quantities. Figure 1 illustrates the distribution of corn in Iowa and surrounding states and
Figure 1. Distribution (percent of cropland) of corn (a) and land with subsurface drainage (b) in Iowa and other midwestern states. The Figure was produced using data from the 1992 Natural Resource Inventory (USDA).
also presents the distribution of land with subsurface drainage. Animals may also be present in these farming systems. The crop rotations, fertilizer inputs, tillage methods, and pest control vary, but are also fairly limited in many respects.

The Iowa MSEA sites utilized two principal crop rotations, continuous corn (Nashua and Treynor sites) and rotated corn and soybeans (Nashua and Walnut Creek sites). The tillage systems in these comparisons included moldboard plowing, disk tillage, ridge-tillage, and no-till, although not all the tillage systems were utilized in all experiments or at all sites. Emphasis was placed on nitrate and the following herbicides at all sites: atrazine \( [6\text{-chloro-N-ethyl-N'}(1\text{-methyl ethyl})-1,3,5\text{-triazine-2,4-diamine}] \), alachlor \( [2\text{-chloro-N}(2,6\text{-diethyl phenyl})-N'(\text{methoxy methyl})\text{acetamide}] \), cyanazine \( (2\text{-[4-chloro-6(ethyl amino)-1,3,5-triazin-2-yl]amino}-2\text{-methylpropenitrile}] \), metolachlor \( [2\text{-chloro-N'(2-ethyl-6-methylphenyl)}-N'(2\text{-methoxy-1-methyl ethyl})\text{acetamide}] \) and metribuzin \( [4\text{-amino-6-(1-dimethylethyl)-3(methylthio)-1,2,4-triazin-5(4H)-one}] \) in water monitoring studies and other experiments. The use of these herbicides in Iowa during 1994 on corn (percent of treated acreage) was 66% for atrazine (7.47 million lb), 13% for alachlor (4.11 million lb.), 38% for metolachlor (10.66 million lb.), and 2% for metribuzin (21,000 lb.). The use of these herbicides in soybeans was 4% for metribuzin (107,000 lb.), and 2% for alachlor (392,000 lb.) in 1994 (4). These state-wide herbicide usage patterns were similar to those observed in one of the Iowa MSEA sites, the Walnut Creek watershed, where atrazine was used on 59 to 67% of the land area during the years 1991 to 1994 (6). Metolachlor was used on 54 to 73% of the land, including uses on both corn and soybean, and alachlor use was only 2 to 13%. Other herbicides that had significant usage in Walnut Creek watershed were trifluralin and pendimethalin, which are soil-applied, and the postemergence herbicides acifluorfen, bromoxynil, bentazon, imazethapyr and glyphosate.

Nitrogen (N) applications in Walnut Creek watershed generally ranged between 90 and 140 kg N ha\(^{-1}\), which are fairly similar to statewide N usage.

### Landscape and Hydrology

The Walnut Creek watershed and nearby study sites in central Iowa (near Ames and Kelly, IA) are situated on fields that have a rolling topography with short gentle slopes which often drain into shallow, closed depressions. The dominant Clarion, Niccollet, and Webster soil association (Typic and Aquic Hapludolls and Typic Endoaquolls) has developed on till of the Dows formation deposited during the Wisconsinan glaciation period, 14,000 to 12,500 years before present (6). The Clarion soil tends to occur on the hill tops and side slopes which transition into Niccollet and Webster soils lower in the landscape. The soils in the depressions and lower side slopes tend to have greater organic carbon (C) contents and more alkaline pH than the soils on the upper side slopes and hill tops (7). These soils are relatively rich in organic C and N and are able
to mineralize substantial amounts of N under favorable conditions of temperature and moisture.

The key hydrologic features in this landscape are the lack of a well developed surface drainage network (the pothole topography) and the relatively low hydraulic conductivity of the deeper till, which leads to poor drainage. Groundwater age at the base of the oxidized till ranges from 3 months to 2.1 years (6). The poor natural drainage has been alleviated by an extensive subsurface (tile) drain system that intercepts about 95% of the groundwater recharge (5). The subsurface drainage network accounts for a substantial fraction of the water flow in Walnut Creek. Walnut Creek flows into the South Skunk River, which in turn flows in a southeastern direction emptying into the Mississippi River south of Burlington, IA.

The Northeast Research Farm of Iowa State University, near Nashua, was used to evaluate the effect of farming practices on 0.4 ha plots on Aquic and Typic Hapludolls (Floyd-Kenyon, Readlyn soil association). Each plot featured a central subsurface drain with a system for collecting subsurface drainage water and for measurement of water discharging from each plot (8, 9). A factorial design with crop rotation and tillage treatments was established on replicated plots, with both phases of the corn and soybean rotation present in each year of the experiment.

Three field-scale watersheds ranging from 30 to 60 ha in the loess hills of southwest Iowa, near Treynor, were monitored for a variety of agronomic and water quality parameters. Two watersheds were cropped to continuous corn with disk tillage and the third was cropped to continuous corn with ridge tillage. Median slopes exceeding 4% within the watersheds have led to significant runoff events (10). However the soils are relatively permeable and groundwater recharge has been estimated at approximately 20 cm annually (11). The soils are classified as the Monona, Dow, Ida, and Kennebec series (Typic Hapludolls, Typic Udorthents, and Cumulic Hapludolls) which overlie Wisconsinan loess.

Herbicides in Surface Water and Groundwater

Herbicides in Walnut Creek were measured using a network of eight monitoring sites that sampled water from hydrologically isolated field drains, aggregated field drains, and surface water. Sampling and analysis procedures are described by Jaynes et al (12) and Hatfield et al. (5). Atrazine and metolachlor were commonly detected in stream water sampled at the base of the watershed over the period from 1990 through 1995. Median concentrations of these herbicides in stream water were generally below 1 µg L⁻¹, but concentrations in individual samples exceeded 10 µg L⁻¹ (12). Atrazine concentrations exceeding the MCL were found most frequently in the months of
May, June and July, but even in these months the frequency of exceedence was 10% or less. Metribuzin and alachlor were detected much less frequently, which was probably due to their lower use in the watershed and their shorter persistence in soils and subsoils. At one site in the watershed, surface runoff and subsurface drainage were directly compared and runoff was found to be a minor component to the total herbicide load leaving the field, although surface runoff was a major component of some monthly totals (12). However, mean atrazine concentrations (1992 to 1995) at two subsurface drainage water sampling sites were 0.10 and 0.15 \( \mu \text{g L}^{-1} \), compared to mean concentrations ranging from 0.44 to 0.67 \( \mu \text{g L}^{-1} \) in three stream water stations (12). Assuming that runoff accounts for the difference in concentrations between subsurface drains and the streams, these data indicate the magnitude of the surface runoff contribution. Both subsurface drains and stream hydrographs show responses to storm events and the greatest concentrations of herbicides in stream water are associated with storm events.

Herbicide losses in subsurface drains were addressed in several different MSEA studies. At the Nashua site, replicated plots with individual subsurface drains examined the effects of tillage on herbicide loss, which ranged from 0.002 to 7.3 g ha\(^{-1}\). The losses of atrazine in the continuous corn rotation were greatest in the ridge-till and no-till systems and least in the moldboard plow system and reached the greatest concentrations within the first month after application. Similar results were obtained for cyanazine applied to corn rotated with soybeans. The mass losses of triazine herbicides tended to parallel the drainage of water in these different tillage systems; moldboard plow had the least drainage, with the chisel and ridge intermediate in drainage, and no-till with the greatest (9). The largest annual average concentrations for the crop rotation treatments (excluding non-detects) were 2.5 \( \mu \text{g L}^{-1} \) for alachlor in 1992, 5.7 \( \mu \text{g L}^{-1} \) for atrazine in 1991 and 4.3 \( \mu \text{g L}^{-1} \) for cyanazine in 1991 (13). Within individual tillage systems, alachlor losses (g ha\(^{-1}\)) from the soybean phase of the rotation were nearly equivalent to the losses of triazine herbicides from corn. The magnitude and temporal pattern of atrazine losses from this study was similar to losses at sites near Ames in central Iowa and other Midwestern USA cropping systems (12, 13, 14, 15). Runoff was not a significant route of water movement at the Nashua site.

Later studies at the Nashua site showed that losses of atrazine in tile drainage were reduced by banding the herbicide, which effectively reduces the rate of application by 66% (13). However, in the same study metolochlor leaching was not statistically reduced by banding.

Herbicide leaching to groundwater was evaluated in several ways. In the Walnut Creek watershed a diffuse network of piezometers was installed to sample shallow groundwater at the margins of farmer's fields (designated as wattershed in Table 1). A production field cropped to corn and soybeans in alternate years was used to monitor groundwater using piezometers installed...
within the field (16). In the production field (Table I), the application rate of metribuzin was 82% (420 g ha\(^{-1}\)) of the average atrazine application (510 g ha\(^{-1}\)) at the field site). The average concentration and detection frequency of metribuzin in groundwater were half that of atrazine over four years of monitoring (Table I). Atrazine and metribuzin were detected less frequently in samples from the network of edge of field wells than in the production field (Table I). This result is likely due to differences in the frequency of atrazine and metribuzin use in the fields next to the wells and placement of these wells at the edges of fields. In addition, deep groundwater beneath another production field was monitored for these same herbicides with similar results (6). These extensive studies of herbicide mobility in soil profiles developed on glacial till show that herbicides do leach into shallow groundwater, but much of the percolating groundwater enters the subsurface drainage system, eventually entering the local stream system. The diversion of groundwater into the subsurface drainage network protects deeper groundwater.

Table I. Detection of Atrazine and Metribuzin in Groundwater Beneath a Single Production Field Within the Watershed and Groundwater from Wells Positioned at the Edge of Field.

<table>
<thead>
<tr>
<th></th>
<th>Field (2.6 m)(^{a})</th>
<th>Watershed(^{b}) (1.5-3.0 m)</th>
<th>Watershed(^{b}) (&gt; 4.6 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atrazine</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Concentration (µg L(^{-1}))</td>
<td>0.21</td>
<td>0.16</td>
<td>0.06</td>
</tr>
<tr>
<td>Detection Frequency (%)</td>
<td>26</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>Freq. Exceeding MCL (%)</td>
<td>1.4</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>No. Observations</td>
<td>837</td>
<td>901</td>
<td>636</td>
</tr>
<tr>
<td><strong>Metribuzin</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Concentration (µg L(^{-1}))</td>
<td>0.11</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Detection Frequency (%)(^{c})</td>
<td>13</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>No. Observations</td>
<td>842</td>
<td>901</td>
<td>636</td>
</tr>
</tbody>
</table>

\(^{a}\)Depth of sampling from wells located within a production field with atrazine applied for two years and metribuzin applied for two years.  
\(^{b}\)Depth of sampling from wells positioned adjacent to fields positioned at various points within the watershed.  
\(^{c}\)No MCL is established for metribuzin.  
compared to metribuzin (as described in Table I) appears to be due to greater persistence of atrazine in soils and subsoils \((8, 16, 18)\). In the production field described in Table I, atrazine was detected in 2 to 15% of soil samples below 45 cm depth, including the two years when atrazine was not applied. However, metribuzin was detected in soil only rarely below 30 cm and only in years when it was applied \((16)\).

The pothole topography limits surface runoff to streams, instead routing runoff water to the depressions (potholes), which are the most extensive artificially drained areas of the field. Mitigating these hydrologic factors is the high organic C content of the pothole soils that adsorbs atrazine to a greater extent than the sideslope soils adjacent to the pothole \((7)\). This greater adsorption tends to retard leaching. However, where surface inlets to the drainage line have been installed, runoff is transmitted directly through the drainage line to surface waters. Deep leaching of atrazine past the drainage lines is further retarded by strong atrazine sorption in deeper, permanently saturated, unoxidized till materials \((17)\).

In addition to the extensive research on glaciated landscapes, the Iowa MSEA investigated herbicide movement in two other landscapes. At the confluence of Walnut Creek and the South Skunk River, the creek crosses the alluvial floodplain of the river. At this site, a sandy alluvial aquifer is present beneath the silty floodplain soils. A monitoring study of groundwater at this site found atrazine in 14% of the samples \((9)\). Studies using small diameter piezometers showed that Walnut Creek supplied water to the alluvial aquifer. Concentrations of atrazine, cyanazine, metolachlor and the degradation products deethylatrazine (DEA), deisopropylatrazine (DIA), and the ethanesulfonic acid of alachlor (metabolite ESA) were found in the groundwater at concentrations below 1 \(\mu g\) L\(^{-1}\) \((20)\). Based on the water flux through the streambed and the herbicide concentrations, it was estimated that these herbicides were transported in greater quantities in stream-fed recharge than would be expected from leaching through soil.

The loess hills of southwest Iowa are relatively permeable and atrazine and metolachlor were detected in both the unsaturated zone and in groundwater over a three year period \((21)\). Atrazine was detected in 30% of the groundwater samples and metolachlor in 17%. Atrazine concentrations were generally below the MCL and the median concentrations for both herbicides were less than 1 \(\mu g\) L\(^{-1}\). The atrazine metabolites DEA and DIA were also detected, but less frequently than atrazine.

**Nitrate in Surface Water and Groundwater**

In contrast to the relatively low concentrations of herbicides in stream water, the yearly median nitrate-N concentration exceeded the MCL of 10 mg...
NO$_3$-N L$^{-1}$ for three of the six years in Walnut Creek during the period from 1992 to 1995 (12). NO$_3$-N concentrations in stream water were greatest in the months of May and June. This incidence of NO$_3$-N concentrations exceeding the 10 mg L$^{-1}$ standard is similar to that found on the Des Moines River during the period from 1980 through 1990 (22). The NO$_3$-N concentrations were not greatly affected by storm events, that suggests that overland runoff was not contributing substantial amounts of NO$_3$-N. Nitrate-N loads measured from large drain outlets show that the vast majority of the NO$_3$-N was delivered to Walnut Creek through the subsurface drainage network (12). Losses from the watershed (averaged over the drainage basin) ranged from 4 to 66 kg N ha$^{-1}$. Burkart and James (23) used an estimated nitrogen balance approach to estimate residual N available for leaching over the entire Mississippi Basin. Their analysis suggested that the upper Mississippi Valley, including central Iowa, southern Minnesota, and western Illinois, was the hydrologic basin producing the largest amounts of residual N (>56 kg ha$^{-1}$). While residual N does not necessarily move to stream water or groundwater, their estimates suggested that even modest improvements in N management were likely to have positive impacts. At the watershed scale, the nitrate concentration in stream water was positively correlated with the fraction of land in row crops (24).

Nitrate in tile drainage water results from two immediate sources: nitrate resulting from the mineralization and nitrification of organic N in the soil and the nitrification of ammonia fertilizer. Several lines of evidence suggest that both processes contribute to the nitrate leaching below the root zone. The NO$_3$-N losses in subsurface drainage are similar when fields were cropped to either corn or soybean, even though no N fertilizer is applied to soybean crops (25, 26). Studies with $^{15}$N-labeled fertilizer showed that a larger fraction of fertilizer N enters the organic N pool in the soil than is lost (leached, volatilized, or denitrified) from the system (27), but this organic N can become mineralized in subsequent growing seasons. Nitrate losses were greatest in the Walnut Creek watershed in the period from November to May, when plants were not present (26). Fall application of anhydrous ammonia was the predominant fertilizer application method for corn production.

Concentrations of nitrate in groundwater tended to decline with increased depth below the watertable surface. Mean NO$_3$-N concentrations (1992-1996) in groundwater at the production field in Walnut Creek ranged from 10.3 mg L$^{-1}$ from the 1.5 to 3 m depth to 1.8 mg L$^{-1}$ in wells deeper than 4.6 m depth. Denitrification in deeper, unoxidized till appears to account for this trend (26). Unoxidized till has greater quantities of organic C, which supports elevated rates of microbial denitrification and methanogenesis relative to the oxidized till above it (28, 29). The particulate carbon driving these microbial processes was apparently incorporated into the till during the last glaciation.

Tillage and rotations affected the loss of nitrate in subsurface drainage from the large plot studies at the Nashua site (9, 25). In a study of four tillage
systems cropped with continuous corn, rotated corn, and rotated soybeans, both phases of the rotation (corn or soybeans) were present during the three-year period. The nitrate concentration (annual rotation x tillage treatment means) in drainage water ranged from 0.86 to 65 mg L\(^{-1}\) \(25\). The mass of NO\(_3\)-N lost in drainage water ranged from 0.89 to 107 kg N ha\(^{-1}\). Losses of NO\(_3\)-N from the continuous corn were consistently greater than losses from the corn-soybean rotation regardless of the tillage system. The effect of tillage on losses of NO\(_3\)-N from the rotated corn and soybeans were relatively minor (Figure 2).

Figure 2. Relative loss of NO\(_3\)-N from moldboard plow (MP), chisel plow (CP), ridge-till (RT) and no-till (NT) cropped to rotated corn (-C) or soybean (-S). Relative loss for each treatment is expressed as a percentage of the mean annual NO\(_3\)-N loss for all treatments (crop-tillage combinations). Mean annual losses were 40.2 kg N ha\(^{-1}\) in 1990, 35.7 kg N ha\(^{-1}\) in 1991, and 9.8 kg N ha\(^{-1}\) in 1992. (Adapted from Reference 9. Copyright 1997, American Society of Agronomy.)

To eliminate the year-to-year differences in NO\(_3\)-N losses, which were largely driven by precipitation patterns, the data in Figure 2 show the NO\(_3\)-N losses from the individual crop-tillage treatments expressed as a percentage of NO\(_3\)-N masses lost in tile drainage averaged across all treatments for that year. Thus, crop-tillage treatments that have greater than average losses exceed 100% while treatments with less than average losses are below 100%. Nitrate-N loss
was slightly greater from the moldboard plow and chisel plow tillage than from the ridge-till and no-till systems and losses were similar from both the corn and soybean phases of the rotation.

As in Walnut Creek, significant amounts of NO$_3$-N were exported in drainage water from the Nashua plots at times when plant uptake is absent or minimal, principally late fall through spring (30). The magnitude of these seasonal losses were highly dependent upon precipitation and temperature variations, particularly in the late fall, winter and spring seasons. This variability was illustrated in a later study at the Nashua site, where soil profile mineral nitrogen (residual N) tended to increase over winter, from 4.7 to 13 kg N ha$^{-1}$ following corn, compared to changes ranging from an 8.5 kg N ha$^{-1}$ loss to a 6.5 kg ha$^{-1}$ increase in N following soybean (31).

Nitrate-N balance and movement was also evaluated in ridge-till and disk tilled continuous corn at the Iowa MSEA site in southwest Iowa. In this topography, water that infiltrates through the hill-top and side-slope soils emerges later as stream baseflow at the foot of the watershed. Nitrate was often present in baseflow concentrations exceeding 10 mg L$^{-1}$ in the watershed managed with ridge-tillage which was monitored extensively (32, 33, 34). This was consistent with the measurement of high nitrate concentrations in both the vadose zone and the saturated zone, with some concentrations exceeding 50 mg N L$^{-1}$ in the same ridge-tilled watershed (33, 34). In the ridge-till watershed, NO$_3$-N leaching loss accounted for 16% of the cumulative fertilizer N input from 1968 to 1991, with NO$_3$-N and NH$_4$-N loss in surface runoff accounting for only 1% of the fertilizer N input (33). In comparison, grain removal accounted for 50% of the fertilizer N input to the system and 31% of the N was either in the soil or was lost through volatilization or denitrification. Clearly, the magnitude of NO$_3$-N leaching (approximately 2.5 to 20 kg N ha$^{-1}$ annually) was partly due to excessive fertilizer N application (170 to 230 kg N ha$^{-1}$) in relation to crop removal (32, 35). Residual soil NO$_3$-N in the root zone after harvest accounted for between 117 and 246 kg N ha$^{-1}$ in both tillage systems. Nitrate concentrations in stream base flow averaged two to three times more in the ridge-till watershed than in the conventional tillage watershed, despite similar N fertilizer applications (32). This combined with greater base flow from the ridge-till watershed results in greater NO$_3$-N loss from this system, but with much less sediment loss (11, 32).

Conclusions, Current Research, and Outlook

The Iowa MSEA project examined the impact of current farming systems on the quality of surface water and groundwater. The research shows that the environmental impact was a product of the climate, soils, geology and farming practices. The glaciated parts of Iowa that have extensive subsurface drainage
are represented by research at the sites near Ames and Nashua and the results from these sites were reasonably consistent. The combination of subsurface drainage, thick till deposits and the slow flux of water through these sediments resulted in little actual or potential contamination of deep groundwater. Herbicide retention (sorption) and degradation processes are sufficient to prevent more extensive contamination. Shallow groundwater is contaminated with herbicides and nitrate which are carried in subsurface drainage to the stream network. Surface waters carried measurable herbicide residues, but the concentrations only occasionally exceeded MCL levels, usually in response to runoff events. The development of newer, low application rate herbicides is changing the spectrum of chemical usage. Although these chemicals were detectable in surface water and groundwater, concentrations were well below health advisory levels (36).

Nitrate concentrations in stream waters regularly exceed the MCL and contribute to N concentrations in the Mississippi River. Excess nitrate in the Des Moines and Raccoon Rivers caused the city of Des Moines to construct and operate a large and expensive nitrate removal plant (37). Both soil and fertilizer N contribute to the N load in surface water, as do both soybean and corn crops. Significant amounts of fertilizer N enter the soil organic matter pool through decomposition of plant residues and microbial immobilization processes. The release of soil organic N through the N mineralization process was highly dependent upon seasonal weather, which can lead to significant N losses during the non-growing season.

The Iowa MSEA results clearly identified nitrate transport from individual fields and agricultural watersheds as the greatest water quality issue. The impact of the Iowa MSEA research was most immediate in the development of follow-up projects designed to mitigate the nitrate problem of excessive nitrate loss. These approaches to reducing nitrate losses on tile-drained lands include the timing and rates of fertilizer application, cover crops, crop rotations, riparian buffers and wetlands (38, 39). Clearly, accurate and timely prediction of nitrogen mineralized from soil would allow fertilizer N applications to be adjusted to account for soil N. In addition, seasonal weather patterns also affect crop demand for nitrogen. Research performed subsequent to the MSEA shows that split applications of fertilizer N with soil testing (LSNT, late spring nitrate test) can impact water quality at the stream scale (40). In this study LSNT-guided application of fertilizer N to one sub-basin of Walnut Creek appears to have started a trend towards lower NO3-N concentrations in stream water. After two years without effect, the LSNT management has resulted in a 30% reduction in NO3-N concentration in the third year. A similar result has been also obtained in the fourth year (D. Dinnes, personal communication).

Other post-MSEA research has examined the use of cover crops, such as oats (Avena sativa L.) or rye (Secale cereale L.) planted into the maturing corn or soybean crop provides active plant uptake of nitrate over a greater period in
fall and spring. In large lysimeters, cover crops were able to reduce nitrate leaching losses from soil (41). Similar field studies show that cover crops can be established under Midwestern conditions and that they reduce nitrate leaching (42). Adoption of cover crops by producers may be limited by seed costs and by the difficulty in establishing a stand following a corn crop, which tends to be harvested later in the year than the soybean crop.

The Iowa MSEA research was a component of the larger multi-state MSEA program. Different impacts on water quality in were observed in different regions that were related to soils, hydrogeology, and agricultural management for both herbicides and nitrogen (48). For instance, there is considerable similarity between the findings of the Mississippi Delta MSEA (described elsewhere in these symposium proceedings) and results from the Iowa and other parts of the Midwest concerning the importance of surface runoff in the transport of pesticides to surface waters. Best management practices (BMP) such as riparian buffers, erosion control practices and cover crops appear to be effective throughout the Mississippi River drainage basin. In contrast, the dynamics of nitrate pollution are substantially different in the Mississippi Delta than in Iowa. While the upper Mississippi River basin streams have nitrate seasonal nitrate concentrations well in excess of 10 mg NO₃-N L⁻¹, the local surface waters of the Mississippi Delta rarely reached that level (43, 44). Smith et al. (45) speculated that riparian zone denitrification was a primary cause of low nitrate concentrations in surface water. Fewer subsurface drains in the Mississippi Delta may also contribute to this difference.

While the effect of soils, climate and geology on contamination of surface water and groundwater were not entirely unexpected, study of the interaction of these factors with agricultural management reveals the complexity of agricultural water quality issues. Certainly, the importance of understanding the factors that control pollutant movement at field and watershed scales was demonstrated. While research has demonstrated that over application of nutrients will lead to water quality problems, the inability to predict plant nutrient demand in concert with accurate, timely assessment of soil nutrient supply limits our ability to make precise fertilizer application recommendations. In addition to the practices described above, off-site N management practices that are currently receiving extensive evaluations include, reconstructed wetlands, tile-line denitrification walls, and riparian buffers. The implementation of the in-field and off-site practices are likely to be driven by economic and regulatory forces. The linkage of Midwestern agricultural pollution with the hypoxia condition in the Gulf of Mexico, with advancing eutrophic conditions in streams and reservoirs, and antibiotics from animal feeding operations (46) underscore the importance of developing production systems that are more efficient in retention of nutrients and organic chemicals.
References


