IN-FIELD NUTRIENT AVAILABLITY AND BALANCES, AND POTENTIAL IMPLICATIONS ON MANAGEMENT SYSTEMS TO REDUCE LOSSES

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Introduction

Losses of the major nutrients, nitrogen (N) and phosphorus (P), from agricultural lands to water resources cause water quality concerns relative to the health of both humans and aquatic systems, and impair uses. Currently, work is underway by the State, with guidance from the U.S. EPA, to develop water quality criteria for N and P to be protective of our lakes and streams.

Right now it is not clear how other cost and benefit factors such as production economics, sustainability and carbon sequestration, and grain quality will be taken into account in the development of the criteria. Because of current water use impairments, and the expectation that the criteria, when developed and implemented, will add to the list of impairments, there is an immediate and continuing need to reduce nutrient losses from agricultural lands.

Knowledge of the factors that affect the fate and transport of nutrients is critical in designing the right practices/systems to implement to effectively and efficiently reduce nutrient losses (i.e. to do the “right thing”). However, it is probably equally as important, if not more so, to use that knowledge to not do the “wrong thing.” Part of the discussion in choosing and implementing improved practices/systems, is predicting and measuring the water quality changes needed to meet the outcomes desired (assuming we know what we want and how much nutrient reduction is needed to get there). The evaluation or assessment of practices/systems can range from being “directionally correct,” to a strictly quantified reduction that is needed in a “performance-based” approach. While the “performance-based” approach worked well for point-source pollution, and is appealing because performance (i.e. meeting water quality criteria) is what is sought, and it gives some flexibility to producers in the way of choice of practices/systems to use, there are some issues/concerns that need to be overcome. The main four are: 1) the number of choices of practices/systems available to producers is fairly limited based on current economic constraints, 2) being able to accurately predict the nutrient reductions (i.e. outcomes) expected for practices/systems under a standard or hypothetical set of homogenous conditions is difficult, 3) the highly variable nature of weather (in time and space), and the highly variable spatial nature of soils and their properties that affect outcomes, makes prediction for realistic field/watershed conditions even more difficult, and 4) the high cost and effort needed to accurately monitor what the outcomes were, especially for large numbers of fields or watersheds is prohibitive. It would seem that at least two things needed to overcome the last three issues are nutrient criteria that allow some exceedence (based on frequency and duration of exceedence, as recommended by the NRI), and an acceptable mathematical modeling approach to qualify outcomes on a temporal basis (although some monitoring would still be needed to confirm water quality improvements).

In the following sections, hydrology and transport mechanisms, as well as nutrient availability and balances, will be discussed relative to potential nutrient losses. Two general landscapes common to Iowa: nearly flat, tile-drained areas; and rolling hills, with well-developed surface drainage will then be briefly discussed relative to the resultant impacts on the need for and choice of management practices/systems to reduce losses.

Hydrology/Transport Mechanisms

Probably the most important hydrologic factor affecting nutrient losses from agricultural lands is the highly variable, both temporally and spatially, soil water infiltration rate. It is this rate, in conjunction with rainfall intensity (both of which can change by the minute, and which makes measurement and prediction so difficult), that determines the volume and timing of surface runoff; and by subtraction the volumes of water that enters the soil to be stored for later evapotranspiration or lost from the root zone via percolation (either to groundwater or back to surface water resources through natural or artificial subsurface drainage). In general, with the exception of possibly more nitrate-nitrogen (NO_3-N) leaching, the higher the infiltration rate and more the infiltration, the lower the field losses of all other nutrient/forms.

As shown in Figure 1, the three transport mechanisms, or nutrient carriers, are made up of two for surface runoff, with nutrients either being dissolved in the runoff water or being associated with the eroded soil/sediment being carried in the surface runoff; and one for subsurface drainage, with nutrients being dissolved in the leaching water. Nutrient losses, as a product of concentrations and masses of carriers, can be reduced by the reduction of either or both of those factors.

Infiltration rate can play a role in concentrations as well as in the masses of carriers. As shown in Figure 1, there is a thin “mixing zone” at the soil surface that interacts with and releases sediment and nutrients to rainfall and runoff water. The volume of rainfall that infiltrates before runoff begins (at the time when the rainfall rate exceeds the infiltration rate), as well as the soil adsorption properties of the nutrient form of interest, affects the amount of a particular nutrient form remaining in the “mixing zone” potentially “available” to be lost. The more infiltration that takes place before runoff begins, the lower the nutrient concentrations in runoff water (and to a lesser degree in sediment).

Nutrient Forms/Availability

Table 1 provides a set of numbers for the important nutrient forms for N and P relating their concentrations in the soil and water of a field (at or near equilibrium) to expected concentrations in the three carriers, surface runoff water, sediment, and subsurface drainage. Although these numbers in reality are highly variable, both temporally and spatially, for simplicity of comparison, a single set of numbers are given to represent the annual averages for a row-crop situation in much of Iowa.

As shown for N in the soil water, NO_3-N dominates over ammonium-nitrogen (NH_4-N); while in the solid soil itself, organic-N dominates. When comparing what is in the soil water with what is in runoff water, the stronger adsorption of NH_4-N compared to NO_3-N (K of 40 versus 0) “traps” the NH_4-N nearer the soil surface so the reduction is less for NH_4-N (part of the reduction between concentrations in soil water at equilibrium, and what is in runoff, is due to dilution as well as incomplete mixing of rainfall-runoff with the surface soil during runoff). On the other hand, that same adsorption is what causes the relative concentrations in subsurface drainage, both relative to what is in soil water, and between NH_4-N and NO_3-N, to be lower for NH_4-N. The ratios of NH_4-N and organic-N concentrations for sediment compared to their respective values for in-place soil are over unity (shown as a single value of 1.33; but this factor, called an "enrichment ratio," generally ranges from about 1.1 to 2.5) which is due to the selective erosion process where the more chemically active smaller and less dense (with greater organic matter content) soil particles are preferentially transported. The "K" values, or adsorption coefficients, shown are calculated as the ratio of nutrient concentration in sediment over that in surface runoff water (organic-N in runoff water is usually less than 2 mg/L).

As shown for P in soil water, and in surface runoff and subsurface drainage, PO_4-P (inorganic or molybdenum-reactive-P) generally makes up more than 60% of the total soluble P; while in the soil, total (organic plus inorganic) P dominates what is classified as plant "available" P determined by one of several soil P tests (in this case a Bray-1 or Mehlich-3 extractant). As with NH_4-N, PO_4-P is somewhat trapped on the soil surface, so runoff concentrations may only be reduced three fold over that in soil water, but concentrations are much lower in subsurface drainage because of adsorption/precipitation of PO_4-P in P-deficient subsoils. As with N, P concentrations in sediment are greater than the in-place soil because of the selective erosion process. Given the very high K value (2700) for total P, and realizing the ratio of the mass of surface runoff water to sediment can be as small as 100 for some rainfall-runoff events, P loss for row-cropped fields is often dominated by that lost with sediment (depending on the degree of erosion).

Nutrient Amounts/Balances

Table 2 shows the N inputs and outputs for corn and soybean. Per the factors used in the state nutrient balance, for a 3% organic matter soil, there would be 60 lb N/ac mineralized (but also immobilized). The fertilizer input was assumed to be 147 lb N/ac, based on sales in 2000 (survey data sometimes indicate a lower rate; from the 2002 survey, the state average on corn was estimated to be 122 lb N/ac, with 94% of the corn acres treated; Iowa Ag Statistics, 2003). It was assumed, in a corn-soybean rotation, the manure generated in the state (minus that directly deposited to pasture land, an amount that would be equivalent to 5 lb N/acre on corn, and volatilization losses) and available to be used would all be applied to corn, giving a state average of roughly 36 lb N/ac. Per the factors used in the state nutrient budget, it was assumed there would be 20 lb N/ac wet deposition and 14 lb N/ac dry deposition, totally 34 lb N/ac. Therefore, total inputs on corn would equal 277 lb N/ac.

On the output side, in addition to immobilization due to crop uptake and storage in roots and stover, l65 bu corn/ac at 0.72 lb N/bu would remove 120 lb N/ac. Because of the amount and availability of NO_3-N (i.e. lack of adsorption) in the soil versus NH_4-N, it is assumed all the N taken up by the corn crop is NO_3-N. And again per the factors used in the state nutrient budget it is estimated that there would be 35 lb N/ac denitrification and NH_3-N volatilization of 25 lb N/ac.

Assuming 4.45 inches of surface runoff and 4.45 inches of subsurface drainage each year (4.45" of water over an acre equals 1,000,000 lb), the concentrations in mg/L given in Table 1 also correspond to lb/ac losses. Under these conditions, it is obvious that NO_3-N leaching losses dominate. For this assessment, losses with sediment were not considered, in part because the source, soil organic N, has evolved over many centuries (however, 5 tons/ac erosion would result in a 20 lb N/ac loss). The overall balance for this example is inputs of 277 lb/ac minus outputs of 260 lb/ac equals +17 lb/ac; a slight excess.

For soybean, the major differences from corn are essentially no fertilizer N input, but N fixation as a legume, is estimated at 100 lb/ac (2 lb/bu of soybean produced). With removal by grain of 168 lb/ac, denitrification of 11 lb/ac, and volatilization and losses to water resources equal those for corn, there is a -89 lb N/ac difference between inputs and outputs. Averaged over the two-year corn-soybean rotation, the difference would be -36 lb N/ac.

Therefore, if producers were to reduce their N application rates on corn significantly below 125 lb N/ac and in rotation with soybean (the rotation that most row-crop producers are now using), there would be concerns for sustainability, decreased organic matter, and carbon sequestration. Grain quality in the way of protein content would likely also go down, particularly if the decrease below 125 lb N/ac was on fields not receiving the average of 36 lb N/ac manure shown in Table 2.

Table 3 shows the P inputs and outputs for corn and soybean. The budget as shown is much simpler than for N with only fertilizer and manure inputs. For the corn-soybean rotation it is logical to apply manure before corn to supply the N needed, and generally there is enough P in the manure to meet the soybean needs the following year. Fertilizer use records also show that it is common to put enough P fertilizer down in the corn year to cover the two-year rotation. Thus the difference between inputs and outputs is positive (8.6 lb P/ac) in the corn year, but negative in the soybean year (-16.0 lb P/ac). The average over the two-year corn-soybean rotation is -3.7 lb P/ac.

Management Practices/Systems

In discussion of nutrient losses and practices/systems to reduce them, the term “excess nutrient” is often used with the implication that if there were no excess nutrients, there would be no losses. There are two problems with applying that logic to Iowa row-crop agriculture; one, under the conditions and assumptions of the examples given for the corn-soybean rotation, there are no “excess nutrients,” and two, in order that sufficient nutrients are available to the plants to obtain economic optimum crop yields, nutrients must be present in significant amounts during the growing season, and therefore are susceptible to loss with rainfall-runoff and subsurface drainage events that can and do happen at any time.

Corn N needs can be used as an example, where between grain, roots, and stover, at least 180 lb N/ac (and probably more) need to be taken up with about 18 inches of transpiring water (about 4 million lb/ac); therefore, the ratio of NO_3-N to water is 45 mg/L. Even if only half the N was taken up passively with water, the average concentration in soil water available to corn roots during the growing season would have to be over 22 mg/L to obtain economically viable yields.

Management practices/systems for the nearly flat, tile-drained areas of Iowa need to be more focused on N because of NO_3-N leaching losses (see Baker, 2001, for a detailed discussion of the potential and limitations of management practices/systems to reduce N losses). In general, N application rate is considered first; however, unlike theories that suggest losses should be decreased by a percentage greater than the percentage reduction in rate, the data do not show that. For example, reducing the N rate from 125 to 100 lb N/ac would likely at best give a 20% reduction in NO_3-N leaching loss. One reason is the large amount of N that is mineralized from Iowa's fertile soils; two data sets illustrate this: one, even with no N applied to a corn-soybean rotation over a five-year period, the average NO_3-N concentration in subsurface drainage was over 5 mg/L; and two, in a study where alfalfa was to be grown, poor stand establishment conditions resulted in monitored plots being fallow over a growing season. At the end of that time, NO_3-N concentrations from the fallow plots exceeded those of corn plots fertilized with 200 lb N/ac.

Although logic would say that timing of N applications should be critical to use efficiency and NO_3-N leaching losses, fall applications do not always show decreased yields and increased leaching losses, and when increased losses are measured, they are usually less than 20% greater than for a spring application. Therefore if corn yields or other measures indicate that most of the N applied in the fall is missing, other processes such as denitrification or volatilization must be significant factors.

Improved methods of N application have been considered, in particular, placing N in the soil in a manner that reduces the flow of water through the zone of application. Although in principal this should reduce NO_3-N leaching losses, on a field-scale, application with a prototype applicator has to date only given mixed results.

Tillage can be a factor in NO_3-N leaching, with generally lower NO_3-N concentrations for conservation tillage, particularly no-till (although there is the potential for increased infiltration and leaching water volumes to negate the lower concentrations with conservation tillage). The question of whether fall tillage enhances soil N mineralization and NO_3-N leaching is not yet resolved.

Management practices/systems for rolling hills, with well-developed surface drainage, need to be more focused on P because of greater potential surface runoff volumes and sediment losses. The Iowa P index addresses this issue (see Mallarino et al., 2002 for a detailed discussion of the factors that go into the P index). In general, P losses are dictated by the available P level of the soil, the rates and methods of P application, the susceptibility of the soil/field to erosion, and the landscape and location of the field in that landscape in relation to a stream or lake.

Limiting P application rates to those that do not increase soil P levels above the optimum range (to high or very high) and soil incorporation of applied P are two ways to reduce runoff losses, especially soluble P losses. Since eroded soils are estimated to carry over 1 lb P per ton of soil lost, erosion control can be critical to reducing P transport to water resources.

Given that the P index provides a long-term estimate of the potential P transport to a water resource, it is noteworthy that the current breakpoint between "low" and "medium" for the index is 2 lb P/ac/yr. If average streamflow is about 9 inches (2 million lb/year), this potential loss would represent an average concentration of 1000 μg P/L, well above the guideline criteria.

In summary, current technology in the way of in-field best management practices/systems is limited in terms of how much reduction in nutrient losses can be achieved for row-crops. Offsite practices such as wetlands (for reduction in NO_3-N transport) and vegetated filter/buffer strips (for reduction in sediment and sediment-P transport) have considerable potential to add to in-field practices/systems. And finally alternative cropping, in the way of small grains and more and longer sod-based rotations (including cover crops), if more economically feasible, could have a major impact on reducing nutrient losses. The questions now are how much reduction is necessary, and who should pay for the implementation of alternative practices when they do not pay for themselves.

References

Baker, J.L. 2001. Limitations of improved nitrogen management to reduce nitrate leaching and increase use efficiency. In: Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection; Proceedings of the 2nd International Nitrogen Conference on Science and Policy. The Scientific World 1(S2), 10-16.

Iowa Ag Statistics. 2003. Compiled by Iowa Agricultural Statistics in cooperation with USDA-NASS and the Iowa Farm Bureau; Des Moines, IA; 137 p.

Mallarino, A.P., B.A. Stewart, J.L. Baker, J.A. Downing, and J.E. Sawyer. 2002. Phosphorus indexing for cropland: Overview and basic concepts. J. Soil Water Cons. 57:440-447.

Table 1. Nutrient forms/availability ("K")[1]

Nitrogen (N)

soluble

	soil[2] water	surface runoff	subsurface drainage
	mg/L		
NH_4-N	1.0	0.5	0.1
NO_3-N	50.0	4.0	15.0

solid/adsorbed

	soil[2]	sediment	"K"
	ppm		L/kg
NH_4-N	15	20	40
NO_3-N	0	0	0
Org-N	1500	2000	• 1000

Phosphorus (P)

soluble

	soil[2]water	surface runoff	subsurface drainage
	mg/L		
PO_4-P	0.6	0.2	0.050
total-P	0.9	0.3	0.075

solid/adsorbed

	soil[2]	sediment	"K"
	ppm		L/kg
available-P	30	40	200
total-P	600	800	2700

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[1] "K," the adsorption coefficient for each nutrient form, affects "availability"; and is calculated as concentration in sediment divided by concentration in runoff water.

[2] Top 12 inches of soil; 3% organic matter.

Table 2. Nitrogen amounts/balance

corn inputs

	soil mineral.	fertilizer	manure	deposition
	lb/ac			
N	60	147	36	34

corn outputs

	immobile.	grain	denitrif.	volatile.	surface runoff	subsurface drainage
	lb/ac					
NH_4-N	-	-	-	25	0.5	0.1
NO_3-N	60	120	35	-	4.0	15.0

inputs - outputs = 277 - 260 = +17 lb/ac

soybean inputs

	soil mineral.	fertilizer	manure	deposition	fixed
	lb/ac				
N	60	1	-	34	100

soybean outputs

	immobile.	grain	denitrif.	volatile.	surface runoff	subsurface drainage
	lb/ac					
NH_4-N	-	-	-	25	0.5	0.1
NO_3-N	60	168	11	-	4.0	15.0

inputs - outputs = 195 - 284 = -89

Overall (corn/soybean rotation): -36 lb N/ac/yr

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[1] Corn and soybean yields of 165 and 50 bu/ac, respectively.

Table 3. Phosphorus amounts/balance

corn inputs

fertilizer	manure
lb/ac	
19.3	16.8

corn[1] outputs

grain	surface runoff	subsurface drainage
lb/ac		
27.1	0.3	0.1

inputs – outputs = 36.1 – 27.5 = +8.6

soybean inputs

fertilizer	manure
lb/ac	
1.9	-

soybean[2] outputs

grain	surface runoff	subsurface drainage
lb/ac		
17.5	0.3	0.1

inputs – outputs = 1.9 – 17.9 = -16.0

OVERALL (corn/soybean rotation): - 3.7 1b P/ac/yr

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[1] Corn and soybean yields of 165 and 50 bu/ac, respectively.

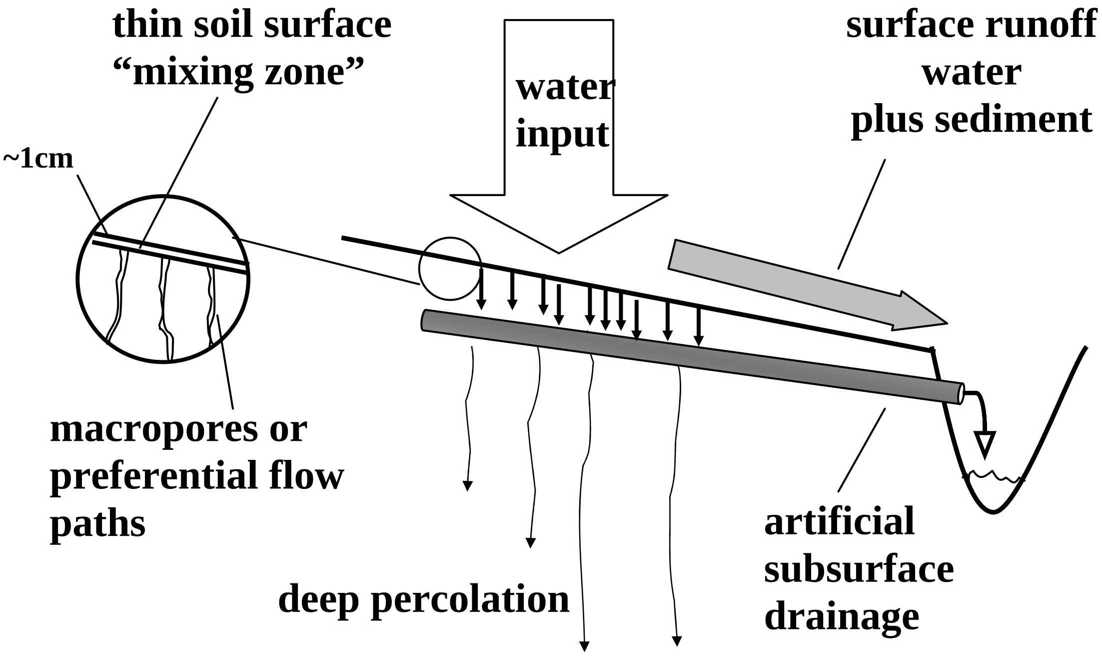

Figure 1. Schematic of transport processes.