Integrating principles of nitrogen dynamics in a method to estimate leachable nitrogen under agricultural systems

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Abstract Surplus nitrogen (N) in ground and surface water is of concern in intensive agricultural regions. Surplus N leaches during lengthy periods where annual crop systems are used in temperate regions. This paper presents a model to estimate the surplus N available for leaching to ground water beneath agricultural systems and applies the model to watersheds in an intensive maize and soybean production system. The model utilizes commonly available georeferenced data on soils, crops, and livestock, making it applicable to watersheds in many regions. The model links stocks of N in soil, crops, livestock, fertilizer and the atmosphere. Nitrogen flow centers on exchange between the soil N stocks. Nitrogen mineralization rates are defined for three soil organic matter pools, crop residue, and manure based on carbon:N ratios. Nitrogen exports from the system are harvested crops, livestock and losses to the atmosphere. Application of the model in 26 Iowa watersheds finds surpluses of 18 to 43 kg-N/ha. Surpluses exceeded measured annual nitrate-N loads in regional streams by amounts equivalent to denitrification rates in groundwater. Deficits in soil N were sufficiently small to suggest that the system is in equilibrium with soils of the region.

Keywords Agriculture; leaching; nitrate; soil

Introduction

Agricultural systems rich in soluble nitrogen (N) have been shown to contaminate groundwater (Nolan *et al.*, 1997; Burkart and Stoner, 2002) and streams (Schilling and Libra, 2000; Howarth *et al.*, 2002), and contribute to hypoxic zones in coastal waters (Turner and Rabalais, 1994). Increased use of N fertilizer in the United States was cited as the prime contributor to coastal eutrophication (National Resource Council, 2000). Solutions to N contamination of aquatic systems by agriculture require a comprehensive representation of N dynamics (Goolsby *et al.*, 1999; Burkart and James, 1999). This paper presents an agricultural-N budget applied to representative watersheds in Iowa, a state that is among the most intensively cropped in the United States.

Methods and data sources

Four GIS raster databases were used to calculate spatially explicit N budgets at a 30-m resolution for analysis at cell and watershed scales. Crop data for 2001 in Iowa were obtained from the National Agricultural Statistics Service (USDA, 2002). Soils and crop-yield data were from the Iowa Soil Properties and Interpretations Database (ISPAID, ISU, 2004). Streams and watersheds were derived from the National Elevation Dataset (USGS, 1999) using methods devised by Tarboton (2002, http://moose.cee.usu.edu/taudem/taudem.html). Inorganic fertilizer use data for 1997, the most recent Census of Agriculture year, were from the US Geological Survey (Barbara C. Ruddy, written communication, 2001). Livestock-production data were from the Census of Agriculture (US Department of

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Commerce, 2000). Climatic data were from the Iowa Environmental Mesonet (http://mesonet.agron.iastate.edu/agclimate/index.php).

Nitrogen budget

The N budget links soil, crop, livestock, fertilizer and atmospheric stocks to estimate surplus N (Figure 1). External flows include fertilizer and atmospheric exchanges such as volatilization, deposition, denitrification, and fixation. The model for flow among stocks is centered on exchange with soil inorganic N resulting in estimates of accumulated surplus or deficit in soil inorganic N.

Inorganic soil nitrogen

Inorganic soil N is soluble and is dominantly nitrate (NO_3) and ammonium (NH_4). NH_4 is readily nitrified to NO_3 under aerobic conditions; so inorganic N not used by crops is leachable as NO_3. Surplus N remains after removal by crop uptake, volatilization and denitrification. Inputs include inorganic fertilizer, atmospheric deposition of inorganic N and mineralized fractions of soil organic matter (SOM), crop residue and manure. Manure and residue N that is not mineralized is immobilized as SOM.

Inorganic fertilizer sources include ammonia, which dominates, and applications of urea, ammonium nitrate, and ammonium sulfate. Adjustments were made to N-fertilizer applications for gaseous losses during application, primarily as NH_4 (Table 1, modified from Meisinger and Randall, 1991). The maize application rate (average: 162 kg/ha) was calculated by subtracting N applied to soybean (5 kg/ha) and oat (45 kg/ha) from each county total and dividing by the area in maize. Application of N to soybean is a by-product of diammonium or monoammonium phosphate.

Redeposition of locally derived atmospheric ammonia and ammonium (NHx) represents the return of local atmospheric emissions to the soil. Local emissions include volatilized manure, inorganic fertilizer, mineralized soil organic matter, and emissions during crop senescence, all of which are described below. Measures of redeposition are not available in this region, but a review of NHx dynamics and movement (Ferm, 1998) showed 50% of the annual volatilized NH_4 was deposited within 50 km of the source. Farther deposition was halved every 400 km. Redeposition of locally derived NHx was simplified to 75% of the local emissions assuming emissions were similar within a 400 km radius.

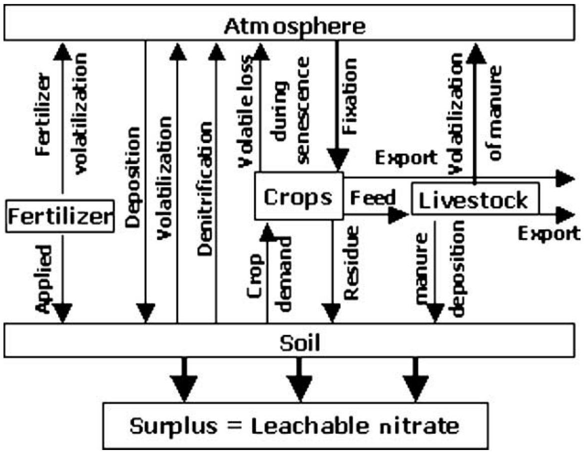

Figure 1 Stocks and flows in N budget

Table 1 N-fertilizer lost on application

Fertilizer type	Soil pH ≥ 7.0			Soil pH < 7.0		
	Urea & N solutions	Ammonium Nitrate	Anhydrous ammonia	Urea & N solutions	Ammonium Nitrate	Anhydrous ammonia
N lost (%)	7.5	7.5	1	2	0	0

Mineralization of SOM was estimated by applying mineralization rates (Table 2) to soil and climatic data. Mineralization is a biological transformation of organic N into inorganic forms. Annually, 5% of mineralized SOM is lost to the atmosphere (Parton *et al.*, 1987). SOM constitutes the principal stock in which N is stored and exchanged. Consequently, SOM is a major source of mobile or inorganic N. SOM is partitioned into three pools (Jenkinson and Raynor, 1977; Van Veen and Paul, 1981). The distribution of N among these pools was calculated from carbon content and C:N ratios in each pool (Parton *et al.*, 1987) similar to those incorporated in the CENTURY model (Parton *et al.*, 1994). Each pool has a residence-time domain and mineralization rate constant determined by the microbial availability of constituent organic compounds (Table 2). The SOM in the upper 18 cm of soils was used to estimate the mass in each pool using the fractions shown in Table 2.

Mineralization varies with temperature and moisture that regulate micro-organism activity. Mineralization rates were modified using the concepts of Jenkinson (1990) and Van Veen and Paul (1981) (Eq. 1).

$$\mathrm{M_{om}} = (1 - \mathrm{e}^{-\mathrm{kt}}) * \mathrm{SOM} * T * W, \tag{1}$$

where: $\mathrm{M_{om}}$ = mass of mineralized N (kg/ha/yr); k = mineralization rate constant (1/yr); t = time (yr); SOM = soil organic matter (kg/ha); T = temperature stress factor; and W = water stress factor. Mineralization rates double with each 10 °C increase in soil temperature to a maximum near 30 °C (Jenkinson, 1990; Van Veen and Paul, 1981). Temperature was accounted for using air temperature as a proxy for soil temperatures (Eq. 2).

$$T = 47.9/(1 + \mathrm{e}^{106/(\mathrm{MAT}+18.3)})(\mathrm{MAT}) \tag{2}$$

where MAT = mean annual temp (°C). Nitrogen mineralization is maximum when soil moisture is near field capacity (Jenkinson, 1990) and W is 1.0. Prolonged saturation results in anoxia, limiting mineralization. Moisture below the wilting point reduces microbial activity and mineralization rates. Maximum mineralization rates operate under soil-moisture deficits producing water tension as small as -100 kPa (Jenkinson, 1990; Linn and Doran, 1984; Van Veen and Paul, 1981). Midwest conditions approximate field capacity during the non-growing season and average growing-season soil-water tension is $\geqslant -100$ kPa except during rare, very dry years (Baker *et al.*, 1979). Soil water content was assumed to support maximum mineralization rates and the water stress factor (W) was set to 1.0.

Table 2 Carbon and nitrogen mass and fractions in soil organic matter

Soil organic matter (SOM) pool	Carbon (Mg/ha)[1]	C:N[2]	N (kg/ha)	Fraction of total soil N (%)	Residence time (yr)[2]	Mineralization rate constant (1/yr)
Active (ASOM)	0.28	8	35	1.6	1.5	67
Slow (SSOM)	11.3	11	1,027	47.3	25	4
Passive (PSOM)	12.2	11	1,109	51.1	1,000	0.001

[1] Jenkinson and Rayner, 1977; [2] Parton *et al.*, 1987

Mineralization of crop residue was estimated by partitioning residues (Table 3) into the active soil organic matter (ASOM) and slow soil organic matter (SSOM). Residue mineralization rates vary by crop type and are related to C:N ratios. Crop residues with large C:N ratios mineralize more slowly and those with small C:N ratios more rapidly (Parr and Papendick, 1978). Mineralization rates for legume residues are consistently larger than those for other crops. Soybean residue mineralizes at rates approximately 1.5 times that of non-legumes (Buyanovsky and Wagner, 1997). An approximation of this difference allocates 100% of legume residue to the ASOM, 70% of non-legume residue to ASOM and 30% to SSOM. Mineralized N is calculated using Eq. 1. The remaining organic N from residues is immobilized in ASOM or SSOM.

Mineralized manure-N was calculated using county livestock inventory data (US Department of Commerce, 2000) and estimates of the N content of manure by livestock class (Lander *et al.*, 1998). Values for excreted N were adjusted for volatilization of NH_x and amine during storage (Lander *et al.*, 1998; Midwest Planning Service, 1985) and application (Schepers and Mosier, 1991). Fractions of net manure-N applied were mineralized (Table 4) or immobilized in the SSOM (Schepers and Mosier, 1991). Adjusted values were distributed uniformly to all 30-m cells where maize was grown.

Crop nitrogen

The stock of N associated with crops requires inputs from fixation and soil inorganic N to balance removal as harvest, crop residue, and gases lost during senescence. Inorganic soil N is derived from inorganic fertilizer, atmospheric deposition, and mineralized fractions of soil organic matter, crop residue, and manure.

Symbiotic fixation converts atmospheric N_2 into plant tissue N through bacteria in legume root nodules. The estimate of annual N fixed by alfalfa was 52% of the N yield (Heichel *et al.*, 1984). The fixation rate used for soybean plant mass was 56% (Patterson and LaRue, 1983). The fixation rate used for pasture cells and legume hay was 70%, an average of values reported by Heichel and Henjum (1991). The ratio of annually fixed N released directly to soil through alfalfa root turnover to that found in the plant mass is 0.47 (Goins and Russelle, 1996 and Heichel *et al.*, 1984). Consequently, fixed N for alfalfa was increased by 47%. Soybean was found to release more than 10% of the total fixed N directly to soil from roots (Brophy and Heichel, 1989) requiring increase in total soybean fixation by this fraction. These rates were applied to all crop components including harvest (Table 5), residue (Table 3) and loss during senescence.

Crop-harvest N contents (Table 5) were applied to yields (ISU, 2004) in each 30-m cell (USDA, 2002). The net export of crop N from a watershed was calculated by subtracting N required for livestock feed from the harvested N. Separating livestock N requirements and net exported harvest-N allows comparison of exported crop and livestock N, an important distinction for evaluating integrated systems.

Crop residue constitutes a mass of N that can be much larger than harvested N (Table 3) for crops common to the region. Only below ground silage maize and forage sorghum biomass was included in estimates, assuming the above ground biomass was harvested. Similarly, only alfalfa roots and crowns were included in residue, on one-third of the area to simulate the three-year rotation commonly used in the region. Estimates of total residue N were based on an above- to below-ground N-content ratio of 1.0, except maize and small grains with a ratio of 1.1 and soybean with a ratio of 1.2 (Buyanovsky and Wagner, 1986). Permanent hay or pasture was assumed to have no residue until it is killed.

Volatile loss of N during crop senescence is the process by which N flows to the atmosphere upon flowering until the crop matures or is harvested. A conservative rate of 25 kg N/ha is used in this analysis for loss during senescence from maize, soybean,

Table 3 Nitrogen in crop residues

Crop	Maize[1]	Maize silage[1]	Soybean[1]	Grain sorghum[2]	Forage sorghum[2]	Alfalfa[3]	Oat[4]	Wheat[4]	Barley[4]	Alfalfa/grass[5]
N (kg/ha)	92	46	75	53	26	37	31	31	52	14.8

[1] Buyanovsky and Wagner (1997); [2] Power and Legg (1978); [3] Shaeffer *et al.* (1991); [4] Narasimhalu *et al.* (1998); [5] Duru *et al.* (1997)

Table 4 Manure nitrogen by animal type

Animal class	Beef cows	Milk cows	Heifers	Other bovines	Breeding hogs	Other hogs	Layers*	Broilers*	Turkeys*	Sheep
Excreted (kg yr^{-1})	57	100	18	32	14	8	56	40	168	7
Applied (kg yr^{-1})	17	27	4	7	3	2	37	24	87	1
Mineralized (%)	30	40	40	30	90	90	90	75	75	75
Immobilized (%)	70	60	60	70	10	10	10	25	25	25

*values for 100 birds

Table 5 Nitrogen in crop harvest (Meisinger and Randall (1991))

Crop	Maize grain	Maize silage	Soybean	Wheat grain	Barley	Oat grain	Small grain	Alfalfa	Tame hay	Wild hay
N (kg/t)	13.2	3.6	55.6	18.5	18.4	19.3	6.0	25.4	15.4	11.0

and wheat. This rate was provided by a consensus of Iowa State University staff, but also falls in the ranges cited by Wetselaar and Farquhar (1980) and Francis *et al.* (1993). An annual loss of 2 kg N/ha was used for alfalfa (Dabney and Bouldin, 1985). All other crops were assumed to lose N through this process at a rate of 22 kg/ha (Schepers and Mosier, 1991) except pasture which was directly consumed before senescence (Sutton *et al.*, 2001).

Livestock nitrogen

The flow of N from crops into livestock for each county was set equal to the sum of N exported in the animal and excreted N. Calculating the N from crop harvest needed to sustain local livestock provides the basis for distinguishing N exported as livestock from that exported directly as crops.

Livestock export of N from watersheds was calculated from market-weight livestock-N content (Table 6). Data on the number of animals sold and milk produced were from the Census of Agriculture (US Department of Commerce, 2000). Animal production was distributed proportionally among all cropland in each watershed.

Atmospheric nitrogen

The atmospheric N stock is accounted for in two pools. One pool accumulates NH_x from volatilized fractions of SOM, inorganic fertilizer, and manure, as well as loss during crop senescence. The other pool represents elemental N that flows to plants through fixation or from denitrification as N_2 and NO_x.

Soil denitrification results from microbial reduction of NO_3 to N_2 and NO_x. Low oxygen levels occur under conditions of high soil water content. Consequently, poorly drained soils provide greater potential for denitrification than well-drained soils. Rates based on soil drainage classifications (Meisinger and Randall, 1991) were applied to the sum of NO_3 derived from fertilizer, redeposition of atmospheric N, and mineralization of SOM, crop residue, and manure after subtracting N flows to crops. Differential rates (Table 7) were applied using soil drainage classes and SOM content.

Immobilized nitrogen

Immobilization of N from crop residues and manure is accounted for in addition to the SOM stock. Immobilized residue-N is the organic N from all crop residues that is not mineralized. This includes 33% of legume and 23% of non-legume residue-N that flows to the ASOM pool (Table 2) and 29% of non-legume residue-N added to the SSOM pool. A fraction of manure-N is immobilized as SSOM at rates specific to each livestock type (Table 4) with a range of 10% for hogs and layers to 70% for cattle.

Results

The primary variable of interest is the surplus or potentially leachable N. Surplus N was the inorganic soil-N stock not accounted for in crop uptake or losses to the atmosphere

Table 6 Nitrogen in livestock

Livestock type	Swine	Feeder pig	Broiler	Pullet	Layer	Turkey	Cattle & cows
Live weight (kg)	113	23.6	2.27	1.36	1.81	10.4	544
N (% live weight)	2.14 [1]	2.14[1]	2.53[2,3,4]	3.3[4,5]	3.3[6]	3.3[6]	2.31[7]
N mass (kg/animal)	2.41	2.41	0.06	0.05	0.06	0.34	12.57

[1]Mahan and Shields, 1998; [2]Stilborn *et al.*, 1994; [3]Szakall *et al.*, 1998; [4]Scott *et al.*, 1982; [5]Oju *et al.*, 1988; [6]Middleton and Ferket, 2001; [7]Fox and Black, 1984

Table 7 Soil denitrification rates

SOM Content (%)	Soil drainage classification				
	Excessively, somewhat excessively	Well	Moderately well	Somewhat poorly	Poorly, very poorly
	Inorganic N denitrified (%)				
<2	3	6	9	13	20
2–5	6	12	13	17	30
>5	8	13	20	25	40

from this stock as expressed in Eq. 3.

$$E = F + M_s + M_r + M_m + A - C - V - S - D, \tag{3}$$

where E = surplus inorganic soil N; F = fertilizer application; M_s = mineralized SOM; M_r = mineralized crop residue; M_m = mineralized manure; A = atmospheric redeposition; C = crop uptake; V = volatilized soil inorganic N; S = volatile N loss during crop senescence; and D = denitrified N.

Another variable of interest is the annual change in soil organic N (SON) after accounting for mineralization of SOM and immobilization of residues and manure. This variable shows where depletion or accumulation of SON may occur and was calculated using Eq. 4.

$$\Delta S_n = I_r + I_m - M_{asom} - M_{ssom} - M_{psom}, \tag{4}$$

where ΔS_n = change in soil N; I_r = immobilized residue; I_m = immobilized manure; M_{asom} = mineralized ASOM; M_{ssom} = mineralized SSOM; and M_{ssom} = mineralized PSOM.

The distribution of surplus N among watersheds in the region ranges from 18 to almost 43 kg/ha (Figure 2A). The largest surpluses were found in headwater watersheds

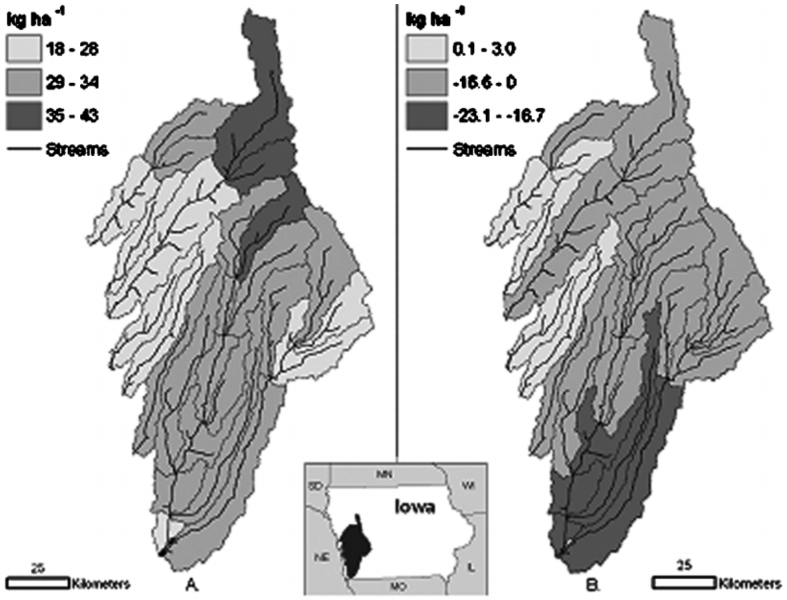

Figure 2 Nitrogen budget results in watersheds of western Iowa. A. Surplus nitrogen. B. Net change in soil organic nitrogen

of most major streams. The narrow range of surplus N reflects the dominance of the maize and soybean rotation on 71% of land in the region. The watersheds with the largest surpluses include broad drainage divides where gentler slopes accommodate the maize–soybean rotation and smaller areas in pasture on steep slopes.

Surplus N was larger than measured annual nitrate-N loads in streams of the region (Figure 3). This difference can readily be explained by denitrification in groundwater (Tomer and Burkart, 2003; Cambardella *et al.*, 1999).

The distribution of budget-components (Figure 3) in watersheds shows that fertilizer is the largest source of inorganic N. Mineralized soil, fixation, and atmospheric redeposition provide similar quantities of inorganic N. Manure contributions were not substantial and were applied only to maize cells. Livestock harvest constitutes the largest removal of inorganic N, although crop harvest removes only a slightly smaller amount. When examined at the 30-m cell scale, there were substantial differences in surpluses between the two dominant crops (Figure 4). The large ranges of surplus N reflect the variability in mineralized SOM. Soybean, however, consistently produces N deficits approximating the surpluses found with maize. Inorganic fertilizer applied to maize contributes substantially to the surplus in maize cells.

Soil organic N (ΔS_n, Eq. 4) among watersheds in the region (Figure 2B) is being accumulated in four watersheds, but depleted in most at rates up to 25 kg/ha. Larger deficits occur in watersheds where larger fractions of the drainage areas have high SOM and smaller slopes. The distribution of net change in SON (Figure 5) shows a clear distinction between maize and soybean. More maize residue is immobilized than soybean and

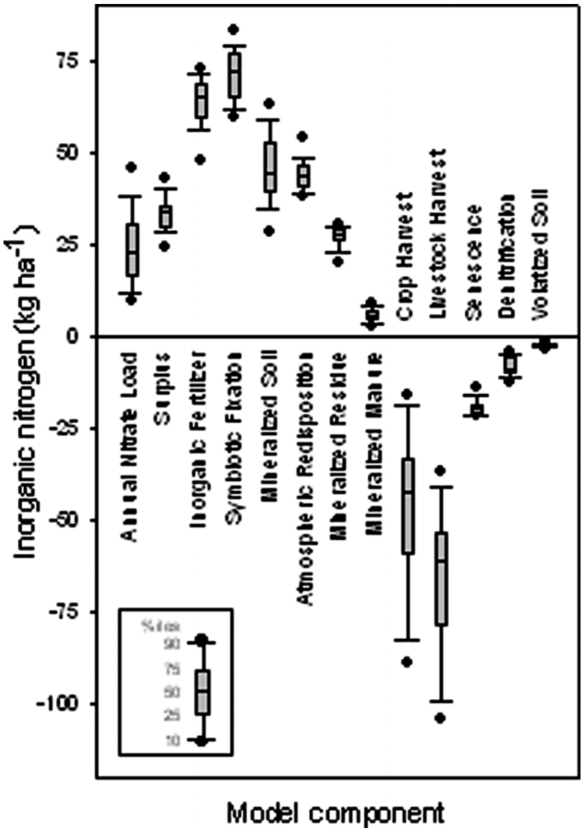

Figure 3 Distribution of inorganic nitrogen among budget components in watersheds

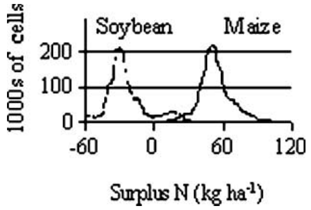

Figure 4 Surplus nitrogen by cell for maize and soybean

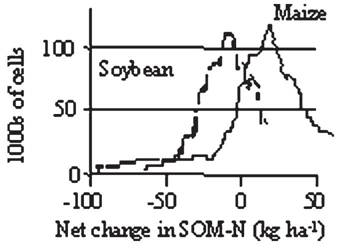

Figure 5 Net change in SOM-N by cell for maize and soybean

manure was applied only to maize, explaining much of the accumulation of SON. With minor exceptions, all soybean cells had depleted soil N. Some of this loss is balanced during the following year under maize. Variability among the cells within crop type reflects variable SOM; thus variability in mineralized SON and denitrification. The effect of these two crops on SON is extremely small values when compared to 75 to 300 Mg/ha of SON in the region. The similarity of the two curves may be an artifact of universal N-fertilizer values for each crop and soybean fixation.

Conclusions

The N budget model presented here can be applied to many intensive agricultural regions. The minimum data required includes soil characteristics and crop and livestock distribution. Climatic data and soil moisture will be required in regions where soil moisture is frequently < -100 kPa or where saturated surface soils are common during the growing season. Better spatial resolution of livestock inventories than that used here will improve the model results.

This N budget was applied to watersheds draining western Iowa, where more than 71% of the land is occupied by maize or soybean. All watersheds yielded surplus or leachable N ranging from 18 to 43 kg N/ha, with variability attributable to mineralized SON and the fraction of land occupied by maize and soybean. The change of SON in all watersheds was extremely small relative to the mass of SON, indicating an apparent equilibrium between the agricultural system and soils. Surplus values exceeded measured annual nitrate-N loads in regional streams by amounts equivalent to denitrification rates. Variability in annual SON changes reflects differences in mineralized SOM transfers to the inorganic N pool that also generate larger denitrification rates.

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