Letter to the Editor

On the need for consistent and comprehensive treatment of the N cycle

Based on their review and interpretation of terrestrial N cycle literature, Krug and Winstanley (2002) call for more comprehensive and consistent approaches to the N cycle. They argue that the 'current conceptual model' is too narrowly focused on N fertilizer inputs and underestimates natural biological N fixation, N mineralized from soil organic matter, and N in geologic deposits that may be transferred to surface and groundwaters.

We agree that a comprehensive and consistent approach to the N cycle is needed. We find, however, that Krug and Winstanley (2002) does not present a consistent or accurate treatment of the N cycle literature and presents some ideas that lack logical or empirical foundation. In previous reviews on acidification of lakes, Krug and Frink (1983), Krug (1991) presented a similar line of argument, in which a dominant scientific paradigm was characterized as being too focused on certain anthropogenic factors that contribute to acidification while underestimating the roles of natural factors. These reviews have been extensively criticized for being inaccurate and overly focused on apparently anomalous data (Havas et al., 1984; Johnson et al., 1984; Norton et al., 1989; Seip, 1993). In response, Krug (1993) argued that skeptically examining the current paradigm and the anomalies that it cannot explain provides a basis for scientific advancement. Responsible skepticism, however, operates within the bounds of accuracy and logic.

To be considered an improvement, new scientific models must account for more of the observed variation than the previous models. To accomplish this, all of the highest quality data must be considered not just anomalous data. Ignoring anomalous data or focusing exclusively on anomalous data are both forms of distorting the empirical description of the phenomena that science attempts to explain. Krug and Winstanley (2002) provide extensive discussion of anomalies, but no indication of how much variation the anomalies represent in comparison to the variation explained by the 'current model.' Additionally, some of the apparent anomalies may represent erroneous or incomplete data, as we discuss later and as was demonstrated by Norton et al. (1989) in the case of lake acidification.

Krug and Winstanley (2002) consider a wide range of models to be the 'current model.' A model presented in Goolsby et al. (1999) that indicates a negative correlation between temporal variation in riverine nitrate flux in the Lower Mississippi River and net N inputs to the basin, and the model of Howarth et al. (1996), which predicts the opposite, are both manifestations of the current model. At some points in their discussion (pages 15–18), the current model appears to consist of those that consider only fertilizer input, which is not an accurate description of the models of Goolsby et al. (1999) or Howarth et al. (1996).

Krug and Winstanley (2002) state that agriculturally managed soils in the US are continuing to lose considerable quantities of organic N through mineralization and erosion (pages 11 and 12.) On page 4 Krug and Winstanley quote Stevenson's (1986) description of the decline of soil organic N in the surface horizon during a 60-year period after initial cultivation. They fail to acknowledge, however, that Stevenson (1986) and Jenny (1933, 1941) also indicated that the decline appears to cease after approximately 60 years when a new equilibrium level is established:

'The assumption is often made that 1–3% of the soil organic matter is mineralized during the course of a growing

season, with net release of equal percentages of N, P and S. This statement must be accepted with reservation, for the reason that the humus content of most soils is in a state of quasi equilibrium. *A net annual release* of nutrients only occurs when organic matter levels are declining.... Any soil under constant management attains a balance between gains and losses of N, P and S. Thereafter, nutrients continue to be liberated but the amounts released are compensated for by incorporation of equal amounts of newly formed humus.' (emphasis in original, Stevenson, 1986 p. 67)

Stevenson (1986) and Paul et al. (1997) reviewed time series data on soil organic N in the surface horizons in several locations and reported general agreement with the quasi equilibrium concept. For instance, the Morrow Plots in Illinois, which were initially cultivated in the 1870s, appear to have reached a new equilibrium level of soil organic N around 1950 (also see Aref and Wander, 1998; Darmody and Peck, 1997).

Stevenson and others recognized that the quasi-equilibrium level of soil organic N might increase or decrease with changes in management. Change in management may explain the soil organic N decline in the corn-soybean field studied by Drinkwater et al. (1998) as well as the increase in fields studied by Karlen and Colvin (1992) and the increase in soil organic C reported by Karlen et al. (1998). Simulation modeling of the North Central US suggest that on average, soil organic C levels in the top 20 cm of agricultural soils had stopped decreasing around 1950, and then began increasing after approximately 1970 (Donigian et al. 1997; Patwardhan et al. 1997; Lal et al. 1999; Fixen and West, 2002). Since soil organic C and N are generally related, it is unlikely that soil organic N levels would be declining while organic C levels are increasing.

Krug and Winstanley (2002) frequently and incorrectly equate net soil N mineralization with a net loss of N from the soil. Nowhere do they discuss the net immobilization of N (microbial incorporation of inorganic N added as fertilizer or atmospheric deposition, or from plant uptake returned as crop residues) that occurs each year as well. Under the quasi equilibrium discussed by Stevenson (1986), immobilization occurs at approximately the same rate as net soil mineralization under constant management. This is the

assumption implicit in analyses of the Illinois N cycle 1945–1998 by David and Gentry (2000). That the David and Gentry (2000) approach allows for a net release of N from soils on an annual basis is demonstrated in David et al. (2001), where the release of N from soils after initial cultivation in Illinois was estimated using the same mass balance approach. Soil depletion of N (net mineralization much greater than immobilization) was a large flux of N in the late 1800s and into the early 20th century, but reached minimal values by the 1950s, when net anthropogenic inputs of N were low as well. This corresponds to low nitrate concentrations in rivers at that time.

On page 10, Krug and Winstanley (2002) cite Hoeft and Peck (2000) on the 'continued loss of soil N by erosion and oxidation (mineralization)...' of soil organic matter in Illinois. Hoeft and Peck (2000), however, discuss only the past loss of organic matter and do not present any data suggesting a continuing loss. Although soil erosion from cropland continues, this does not necessarily lead to a net depletion of N in soils because soils have some capacity to replace the eroded organic N with new organic N. The rate of this regeneration is known as the soil loss tolerance value. At the time of the 1997 National Resources Inventory, 21% of the cropland in the US was eroding at rates greater than the soil loss tolerance value (USDA, 2000). This estimated erosion is based on the Universal Soil Loss Equation, which does not adequately represent deposition of eroded soil within eroding fields (Moore and Wilson 1992). Consequently a considerable portion of the estimated soil loss represents losses from portions of fields that are gained by other portions of the same fields. When this is taken into account, the portion of agricultural fields with an erosion rate greater than the tolerance value would probably be considerably less than 21%. This loss is an important concern, but these data do not support a notion of generally high rates of soil organic N depletion from erosion and mineralization in the continental USA.

The decline in soil organic matter after initial cultivation and the new equilibrium concept are based on observations in soil surface horizons; relatively little is known about mineralization of soil

organic N below 30 cm. A limited amount of data on soil organic carbon suggests that net loss below 25 cm is considerably less than that observed in the surface horizon (Mann, 1985). Collins et al. (1999) compared soil C in uncultivated soils to neighboring soils that had been in long-term cultivation at six locations in the North Central US. They reported the greatest absolute and relative losses of C occurred in the top 20 cm of the soil profile. In three of six locations, there was little difference between cultivated and uncultivated soils below 20 cm. There was no evidence of depletion of soil organic C below 50 cm in all three of the sites that were sampled to that depth. It is also interesting to note that the total soil N content reported by Gentry et al. (1998) for a field in the Embarras River Watershed (ERW) below 50 cm (3275 kg N/ha) is within the range of values that Hopkins and Pettit (1908) reported for the most common soil type (Brown silt loam) in Champaign County (3091–4704 kg N/ha) sampled around 1901. The initial results ($n = 3$) of our re-sampling of sites that had been sampled in Illinois circa 1900 also indicate little change in soil organic N below 50 cm. Additional monitoring is certainly needed, but, existing data do not support the assertion that large declines of organic matter in subsoils have occurred or are continuing to occur in the continental USA.

In the absence of explicit soil N data demonstrating a continuing decline in soil organic N, Krug and Winstanley's conclusions about this phenomenon are based on high riverine N and partial N budgeting ('…the ERW budget indicates that the ERW soil N reservoir is still being depleted….' p. 11), which is the approach that they criticize. In other portions of their analysis, they argue that leaching of N from geological materials, soil erosion and high natural biological N fixation may be significant terrestrial N sources contributing to riverine N. If these are significant sources of riverine N, it is unclear why Krug and Winstanley conclude on page 11 that high riverine N export is an indication of depletion of soil organic N rather than a result of some combination of these other sources.

Although natural biological N fixation or geologic N may provide a limited amount of riverine N in Illinois or in the MRB, there is little evidence to indicate that these sources have contributed to the increase of N in surface waters since the 1950s. We agree that there is some evidence for continuing net loss of soil organic N in tile drained watersheds. Riverine N export is somewhat greater than net nitrogen inputs in these settings. This may be partly due to the expansion of artificial drainage systems in the last 50 years, which would have improved aeration and mineralization of soil organic matter, which would cause a change in the quasi-equilibrium.

Krug and Winstanley argue that the mass balance approach used by Goolsby et al. (1999), David et al. (1997) is internally inconsistent for referring to mineralization of soil organic N as an input to the system while also recognizing soil organic N as being already in the system. We agree that it is semantically inaccurate to label mineralization as an input, but it is not relevant to the calculation of a mass balance because processes that deplete an internal stock, such as mineralization of soil organic N, are mathematically the same as external inputs. Similarly, processes that add to the internal stock are mathematically the same as outputs. This is evident from the basic equation for a mass balance:

$$Input - Output = Accumulation - Depletion$$

which can be rearranged to:

$$Input - Output + Depletion - Accumulation = 0.$$

When Goolsby et al. (1999), David et al. (1997) added mineralization (depletion) of soil organic N to external inputs to the system, they were following a mathematically justifiable mass balance approach.

Krug and Winstanley (2002), on the other hand, suggest that soil N depletion should be added to riverine N output to determine a watershed N deficit for the Embarras River Watershed (page 11). However, depletion and outputs have different arithmetic signs in a mass balance. Since depletion of soil organic N can contribute to riverine N export, adding these terms together leads to double counting of N and is, therefore, mathematically and logically unjustifiable.

Estimates of annual gross mineralization discussed by Krug and Winstanley (2002) may also

involve double counting of N since the same N atoms may be involved in mineralization and immobilization several times within a single growing season. Annual N budgets that assume soil organic N is in steady state appear to account for a high degree of the spatial and temporal variability in riverine N (Howarth et al., 1996; McIsaac et al., 2001, 2002b). These models will likely be improved over time, and if Krug and Winstanley have a better model, we welcome a quantitative description of it and a demonstration of its effectiveness.

Krug and Winstanley (2002) argue that N removed from agricultural fields in eroded soil should be part of watershed N budgets. They cite estimates of soil adsorbed N loss from agricultural fields in the US Corn Belt on the order of 35 kg N/ha-year, which roughly correspond to average estimated rates of soil erosion from cropland (~ 6 ton/ac) in the region (Doering et al., 1999). This estimate of soil erosion was based on simulation modeling that assumed uniform slope within fields. In actual fields, changes in slope and soil cover can cause soil eroded from one part of a field to be deposited in another portion of the same field (Moore and Wilson, 1992; Walling 1991). Because of this and other sediment deposition, it has long been recognized that sediment (and therefore sediment bound N) transported at the watershed scale is often only 5–20% of the sum of estimated soil erosion in the fields within watersheds greater than approximately 100 km² (Walling, 1991). Thus, field scale estimates of N transport in soil eroded from agricultural fields are not directly applicable to watershed scale N budgets. Furthermore, particulate N is measured in riverine N export at some US Geological Survey monitoring stations. Analyses that use these data (Goolsby et al., 1999; Howarth et al., 1996) include the watershed scale effects of soil erosion. Goolsby et al. (1999) developed an N budget for the MARB that included riverine total N export, and thus this analysis included the effects of erosion. [We discuss the Goolsby et al. (1999) N budget in more detail in McIsaac et al. (2002a).]

The edge of field N losses reported by Doering et al. (1999) were based on a simulation model that did not include artificial subsurface (tile)

drainage. This would lead to overestimation of overland flow and soil erosion, and underestimation of N transport to rivers by subsurface drainage. Contrary to the suggestion of Krug and Winstanley, these simulation results are not applicable to the Embarras River Watershed where tile drainage is extensive. Doering's estimated N loss by leaching in the corn belt was only 1 kg N/ha-year, when it has been demonstrated that N leaching losses in tile drainage are typically 20–40 kg N/ha-year (Randall and Goss, 2001; Mitchell et al., 2000). Soil erosion in these flat regions also tend to be less than the average simulated by Doering et al. (1999).

On pages 15–18, Krug and Winstanley identify a number of apparent anomalies, which they claim cannot be explained by the 'current model' because N concentrations in surface and ground water appear to be unrelated to N fertilizer input. Several of these situations involve high N concentrations that could have resulted from N mineralized from soil organic matter, legumes or animal manure. But the studies that Krug and Winstanley (2002) had identified as working under the current model (e.g. Goolsby et al., 1999; David and Gentry, 2000; David et al., 1997) had included these sources of N in their analysis. Thus, it appears that their characterization of the 'current model' is inconsistent.

Additionally, each of these apparent anomalies is presented without sufficient detail to evaluate the quality of the apparently anomalous data or the applicability of any specific model. On page 18, Krug and Winstanley refer to decreased N concentrations in the Lower Illinois River in the 1970s, despite increased N fertilizer use in this period. This apparent decrease is also associated with a change in the agencies that conducted the measurements (McIsaac et al., 2000). The Central Illinois Public Service (CIPS) Company measured nitrate concentrations in the Lower Illinois River and two other locations 1955–1971, which were published by the Illinois State Water Survey (Harmeson et al., 1973). Concentrations measured by CIPS had greater mean and variance than concentrations reported by USGS, Illinois EPA or ISWS for nearby sampling locations (McIsaac et al., 2002b). Thus the apparent decline in concentrations after the early 1970s is at least partly a con-
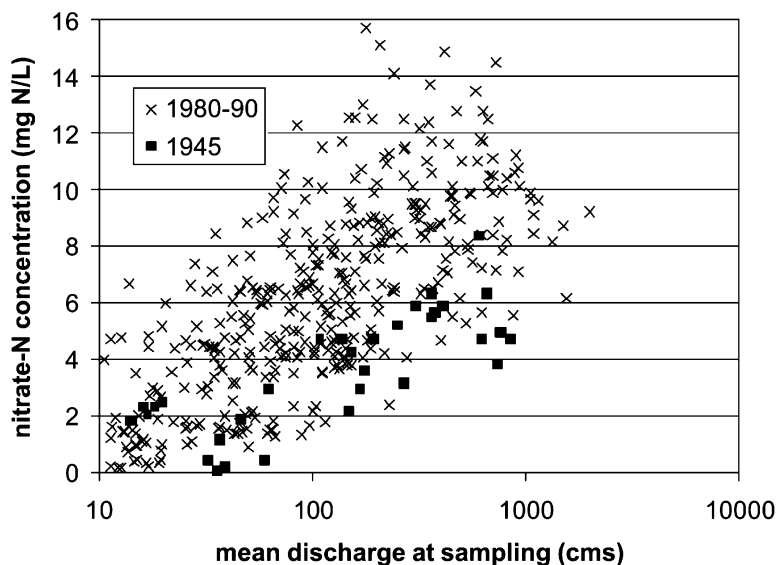
Fig. 1. Nitrate-N concentration for the Des Moines River at Des Moines for the 1945 water year and for the 1980–1990 water years plotted as a function of discharge at sampling. Concentrations in 1945 were determined on composite samples collected over periods of approximately ten days while concentrations in 1980–1990 were determined on samples collected on one day. Data were obtained from USGS National Water Information Service (2002) and USEPA (2002) STORET web sites.

sequence of erratic and probably erroneous methods used by CIPS.

On page 17 Krug and Winstanley (2002) refer to Keeney and DeLuca (1993) who had tentatively concluded that nitrate concentrations in the Des Moines River had not changed between 1945 and the 1980s even though total N input to the basin had more than doubled. This conclusion was based on only one year of riverine nitrate data collected in 1945 at Des Moines that was compared to data collected 35 km downstream at Runnells, Iowa in the 1980s. Moreover, the 1945 average value used by Keeney and DeLuca (5.0 mg N/L) does not correspond to the average value we calculated (3.6 mg N/L) from the original observations obtained from the US Geological Survey National Water Information System (2002)web site. An examination of the individual observations as a function of discharge provides evidence of an increase in concentrations (Fig. 1) between 1945 and the 1980s. Goolsby et al. (1999, 2000) and the Iowa Department of Natural Resources (2001) also present summaries of more extensive historical data that indicate nitrate in Iowa and other Midwestern Rivers has increased substantially since the 1950s.

Although they indicate concern about the scientific characterization of the N cycle prior to human development, it is curious that Krug and Winstanley do not cite work that presents data on N transport from undeveloped watersheds (e.g. Dodds et al., 1996; Clark et al., 2000). In addition, Krug and Winstanley (2002) never present a complete mass balance of N for a watershed or region for any time period that would summarize or attempt to balance their N fluxes. This would provide a model that could be empirically tested. We recommend a more thorough and critical examination of data and more rigorous testing of specific models than provided by Krug and Winstanley (2002).

References

Aref S, Wander MM. Long-term trends of corn yield and soil organic matter in different crop sequences and soil fertility treatments in the Morrow Plots. Adv Agron 1998;62:153–197.

Clark GM, Mueller DK, Mast MA. Nutrient concentrations and yields in undeveloped stream basins of the United States. J Am Water Res Assoc 2000;36:849–860.

Collins HP, Blevins RL, Bundy LG, Christenson LG, Dick WA, Huggins WA, Paul EA. Soil organic matter dynamics in corn-based agroecosystems of the central USA: results from 13-C abundance. Soil Sci Soc Am J 1999;63:584–599.

Darmody RG, Peck TR. Soil organic carbon changes through time at the University of Illinois Morrow Plots. In: Paul EA, Paustian K, Elliott ET, Cole CV, editors. Soil Organic Matter in Temperate Agro-ecosystems: Long-term Experiments in North America. Lewis Publisher, 1997. p. 161–169.

David MB, McIsaac GF, Royer TV, Darmody RG, Gentry LE. Estimated current and historical N balances for Illinois. Sci World 2001;1:597–604.

David MB, Gentry LE. Anthropogenic inputs of nitrogen and phosphorus and riverine export for Illinois, USA. J Environ Qual 2000;29:494–508.

David MB, Gentry LE, Kovacic DA, Smith KM. Nitrogen balance in and export from an agricultural watershed. J Environ Qual 1997;26:1038–1048.

Dodds WK, Blair JM, Henebry GM, Koelliker JK, Ramundo R, Tate CM. Nitrogen transport from tallgrass prairie watersheds. J Environ Qual 1996;25:973–981.

Doering OC, Diaz-Hermelo F, Howard C, Heimlich R, Hitzhusen F, Kazmierczak R, Lee J, Libby L, Milon W, Prato T, Ribaudo M, Evaluation of the Economic Costs and Benefits of Methods for Reducing the Nutrient Loads to the Gulf of Mexico. Topic 6. Report of the Integrated Assessment on Hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 20. NOAA Coastal Ocean Program, Silver Spring, MD. 1999; 115 pp.

Donigian AS, Patwardhan AS Jr, Chinnaswamy RV, Barnwell TO. Modeling soil carbon and agricultural practices in the central US: an update of preliminary study results. In: Lal R, Kimble JM, Follett RF, Stewart BA, editors. Soil Processes and the Carbon Cycle. Boca Raton, FL: CRC Press, 1997. p. 499–518.

Drinkwater LE, Wagoner MW, Sarrantonio M. Legume-based systems have reduced losses of nitrogen and carbon. Nature 1998;396:262–265.

Fixen PE, West FB. Nitrogen fertilizers: Meeting contemporary challenges. Ambio 2002;31:169–176.

Gentry LE, David MB, Smith KM, Kovacic DA. Nitrogen cycling and tile drainage nitrate loss in a corn/soybean watershed. Agric Ecosyst Environ 1998;68:85–97.

Goolsby DA, Battaglin WA, Aulenbach BT, Hooper RP. Nitrogen flux and sources in the Mississippi River Basin. Sci Total Environ 2000;248:75–86.

Goolsby DA, Battaglin WA, Lawrence GB, Artz RS, Aulenbach BT, Hooper RP, Keeney DR, Stensland GJ, Flux and Sources of Nutrients in the Mississippi-Atchafalaya River Basin. Topic 3. Report of the Integrated Assessment on Hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 17. NOAA Coastal Ocean Program, Silver Spring, MD 1999; pp. 89.

Harmeson RH, Larsen TE, Henley LM, Sinclair RA, Neill JC. Quality of Surface Waters in Illinois 1966–1971. Ill State Water Surv Bull 56, ISWS, Champaign IL 1966;1973:100.

Havas M, Huchinson TC, Likens GE. Red herrings in acid rain research: common misconceptions regarding the effects of acid deposition on aquatic ecosystems. Environ Sci Technol 1984;18:176a–188a.

Hoeft RG, Peck TR. Soil testing and fertility. Illinois Agronomy Handbook 2001–2002. College of Argiculture, Consumer and Environmental Sciences. Urbana: University of Illinois, 2000. p. 84–124.

Howarth RW, Billen G, Swaney D, Townsend A, Jaworski N, Lajtha K, Downing JA, Elmgren R, Caraco N, Jordan T, Berendse F, Freney J, Kudeyarov V, Murdoch P, Zhao-Liang Z. Regional nitrogen budgets and riverine N and P fluxes for the drainages to the North Atlantic Ocean: natural and human influences. Biogeochemistry 1996;35:75–139.

Hopkins CG, Pettit JH. The fertility in Illinois soils. Ill Agric Exp Stat Bull 1908;123:294.

Iowa Department of Natural Resources, Geological Survey Division. Nitrate Nitrogen in Iowa Rivers: Long-Term Trends. Water Fact Sheet 2001-5, Iowa City, Iowa, USA, 2001. http://wqm.igsb.uiowa.edu/publications/fact%20sheets/nitrate/NUTRIENTLOAD.htm.

Jenny H. Soil fertility loss under Missouri conditions. Missouri Agricultural Experiment Station Bull 1933;324:30.

Jenny H. Factors of Soil Formation. NY: McGraw Hill, 1941. p. 244.

Johnson NM, Likens GE, Feller MC, Driscoll CT. Acid rain and soil chemistry. Science 1984;225:1424–1425.

Karlen DL, Kumar A, Kumar RS, Cambardella CA, Colvin TS. Tillage system effects on a 15-year carbon based and simulated N budgets in a tile drained Iowa field. Soil Tillage Res 1998;48:155–165.

Karlen DL, Colvin TS. Alternative farming system effects on profile nitrogen concentrations on two Iowa farms. Soil Sci Soc Am J 1992;56:1249–1256.

Keeney DR, DeLuca G. Des Moines River nitrate in relation to the watershed agricultural practices: 1945 vs. 1980s. J Environ Quality 1945;1993(22):267–272.

Krug EC. Review of acid-deposition-catchment interaction and comments on future research needs. J Hydrol 1991;128:1–27.

Krug EC. Review of acid-deposition-catchment interaction and comments on future research needs-reply. J Hydrol 1993;142:493–496.

Krug EC, Frink CR. Acid rain on acid soil: a new perspective. Science 1983;221:520–525.

Krug EC, Winstanley D. The need for comprehensive and consistent treatment of the nitrogen cycle in nitrogen cycling and mass balance studies: I. Terrestrial nitrogen cycle. Sci Total Environ 2002;293:1–29.

Lal R, Kimble JM, Follett RF, Cole CV. The Potential of US Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Baca Ratton, FL, USA: Lewis Publishers, 1999. p. 128.

Mann LK. A regional comparison of carbon in cultivated and uncultivated Alfisols and Mollisols and in the central United States. Geoderma 1985;36:241–253.

McIsaac GF, David MB, Gertner GZ, Goolsby DA. Nitrate flux to the Gulf of Mexico. Nature 2001;414:166–167.

McIsaac GF, Royer TV, David MB, Weubbles DJ, Dawson JO, Sandiford G, Review of Illinois State Water Survey Contract Report 2000–2008: A Contribution to the Characterization of Illinois Reference/Background Conditions for Setting Nitrogen Criteria for Surface Waters in Illinois' Department of Natural Resources and Environmental Sciences Report 2000–2003, University of Illinois, Urbana. 2000; pp 26. Available online <http://research.nres.uiuc.edu/report00-03/>.

McIsaac GF, David MB, Gertner GZ, Goolsby DA. Relating N inputs to the Mississippi River Basin and nitrate flux in the Lower Mississippi River: A comparison of approaches. J Environ Qual 2002a;31:1610–1623.

McIsaac, GF, Short M, Terrio P, Groschen. G, Nitrate concentrations in Illinois rivers 1967–1974: Comparison among reporting agencies. J Am Water Resources Association 2002b; (in review).

Mitchell JK, McIsaac GF, Walker SE, Hirschi MC. Nitrate in river and subsurface drainage flows from an east central Illinois watershed. Trans Am Soc Agricultural Eng 2000;43:337–342.

Moore ID, Wilson JP. Length-slope factors for the Revised Universal Soil Loss Equation: simplified method of estimation. J Soil Water Conserv 1992;47:423–428.

Norton SA, Brakke DF, Hendricksen A. Red Herring lakes and streams in the acid rain literature. Sci Total Environ 1989;83:113–125.

Patwardhan AS, Donigian AS Jr, Chinnaswamy RV, Barnwell TO. A retrospective modeling assessment of historic changes in soil carbon and impacts of agricultural development in central USA, 1900 to 1990. In: Lal R, Kimble JM, Follett RF, Stewart BA, editors. Soil Processes and the Carbon Cycle. CRC Press: Boca Raton, FL, 1997. p. 485–498.

Paul EA, Paustian K, Elliott ET, Cole CV, editors. Soil Organic Matter in Temperate Agroecosystems: Long Term Experiments in North America. Boca Raton, FL: CRC Press, 1997. p. 414.

Randall GW, Goss MJ. Nitrate loss to surface water through subsurface, tile drainage. In: Follett RF, Hatfield JL, editors. Nitrogen in the Environment: Sources, Problems and Management. Amsterdam: Elsevier Science, B.V, 2001. p. 95–122.

Seip HM. Review of acid-deposition–catchment interaction and comments on future research needs—comment. J Hydrol 1993;142:483–492.

Stevenson FJ. Cycles of Soil: Carbon, Nitrogen, Phosphorus, Sulfur, Micronutrients. New York: John Wiley and Sons, 1986. p. 380.

US Department of Agriculture. 2000. The National Resources Inventory. http://www.nrcs.usda.gov/technical/land/pubs/97highlights.html.

US Environmental Protection Agency. 2002. STORET. http://www.epa.gov/storet/ (Accessed July, 2002).

US Geological Survey. 2002. NWISWeb Data for the Nation. http://waterdata.usgs.gov/nwis/ (Accessed July, 2002).

Walling DE. Measuring sediment yield from river basins. In: Lal R, editor. Soil Erosion Research Methods. Soil and Water Conservation Society. USA: Ankeny, Iowa, 1991. p. 39–74.

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