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A Contribution to the Characterization of Illinois Reference/Background Conditions for Setting Nitrogen Criteria for Surface Waters in Illinois

by
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A CONTRIBUTION TO THE CHARACTERIZATION OF ILLINOIS REFERENCE/BACKGROUND CONDITIONS FOR SETTING NITROGEN CRITERIA FOR SURFACE WATERS IN ILLINOIS

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FINAL REPORT

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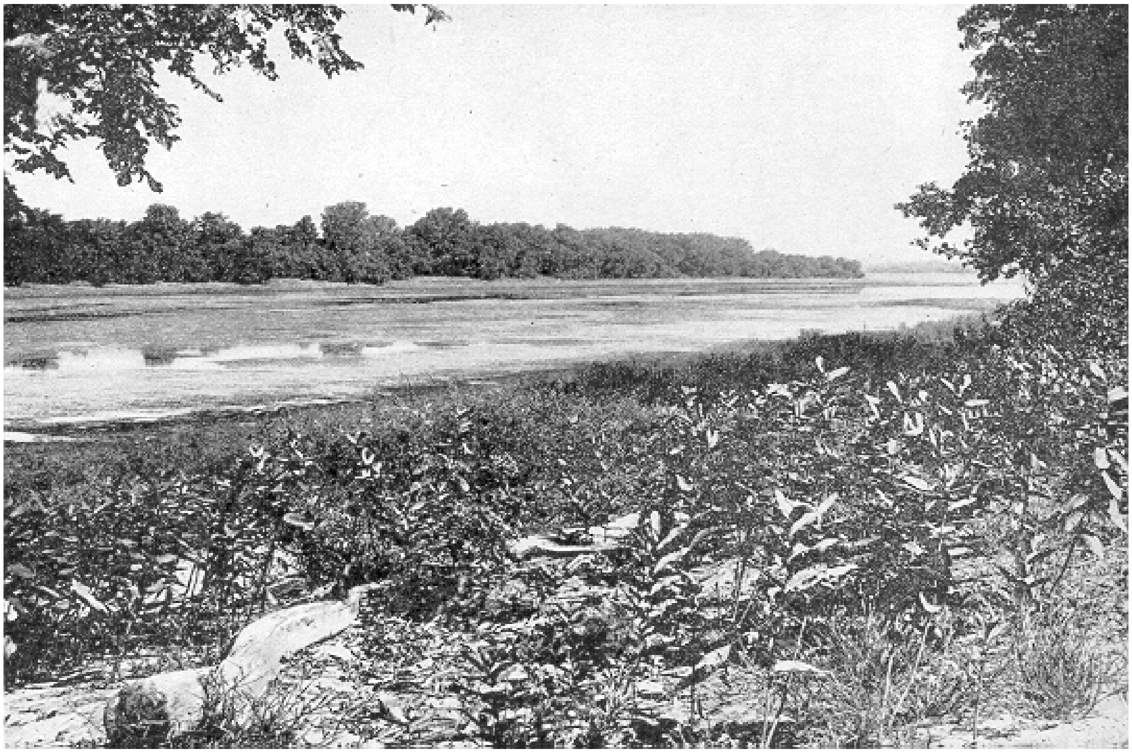

The pre-1900 condition along the Lower Illinois River
by Quiver Lake in the summer.
Source: Kofoid, 1903, Plate 15.

This three-mile long lake running parallel to the Illinois River was fed in part by the Spoon River, the most pristine 19th century river in the Illinois River Basin, and in summer by springs issuing from sand at the base of a bluff along its eastern shore.

Quiver Lake illustrates what visitors to the Lower Illinois River in its undisturbed state had seen:

"The aquatic environment...impresses the visiting biologist who for the first time traverses its river, lakes, and marshes, as one of exceedingly abundant vegetation, indeed almost tropical in its luxuriance...he will find acres upon acres of 'moss,' as the fishermen call it— a dense mat of mingled *Ceratophyllum* and *Elodea* choking many of the lakes from shore to shore, and rendering travel by boat a tedious and laborious process.... The carpets of *Lemnaceae* will be surprising, and the gigantic growths of the semiaquatic *Polygonums* will furnish evidence of the fertility of their environment" (Kofoid, 1903, pp. 236-237).

Pictured from the shore, the surface of Quiver Lake is almost entirely weed choked, permitting reflection from only a small fraction of the lake surface. If an aerial photograph had been taken, as with the river and lakes of Figure 23 with their minor weed coverage, little open water would have been seen in Quiver Lake.

UPDATE
November 15, 2000

P. xi, lines 1-5, change to:

"...Illinois River in 1894-1899 was reported to be 3.68 mg N/l and additional large amounts of nitrogen not measured were stored in the then-luxuriant growth of aquatic (and other) vegetation and transported in copious, albeit, unmeasured amounts of organic debris. In view of the many uncertain adjustments that have to be made in comparing these historical data with recent data, we can not conclude that the Lower Illinois River was any more N rich in the 1990s than it was in the 1890s."

P.9, line 15, add:

"Travelling further up the Illinois river, Schoolcraft described the water of Lake Peoria as 'beautifully clear', the Vermilion River as 'a fine clear stream', the Au Sables River as 'pellucid', and he mentions 'small streams of clear water' in depicting the prairie environment. However, we discuss later (page 71) the difficulties in trying to interpret 19th century descriptions of clear water, which in the context of secchi depths was subjectively different from what people living in the 20th century would call clear water."

P. 29, line 1, add:

"In summary, microbiologists are acquiring a new and more life-like view of the underground. The geosphere provides waters of the deep subsurface with ingredients necessary to support life, including fixed forms of nitrogen (Chalk and Keeney, 1971; Stevenson, 1972; Power et al., 1974; Reeder and Berg, 1977; Strathouse et al., 1980; Heaton et al., 1983; Hendrey et al., 1984; Spitzy, 1988; Ranganathan, 1993; Simpkins and Parkin, 1993; Parkin and Simpkins, 1995).

"In Illinois — a Corn Belt state whose ground waters are reported to suffer from NO_3-N contamination — the average concentration of NH_4-N in ground water is greater than NO_3-N. Unlike NO_3-N, concentration of NH_4-N increases with depth and is correlated with the products of mineral weathering (Warner, 2000). Researchers in the United States and Canada have conclusively shown that uncontaminated ground waters convert reduced geologic NH_4-N to oxidized NO_3-N. In such cases values of NO_3-N range from 0.2 to 2,000 mg NO_3-N/l (Chalk and Keeney, 1971; Power et al., 1974; Reeder and Berg, 1977; Strathouse et al., 1980; Hendrey et al., 1984). Illinois State Water Survey data (Holm, 1995) suggest that it is possible that oxidation of geologic nitrogen may be responsible for pockets of >10 mg NO_3-N/l in the relatively deep ground waters of the Mahomet aquifer of Illinois.

"Sources of N in the geosphere must be taken into account when conducting N mass-balance studies."

P. 30, line 1, add:

"But this is not supported by the historic record. During the 1940s in Illinois nearly 6,000 well samples from private water supplies of all types from all sections of the state showed that 20 percent had >10 mg NO_3 N/l. In counties in central Illinois more than 40 percent had >10 mg NO_3 N/l and more than 20 percent had > 100 mg NO_3 N/l (Weart, 1948). These water supplies were reported to show no correlation with animal and/or human wastes. In 1970 Illinois State Water Survey scientists acknowledged the earlier high nitrate ground water values and added, 'the records show this happened long before commercial, nitrogen fertilizer usage became significant' (Harmeson and Larson, 1970). The standing-nitrogen-cycle paradigm cannot explain such phenomena.

"Similarly, in the Canadian Prairie Provinces >10 mg NO_3-N/l were found in up to 25% of wells tested and frequencies today are generally no higher than levels measured earlier back to the 1940s (Harker et al., 1997), e.g.

"'The same degree of contamination was reported in the 1940s, so nitrate levels may not be increasing under current agricultural practice' (Fairchild et al., 2000).

"Survey of well water around agriculture in Central Canada (Ontario) found that:

"'The share of wells with nitrate levels more than 10 milligrams per litre recorded in 1991-1992 did not differ significantly from that reported in 1950-1954. Surveys carried out between these dates indicated that about 5 to 20% of drinking water wells had levels greater than the Canadian drinking water guideline. These results suggest that agricultural activity over the past 50 years has not significantly changed the amount of nitrate added to groundwater' (Fairchild et al., 2000).

"In summary the widespread and intensive use of chemical-N fertilizers in the latter half of the 20th century appears not to have increased ground-water nitrate concentrations for much of the Canadian breadbasket."

P. 46, line 3, add:

"A review of the literature reported, 'In waterlogged soils amended with 1 % straw, or less, nitrogen fixation rates up to 150 kg ha^{-1} a^{-1} were achieved; with 5 to 20 % straw and waterlogged conditions 500 to 1000 kg ha^{-1} a^{-1} were fixed. The responsible organism was *Clostridium butyricum* and Meiklejohn (1967) also found that the number of clostridia increased considerably when approximately 678 to 1356 kg/ha of compost was added to the soil' (Stewart, 1969).

"That addition of readily-available carbohydrates to terrestrial soils also greatly increases the numbers of N-fixing bacteria, as well as other N-cycle bacteria, has been long known, as can be seen in reviews from the early 20th century (e.g., Wakesman, 1924; Pieters, 1927). Some of the N fixed will be lost to the hydrosphere and atmosphere and, therefore, amounts of N retained in aquatic and wetland sediments will be less than the amounts fixed in them."

P. 50, line 50, add:

“The flush of such fertilizing elements into the aquatic environment also stimulate the growth of vascular aquatic vegetation in whose root zones and on whose aquatic surfaces nitrogen-fixing bacteria and algae flourish (Holm et al., 1969; Stewart, 1969; Allen, 1971; Yoshida and Ancajas, 1971; Goering and Parker, 1972; Patriquin and Knowles, 1972; Head and Carpenter, 1975; Hough and Wetzel, 1975; Jones et al., 1979; Blotnick et al., 1980; Baker and Orr, 1986; DeLaune et al., 1986).”

P. 53, line 30, change to:

“...oxides of N that are lost to the atmosphere. This is shown by the review of Woodmansee and Wallach (1981) who generalize the world literature into their figure 5, which shows the enhanced gaseous-N volatilization losses that fire induces through nitrification and denitrification.”

P. 53, line 48, add:

“The experiments and review of the world’s literature by Anderson et al. (1988), which support the earlier review of Woodmansee and Wallach (1981), is, in turn, supported by the later review of Levine et al. (1996), who continue to report that ‘burning also enhances the biogenic emissions of NO and N_2O (Anderson et al., 1988; Levine et al., 1988; Johansson, Rodhe, and Sanhueza, 1988; Levine et al., 1990).’”

P. 58, line 30, add:

“Boughey et al. (1964) found that the almost universal burning of African grasslands prior to planting of crops appears to have the benefit of destroying plant allelopathic toxins that suppress nitrifying soil bacteria.”

P. 62, line 4, add:

“Additional N was probably also mobilized by urine, because urea, like NH_4-N, dissolves organic matter from soils (Kelly, 1981). Whereas organic-N was not measured in the cow urine-leaching experiments of Stout et al. (1997), Managhan and Barraclough (1993) did measure organic-C mobilized from soil in their cow urine experiments. Cow urine initially mobilized about 1,000 mg soil C/l above reference soil-water C concentration, decreasing to 300 mg C/l above reference concentration after 3 days and about 50 mg C/l above reference concentration after 13 days. Assuming a C:N ration of 10, the amounts of soil organic N solubilized by urine can be estimated.”

P.72 , line 32, add:

“Palmer (1903) reports that ‘The presence of chlorine in water in amounts exceeding the normal quantity generally indicates that the water has been polluted by animal matters...’ For example, Palmer reports the average concentration of chlorine at Averyville, north of Peoria, to be 30.2 mg/l in 1897-1899. At Grafton, Palmer reports the average concentration of chlorine in the Illinois River in 1899-1902 to be 12.6 mg/l. For the same years, Palmer reports the average concentration of chlorine in the Mississippi River at Grafton to be 2.92 mg/l. With an average concentration of TN of 1.59 mg N/l, the Mississippi River could also be classified as eutrophic according to the trophic criteria suggested by USEPA (USEPA, 2000b), even though it had a low chlorine concentration. In comparison, Palmer reports the average concentration of TN in Lake Michigan in 1899-1900 to be about 0.4 mg N/l, which according to the trophic criteria suggested by USEPA (USEPA, 2000a) would represent oligotrophic conditions. The average concentration of chlorine in Lake Michigan was reported to be about 3.2 mg/l, about the same as in the Mississippi River and only slightly less than in the Spoon River.

"Palmer also reports an average concentration of TN in the Kankakee River at Wilmington (1896-1900) of 2.86 mg N/l. Average chlorine concentration was reported to be 2.88 mg/l. He reports that 'The organic matters contained in the waters of this stream are almost entirely of vegetable origin, for no considerable amount of sewage is discharged into it, that of Kankakee (population 13,995) about 35 miles from the mouth and 25 miles above the point of collection, being the most important.' Palmer reports that 'there is a considerable diminution in the proportions of nitrates during the warm summer months, this diminution doubtless being in part the result of growth of vegetation in the flowing waters of the stream, in part the result of assimilation of nitrates by the vegetation of the headwaters in the Kankakee marshes, which during this portion of the year constitute the chief source of supply.' 'The higher nitrates during the high water season are in part due also to the leaching of nitrates from the soil by the run-off and the discharges from the tile drains, which occur chiefly during the seasons of lower temperature and greater precipitation.' Again, this is evidence of hypertrophic conditions well before the use of artificial nitrogen fertilizer."

P. 73, delete lines 27-33: "About 0.42 mg/l...of 4.82 mg N/l."

P. 75, delete lines 5-20:

P.89, line 31 add:

"The nitrogen loads at Kampsville shown in Figure 20 are unadjusted for the weir. Palmer (1903, Appendix) reports that the quantities of organic-N in the river at Kampsville '... were in the high water season not less than six and possibly as much as twelve times as great as the quantities contained in the water of the Des Plaines at Joliet, which comprises that of the Upper Des Plaines, the Chicago Main Drainage Canal or Sanitary Canal, and the Illinois and Michigan Canal.' This range reflects the uncertainty in calculating nitrogen loads at Kampsville due to the influence of the weir on flow. Palmer recognizes that some organic-N was transformed into inorganic-N and that the river purified itself to some extent. He also reported that 'The enormous quantities of nitrates found in the water at Averyville and Kampsville during March and April, the freshet season, are in the main derived from the leaching of surface soils by the run off and the discharges of tile drains.' The great diminution in the concentration of chlorine at Averyville and Kampsville in spring is further evidence of the non-animal and non-point sources of the spring freshet waters.

"Goolsby et al. (1999) report that rates of nitrogen mineralization in soils can be greater than 40,000 kg N/km^2/yr in virgin cultivated land. They also report that this mineralization rate in virgin cultivated soils is 3-5 times higher than the mineralization rate measured beneath Illinois soybean and corn crops in recent years (David et al., 1997). However, Goolsby et al. do not relate the high mineralization rate in virgin cultivated soils to leaching and run-off in Illinois in the 19th century."

P. 105, line 44, add:

"Conversely, relying on the soil's natural humus-bearing store of nitrogen, farmers lose control over the leaching of NO_3-N. This is now becoming recognized as a possible down-side of organic farming. It is now recommended not to build up soil organic matter to the degree that it can meet corn's peak season nitrogen demand, because this much soil organic matter presents a NO_3-N leaching problem during the dormant season (e.g., Pang and Letey, 2000)."

P. 108, line 10, add:

"Overall, 'Approximately 23% of the state was wetland prior to European settlement....there are only an estimated 870,000 acres of the original 8.2 million acres of natural wetlands remaining within the state' (Illinois Department of Natural Resources, 2000)."

P. 117, line 8, add:

"Overall, the effect of draining and leveeing has reduced Illinois wetlands and its lush, N-rich vegetation from an estimated 8.2 million acres to 870,000 acres (Illinois Department of Natural Resources, 2000). The Wetlands Initiative (Wetland Matters, 1999) cites the loss of the critical nitrogen-removing capacity of wetlands as an important cause of the historical increase in nitrate concentration in the Illinois River from <1.5 mg N/l at the end of the 19th century to average concentrations >5.0 mg N/l in recent years. Kofoid (1903) reports that in the 1890s Thompson's Lake was supplied with water mainly from the Illinois River, but had an average concentration of total nitrogen about 1.5 mg N/l less than the Illinois River. This could be an indication of assimilation, denitrification, and burial of N in this backwater lake. The Wetlands Initiative reports that restoring only 407,000 acres of wetlands in Illinois (about 5% of the 1780 wetlands), primarily on flood prone bottomland throughout the watershed, would remove 101,000 tons (80%) of today's nitrate load from the Illinois River."

"Assuming that all 2 million acres of wetland drained in the entire MRB in 1900 were drained exclusively in Illinois, this would leave 6.2 million acres of wetland to take up and transform soluble N from the drainage of the remaining 28.8 million acres of land in Illinois. Given that the concentration of TN in the lower Illinois River was about 24 percent less in the 1890ss than the 1990s, and assuming this 24 percent difference holds for flux of TN in Illinois' surface waters — now estimated at about 0.5 billion lbs/yr (David and Gentry, 2000a, b) — then these wetlands would have to be transforming only 4.1 lb N/acre/yr (4.6 Kg N/ha/yr) from the non-wetland areas to account for the difference between amounts of N in solution in the 1890s versus the 1990s. Put another way, the 6.2 million acres of wetlands would needed to have transformed only 19.1 lb N per acre (21.4 kg N/ha/yr) of wetland to produce a lush 6.2 million acre crop of N-rich aquatic and wetland vegetation every year to account for the difference in total N in solution between 1890s and 1990s surface water."

P.121, line 43 add :

"David et al. (1997) is reported to be one of only a few detailed studies 'to have linked field N budgets, NO_3^- loss in tile drained watersheds and surface water NO_3^- loads' (David et al., 1997) The study characterizes the tile-drained portions of east-central Illinois and the Upper Embarras watershed as homogeneous. From this David et al. apply field nitrogen budgets and averaged NO_3^- losses in two tile-drained watersheds draining into the Embarras River to determine, among other things, how much of the Embarras NO_3^- came from these heavily fertilized fields. The data show that the nitrate yield from the watershed that received almost 50% more fertilizer than the other watershed had a nitrate yield about 25 % less. David et al. also report that 'Even if fertilization were reduced or eliminated, the overall disturbance from agricultural production in the Embarras River watershed would still lead to high NO_3^- concentrations and export, depending on the timing of precipitation events.'

"Porter (2000), in a study of algal and macroinvertebrate responses to nonpoint source pollution relative to natural factors in the Corn Belt in 1997, concludes that 'Nutrient concentrations and the abundance of algae during low-flow conditions were not related directly to rates of fertilizer application or the number of livestock in Midwestern stream basins; however, rates of stream metabolism (P_{max} and R_{max}) increased significantly with indicators of agricultural intensity.' Porter finds that algal-nutrient relations were more of a function of landscape characteristics, hydrology, and rainfall-runoff characteristics than agricultural land use, which is relatively homogeneous throughout the region. Porter recommends that 'Improved understanding of natural factors and algal-nutrient relations that contribute to chemical and biological indicators of eutrophication in lotic systems could enhance the development of water quality criteria within and among ecoregions in the U.S. (e.g., Level III; Omernik 1986).' "

P.127, lines 34-37, delete:

"Concentration of measured TN.....before declining." Replace with:

"The concentration of TN at Havana was reported to be 3.68 mg N/l in the 1890s (Table 11), a period of drought. Although there are few measurements of TN in the Lower Illinois River in more recent years, the concentration of TN can be estimated. The concentration of TN in Peoria Lake in March-October 1967 is reported by Evans and Wang (1970) to be 8.85 mg N/l: nitrate-N was 4.33, ammonia-N 1.15, and organic-N was 3.37 mg N/l. The concentrations of ammonia-N at Havana and Meredosia in 1967-1971 were 1.39 and 1.0 mg N/l respectively (Healy and Toler, 1978). [Note the ammonia-N value reported by Harmeson et al. (1973) for Meredosia using a different method of chemical analysis was 0.57 mg N/l.] These values decrease to 0.49 and 0.28 mg N/l in 1972-1974 (Healy and Toler, 1978). The concentration of TN at Valley City in 1975-1982, according to data in STORET, was 5.50 mg N/l: ammonia-N 0.41, organic-N 1.21, and NO_2+NO_3-N 3.98 mg N/l. The concentration of TN at La Grange in 1993-1998 using grab samples was 4.82 mg N/l: ammonia-N 0.16, organic-N 0.89, and NO_2-N+NO_3-N 3.77 mg N/l (USGS, La Crosse, WI, 1999).

"Using these data and the measured 1967-1971 NO_3-N concentration of 6.2 mg N/l at Meredosia (Harmeson et al., 1973), we estimate the concentration of TN at Meredosia in 1967-

1971 to have been about 9.5 mg N/l: ammonia-N 1.0, organic-N 2.2, and NO_2+NO_3-N 6.3 mg N/l.

"Valley City (river mile 60) is downstream from Havana (river mile 120) and Meredosia (river mile 71). As N concentration can decreases downstream, possible adjustments need to be made when comparing Havana and Valley City data. Average concentration of TN at Havana in 1897-1899 was 3.3 mg N/l and at Kampsville (river mile 32) 2.6 mg N/l (Palmer, 1903). Given these limited data, it is not possible to provide a precise adjustment for TN concentrations. Perhaps an upward adjustment of the Valley City TN data of ~0.4 mg N/l is reasonable when comparing them with Havana data.

"However, there seems to be little difference in NO_3-N concentrations along the lower Illinois River. In 1897-1900 the concentration of NO_3-N at Havana was 1.20 mg N/l and at Kampsville 1.17 mg N/l. Average concentration of NO_3-N at Meredosia in 1975-1976 was 4.3 mg N/l and at Valley City 4.2 mg N/l (STORET). In 1990-998 the average concentration of NO_3-N at Havana was 4.36 mg N/l and at Valley City 4.40 mg N/l.

"Returning to the difference in climatic conditions between the 1890s and the 1990s, we must adjust the Havana data in order to compare them with the recent Valley City and La Grange data. Average annual state-wide precipitation in 1894-1899 was 35.5 in and in 1993-1998 it was 41.4 in (personal communication, Jim Angel, ISWS, September 22, 2000). There were also differences in the seasonal distribution of precipitation: in 1894-1899 average April-June precipitation was 10.6 in, and in 1993-1998 it was 15.1 in. In recent decades, higher rainfall generally has been associated with higher concentrations of TN in the MRB (Goolsby et al., 1999). However, we do not have an extensive data base to determine the relationships between climatic and landscape conditions in the 19th century and precipitation-runoff-TN concentrations.

"In 1921-1922, the concentration of TN near Pearl (river mile 43) was reported to be 2.85 mg N/l (Hoskins et al., 1927), although the representativeness of the 13-month sample is unknown. Hoskins concludes that '.. in 1921 the total volume of pollution contributed by Chicago to the Illinois River was about two and three-fourths times as great as the amount added just prior to the opening of the main drainage canal, and that since the opening of the canal in 1900 this pollution has just about doubled in total volume. However, the amounts of diluting water withdrawn from Lake Michigan have been gradually increased during this interval, so that the net effect has been to actually reduce rather than to increase the total nitrogen and oxygen consumed content as measured in terms of concentration.'

"The concentrations of TN in the Kankakee and Spoon Rivers in 1921-1922 were reported by Hoskins et al. to be 3.30 and 3.54 mg-N-l respectively. These values are higher than the values of 2.86 mg N/l reported by Palmer (1903) for the Kankakee and 2.59 mg N/l reported by Kofoid (1903) for the Spoon in 1896-1900.

"The Hoskins et al. data also show a very marked seasonal cycle in the concentration of both TN and NO_2+NO_3-N in the major tributaries to the Illinois River. The concentrations of TN in the Kankakee, Des Plaines, Fox, Vermilion, Mackinaw, and Spoon Rivers in 1921-1922 peaked in December and the monthly average in these tributaries was 6.7 mg N/l. The concentration of

TN in all these rivers was lowest in summer (June-August) and averaged 1.54 mg N/l in the lowest months. The concentration of NO_2+NO_3-N in these rivers peaked in December and averaged 5.14 mg N/l. The concentration of NO_2+NO_3-N in all these rivers was lowest in August and averaged 0.05 mg N/l. The amplitude of the seasonal cycle of NO_2+NO_3-N in these tributaries in 1921-1922 was thus considerably greater than the average amplitude for NO_2+NO_3-N in all Illinois rivers in 1996, as shown in Figure 15.

"Hoskins et al. data also show a pronounced seasonal variation of TN and NO_3+NO_2-N concentrations in the Lower Illinois River. At river mile 26, the monthly concentration of TN peaked at 5.3 mg N/l in January and reached a monthly minimum of 1.23 mg N/l in June. The monthly concentration of NO_2+NO_3-N peaked at 3.20 mg N/l in December and reached a monthly minimum of 0.70 mg N/l in June.

"The average monthly concentration of TN in the above six tributaries for the 12 months August 1921-July 1922 was 3.6 mg N/l, which was about 23 % higher than the concentration in the Illinois River at river mile 26.

"Yet other adjustments must be made when comparing TN concentrations in the 1890s and 1990s. Extensive areas of wetlands and aquatic vegetation that existed in the Illinois River Basin in the 1890s no longer exist. As wetlands and aquatic vegetation generally reduce the measured concentration of TN in rivers, the concentration of TN at Havana in the1890s needs to be adjusted upwards when comparing it with the measured concentrations in the Lower Illinois River in the 1990s. Goolsby et al., 1999 (p.70), for example, report that 'Nitrogen transported in particles larger than about 2 millimeters escape collection in water samples and thus is not measured and is not included in the yield estimates.'

"Further complicating the comparison of historical N data over time are the different sampling protocols and analytical techniques that have been used, the construction of levees, and other factors.

"The reported concentration of TN at Havana in 1894-1899 was 3.7 mg N/l and at La Grange in 1993-1998 it was 4.8 mg N/l. In view of the uncertain adjustments that have to be made in comparing these historical data with recent data, we can not conclude that the Lower Illinois River was any more N rich in the 1990s than it was in the 1890s.

P. 131, replace Figure 30 with the revised Figure 30 (page 9 of Update)..

P. 133, lines 29-30, delete "- flow and methods ..... 5.5 mg N/l" and add:

"In view of the many uncertain adjustments that have to be made in comparing these historical data with recent data, we can not conclude that the Lower Illinois River was any more N rich in the 1990s than it was in the 1890s."

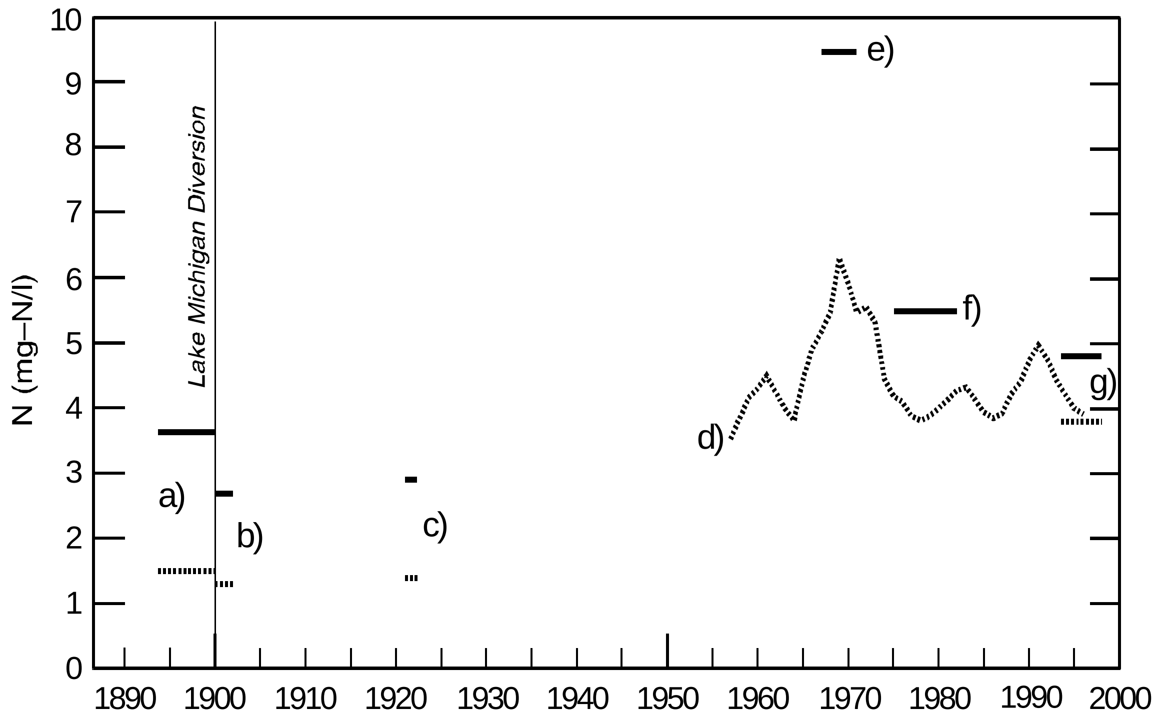

Figure 30. Concentration of nitrogen in the Lower Illinois River, 1894-1998**.**

TN (ammonia-N+organic-N+NO_2-N+NO_3-N) is shown with solid lines**.**
NO_2-N+NO_3-N is shown with dashed lines.

a) Havana, 1894-1899 (Kofoid, 1903 and Palmer, 1903).
b) Havana, 1900 and Kampsville, 1900-1902 (Palmer, 1903).
c) River mile 43, 1921-1922 (Hoskins et al., 1927).
d) Meredosia, 1955-1971 (Harmeson and Larson, 1969; Harmeson and Larson, 1970; Harmeson et al., 1973), 1971-1976 (STORET); Valley City 1975-1998 (STORET) - 5-year moving averages 1957-1996.
e) Meredosia 1967-1971 NO_3-N concentration of 6.2 mg N/l at Meredosia (Harmeson et al., 1973), plus 1.0 mg/l ammonia-N (Healy and Toler, 1978), plus estimates of 0.1 mg/l NO_2-N, and 2.2 mg N/l organic-N (see text).
f) Valley City, 1975-1982 (STORET).
g) La Grange, 1993-1998 (USGS, LTRMP, La Crosse, WI, 1999).

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A CONTRIBUTION TO THE CHARACTERIZATION OF ILLINOIS REFERENCE/BACKGROUND CONDITIONS FOR SETTING NITROGEN CRITERIA FOR SURFACE WATERS IN ILLINOIS

EXECUTIVE SUMMARY

The United States Environmental Protection Agency (USEPA) National Regional Nutrient Criteria Development Program is developing regional-specific criteria for total nitrogen concentrations in surface waters and downstream coastal areas. These criteria will provide the foundation for states to set total nitrogen[1] standards to remedy impairments caused by nutrient overenrichment and to protect designated uses. Reference conditions representing minimally impacted surface waters will be developed for each ecoregion.

All nutrient criteria must be based on sound scientific rationale.

The first element of a nutrient criterion identified by USEPA is "... historical data and other information to provide an overall perspective on the status of the resource." The second element includes " ... a collective reference condition describing the current status." A further element requires "... attention to downstream consequences."

The USEPA recognizes that nutrient concentrations in surface waters are primarily affected by the rate of weathering and erosion from watershed soils. Human activity has at least two effects on the natural load of nutrient inputs to surface waters through disturbance of the vegetation, and the addition of nutrient-containing material, such as fertilizer. At the heart of the overenrichment problem are the rates of production and decomposition of organic materials, of which nitrogen is a component.

This report provides a contribution to the setting of reference/background conditions for Illinois through the provision of historical data, the evaluation of the current status of water resources against historical conditions, and some attention to downstream consequences. A particular focus of downstream consequences is hypoxia in the Gulf of Mexico, which is alleged to be caused by the flux of excess nitrogen from the Upper Mississippi, Ohio, and Missouri River Basins.

The concept of biogeochemical cycling of nitrogen provides an appropriate and necessary framework for understanding landscape influences on water quality throughout the Illinois River Basin.

Changes in the Illinois River Valley and its system of tributary streams and lakes are well recognized, but this is the first attempt to assess in some detail how such changes have affected the aquatic carbon, oxygen, and nitrogen cycles; the latter specifically as to the impact of such watershed changes on the nature and quantity of aquatic nitrogen, as well as on the nitrogen cycle within the terrestrial reservoir. This is seen in the accompanying time line of the estimated nitrogen richness of the Illinois landscape.

[1]Total nitrogen = organic-N + ammonia-N + nitrite-N + nitrate-N. Any of these species of N can be transformed into any other species and all can become biologically available.

Scientists studying soils and crops from the mid-19th through mid-20th centuries have developed a deep understanding of natural conditions and the impacts of human activities on the large reservoirs of nitrogen in soils and plants. Human activities have greatly altered the natural nitrogen cycle. The early scientists documented that cultivating virgin land typically depleted nitrogen and carbon stored in these reservoirs by about 50 percent in the first 60-70 years of cultivation. One consequence of the large amount of nitrogen removed from soils was increased transfer of nitrogen to surface waters and ground waters. The depletion of nitrogen from soils in the Mississippi River Basin was so great that crop yields declined throughout the 19th and early 20th centuries.

By mid-20th century, large amounts of artificial fertilizer became available at reasonable cost. The extensive use of nitrogen fertilizer, improved plant varieties, and agronomic practices increased crop yields. Nitrogen fertilizer also began to replenish some of the large amounts of nitrogen previously removed from the soil.

In the 1970s, profound changes occurred in the perception of the natural nitrogen cycle and human modification of that cycle. Large reservoirs of nitrogen in soils and plants, and the cycling of nitrogen within and between these reservoirs and the hydrosphere and the atmosphere were no longer acknowledged by most scientists to be key components of the nitrogen cycle. Studies of the nitrogen cycle, and human impacts on the nitrogen cycle, have been restricted largely to consideration of nitrogen fluxes from the earth's surface to the atmosphere and the hydrosphere. It was determined that human activities, especially fossil-fuel combustion and fertilizer use, had doubled the intensity of the natural nitrogen cycle and many lands, including much of Illinois, had become nitrogen saturated. Increasing concentrations of nitrogen in surface waters was given as evidence of nitrogen saturation and leakage. This new limited edition of the nitrogen cycle became cast in concrete and is referred to in this report as "the new, standing nitrogen-cycle paradigm."

This report chooses to revert to the earlier, scientifically more complete and defensible definition of the nitrogen cycle, which includes recognition of the magnitude and importance of soil-plant reservoirs and exchanges. By documenting from an extensive search of the scientific literature the major changes in ecosystems and soil nitrogen that have occurred over centuries, this report puts into perspective the present status of nitrogen resources — as required by USEPA.

Within this paradigm, this report examines the impact on nitrogen concentrations in surface waters in Illinois during occupation of the land by Native Americans, bison, and many other animals and birds. Theoretical impacts are complemented by written accounts of early settlers and scientific observations made under similar conditions. It is concluded that the landscape and surface waters were more nitrogen saturated at this time than today. These pre-European-settlement conditions were selected as the reference/background conditions.

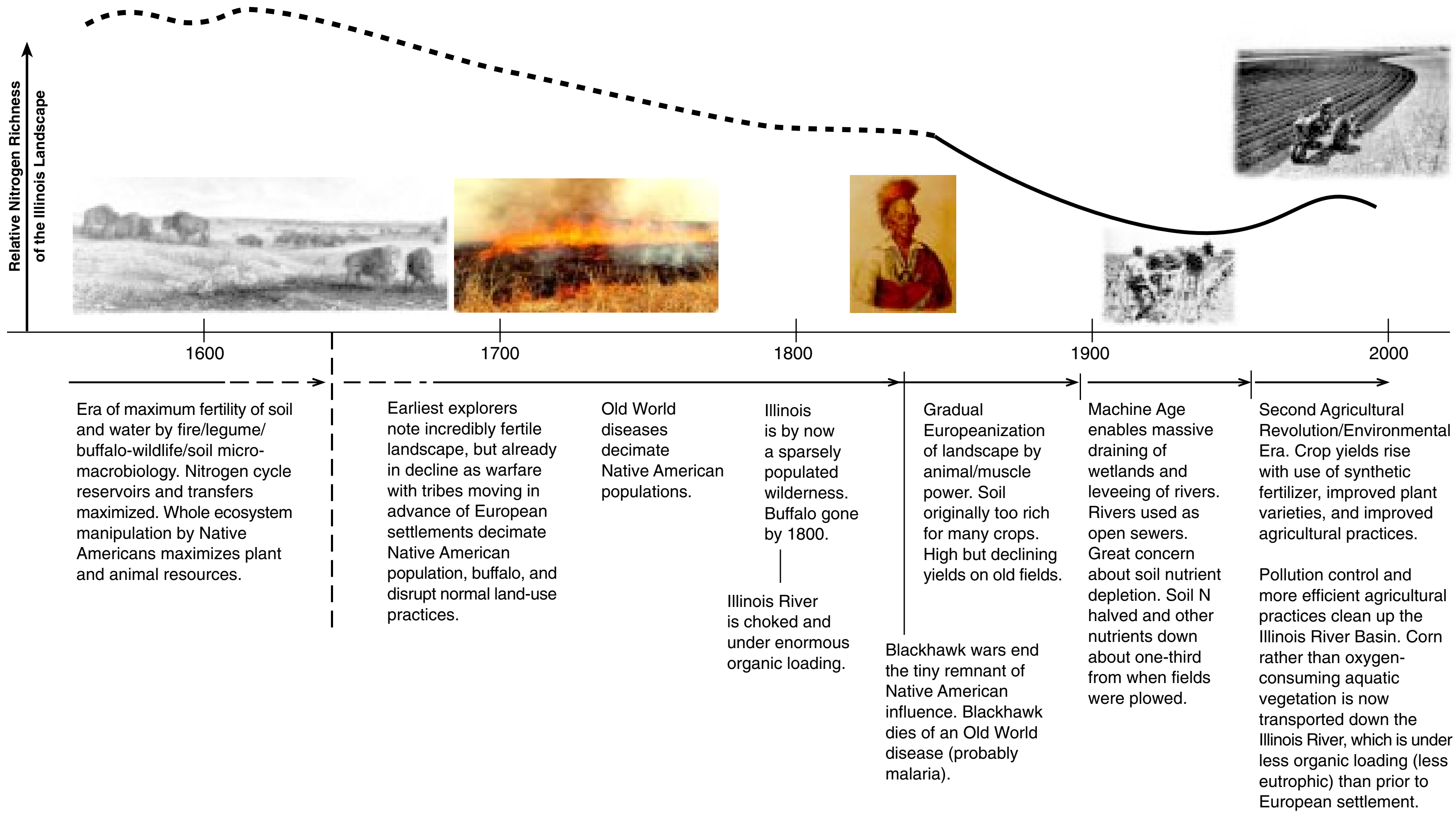
During the period of early European settlement, the populations of Native Americans and bison were eliminated and the landscape became less nitrogen saturated. Nevertheless, even in the 1820s, the Illinois River appears to have been hypertrophic, i.e. nutrient overenriched. As late as the 1850s, the amount of sediment transported by the Mississippi River was more than twice the amount transported in recent decades. The source of the sediment is soil erosion, which is reported to be the major sort of N delivery from agricultural lands. Thus, the N load in the Mississippi River was declining. The average annual concentration of total nitrogen in the Lower Illinois River in 1894-1899 was 3.68 mg N/l, and additional large amounts of nitrogen not measured were stored in plankton and luxuriant aquatic vegetation and transported downstream in copious amounts of organic debris. Allowing for the unmeasured flux of nitrogen as plankton and for low flow, the adjusted average annual concentration of total nitrogen in the Lower Illinois River in 1894-1899 is estimated to have been about 5.5 mg N/l.

This report also examines the impact of European settlement and agriculture on the nitrogen cycle and water quality. Scientific data show that the average concentration of total nitrogen in the Lower Illinois River increased to about 10 mg N/l by mid-20th century and subsequently decreased to 4.8 mg N/l in the 1990s. The annual concentration of nitrate in the Lower Illinois River peaked at about 6.2 mg N/l in 1967-1971 and subsequently decreased to about 3.8 mg N/l in 1993-1998. These improvements in water quality are associated with an increasing amount of dissolved oxygen in the river. The reductions in the concentrations of all forms of nitrogen are attributable to both point- and nonpoint-source pollution control.

The main conclusions of this report are that, in establishing scientifically sound reference/background conditions, it is necessary to quantify in a common unit all forms of nitrogen (in solution, as solids, and as gases; and organic and inorganic forms) and all sources, reservoirs, transformations, and fluxes of nitrogen in a common unit; and to understand interactions between nitrogen and other biogeochemical cycles of, for example, water, oxygen, carbon, and phosphorous. Criteria for setting nitrogen standards must recognize the great complexity of the nitrogen cycle and its interdependence with other variables, cycles, and anthropogenic influences.

This report is the first step of many needed to establish the objective, scientifically sound basis necessary for characterization of reference/background conditions in Illinois and for understanding the role of agriculture and other activities on the nitrogen cycle.

Key words: nitrogen; nitrate; organic nitrogen; ammonia; overenrichment; biogeochemical cycles; Illinois River; Mississippi River; hypoxia; nutrient criteria; nutrient standards; agriculture.



Relative nitrogen richness of the Illinois landscape before and after European settlement.

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The views expressed in this report are those of the authors and do not necessarily reflect the views of the Illinois Department of Natural Resources.

COMMON UNITS OF CONVERSION

Pound (lb) = 0.454 kilograms (kg)
Acre (ac) = 0.405 hectares (ha)
lb/ac = 1.12 kg/ha
milligrams per liter (mg/l) = parts per million (ppm)
mg NO_3/l = 0.23 mg NO_3-N/l
mg NH_4/l = 0.78 mg NH_4-N/l

SOURCES CITED IN TEXT

The list of references includes only primary references and does not include secondary references mentioned in quotes. Where quotations are from a book or large report, in addition to author and date, page numbers are provided to assist the reader. Page numbers are also provided for specialized information, facts, concepts, and so on from books or large reports. For quotations from articles or article-sized reports, only author and date are provided.

INTRODUCTION

Administrative Background

The President's *Clean Water Action Plan: Restoring and Protecting America's Waters* (The White House, 1998) — the Plan — has set into motion a new strategy for combating organic enrichment (cultural eutrophication) stimulated by anthropogenic additions of nutrients to surface and coastal waters. The new strategy is to establish reference/background water-quality conditions for the setting of water-quality criteria and standards for different types of water bodies within the 14 different nutrient ecoregions mapped by the United States Environmental Protection Agency (USEPA) (Figure 1; USEPA, 1999). The USEPA will consider a degree of "impairment" above "pristine" conditions in setting criteria and standards. States have the option to define alternative defensible ecoregions.

The first element of a nutrient criterion identified by USEPA is "... historical data and other information to provide an overall perspective on the status of the resource." The second element includes " ... a collective reference condition describing the current status." A further element requires "... attention to downstream consequences."

The USEPA recognizes that nutrient concentrations in surface waters are primarily affected by the rate of weathering and erosion from the soils in the watershed. Human activity has at least two effects on the natural load of nutrient inputs to surface waters through disturbance of the vegetation, and the addition of nutrient-containing material, such as fertilizer. At the heart of the overenrichment problem are the rates of production and decomposition of organic materials, of which nitrogen (N) is a component.

The criteria will provide the foundation for states to set total nitrogen (TN)[1] standards to remedy impairments caused by nutrient overenrichment and to protect designated uses. Reference conditions representing minimally impacted surface waters will be developed for each ecoregion.

All nutrient criteria must be based on sound scientific rationale.

In establishing this new strategy, the Plan recognizes that cultural eutrophication is linked to the supply of nutrients from the watershed, as mediated by terrestrial biogeochemical processes. The Plan also recognizes that the degree to which cultural eutrophication degrades water quality is also dependent upon internal biogeochemical processes of the receiving waters.

The Plan recognizes that cultural eutrophication also can be a function of nutrients in drainage received from upstream surface waters. Therefore, downstream effects are to be considered in setting nutrient criteria and standards. To this end, concentrations of N in the Mississippi River and hypoxia in the Gulf of Mexico are of special importance to Illinois.

The two nutrients of greatest concern are N and phosphorus (P): with P believed to be primarily derived from nonagricultural point sources and N primarily derived from agricultural runoff, the latter principally from N fertilizer (CENR, 1999), with agriculture contributing P principally through soil erosion, e.g.,

"Most of the P lost from cropland is not in solution but is bound to eroded soil particles (National Research Council, 1993).... Inputs of P from mineralization were not established in this report." (Goolsby et al., 1999, p. 49).

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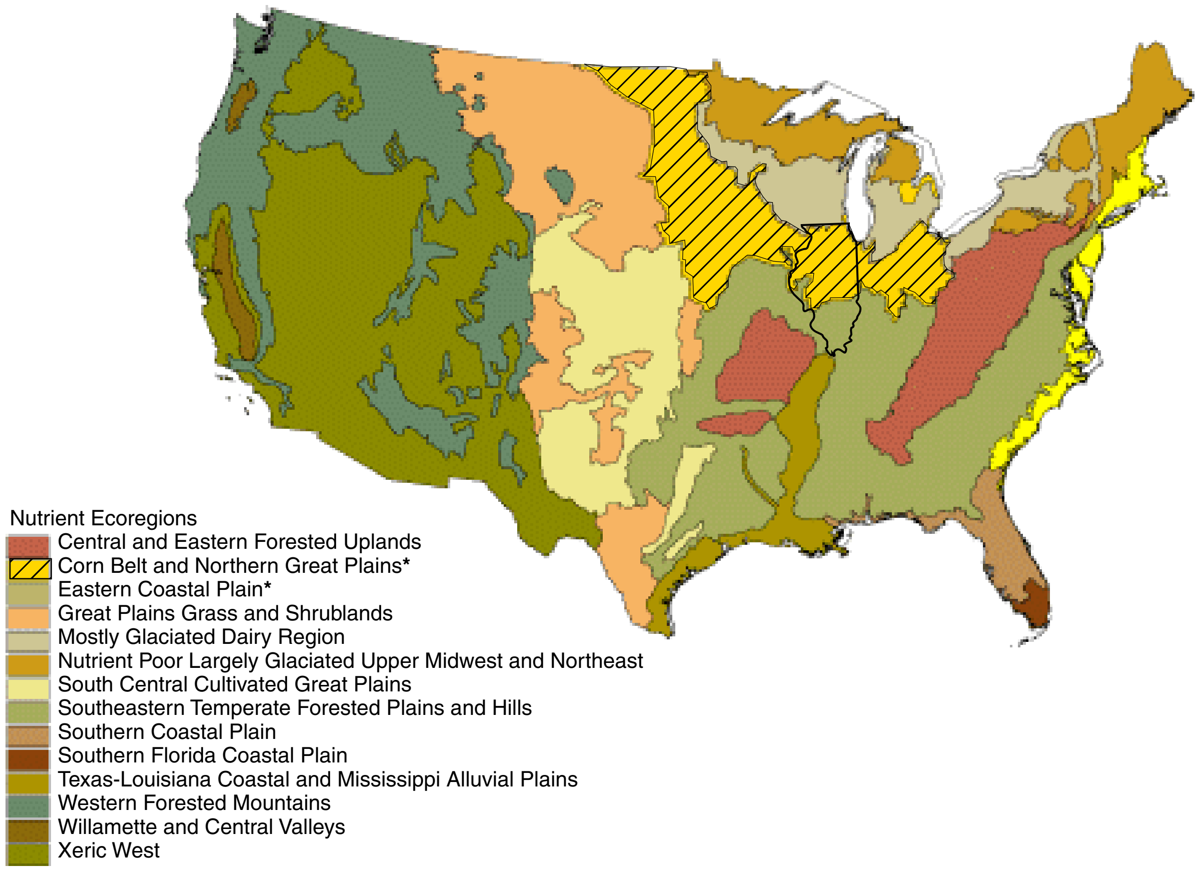
[1]TN = organic-N + NH_4-N + NO_2-N + NO_3-N. Any of these species of N can be transformed into any other species and all can become biologically available.



***Note:** The state of Illinois has ecoregions of: Corn Belt and Northern Great Plains, and Eastern Coastal Plain

Figure 1. Nutrient ecoregions for which numeric reference/background water-quality criteria and standards are to be established.
Source: Posted on www.epa.gov/OST/standards/ecomap.html, revised April 13, 1999.

The Committee on Environment and Natural Resources (CENR) recognizes N as being the most important limiting nutrient in the Gulf of Mexico and P as the most important limiting nutrient for the surface waters of the Mississippi River Basin (MRB). The CENR also recognizes that N can be the limiting nutrient in some surface waters in the MRB. Criteria and standards for P are to be set also, but these are not the subject of this report.

For the Illinois River Basin (IRB) and the MRB, the agricultural nutrient of greatest concern is N. Excessive runoff of agricultural N is said to be causing extreme cultural eutrophication (seasonal hypoxia — summertime putrification due to exhaustion of dissolved oxygen (DO) in the northern Gulf of Mexico adjacent to the discharge of the Mississippi River system. The IRB has been identified as a key culprit (Beardsley, 1997), reportedly having the highest rate of N-fertilizer addition and the highest rate of pollution-N runoff in the MRB (Goolsby et al., 1999). To ameliorate the problem, the National Hypoxia Assessment has identified a number of possible strategies including: a) a 45 percent reduction in MRB N-fertilizer application, and b) a 20 percent reduction in N-fertilizer application, combined with the creation of 5 million acres of wetland, plus a wide range of changes in agricultural practices to be implemented in the MRB (CENR, 1999). Out-of-state export of N and downstream effects are important parameters for the setting of the new Illinois reference/background conditions and surface-water-quality criteria and standards.

In establishing new water-quality criteria and standards for surface water/background conditions, the Plan recognizes that “research to improve the basis for understanding and assessing nutrient over-enrichment problems is critical....” The USEPA is developing “...a strategy to establish an objective, scientifically sound basis for assessing nutrient over-enrichment problems.” A key element of the Plan is “a new cooperative approach” to watershed protection in which state, tribal, federal, and local governments, and the public are involved. “States are to use nutrient criteria established by USEPA as the basis for adopting water-quality standards” (The White House, 1998).

Accordingly, the USEPA has put together Regional Technical Assistance Groups to help develop and administer the Nutrient Criteria Program, to establish regional criteria, and to review proposed State and tribal reference/background nutrient conditions and the criteria based on them for each region. Illinois is located in USEPA Region 5.

Nature and Scope of Report

This report is the first step of many needed to establish the objective, scientifically sound basis necessary for the characterization of reference/background conditions in Illinois. This report’s scope is defined by its nature as a first step in researching Illinois’ reference/background conditions, the relevance of these background conditions to the establishment of the new federal water-quality criteria, the water-quality interests of the State, and the objective of the Illinois Council on Food and Agricultural Research (C-FAR) to “develop economically and environmentally responsible food production systems.”

Fortuitously, the nature of Illinois’ pre- and post-European settlement landscapes, the nature of the eutrophication problem as related to agriculture, and the interests of the above parties rationally coincide in such a way as to enable the definition of an eloquently simple, yet effective, preliminary research design.

For this research, the characterization of Illinois reference/background conditions and the impact which human activities have since had on Illinois water quality can be simplified by defining the problem in terms of human impact on the two great natural landscape elements first seen by European explorers and the early settlers who followed them.

In this section of the Introduction the two major landscape elements and the scientific framework for studying them are introduced.

Two Great Landscape Elements

One great natural landscape element of the "Prairie State" is terrestrial.

In 1820, prior to extensive European settlement, prairie — mostly moist (tallgrass) prairie — covered an estimated 22 million acres of Illinois' 35 million acres of land (Iverson et al., 1989). As European settlement progressed, the prairie was progressively plowed under and transformed into the great American breadbasket. By 1900, 10.0 million acres of Illinois were in cropland; in 1976, 19.5 million acres (Steffeck et al., 1980); and in 1998, 23.0 million acres (Dan Towery, Conservation Technology Information Center, personal communication, September 14, 1999).

By the 1990s, only a little more than 2,000 acres of Illinois prairie remained (Samson and Knopf, 1994; Illinois Natural History Survey, 1999). The highly fertile soil formed under pre-European settlement prairie has become the literal foundation of America's Corn Belt (e.g., Iverson et al., 1989; Samson and Knopf, 1994).

The Corn Belt is mapped by the USEPA as one of 14 U.S. water-quality nutrient ecoregions and, like the prairie it replaced, the Corn Belt covers most of Illinois (Figure 1; Iverson et al., 1989).

The other great Illinois landscape element that greeted the eyes of early Europeans was the aquatic landscape element that drained the vast Illinois prairie: the Illinois River. The Illinois River was named after the Native Americans whom European explorers found living along its banks (Buck, 1967). Later, the State would adopt the Illinois River's name (Quaife, 1918). The Illinois River system of streams, lakes, marshes, and wetlands that drained the vast pre-European-settlement prairie now drains the vast, heavily fertilized, post-European-settlement Corn Belt (Steffeck et al., 1980; Iverson et al., 1989). As noted by Forbes (1887), and still the case today (e.g., Sefton et al., 1980), the streams and rivers of the IRB dominate the fluvial aquatic environment of the State, as do the fluvatile lakes that are part of the Illinois River system, e.g.,

"The lakes of Illinois are of two kinds, fluvatile and water-shed. The fluvatile lakes, which are much more numerous and important, are appendages of the river system of the State, being situated in the river bottoms and connected with the adjacent streams by periodic overflows. Their fauna is therefore substantially that of the rivers themselves, and the two should, of course, be studied together" (Forbes, 1887).

In its pre-European-settlement state, the Illinois River more resembled a lake than a river, as the Mills et al. (1966) endorsement of Barrows' (1910) description notes:

"The Illinois is a river of relatively insignificant volume. Its natural low-water discharge is less than that of the Rock River and but a small fraction of that of the upper Mississippi and Ohio rivers. The nearly level channel and small volume result in a very sluggish river, which has been described as a stream that 'more nearly resembles the Great Lakes than an ordinary river,' and again as one that 'partakes more of the nature of an estuary than of a river.' It is wholly unequal to the task of washing forward the sediment delivered by its headwaters and its numerous tributaries.... The average fall of the lower Illinois is less than that of the Mississippi below the mouth of the Illinois. This is the reverse of the normal relation between tributaries and their main streams" (Mills et al., 1966).

The linkage between soil and water quality has been long recognized in Illinois. Naturalists and scientists have long related the great natural fertility of most of Illinois' surface waters to the great natural fertility of most of her soil: those created under moist (tallgrass) prairie vegetation (Forbes, 1887; Kofoid, 1903; Palmer, 1903; Schoolcraft, 1918; Thompson and Hunt, 1930; Bellrose, 1941; Larimore and Smith, 1963; Sefton et al., 1980; Sorenson et al., 1999).

Early on, scientists recognized that the vast quantities of N-rich aquatic plants (both macrophyte and algae) naturally found in the river system required massive amounts of nutrients, especially N, to support their growth and that that nutrient supply was coming from the soils of the watershed. Scientists studying the surface waters of the IRB used N as a surrogate for overall nutrient status (Kofoid, 1903; Palmer, 1903), much as N was long used as a surrogate for overall soil-nutrient status (e.g., Conner, 1922; Albrecht, 1938; Viets and Hageman, 1971; Welch, 1979; Stevenson, 1986).

However, for more than a hundred years scientists have often observed that light, rather than nutrients, was the factor limiting primary productivity (e.g., Forbes, 1887; Kofoid, 1903; Palmer, 1903; Thompson and Hunt, 1930; Bellrose, 1941; Larimore and Smith, 1963; Sefton et al., 1980; Munn, Osborne, and Wiley, 1989; Wiley, Osborne, and Larimore, 1990; Sorenson et al., 1999). To quote the U.S. Geological Survey's recent review and study of today's status of light versus nutrient limitation of surface-water primary productivity:

"The effects of cultural eutrophication are best evaluated by integrated evaluation of physical, chemical, and biological conditions and responses.... Although previous studies frequently have determined that nutrients are rarely limiting in agricultural streams of the Midwest (Munn, Osborne, and Wiley, 1989; Wiley, Osborne, and Larimore, 1990), the availability of light (mediated by riparian shading and water turbidity) differs among streams and rivers, resulting in high rates of primary productivity where light conditions are favorable....

"Chemical indicators of eutrophication (for example, nutrient concentrations) may be revealed only when in-stream rates of nutrient flux exceed rates of nutrient uptake by algae or other aquatic plants in combination with other biogeochemical processes such as denitrification (Hill, 1983, 1988)....

"Differences in soil and riparian-canopy conditions in watersheds of the Midwest are likely to influence eutrophication processes in major tributaries to the Mississippi River, as well as eutrophication and hypoxia issues in the Gulf of Mexico" (Sorenson et al., 1999, p. 3).

Nevertheless, nutrient-induced cultural eutrophication is a societal concern in Illinois and the nation. In situations where agricultural enrichment of N and other nutrients is capable of enhancing primary (plant) productivity, many of Illinois' surface waters may be considered potentially sensitive to cultural eutrophication by nutrients in runoff. For such waters of naturally great fertility, relatively modest additions of nutrients from human activities may be all that is hypothetically needed to boost primary productivity beyond surface-water assimilatory capacity, i.e., enhanced primary productivity may boost the rate of decaying biomass beyond the rate of oxygen supply, thereby turning surface waters putrid. For the same reasons, such waters are also potentially sensitive to organic loading from human and animal wastes: this being, historically, Illinois' prominent experience with anthropogenic surface-water putrification (Palmer, 1903; Leighton, 1907; Collins, 1910; Cooley, 1913; Larimore and Smith, 1963; Mills et al., 1966; Butts, Evans, and Lin, 1975; Butts and Evans, 1978; Talkington, 1991).

In Illinois, it has been shown that putrification not only diminishes surface waters' aesthetic attributes, putrification also diminishes their utility as sources of potable water, fisheries, and recreation (e.g., Forbes, 1887; Kofoid, 1903; Palmer, 1903; Leighton, 1907; Collins, 1910;

Larimore and Smith, 1963; Sefton et al., 1980). And, as previously discussed, water-borne transport of nutrients outside of Illinois, especially N, is also a concern.

In summary, it is necessary to understand the impact of human activities on prairie soil on the organic-N load of the waters of the Illinois River system — and the load of the Mississippi River, which ultimately receives the Illinois River's drainage — to determine how human activities have altered Illinois' reference/background, water-quality conditions. Since agriculture has been identified as the largest contributor to nonpoint source runoff (Goolsby et al., 1999), this report focuses on agricultural activities.

Regarding the use of the Illinois River as a surrogate for defining Illinois' reference/background water-quality conditions, the Illinois River is "called the 'most studied' river in the world" (Mills et al., 1966). The quantity and quality of information offers us the best opportunity for evaluating the impact of agricultural practices on surface-water quality. Such historic information also provides a reality check for evaluating the validity of the standing N-cycle paradigm — the conceptual framework used by most scientists to understand, model, and explain such impact. Furthermore, Palmer (1903) stated that the tributaries contain organic matter in proportion to that of the Illinois River itself. Thus, we view the Illinois River as integrating water-quality conditions in the Illinois River watershed.

Biogeochemical Cycles

In order to understand the standing N-cycle paradigm and its significance for establishing reference/background conditions and the impacts of agriculture on the N cycle, we first consider the N cycle itself in the context of biogeochemical cycles.

The concept of **biogeochemical cycles** is an important part of the framework for this assessment. It is a concept that recognizes the dynamism of multiple, complex processes in the earth, atmosphere, hydrosphere, and biota that move, transform, and store chemicals. The term biogeochemical cycles expresses interactions among the organic **(bio-)** and inorganic **(geo-)** worlds, and focuses on chemistry **(chemical**), and the dynamism and interconnections among the processes **(cycles)**. A separate biogeochemical cycle can be identified for each chemical element.

On a global scale, the total amount of N is fixed. However, what is important to this study is the fact that N constantly moves from one reservoir to another. It also combines with other elements, such as oxygen and hydrogen, to form a variety of chemical compounds.

Water (H_2O) exists in three forms: liquid, solid, and vapor. The movement of water between the earth, atmosphere, biota, and oceans is of central importance to this assessment of nutrients. Most importantly, water is the medium that transports dissolved nutrients and particulate matter from the land to the streams, rivers, lakes, and reservoirs. From the land and surface waters, water either returns to the atmosphere through the processes of evaporation and transpiration, enters ground-water aquifers, or continues its flow into the oceans of the world. Evaporation from the world's oceans results in the flux of large amounts of water vapor into the atmosphere. Carried by the winds and condensed in the atmosphere, this water vapor is returned to the earth as precipitation. This movement of water is called the **hydrologic cycle**.

Many aspects of the hydrologic cycle are important in this assessment. The amount, type, and intensity of precipitation affect the rate of surface-water runoff, erosion, ground-water recharge, and leaching. In combination with land cover, land-use practices, soil, geomorphologic and climatic factors, and atmospheric deposition, the amount, type, and intensity of precipitation affect the concentrations and loads of nutrients and sediments in surface water and ground water.

Three parts of the hydrologic cycle are pertinent to the fate and transport of nutrients in ground water that may ultimately leave Illinois by surface water: i) recharge to ground water by the infiltration of precipitation through the unsaturated zone, ii) migration through the saturated zone, and iii) discharge of ground water to surface-water bodies.

In this report, we examine the N cycle in terms of its major components: reservoirs, fluxes, and transformations. Soils, plants and animals, the atmosphere, and surface waters and ground waters store a lot of N in their reservoirs. Movement of N within and among the reservoirs constitutes the fluxes. Chemical transformations from one form of N to another occur both within the reservoirs and during the fluxes.

The Nitrogen Cycle and Some Human Impacts on the Nitrogen Cycle

The N cycle can be studied on global, national, state, and smaller scales. It can be described as the transfers of N among and within four major spheres or reservoirs: geosphere, biosphere, hydrosphere, and atmosphere.

Under the standing N-cycle paradigm, the impact of agriculture on water quality is understood and modeled as being one of cultural eutrophication, i.e., organic enrichment. By definition, adding fertilizer enhances crop yields above and beyond what the soil's "natural" fertility (current nutrient status sans fertilizer) can produce. Thus, by definition of the standing N-cycle paradigm, farmers cause fertilizer nutrients to leak to surface waters above and beyond what would "naturally" leak.

Also, by definition, agricultural practices of soil preparation (e.g., plowing and draining), which are modeled as enhancing the leakage of both "natural" and fertilizer-added nutrients from soil to surface waters are those considered in the standing paradigm (e.g., Talkington, 1991; Turner and Rabalais, 1991; Ver, McKenzie, and Lerman, 1994; Kinzig and Socolow, 1994; Puckett, 1995; Jordan and Weller, 1996; David et al., 1997; Vagstad, Eggstad, and Hoyas, 1997; Van der Hoek et al., 1998; Burkart and James, 1999; Doering et al., 1999; Downing et al., 1999; Goolsby et al., 1999; Rabalais et al., 1999; Smil, 1999; U.S. Geological Survey, 1999a; David and Gentry, 2000a, b).

In regard to N, agricultural practices of fertilization and soil preparation are universally considered as unnaturally N saturating the landscape, thereby enhancing the flow of N to surface- and ground waters, especially in the form of NO_3-N (Dawes, Larson, and Harmeson, 1969; Commoner, 1968, 1970; Harmeson and Larson, 1970; Kohl, Sheaver, and Commoner, 1971; Turner and Rabalais, 1991; Jordan and Weller, 1996; David et al., 1997; Van der Hoek et al., 1998; Downing et al., 1999; Goolsby et al., 1999).

Thus, the standing paradigm of agriculture's influence on surface-water quality is, by definition, a one-way street toward increased eutrophication, i.e., enrichment above and beyond what is defined to be the "natural" fertility of both soil and water.

However, objective analysis of historic observations, biological and chemical observations, and data of the Illinois River system and its watershed indicate a need to re-examine the definitions and concepts the standing paradigm uses to model agriculture's impact on surface-water quality.

We start with the standing paradigm's definition of "natural" soil fertility.

Most scientific experts researching the effects of agriculture on water quality treat plowed fields as always having been plowed fields. Objective analysis shows otherwise. It is well documented that the first European settlers who laid eyes on Illinois were not greeted by vast, long-established farm fields stretching out farther than the eye could see, and which needed massive additions of chemical fertilizers to sustain their productivity. It is well known that pre-European-settlement conditions in the Illinois River watershed were dominated by prairie of extraordinary natural productivity. While Native Americans did manage the land to maximize its fertility, such management techniques did not include massive additions of chemical-N fertilizer (Buck, 1912, 1967; Welch, 1979; Iverson et al., 1989; Samson and Knopf, 1994; Illinois Natural History Survey, 1999).

Nevertheless, the fertility of the IRB prior to European settlement probably was even greater than today's heavily fertilized landscape. For example, Illinois Agricultural Experiment Station Bulletin 761, *Nitrogen Use and Behavior in Crop Production*, states:

"Early Illinois settlers found millions of acres of soils rich in organic matter. As bacteria decomposed this material, nitrogen was converted from organic to inorganic forms, which became available for plant uptake. During the first decade of cultivation, the prairie soil was apparently too rich for wheat: the wheat tended to grow too tall and then fall over, or lodge, thus reducing grain yields" (Welch, 1979, p. 10).

This is a most remarkable observation once one realizes that of all crops, wheat has the most difficulty in obtaining nitrogen, e.g., "wheat is nearly helpless in obtaining it" (Snyder, 1905, pp. 216-217).

Regarding corn, even under methods of cultivation considered less than optimal for even the early 1800s, "the corn grew 'from 12 to 15 feet high on average'" (Buck, 1967, p. 133) with a single ear of corn growing from the top of each of these giant Jack-in-the-beanstalk-size corn plants (Buck, 1912).

Such luxuriaent vegetative growth accompanied by depauperate growth of grain is the consequence of massive nitrogen overfertilization (Snyder, 1905, p. 213). Even deliberate, massively overfertilized field experiments (e.g., Sabey et al., 1975; Motavalli et al., 1989) only begin to approach the fertility documented for Illinois' native prairie soil (Buck, 1912, 1967; Welch, 1979). Clearly, massive amounts of N were being fixed naturally from the atmosphere in Illinois' tallgrass prairie soils.

However, after the introduction of European agricultural practices, N fixation and the store of fixed N declined, along with other nutrients. For example, early study at the Morrow Plots at the University of Illinois in Urbana-Champaign indicated a loss of about 20 percent of soil N after just 16 years of growing corn. Studies in Illinois, Indiana, and Wisconsin for a variety of crops indicated a loss of about one-third of soil P after about 50 years (Hopkins, 1910, pp. 559-560). A century of mining the soil of its nutrients [e.g., N, P, potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg)] has caused soil natural fertility and crop yields to decline to the point that massive additions of nutrients became necessary (e.g., Conner, 1922; Albrecht, 1938; DeTurk, 1938; Whiteside and Smith, 1941; Viets and Hageman, 1971; Odell et al., 1984; Stevenson, 1986), which, along with improved plant varieties and agronomic practices improved yields (Viets and Hageman, 1971; Stevenson, 1986; Avery, 1991; Zimdahl, 1999).

Accordingly, we will not simply assume that the current "natural" (unfertilized) soil nutrient status and N-fixing capacity is that of pre-European-settlement soil. In place of the standing paradigm's simplifying assumption, we will use best available data and science to estimate the pre-European-settlement nutrient status of the Illinois prairie landscape.

Regarding the modeling of the transmission of watershed nutrients to surface waters prior to European settlement, the standing paradigm assumes that tallgrass watersheds released very little of their nutrients to surface waters. Pre-settlement surface waters of tallgrass prairies are assumed to be nutrient-poor (oligotrophic), low-organic-load waters, e.g.,

"...before Europeans settled and plowed the tallgrass prairie, the natural lakes (oxbow) fed by prairie streams and rivers were oligotrophic" (Dodds et al., 1996).

By definition, oligotrophic waters are so low in nutrients that the paucity of algae (and suspended sediments) results in them having transparencies (secchi depths) greater than 12 feet (e.g., Carlson, 1977): 26 feet by the USEPA's new proposed reference water-quality criteria. Overall, the soils, vegetation, and waters of tallgrass prairies are assumed to be naturally undisturbed prior to European settlement and, with this, low in NO_3-N. The flux of N and other nutrients from prairie watersheds is also assumed to be extraordinarily low naturally (National Research Council, 2000, pp. 100-101; Goolsby et al., 1999). This has been a long-standing paradigm, held by such notables as Barry Commoner (1970), Aldo Leopold (1949), and H.H. Bennett, the Father of the Soil Conservation Service. The latter, in his classic textbook, *Soil Conservation*, stated that both the Mississippi and Missouri Rivers were clear-water, oligotrophic rivers prior to European settlement, which became turbid only during times of flood (Bennett, 1939, p. 1).

It is against this perceptual standard of reference/background conditions that the impacts of agricultural (and other anthropgogenic) activities in the MRB are measured. To compound the problem, previous attempts to establish reference/background conditions have relied on rather simplistic global analyses. Maybeck (1982), for one, recognizes the paucity and poor quality of data used to establish reference/background conditions in temperate regions.

As with the rest of the MRB, the Illinois River is asserted to have been a clear-water stream prior to European settlement, which only became turbid during times of flood (Mills et al., 1966). The Illinois River system today is asserted to be under greater nutrient and organic loading (more eutrophic) than it was prior to European settlement (Talkington, 1991, pp. 29-32).

Consequently, for Illinois, we recognize the need for detailed, objective analysis of historic observations, biological and chemical observations, and data of the Illinois River system and its watershed to examine the standing paradigm's assumed surface-water quality status prior to the conversion of Illinois' prairie to Corn Belt.

In 1821, the Illinois River was described by Schoolcraft as follows:

"AUGUST 5th. We entered the Illinois River at an early hour. The point of confluence is twenty-five miles above the junction of the Missouri. It presents to the eye a smooth and sluggish current, bordered on each side by an exuberant growth of aquatic plants, which in some places reach nearly across the channel. We soon found the water tepid and unpalatable, and oftentimes filled with decomposed vegetation to a degree that was quite offensive" (p. 85).

And:

"*August 9th*. About nine o'clock in the morning we came to a part of the river, which was covered for several hundred yards with a scum or froth of the most intense green color, and emitting a nauseous exhalation, that was almost insupportable. We were compelled to pass through it. The fine green color of this somewhat compacted scum, resembling that of verdigris, led us at the moment to conjecture, that it might derive this character from some mineral spring or vein, in the bed of the river, but we had reason afterward to reject this opinion. I directed one of the canoemen to collect a bottle of this mother miasmata, for preservation, but its fermenting nature baffled repeated attempts to keep it corked. We had daily seen instances of the powerful tendency of these waters to facilitate the decomposition of floating vegetation, but had never observed any so matured and complete state of putrefaction. It might certainly justify an observer, less given to fiction than were the ancient poets, to people this stream with hydra" (p. 91).

Part of the general description of the character of the Illinois River in 1821 was:

"We found the duck and mallard, black duck, teal, and brant, in great numbers upon all parts of the stream. It is also well stocked with the cat and buffalo fish, and the gar, besides some other species, which are more esteemed. The first mentioned species are not generally eaten in the summer months. But when taken among other fish, are sometimes given as food to hogs..." (Schoolcraft, 1918, p. 98).

The above description sheds light on a cultural peculiarity observed of the Native Americans who lived on the banks of the Illinois River. Whereas Native Americans throughout the United States were skilled fishermen wherever fish were available, those living along the watercourses of the Illinois River apparently had little use for fish. Even though the Native Americans encountered by European explorers and early settlers "lived along the water courses and in the groves much as did the first white settlers...[t]hey cared little for fish but ate it when other food was scarce" (Buck, 1967, pp. 7-8).

To give an idea of what Illinois was like in the 1820s, when Schoolcraft made his observations:

"In 1823, Springfield was a frontier village containing a dozen log cabins; the site of Peoria was occupied by a few families, and that of Chicago by a military and trading post" (Starrett, 1972).

As previously mentioned, long ago Kofoid (1903) and Palmer (1903) by scientific observation, deduction, and verification, recognized that the soil of the Illinois River watershed was naturally supplying massive amounts of nutrients, particularly N, which supported the growth of vast quantities of aquatic plants (both macrophytes and algae) naturally found in the Illinois River system. Later research would verify that aquatic plants require huge amounts of external-source nutrients to grow, particularly N. Namely, later research has shown that aquatic plants are not N-fixing (except for blue-green algae), but have a crude protein content of 10 percent to 50 percent and a carbon (C):N ratio generally within a range of 5 to 20, which makes them even more N rich than the N-fixing, high-N-content legumes (Allgeier, Peterson, and Juday, 1934; Jacobs and Elderfield, 1934; Misra, 1938; Boyd, 1968; Moore, 1969; Hutchinson, 1975, pp. 371-405; Reddy, 1983; Ostrofsky and Zettler, 1986; Stevenson, 1986, Table 5.3). Accordingly, the massive amounts of aquatic vegetation, which earlier observers stated grew naturally in the Illinois River system (e.g., Kofoid, 1903; Palmer 1903; Sauer, 1916; Schoolcraft, 1918) required extraordinary amounts of nutrients. They had an extraordinarily huge N requirement, which was largely met by a huge natural supply of fixed N coming from the surrounding prairie. All of the above observations indicate that N fixation was occurring at remarkably high rates in order to support the luxuriant growth of prairie vegetation, maintain a prodigious soil N reservoir, while at the same time leaking great amounts of fixed N to the hydrosphere.

Accordingly, we will not simply assume that before the Illinois prairie was converted to Corn Belt that its surface waters were nutrient-poor, oligotrophic waters of remarkable clarity and low nutrient and organic loading. The reality is that the Illinois River system was hypertrophic prior to the conversion of prairie to Corn Belt (Forbes, 1887; Kofoid, 1903; Needham and Hart, 1903; Palmer, 1903; Cooley, 1913; Sauer, 1916; Schoolcraft, 1918; Greenbank, 1945) — not oligotrophic as assumed.

Consistent with our treatment of the definition of "natural" soil fertility, in place of the standing N-cycle paradigm's assumed oligotrophy of pre-European settlement surface-water quality, this report will use best available data and science to estimate the presettlement nutrient status of the Illinois prairie landscape and the movement of these nutrients, particularly N, to the hydrosphere.

The way scientists view the world, including the N cycle and modifications to the N cycle, is expressed in conceptual models or paradigms.

It has been observed that:

"Science is not the cumulative process portrayed in the textbooks; it is a succession of revolutions, in each of which one conceptual world view is replaced by another. But Kuhn sees no ground for believing that the new paradigm gives a better understanding of the world than did the old.... We may, says Kuhn, 'have to relinquish the notion, explicit or implicit, that changes of paradigm carry scientists and those who learn from them closer and closer to the truth'" (Wade, 1977).

Kuhn's observation appears relevant for the N cycle. Contrary to the perception of inevitably relentless progress in scientific knowledge, the current understanding of the N cycle represents a step down from that of the well-founded N-cycle paradigm it replaced.

The agreement between the assumed state of Illinois before European settlement and that modeled by the new N-cycle paradigm is achieved by erroneously quantifying the magnitude of the N cycle (and anthropogenic influence on it) in terms of atmospheric N fixation. Unlike the well-founded N cycle it replaced, the current N-cycle paradigm incorrectly defines N gas (N_2) in the atmosphere as the earth's dominant N reservoir and, thus, the source from which flows essentially all of our biological, useful N.

For example:

"Over 99.9 percent of the nitrogen in global biogeochemical reservoirs is stored in a form inaccessible to almost all living organisms: diatomic nitrogen either in the atmosphere or in solution in the ocean. The strong triple bond of the N-N molecule makes it nearly inert. To most of the biosphere, therefore, the nitrogen in the atmosphere is like the ocean to a thirsty person: amazingly abundant but not quite in the right form. Only a few species of aquatic and terrestrial bacteria and blue-green algae can convert N_2 into ammonium (NH_4^+) through the process of biological nitrogen fixation. This biological pathway provides the dominant natural flow of fixed nitrogen on the planet. Lightning, however, provides a nonbiological pathway for nitrogen fixation...rate of 3×10^{12} grams of nitrogen per year (3 Tg(N)/yr) [3 million metric tons N/yr], is only a few percent of the rate of [natural] biological nitrogen fixation.... Humans have approximately doubled the global rate of nitrogen fixation, from the 130 Tg(N)/yr fixed in preindustrial times...to nearly 280 Tg(N)/yr fixed today" (Kinzig and Socolow, 1994).

Based on this definition of the N cycle, the new scientific consensus is that some 80 million metric tons/yr of chemical-N fertilizer (11 million in the United States), some 20 million tons of N/yr fixed by combustion [6 million in the United States (United Nations Environment Programme, 1993)], plus about another 50 million metric tons equally contributed by recycling of anthropogenic organic wastes and agricultural plantings of N-fixing legumes, in total, represent a doubling of the N cycle from preindustrial times to a current level somewhat over 200 million metric tons N/yr (Kinzig and Socolow, 1994; Galloway et al., 1995; Galloway, 1998; Smil, 1999; Tables 1-4).

Table 1. Annual World Consumption of Nitrogen Fertilizer, Millions of Metric Tons

YEAR	*N*	*YEAR*	*N*
1959/60	9.54	1979/80	57.22
1960/61	10.48	1980/81	60.78
1961/62	11.59	1981/82	60.45
1962/63	13.14	1982/83	61.19
1963/64	14.76	1983/84	67.66
1964/65	16.47	1984/85	70.65
1965/66	19.10	1985/86	69.83
1966/67	22.18	1986/87	71.49
1967/68	24.21	1987/88	75.60
1968/69	26.25	1988/89	79.61
1969/70	28.47	1989/90	79.19
1970/71	31.76	1990/91	77.24
1971/72	33.53	1991/92	75.46
1972/73	36.14	1992/93	73.63
1973/74	39.20	1994	72.25
1974/75	38.43	1995	77.99
1975/76	44.42	1996	83.02
1976/77	45.26	1997	81.18
1977/78	49.12		
1978/79	54.25		

Sources: 1960-1993 data (G. Harris, personal communication, January 24, 1995); 1994-1997 data (S. Simpson, personal communication, December 20, 1999).

Table 2. Annual Consumption of Nitrogen Fertilizer in the United States ending June 30, Thousands of Metric Tons

YEAR	*N*	*YEAR*	*N*
1960	2,483.4	1980	10,345.8
1961	2,748.9	1981	10,814.9
1962	3,056.6	1982	9,961.7
1963	3,563.7	1983	8,278.2
1964	3,948.0	1984	10,060.6
1965	4,207.1	1985	10,423.8
1966	4,831.0	1986	9,454.9
1967	5,466.6	1987	9,260.0
1968	6,156.4	1988	9,534.0
1969	6,310.5	1989	9,607.5
1970	6,765.3	1990	10,045.9
1971	7,377.2	1991	10,237.2
1972	7,276.2	1992	10,381.9
1973	7,523.7	1993	10,332.0
1974	8,305.6	1994	11,467.0
1975	7,800.9	1995	10,628.7
1976	9,443.3	1996	11,159.2
1977	9,657.2	1997	11,203.4
1978	9,037.9	1998	11,160.5
1979	9,718.2		

Source: Data adapted from Table 1 (Anonymous, 1998).

Table 3. Annual Consumption of Nitrogen Fertilizer in Illinois, Thousands of Metric Tons

YEAR	*N*	*YEAR*	*N*
1970	521.0	1985	920.2
1971	588.3	1986	857.5
1972	511.3	1987	762.8
1973	491.7	1988	851.2
1974	653.0	1989	863.7
1975	735.3	1990	813.7
1976	844.0	1991	912.7
1977	881.1	1992	863.0
1978	706.5	1993	785.1
1979	821.7	1994	931.1
1980	936.8	1995	802.2
1981	901.9	1996	890.0
1982	930.9		
1983	703.4		
1984	946.5		

Source: Data adapted from Hoeft (1998).

Table 4. Estimated World Anthropogenic Nitrogen Emission to the Atmosphere from 1860 to 1990, Millions of Metric Tons

YEAR	*N*	*YEAR*	*N*
1860	0.4	1930	4.9
1870	0.7	1940	5.7
1880	0.9	1950	6.8
1890	1.3	1960	11.8
1900	2.2	1970	17.6
1910	3.3	1980	22.1
1920	4.2	1990	23.9

Sources: Estimated 1860 to 1980 world N emission data (Dignon and Hameed, 1989). Estimated 1990 world N emission data (United Nations Environment Programme, 1993) with missing data for South America, Africa and Oceania filled in with most recent data from Dignon and Hameed (1989).

The error of defining N_2 as the earth's dominant N reservoir and, thus, the source from which flows essentially all of our biological, useful N, is so fundamental that the error profoundly influences all aspects of estimates of anthropogenic impact on the biospheric N cycle. Because of the importance of this error, additional documentation is provided to show that this is indeed the consensus definition. To quote the introduction of Galloway's overview paper of the "First International Nitrogen Conference 1998:"

"As an introduction to this collection of papers on nitrogen, this overview discusses the natural N cycle, examines the degree that food and energy production have altered the N cycle, and reviews the consequences of these alterations on earth system processes....

"Imagine that you were to double the amount of nitrogen that you ate. Further imagine that some of the processes occurring in your body were limited by nitrogen (e.g., ability to synthesize fat), and that other processes were adversely affected by nitrogen (e.g., organ function). If this was the case, then a doubling of your N intake would make you larger, and you would suffer damage to critical components of your body. Not the best of all worlds.

"Speaking of worlds, the supply of reactive N to global terrestrial ecosystems has doubled as a consequence of human activity. The additional nitrogen has increased the productivity, and damaged components of the terrestrial and aquatic ecosystems..." (Galloway, 1998).

Or, said another way:

"Nitrogen is the major nutrient limiting productivity in most terrestrial habitats, including these Minnesota grasslands. The species composition, diversity and functioning of these and many other ecosystems depend on the rate of nitrogen supply and are thus being altered by increased atmospheric nitrogen from agriculture and combustion of fossil fuels" (Tilman and Downing, 1994).

And, to quote the introduction of Smil's 1999 review paper, "Nitrogen in crop production: An account of global flows," for *Global Biogeochemical Cycles*:

"Human interference in the global nitrogen cycle has become a topic of increasing research attention (Smil, 1990, 1991, 1997a; Kinzig and Socolow, 1994; Galloway et al., 1995; Jordan and Weller, 1996; Vitousek et al., 1997). Compared to the preindustrial era, human activities have roughly doubled the amount of reactive N that enters the element's biospheric cycle (Galloway et al., 1995; Smil, 1997a)....

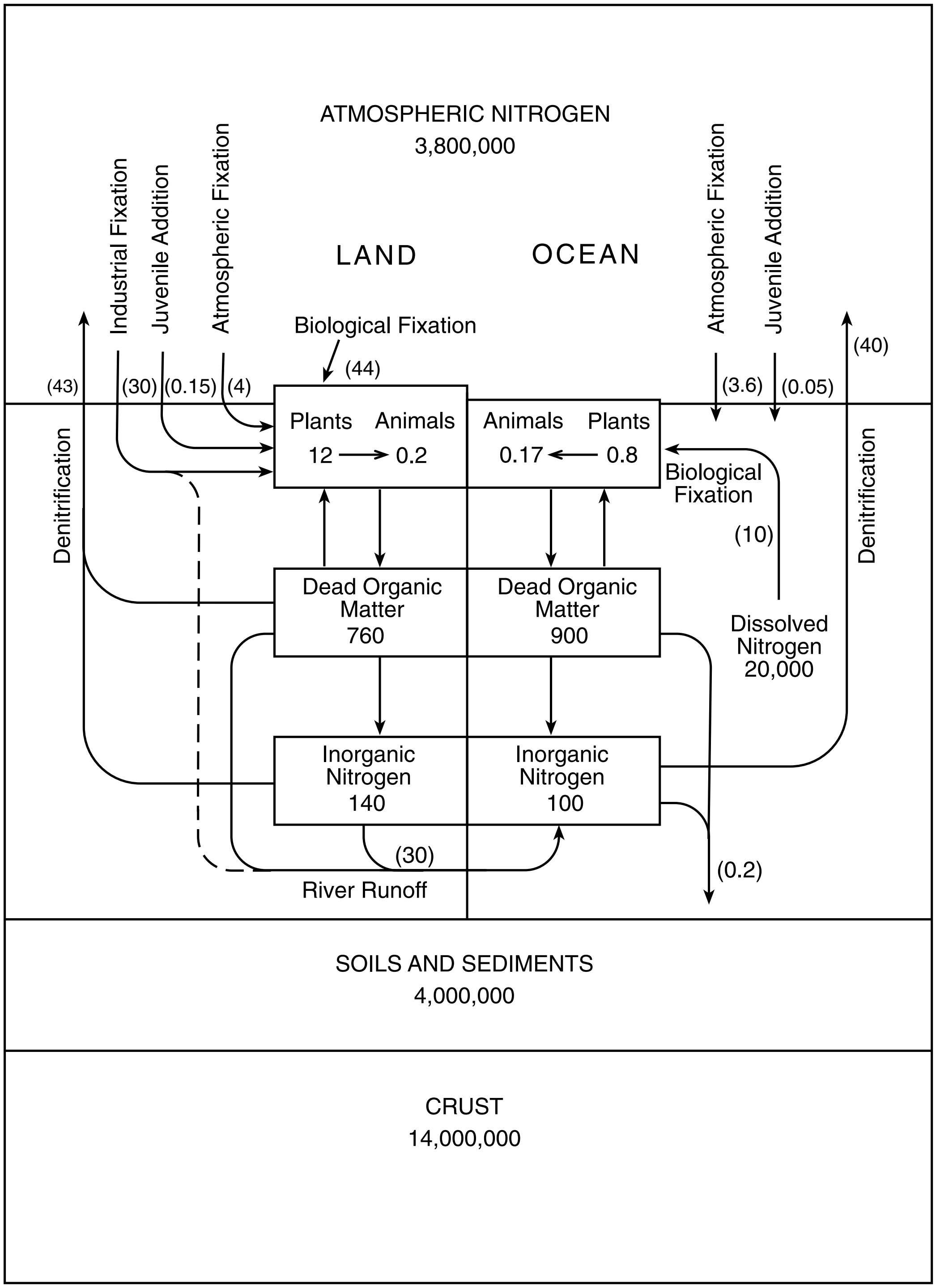
"Crop production is by far the single largest cause of human alteration of the global N cycle: *Rhizobium* bacteria symbiotic with leguminous crops fix much more N than would be the case if natural plant communities were occupying the same space, and N applied to fields in synthetic fertilizers (now about 80 Tg N yr^{-1}) is about four times as large as is the total amount of the element that humans fix by burning all fossil fuels (Galloway et al., 1995; Smil 1997a)" (Smil, 1999).

However, the earlier scientific literature on the N cycle, both the more general scientific literature — such as *Scientific American* (e.g., Delwiche, 1970) — and the more hard-core geochemistry and ecology literatures (e.g., Feth, 1966; Stevenson, 1972; Baur and Wlotzka, 1978; Furley and Newey, 1983) report that there is about as much N contained in soil and sediment — about 4 million billion ($4x10^{15}$) metric tons N — as there is in the atmosphere (Figure 2). Indeed, the earth itself is estimated to contain approximately 50 times more N as NH_4-N than the total amount of N in the atmosphere (Stevenson, 1982a). Some of this juvenile N that comprised the earth's original atmosphere still leaks out through volcanoes and geothermal waters to this day (Clarke, 1908, pp. 139-171, 212-237; Figure 2).

The older literature also reports what is obvious from the size of other biospheric cycles of the other chemical elements, such as the C cycle: namely, the biospheric N cycle is massively larger than the now asserted 100 million metric tons/yr. The older literature documents that the natural biospheric-N cycle is on the order of 10 billion ($10x10^9$) metric tons N/yr (Beevers and Hageman; 1969; Viets and Hageman, 1971; Soderlund and Svensson, 1976) with the natural terrestrial component of the N cycle estimated to be on the order of 6 billion ($6x10^9$) metric tons N/yr (Rosswall, 1976; Figure 3).

Thus, the reported anthropogenic ~100 million metric ton N/yr increase does not represent a doubling of the 10 billion tons N/yr natural biospheric-N cycle: it represents about a 1 percent increase.

The older literature, which existed under the previous N-cycle paradigm, such as the prestigious SCOPE 7 Report on global cycles of N, P, and S (Svensson and Soderlund, 1976) and other contemporary authoritative experts of that time talked openly and plainly about the N cycling between soil and plants as a major portion of the global N cycle and that one much larger than global atmosphere and hydrosphere exchanges of N (e.g., Figures 2 and 3). Such statements of fact were based on a wealth of information and knowledge, including the enormous natural production of NO_3-N: NO_3-N being arguably the most important form of N taken up by terrestrial



Units in 10^9 metric tons, transfer rates (in brackets) in millions of metric tons

Figure 2. The global distribution and quantities of nitrogen in reservoirs within the general circulation.
Source: From Figure 3.8 of Furley and Newey (1983) based on data of Delwiche (1970).

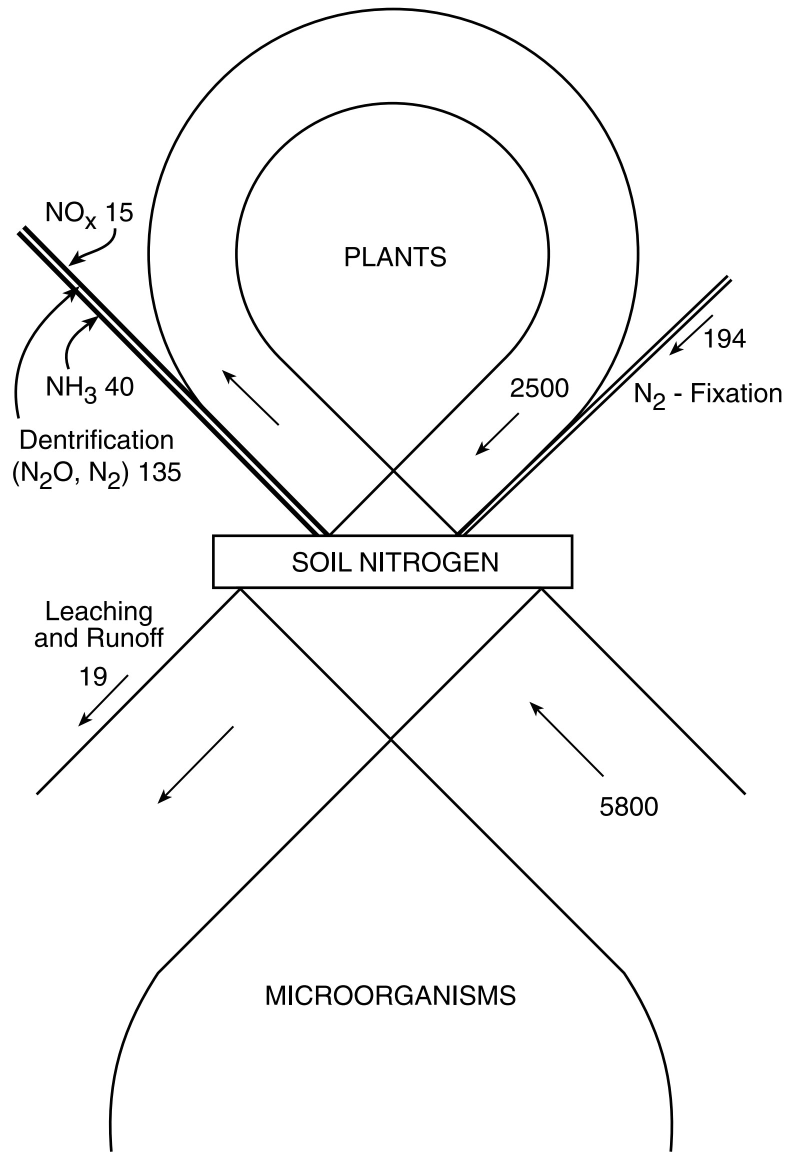


Figure 3. The global soil nitrogen cycle.
Source: From Figure 5 of Rosswall (1976). Data in millions of metric tons.

plants. For example, in a 1971 review of NO_3-N's role in the N cycle the U.S. Department of Agriculture (USDA) estimated that 100,000 research experiments had been conducted just on the leaching of NO_3-N in soil water alone (Viets and Hageman, 1971).

Today, with the shift to the new, standing N-cycle paradigm, many thousands of lifetimes of work on the N cycle, which do not support the current understanding, appear to have been removed from the awareness of the scientific community.

An unfortunate consequence is that, by excluding 99 percent of the global biospheric N cycle, the current understanding of the N cycle removes the framework necessary for scientists and policymakers to consider how human activities may have altered portions of the now scientifically invisible 99 percent of the N cycle. Also, by removing the bulk of the N cycle from the awareness of today's scientists, the shift to the new understanding has removed most of the body of knowledge that scientists could use to improve scientific understanding of the nature and quantity of the tiny fraction of the N cycle that is still recognized — atmospheric N fixation itself. Indeed, the researchers of the SCOPE 7 Report, in considering the more comprehensive N cycle, observe that the cycle of fixed N between the earth and the atmosphere has an error in it equal to or larger than the estimated amount of atmospheric N fixation itself (Soderlund and Svensson, 1976).

On the other hand, restoring the fruits of these many thousands of lifetimes of scientific research on the N cycle presents us today with a remarkable opportunity to vastly improve the current understanding.

In regard to understanding how agricultural activities have influenced terrestrial-N reservoirs, and through this the transfer of N to the hydrosphere, we must consider not only the fruits of the Second Agricultural Revolution (the current era of machines and chemical fertilizers), but we must consider also the fruits of the First Agricultural Revolution (the era of the animal-powered plow-and-hoe agriculture). In regard to the fruits of the First Agricultural Revolution, the SCOPE 7 Report on global cycles of N, P, and S (Svensson and Soderlund, 1976), Rosswall (1976) estimated that agricultural practices have reduced the amount of N in world soils by 13 billion metric tons in the previous 60 to 70 years.

Using Rosswall's (1976) value, 1 to 3 percent of soil N is biologically mineralized to NO_3-N and NH_4-N per growing season (and assuming this value for a calendar year); just for this component of the soil N cycle, human activities have reduced the global terrestrial biospheric N cycle by some 130 million to 390 million metric tons NH_4-N + NO_3-N/yr. This decrease in the terrestrial biospheric flux of NH_4-N + NO_3-N/yr can be compared to the about 80 million metric tons N/yr of chemical-N fertilizer now added to terrestrial biosphere per year (Table 1). It also can be compared to the estimated total anthropogenic N increase of 150 million metric tons N/yr to the entire global biospheric N cycle.

Regarding the effects of agriculture on the soil-N reservoir in the United States, the USDA's Agricultural Research Service's Agriculture *Agriculture Handbook No. 413* reports that in the conterminous United States, agricultural activities are estimated to have reduced the store of soil N by 1.75 billion tons (Viets and Hageman, 1971, p. 14) with Midwest Corn Belt soils undergoing the greatest loss: soil N estimated to have been halved by past agricultural practices (Commoner, 1970; Stevenson, 1986, p. 55).

Using the 2 percent annual soil-N mineralization rate currently employed for U.S. agricultural soils (e.g., Burkart and James, 1999; Goolsby et al., 1999), agricultural land-use practices have decreased the N cycle in the United States by 35 million tons N/yr. This value can be compared to a high of about 11 million tons N/yr of chemical N fertilizer added to U.S. agricultural soils in recent years (Table 2).

Finally, employment of a more realistic definition of the effect of agriculture on the terrestrial/biospheric N cycle provides more realistic assessment of N transfers from the terrestrial to other components of the global N cycle. Since the early years of the well-founded N-cycle paradigm and long before the era of chemical-N fertilizer, it was recognized that, on average, about a third of soil NO_3-N was lost to the hydrosphere (e.g., Storer, 1905, p. 341). Rosswall (1976) and others (e.g., Viets and Hageman, 1971; Stevenson, 1986, pp. 145-149), in reviewing more recent scientific research, estimate that 20 - 30 percent of the billions of tons of natural N removed from soil was lost as NO_3-N to the hydrosphere — a range of values still used today for N so lost from applied N fertilizer (Turner and Rabalais, 1991), e.g.,

"When nitrogen-based fertilizer is applied to a field, it can move through a variety of paths to downstream aquatic ecosystems. Some fertilizer leaches directly to groundwater and surface waters, varying from 3 to 80 percent of the fertilizer applied, depending on soil characteristics, climate, and crop type (Howarth et al., 1996). On average for North America, about 20 percent leaches directly to surface waters (NRC, 1993a)" (National Research Council, 2000, p. 25).

Given that a loss of 13 billion metric tons of N over 60-70 years represents an average loss of 200 million tons of natural soil N/yr, this calculates as an average transfer of 40 to 60 million metric tons $N0_3$-N/yr to the hydrosphere during the 20th century.

This range of values can be compared to the 16 to 24 million metric tons NO_3-N/yr similarly estimated to be leached to the hydrosphere from the annual use of ~80 million metric tons of chemical -N fertilizer/yr globally (Table 1).

In conclusion, the weight of the evidence compels us to abandon the current consensus definition of the effect of agriculture on the N cycle — which is based on the implicit assumption that the soil's "natural" N-fixing ability in the absence of modern Europeanized humanity is trivial; that the soil's "natural" fertility is its current nutrient status sans fertilizer addition and, therefore, fertilizer additions cause nutrients to leak to surface waters above and beyond what would "naturally" leak. Clearly, the natural condition encountered by the first European explorers and settlers in Illinois was not long-established corn and soybean fields stretching out farther than the eye could see.

Thus, in order to scientifically assess the effect of post-European-settlement agriculture on the N and other nutrient cycles and, ultimately, the effect of agriculture on organic loading (eutrophication) of Illinois' surface waters, the following section "Reference/Background Pre-European-Settlement Conditions" assesses what the reference/background, pre-European-settlement background state of the IRB really was. "Water-Quality Reference/Background Conditions" discusses water-quality conditions during pre-European-settlement times. "Some Effects of Agriculture on Watersheds" and "Some Other Anthropogenic Effects on Nitrogen Water Chemistry " discuss some effects of agriculture and other activities on watersheds and nitrogen water chemistry. From this, assessment of the impacts of post-European agriculture is made. "Conclusions" presents conclusions and recommendations for additional research. References are provided at the end of the report.

REFERENCE/BACKGROUND PRE-EUROPEAN-SETTLEMENT CONDITIONS

The standing N-cycle paradigm's definition of the pre-settlement, reference/background condition was stated by Commoner (1970):

"2. THE NATURAL NITROGEN CYCLE.

"The soil is a useful place to begin. Nitrogen is crucial in the soil economy.... Slowly, bacteria release nitrate from humus and decaying organic wastes — manure and the residues of animals and plants. The resultant concentration of nitrate in the soil water is very low and the roots need to work to pull it into the plant....

"When the United States was settled, the soil system was in this natural condition.... In virgin land only a very small amount of nitrate escapes the plant's root systems and leaches out into surface waters, or escapes to the air in volatile compounds: nitrogen gas, ammonia, and nitrogen oxides; and the last two are soon returned to the earth in rain and snow.

"In natural waters a similar nitrogen cycle prevails, except that the large reserve of organic nitrogen represented by the soil humus is lacking...organic nitrogen is quickly converted into inorganic form; the bacteria of decay free nitrogen from its organic combination with carbon and hydrogen, and unite it with oxygen to form, ultimately, nitrate...nitrate in turn nourishes the aquatic plants, chiefly algae; these in turn furnish food for fish and other animals, and the cycle is complete. In a balanced natural system the amounts of organic nitrogen and nitrate dissolved in water remain low, the population of algae and animals is correspondingly low, and the water is clear and pure. And because the natural nitrogen cycle in the soil is tightly contained, relatively little nitrogen is added to the water in rainfall, or in drainage from the land."

Commoner did not himself develop this hypothetical romantic model of the Rousseauian Perfect Natural State. As documented earlier in "The Nitrogen Cycle and Some Human Impacts on the Nitrogen Cycle," it had been the consensus hypothesis among the earlier conservation elite for nearly a century. Nevertheless, it was Commoner who applied the hypothetical Perfect Natural State model specifically to N. And it was he who established it as the new standing N-cycle paradigm and its progeny — the N-overfertilization issue. It is a world view held to this day that the land prior to European settlement was undisturbed and leaked but extraordinarily low amounts of N to the hydrosphere (e.g., National Research Council, 2000, pp. 100-101; Goolsby et al., 1999).

Clearly, by this new, standing N-cycle paradigm, the natural state of the hydrosphere was one where NO_3-N concentrations did not rise high enough (0.3 milligrams per liter or mg/l) to turn water a murky green (Commoner, 1970). Let alone could NO_3-N concentrations naturally rise to the much higher 10 mg NO_3-N/l level that may initiate blue baby syndrome (infantile methemoglobinemia) in pregnant women (Commoner, 1970). Let alone could concentrations of NO_3-N in soil water naturally rise to such catastrophic levels as to cause plant materials to be poisoned by NO_3-N concentrations great enough to threaten the health of those who ate such NO_3-N-poisoned food, e.g., "...concentration of nitrate in the soil water is very low and the roots need to work to pull it into the plant" (Commoner, 1970).

It was this hypothetical natural (reference/background) condition that Commoner, and later others, used as the reference/background condition to assess the effect of modern agriculture on water quality. Whereas this philosophical consensus of oligotrophy of tallgrass prairie surface waters now exists, it is not based on the reality of actual historic observation and measurement — the historic observations instead show the Illinois River to have been naturally hypertrophic ("The Nitrogen Cycle and Some Human Impacts on the Nitrogen Cycle").

Commoner assessed the effects of agriculture on the water quality of the Illinois River system by asserting that the Illinois River in its pristine state was literally a river of flowing Perrier. Against this utopian setting (asserted as real fact) of rivers of flowing Perrier, the present state of surface-water quality was compared:

"A particularly useful set of data is available on the nitrate content of the rivers of Illinois where for the last 25 years the Illinois State Water Survey has been making increasingly detailed studies of the quality of surface waters. Illinois is intensively farmed (about 60% of the state's area is in crop land) and the system of farming involves very heavy use of inorganic chemical nitrogen fertilizer. As in most parts of the U.S., the use of inorganic nitrogen fertilizer has increased by an order of magnitude in the last 20-25 years....

"Other possible sources of stream nitrogen are animal wastes from feedlots, urban sewage, and nitrogen compounds present in rain and snow. Feedlots are relatively scarce in Illinois and may be disregarded as a significant source of stream nitrogen. Precipitation can also be ruled out as an important source of river nitrate since the average nitrate nitrogen content of precipitation in that area is about 0.1-0.2 ppm, whereas the Kaskaskia and the Sangamon exhibit nitrate-nitrogen concentrations in excess of 5 ppm....

"What are the consequences of the nitrate levels which have been induced in Illinois surface waters by intensive nitrogen fertilization? The Illinois State Water Survey data show that all of the State's rivers which traverse heavily farmed land — and this compromises all but a few of the State's streams — have nitrate levels which are far in excess of those which lead to heavy algal growth (this level is usually estimated at about 0.3 ppm of nitrogen). Indeed, the survey has recently announced that the State's streams, as a whole, have now become eutrophic — so burdened with nutrients as to support algal blooms, which impose a sufficient organic load on the water to deplete its oxygen supply....

"Illinois also faces a health hazard due to the high nitrate levels of most of its rivers. The acceptable limit for the nitrate-nitrogen concentrations of potable water established by public health agencies is 10 ppm.... It has also been reported that about 25% of Illinois groundwaters from shallow wells of 25 ft. depth or less, contain more than 10 ppm of nitrate-nitrogen and that groundwater derived from fertilized fields frequently contains over 14 ppm of nitrate-nitrogen in the spring months. It would appear, therefore, that in the rural regions of Illinois the intensive use of nitrogen fertilizer has created a public health problem due to high levels of nitrate in potable water....

"5. EXCESSIVE NITRATE IN FOODS

"Under natural circumstances, before the intrusion of modern agriculture, nearly all of the soil nitrate which nourishes the plant is converted to protein and other organic plant constituents; in most plants relatively little of the observed nitrogen accumulates as nitrate. However, at the heavy rates of chemical fertilization now widely used in the U.S., this situation has been changed; plants grown on soil heavily fertilized with nitrate contain much-increased amounts of nitrate. For example, a lettuce crop grown on Missouri soil without added nitrogen contained about 0.1% of nitrate-nitrogen; given 100 lb/acre of nitrate fertilizer the lettuce nitrate content increased to 0.3% and at about 400 lb of nitrogen fertilizer per acre, the nitrate content of the crop reached a maximum of 0.6%. Other possible causes of nitrate accumulation in crops are weather conditions, light intensity, and time of harvest....

"The increasing importance of nitrate poisoning in livestock, which has been widely noted, also suggests that the nitrate levels of crops which are used in livestock feeds have been increasing in recent years" (Commoner, 1970).

Whereas contemporary measurements of NO_3-N in food (Viets and Hageman, 1971) soon caused the NO_3-N food poisoning issue to disappear, worrisomely high concentrations of NO_3-N in ground waters and surface waters sustained the NO_3-N-in-water issue. And the new, standing N-cycle paradigm produced its own supporting set of self-sustaining "scientific facts," such as: "that before Europeans settled and plowed the tallgrass prairie, the natural lakes (oxbow) fed by prairie streams and rivers were oligotrophic" (Dodds et al., 1996)[2]; that the soils, vegetation and waters of tallgrass prairies were naturally low in NO_3-N, and the flux of N out of prairie water-sheds is naturally extraordinarily low (Goolsby et al., 1999); and, as reported by the Illinois State Water Survey itself, the consensus that the Illinois River is under greater organic loading (more eutrophic) than it was prior to European settlement (Talkington, 1991, pp. 29-32).

Regarding the new standing paradigm's assessment of soil fertility, it is correct in its asserted general relationship between concentration of plant-available N in the soil and the concentration of N in the plant. This is shown in Figure 4, which illustrates that increasing the rate of N fertilization not only increases crop yield, it also increases the concentration of N in that crop.

However, the soil/plant-N relationship is being applied incorrectly under the standing N-cycle paradigm, as it incorrectly assumes oligotrophy for the soils and waters of Illinois' prior to European settlement when, in fact, they were hypertrophic ("Two Great Landscape Elements"). Indeed, the standing N-cycle paradigm is not only inconsistent with the older scientific literature, but it also survives in spite of the fact that it is also inconsistent with the modern scientific literature. As documented earlier, naturalists and scientists up to the present day relate the great natural fertility of most of Illinois' surface waters to the great natural fertility of most of Illinois'soils, i.e., those created under moist (tallgrass) prairie vegetation (Forbes, 1887; Kofoid, 1903; Palmer, 1903; Schoolcraft, 1918; Thompson and Hunt, 1930; Bellrose, 1941; Larimore and Smith, 1963; Sefton et al., 1980; Sorenson et al., 1999).

Contrary to the predictions of the standing N-cycle paradigm, the historic description of Illinois' pre-European-settlement landscape indicates that truly massive amounts of NO_3-N and other biologically available forms of N were naturally released from Illinois' soils. The amounts of NO_3-N were not only promoting the luxuriant growth of Illinois' tallgrass prairie vegetation, the supply was so excessive that massive amounts of NO_3-N were getting past the plant roots and into the water, thereby promoting the suffocating growth of N-rich aquatic vegetation and algae in Illinois' surface waters.

The luxuriant growth of N-rich terrestrial prairie and aquatic vegetation indicate that the pre-European-settlement landscape of Illinois was an N-saturated landscape, which, if seen today in an agricultural setting, would be said to be suffering from massive "overfertilization." Truly prodigious amounts of N fixation were occurring in the absence of modern European agriculture. Other data and observations available allow further evaluation of the N-saturated status of the pre-European Illinois landscape.

First, we can use the soil/plant relationship to test the NO_3-N status of the pre-European Illinois landscape, as Commoner and others used it to test the NO_3-N status of Corn Belt soils treated with chemical-N fertilizers.

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[2]By definition, oligotrophic waters have transparencies (secchi depths) greater than 12 feet (e.g., Carlson, 1977): 26 feet by the USEPA's technical guidance for new proposed reference water-quality criteria.

As seen in Figure 4, increasing additions of chemical-N fertilizer increase plant-available N to the degree that N not only increases plant yield, it also increases the N content of that greater quantity of plant material. However, well before optimum crop yield is achieved in response to increasing N, the soil becomes N-saturated and progressively greater amounts of N are leached to the hydrosphere in response to increasing N.

Conversely, whereas losses of NO_3-N to the hydrosphere increase with increasing biologically available N, for plant productivity, the benefit of increasing soil N progressively decreases (Figure 4). In agriculture, this is known as the law of diminishing returns — the unit increase in yield per unit N-fertilizer addition levels off to approach zero. Given the ever-increasingly unfavorable cost/benefit ratio and increasingly negative environmental impact with increasing N fertilizer application, agronomic-fertilizer recommendations are not made for achievement of maximum yield. But, rather, on the basis of economics alone, fertilizer recommendations are made for maximum benefit (maximized profits) from the use of N fertilizer, not for maximum crop yield (see "Plowing and Fertilizing").

The hypertrophic status of Illinois' pre-European-settlement terrestrial and aquatic landscape suggests that the soil/plant N relationship may need to be extended beyond the point of maximum yield as is done in Figure 5, which shows that with truly monumental additions of N

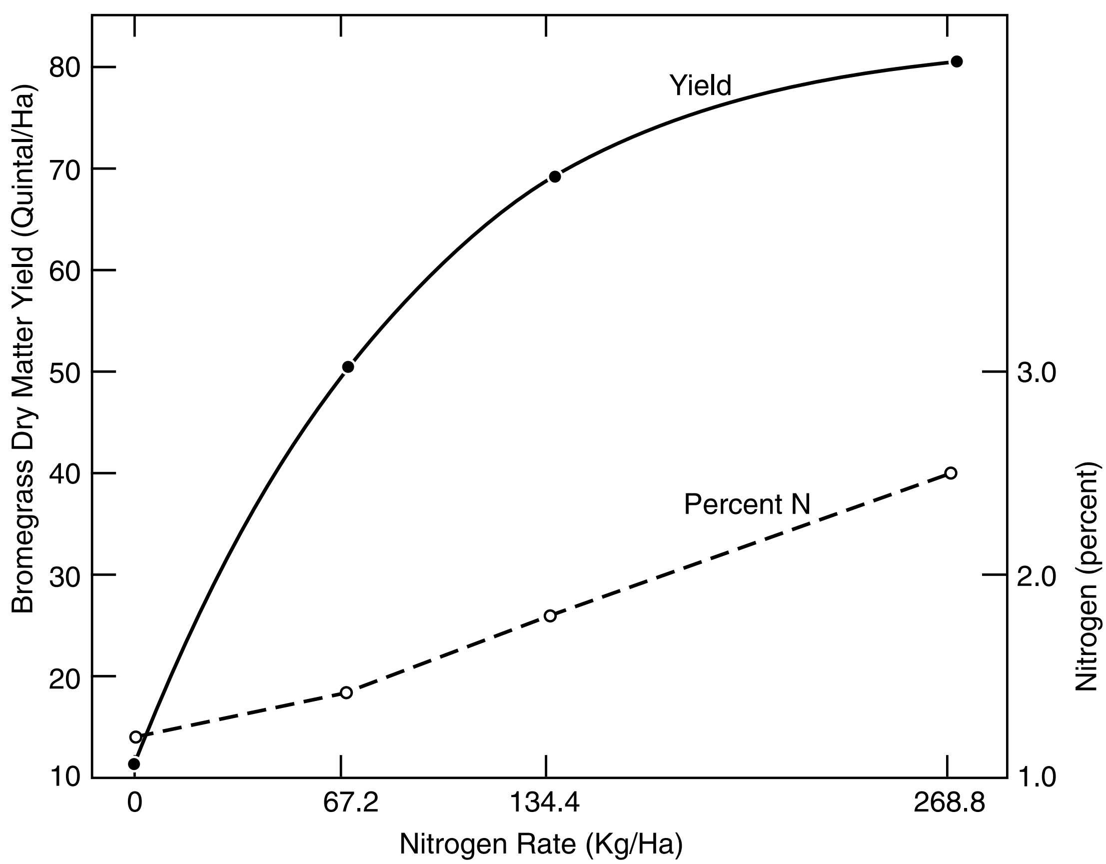

Figure 4. Yield and nitrogen content of bromegrass in relation to quantity of chemical nitrogen fertilizer applied.
Source: Figure 2 of Munson and Nelson (1973).

fertilizer it is possible to actually decrease crop yield. In modern agriculture, Figure 5 is a technical and experimental point rather than a practical one — farmers do not overfertilize with N fertilizer to achieve optimum (maximum) yield, let alone overfertilize to the extraordinary extent of decreasing yields. On the other hand, agronomists researching the theoretical limits of plant nutrient response do, on occasion, overfertilize with N to the extent of reducing crop yield.

From these extreme soil/crop N relationship experiments, we know that when N fertilization exceeds that which produces maximum yield, not only does yield decrease, the concentration of N in plant material rises sharply with increasing N fertilizer application (Figure 5).

Figure 5 and the 19th century data indicate that the amount of NO_3-N present in Illinois agricultural soils of the early 1800s was so high as to represent overfertilization well beyond the range of optimum yields — so far beyond optimum yield that such conditions are unheard of today, even for highly fertile soils that researchers have deliberately massively overfertilized (e.g., Sabey, Agbin, and Markstrom, 1975; Motavalli, Kelling, and Converse, 1989).

The soil/plant N relationship (Figure 5) suggests that there may have been an NO_3-N food problem in the early years of Corn Belt agriculture. If plant material was ingested before the NO_3-N taken up by the plant is converted to protein, or if drought or other plant stressors hindered the transformation of plant NO_3-N to protein (Hanway and Englehorn, 1958; Viets and

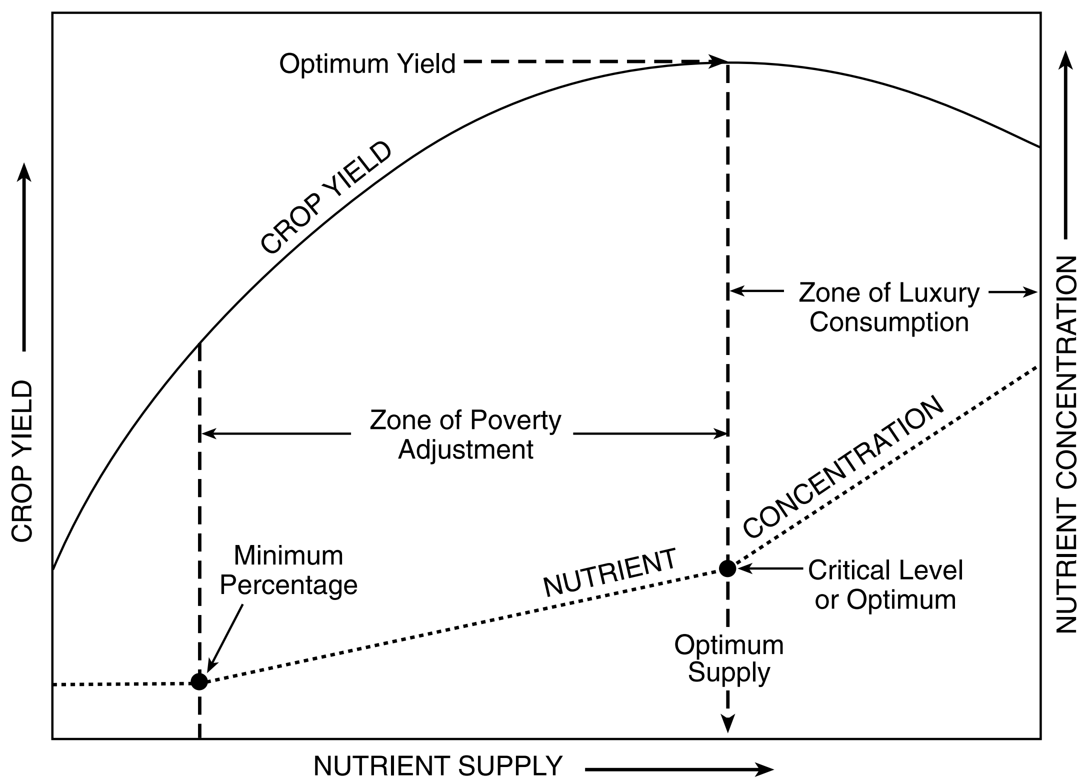

Figure 5. Generalized relationships between nitrogen supply, crop yield, and nitrogen concentration of crop.
Source: Adapted from Figure 1 of Munson and Nelson (1973).

Hageman, 1971; Canvin and Atkins, 1974), early Corn Belt crops could have contained poisonous concentrations of NO_3-N.

This has been shown to be the case. Literature reviews show that NO_3-N concentrations in crops could be so high that NO_3-N poisoning of livestock by feed crops was a widespread problem in the early years of agriculture on the North American prairie, with concentrations of plant NO_3-N being at least three times higher than the highest values seen today (e.g., Mayo, 1895; Davidson, Doughty, and Bolton, 1941; Wright and Davidson, 1964; Viets and Hageman, 1971; Deeb and Sloan, 1975).

Having laid the scientific foundation of the soil/plant N relationship for assessing landscape NO_3-N status, we are now able to assess a range of possibilities. At one end of our assessment's spectrum of possibilities lies the assertion of the standing N-cycle paradigm, e.g.,

"Under natural circumstances, before the intrusion of modern agriculture, nearly all of the soil nitrate which nourishes the plant is converted to protein and other organic plant constituents; in most plants relatively little of the observed nitrogen accumulates as nitrate. However, at the heavy rates of chemical fertilization now widely used in the U.S., this situation has been changed; plants grown on soil heavily fertilized with nitrate contain much-increased amounts of nitrate" (Commoner, 1970).

At the other end of our assessment spectrum lies the N overfertilization inferred from the historically observed hypertrophic status of the early Illinois terrestrial and aquatic landscape. Here, in the tallgrass prairie of the Upper Midwest, the scientific literature shows that NO_3-N poisoning occurred in both beef and dairy cattle grazing on tallgrass prairie vegetation. After the era of chemical-N fertilizer, veterinarians found NO_3-N poisoning still occurring in cows and cattle grazing on wildland moist prairie vegetation, but not in cows and cattle grazing on fertilized pastures growing domesticated grasses (Sund, Wright, and Simon, 1957; Simon et al., 1958, 1959).

The NO_3-N poisoning of livestock grazing wildland prairie vegetation is not a phenomenon unique to the Upper Midwest. Livestock poisonings from enormous concentrations of NO_3-N in the plants of the prairie were also documented as occurring widely in other parts of the world prior to the era of chemical N fertilizer (e.g., Rimington and Quin, 1933; Williams and Hines, 1940). Thus, the indications derived from the soil/plant N relationship support previous findings that soil-NO_3-N levels were at least as high under native tallgrass prairie vegetation as they are in the "heavily fertilized" soils of the Illinois and Midwest Corn Belt — whose soils are not fertilized to optimum crop yields, let alone so heavily fertilized as to exceed optimum crop yield (Figure 5).

Finally, historic NO_3-N data directly inform us as to whether appreciable amounts of NO_3-N naturally get past the root zone of the native prairie and, thereby, pass into the hydrosphere. The following data show that, in spite of the standing paradigm's assertion that natural concentrations of NO_3-N in soil are low, and but little of these naturally low concentrations of NO_3-N ever gets past the root zone, the naturally huge quantities of NO_3-N (and other forms of N) generated in prairie soils do naturally get past the root zone and leach into the hydrosphere to varying degrees.

Research from USDA in Colorado indicates that more NO_3-N passes through the root zone into ground water under virgin prairie than in drier landscapes (Table 5). This is predicted by the long-known relationship between soil moisture and N mineralization in soils that are not water-logged — increasing moisture translates to increased rate of soil organic N being mineralized to NO_3-N (Mayo, 1895 Buckman, 1910; Brady, 1974, p. 430; Bouwman et al., 1993).

Indeed, the mean concentration of NO_3-N in ground water at the water table under virgin prairie is 11.5 mg NO_3-N/l (Table 5), which is in excess of the public health standard (10 mg NO_3-N/l).

As one moves further east, soil-N content naturally increases (e.g, Schreiner and Brown, 1938; Jenny, 1941, pp. 113-120; Stevenson, 1986, pp. 52-53). In central Nebraska, this is accompanied by increasing nitrate in the subsoil. Anywhere from 6.2+ to 12.7+ metric tons NO_3-N/ha have accumulated naturally in the deep subsoils of the prairie loessal soils of central Nebraska under flat interfluvial landscape elements. Overall, it is calculated that this 25,000- square-kilometer (km^2) region of deep loessal prairie soils contains 12,500,000 metric tons of NO_3-N. (Boyce et al., 1976).

In terms of concentration of NO_3-N in soil water, whereas the standing paradigm would have us believe that concentration of NO_3-N is naturally well under 0.3 mg/l, given a typical moisture content of 10 percent (Boyce et al., 1976) and assuming a bulk density of 1.7, the calculated concentration of NO_3-N in this Nebraska prairie subsoil water typically ranges from 400 to 800 mg NO_3-N/l.

It is interesting to note that the effect of agriculture on this subsoil NO_3-N has been to decrease it to a small fraction of its pre-agricultural amount (Boyce et al., 1976).

As one moves further east, the quantity of prairie soil N continues to increase naturally with increasing wetness (e.g, Schreiner and Brown, 1938; Jenny, 1941, pp. 113-120; Stevenson, 1986, pp. 52-53) — as would the mineralization of soil N to NO_3. However, increasing soil N is not always accompanied by increasing soil-NO_3-N content. Moving into eastern Nebraska, as precipitation and leaching continue to increase, the amount of NO_3-N able to accumulate in subsoils decreases: even under the impediment that flat topography and deep, heavy textured loessal soils present to drainage (Boyce et al., 1976).

Moving further east and into the even moister grasslands of the IRB, the relatively copious flushing of water enabled massive inputs of nutrients from the N-rich watershed into surface waters to support massive, jungle-like growth of N-rich aquatic plants and algae, which researchers, then and now, consider to be the natural state of the IRB (Forbes, 1887; Kofoid, 1903; Schoolcraft, 1918; Mills et al., 1966; Starrett, 1972; Bellrose et al., 1983; Talkington, 1991). The following example appears typical for the lower 220 miles of the ~260 miles of the Illinois River itself:

Table 5. Average NO_3-N in 6-Meter Soil Profiles and Water at the Surface of Water Tables in Colorado

Land type	*Number of soil profiles*	*NO_3-N in 6 m (kg/ha)*	*Number of water tables*	*NO_3-N Mean (mg/l)*	*NO_3-N Range (mg/l)*
Virgin Prairie	17	101	8	11.5	0.1-19
Dryland	21	292	4	7.4	5-9.5

Source: Data adapted from Table 11 (Viets and Hageman, 1971).

The aquatic environment at Havana [on the Illinois River] impresses the visiting biologist who for the first time traverses its river, lakes, and marshes, as one of exceedingly abundant vegetation, indeed almost tropical in its luxuriance...he will find acres upon acres of 'moss,' as the fishermen call it — a dense mat of mingled *Ceratophyllum* and *Elodea* choking many of the lakes from shore to shore, and rendering travel by boat a tedious and laborious process.... The carpets of *Lemnaceae* will be surprising, and the gigantic growths of the semiaquatic *Polygonums* will furnish evidence of the fertility of their environment" (Kofoid, 1903, pp. 236-237). compilation of early descriptions of the streams and tributary rivers of Illinois River depict the banks and pools of these waters as rich in aquatic and wetland vegetation: the bottoms of riffles and more swift-flowing sections as coated with epiphytic algae, mosses, and other N-rich aquatic vegetation (Larimore and Smith, 1963). Old descriptions are commonly of streamflow carrying plant debris (Kofoid, 1903).

In other aquatic environments of the prairie, environmental factors prevented the luxuriant growth of vegetation, apparently allowing much of the NO_3-N leached from prairie soils to remain in solution, rather than become incorporated into luxuriant plant growth, e.g.,

"NITRATE IS NOT A NEW PROBLEM

The deleterious effects of excess nitrates on human and animal health is not a new discovery. Nitrates were used for a long time in internal medicine as depressants, but were phased out because of their severe depression of the heart....

Many western U.S. creeks were given unflattering names by the miners because of the pharmacological properties of the water" (Viets and Hageman, 1971, p. 5).

And:

"The first set of erroneous assumptions is made by the naturalists and ecologists who are genuinely concerned about eutrophy of our waterways and nitrates in our ground water supplies. Although many lakes have become eutrophic, we are misled into believing this is a general and recent situation. Wadleigh and Britt (1969) pointed out the great number of reservoirs in the Great Plains area that were made by man and protected against sedimentation by him now hold water of excellent quality, where once there were only buffalo wallows unsuitable for drinking or even washing. Many western creeks, namely in the mining days, did not get their impolite names from the use of Chilean nitrates on farmland" (Viets, 1970).

Clearly, the waters described above are not only much higher than the 0.3 mg NO_3-N/l value cited as bringing on marked cultural eutrophication, their NO_3-N values are probably higher than the 10 mg/l health value established for blue baby syndrome.

Regarding comparison of the more western situation with that of Illinois, direct comparison of NO_3-N concentration is not possible because of the large-scale uptake of NO_3-N by the naturally luxuriant growth of aquatic vegetation. Or, as Kofoid (1903) observed:

"The *total organic nitrogen* [emphasis his] includes all nitrogen that is in combination with carbon (together with other elements) in the tissues of living plants and animals and in many of the waste products of the latter.... It thus indicates the potential fertility of the water" (Kofoid, 1903, p. 193).

And:

"The nitrates are the final products of the oxidation of nitrogenous matters...the nitrates do, for the latter indicate mainly the unutilized portion of the nitrogenous plant food immediately available...the inference is justified that the nitrates shown by chemical analysis in the water of a lake or stream, especially during the growing period of vegetation, afford no reliable basis for judgement as to its plankton production" (Kofoid, 1903, pp. 196-197).

Given the importance of reference/background conditions of surface waters, scientific assessment will be conducted after knowledge is laid down regarding the identification and assessment of relevant elements of Illinois' pre-European-settlement landscape.

In this regard, the confounding effect that the aquatic vegetation factor has on NO_3-N concentration can be circumvented by looking at old Illinois well-water data for the 1890s-1930s. Unlike today's data, which increasingly emphasize the chemistry of wells shallower than 25 feet, most of these old data were taken from relatively deep wells (Table 6).

The depth of these old wells is an asset. Whereas the time period of sampling is after European settlement, the fact that these are deeper ground waters makes their time of origin from the surface (barring what leakage may occur) significantly pre-date the time of sampling — the time of sampling itself being early enough to significantly predate the putative contaminating effects of the use of chemical N fertilizer, which is reportedly driving up NO_3-N concentrations in shallow ground waters to exceed the present-day 10.0 mg NO_3-N/l health standard.

The old Illinois well water data presented in Table 6 are generally not for shallow wells — such as the less-than-25-foot-deep wells that Commoner (1970) used, which tend to have higher levels of NO_3-N relative to deeper wells. Deeper wells have long been preferred for water supply for obvious practical reasons; it has been long recognized that deeper wells are typically more reliable sources of water as they are less subject to drying out during periods of drought and are less subject to contamination from the surface (the overall trend of decreasing concentrations of NO_3-N with increasing depth in the soil and the ground water being long known (e.g., King and Whitson, 1902; George and Hastings, 1951; Cambardella, 1999).

It has long been popular to attribute the trend of older ground waters containing less NO_3-N to increasing NO_3-N pollution, based on the assumption widely held by many early microbiologists that the subsurface is sterile (George and Hastings, 1951; Viets and Hageman, 1971; Fliermans and Balkwill, 1989; Korom, 1992; Madson and Ghiorse, 1993) — an assumption that has the "benefit" of producing conclusions that support the standing N-cycle paradigm.

However, the prima facie evidence did not support the raising of such an assumption to fact:

"What becomes of the nitrate? One can hardly assume that the formation of nitrate is a recently acquired trick of nature or that not enough time has elapsed for water in the outcrop to move down to depths of several hundred feet. It must be necessarily assumed that something happens to the nitrate in transit" (George and Hastings, 1951).

To quote the conclusion of a review article on subsurface microbiology:

"**Conclusions**

"The traditional scientific concept of an abiological terrestrial subsurface is not valid. The reported investigation has demonstrated that the terrestrial deep subsurface is a habitat of great biological diversity and activity that does not decrease significantly with increasing depth" (Fliermans and Balkwill, 1989).

Korom (1992) in a review of natural denitrification in ground water reported:

"Geomicrobiology has been aided by recent developments of aseptic subsurface sampling techniques. By the 1980s a number of studies done under aseptic conditions provided convincing evidence that subsurface surface environments support an abundant microbial population of great diversity [e.g., Ghiorse and Balkwill, 1983; Hirsh and Rades-Rohkohl, 1983; Fredrickson et al., 1989]. The latter [Fredrickson et al., 1989] found a diverse bacterial community with a population that did not decrease with depth, even at 260m below the land surface!"

And as Madsen and Ghiorse (1993) report in their review of ground-water microbiology: "...assuming that the biomass per kilogram of subsurface sediments is 1000-fold less on average

Table 6. Illinois 1890s-1930s Public Ground-Water Supplies Whose NO_3 Values Equaled or Exceeded Today's Health Standard

Station	*NO_3 (mg/l)*	*Water supply type and depth (ft)*	
Anna	74.4	Well	650
Bradley	70.7	Wells	337 and 340
Chandlerville	55.3	Well	32
East Dundee	131.1	Springs	
Erie	62.0	Well	567
Eureka	44.7	Well	27
Geneva	44.3	Spring	
Germantown	44.3	Well	16
Greenville	91.9	Wells	45 and 50
Keithsburg	88.6	?	
Lacon	83.3	Wells	60
Mount Morris	70.7	Well	725
New Holland	88.6	Well	70
New Holland	79.5	Well	74
Petersburg	62.0	Well	60
Plainfield	61.9	Well	104
Roseville	50.9	Well	19
San Jose	53.1	Wells	>85
Shannon	53.1	Wells	200
Silvis	79.7	Well	28
<u>Peoria</u>			
W.T. Grant Co.	174.0	Well	84
<u>Peoria County</u>			
Midland Brewery	62.0	Well	76
Peoria Packing Co.	53.2	Well	52
Peoria Service Co.	53.2	Well	94
Stuber & Kuck Co.	53.2	Well	65
<u>Tazewell County</u>			
Moran Markets	49.6	Well	72
Soldwedel Creamery	47.9	Well	103

Note: Today's public health standard for NO_3 in drinking water is 44.3 mg NO_3/l (10 mg NO_3-N/l).
Sources: Data from Habermeyer (1925) and Buswell (1938, 1940).

than that found in the top 1m of agricultural soil, then the total biomass in subsurface habitats may be 40 times greater than that in the top 1m of soil."

Nevertheless, in spite of the overall relative deepness of the Illinois water-supply wells, Table 6 shows that levels of NO_3-N were much higher than predicted by the standing N-cycle paradigm. Indeed, of all Illinois ground-water supplies for which there are chemical data, about 5 percent equaled or exceeded the present NO_3-N health standard in the 1890s-1930s.

If leakage was responsible for these high readings, we would, for example, need a 5 percent leakage rate from shallower ground waters having >900 mg NO_3/l (>200 mg NO_3-N/l) to produce such results. And this leakage of extraordinarily NO_3-N-rich shallow ground water would be occurring before the era of chemical-N fertilizer, which is only in recent decades being said to raise appreciable areas of shallow ground waters to exceed the present 10 mg NO_3-N/l health standard.

Holm (1995) has shown that deep, aged, well waters in the absence of leakage from the surface exceed the present 10 mg NO_3-N/l health standard in 9 percent of the wells sampled in the Mahomet Aquifer.

It is interesting to note that, in spite of the popular belief that NO_3-N concentrations have been increasing in our ground-water supply, the long-term record for Illinois water-supply wells does not show an increase in problem NO_3-N concentrations. Today, about one percent of community water-supply wells have concentrations of NO_3-N exceeding the 10 mg/l present-day health standard (Illinois Environmental Protection Agency, 1990, Table 124; Warner, 2000, Table 5-1, Figure 5.2), as opposed to about 5 percent of reported measurements for the 1890s-1930s period (Table 6).

Cooperative research between the U.S. Geological Survey and the State of Texas on NO_3-N in ground water prior to the era of chemical-N fertilizer appeared similar to that of Illinois. To quote the abstract of their findings:

"Ground water in many parts of Texas contains nitrate in excess of 20 ppm (parts per million) as nitrate. About 3,000 of the 20,000 nitrate determinations made of water from wells in Texas showed more than 20 ppm of nitrate. The public water supplies of 27 Texas towns and cities contained more than 50 ppm of nitrate. Most of the high nitrate in ground water is found in wells less than 200 ft deep and mainly in water from late Tertiary and Quaternary formations; however, high nitrate was found in water from all kinds of rocks of all ages. The presence of high nitrate in ground water appears to be unrelated to rainfall, geography or cultivation" (George and Hastings, 1951).

Furthermore, George and Hastings (1951) presented information that predicted the apparent future increase of NO_3-N since measured in ground water: "Nitrate is probably more prevalent in water from shallow wells throughout the United States than is generally known," as analysts have shied away from analyzing NO_3-N as well as shallow wells, instead preferring to sample and analyze deeper, more productive wells. However, as George and Hastings (1951) noted, the increasing interest in sampling shallow wells, and increasing interest in measuring NO_3-N could, in and of itself, give the appearance of increasing NO_3-N "contamination" of ground water.

The subjectivity-of-observation problem is well known to the scientific community. Using geology as an example:

"The value of the recent volcanological record is obvious to geologists.... The limitations of the volcanological record are not as obvious, however, and require continued emphasis to caution anyone brash enough to mistake the record for the reality" (Simkin et al., 1981, p. 22).

Some of the illustrations Simkin et al. (1981) used to demonstrate subjectivity were the record of volcanic activity markedly jumping up after the invention of the printing press, markedly jumping down during World War I and World War II, and rebounding after the wars.

Unfortunately, subjectivity of ground-water N measurement appears to be a problem that has yet to be adequately resolved.

In the next section, we consider factors that biogeochemically shaped the pre-European-settlement terrestrial landscape of Illinois, from which N was transferred to the hydrosphere.

A Pyrrhic Landscape

"The myth persists that in 1492 the Americas were a sparsely populated wilderness, 'a world of barely perceptible human disturbance.' There is substantial evidence, however, that the Native American landscape of the early sixteenth century was a humanized landscape almost everywhere. Populations were large. Forest composition had been modified, grasslands had been created, wildlife disrupted, and erosion was severe in places. Earthworks, roads, fields, and settlements were ubiquitous. With Indian depopulation in the wake of Old World disease, the environment recovered in many areas. A good argument can be made that the human presence was less visible in 1750 than it was in 1492....

"In the ensuing forty years, scholarship has shown that Indian populations in the Americas were substantial, that the forests had indeed been altered, that landscape change was common- place. This message, however, seems not to have reached the public through texts, essays, or talks by both academics and popularizers who have a responsibility to know better" (Denevan, 1992a).

Some Effects of Fire on Vegetation

With but few exceptions (such as the northern spruce/fir forest), the ecosystems encountered by European explorers and early settlers were not mature (climax), undisturbed ecosystems. Indeed, whole ecologies — from the Douglas-fir forests and the redwood forests of the West, to the grasslands of the interior, to the pine forests of the East Coast — literally owe their existence to the use of fire by pre-settlement Native Americans.

To quote a review from *Scientific American*:

"Before Europeans came to North America, fires periodically swept over virtually every acre on the continent which had anything to burn.... Most prehistoric fires were undoubtedly the work of man.

"Notwithstanding the popular conception, American Indians were not cautious in using fire. They did not conscientiously put out camp fires nor, unless their villages were threatened, did they try to keep fires from spreading. Often they burned intentionally — to drive game in hunting, as an offensive or defensive measure in warfare, or merely to keep the forest open to travel.... In the narratives of the explorers of North America are numerous accounts of traveling for days through smoke from distant fires, and the passing through burned-over prairies and woodlands....

"Most ecologists believe that a substantial portion of North American grasslands owe their origin and maintenance to fire.... [In the absence of fires set by Native Americans] large parts of these grasslands are now being usurped by such shrubs as mesquite, juniper, sagebrush and scrub oak. Mesquite alone has spread...until it now occupies about 70 million acres of former grassland" (Cooper, 1961).

Early explorers concluded that much of the “natural vegetation” they encountered was not natural at all, as the prairies were growing up into trees after the government cleared the landscape of Native Americans to make open the land for European settlement:

“Speaking of the tall-grass prairies east of the Mississippi, Wislizenus in 1839, Hind in 1857, Marsh in 1864, Asa Gray in 1884, and many others reported forests replacing prairies as soon as Indian burning stopped. Asa Gray wrote:

“‘There is rainfall enough for forest on these actual prairies. Trees grow fairly well when planted; they are coming up spontaneously under present opportunities; and there is reason for thinking that all the prairies east of the Mississippi, and of Missouri up to Minnesota, have been either greatly extended or were even made treeless under Indian occupation and annual burnings”’ (Stewart, 1951).

Also:

“In the early nineteenth century Thomas Jefferson shrewdly suggested that fire hunting was the most probable cause of the origin and extension of the vast prairies in the western country’” (Pyne, 1983).

In summary, the following can be stated:

“An examination of all the published theories reveals a rather amazing uniformity in the accounts written in the very early period by men who saw the prairies before great changes had taken place in the Indian populations (Sauer, 1950). These writers were almost unanimous in their conclusion that prairie fires were responsible for the absence of trees” (Curtis, 1959, p. 296).

The original scientific observers commonly recognized that Native American civilizations had a significant hand in the prairies. Later on, when many of the intellectual elite abandoned the Baconian view of nature for the romantic Rousseauian view of the Perfect Natural State, science would continue to provide increasing support for the scientific findings of the original observer. However, the conclusions often derived would be to support the dogma of the Perfect Natural State, as we see from the above quote of Denevan (1992a).

Nevertheless, there are numerous notable exceptions. For example, Jenny (1941, p. 183) stated that Marbut (the Father of modern American soil science), from his study of prairie soils, did not believe them to be natural (climatically induced, i.e., Marbut did not believe that prairies and the soils they form were there because the climate was too dry to grow trees). Jenny observed that, besides Marbut, many biologists did not believe American prairie soils to be natural, climatically induced soils. Rather, they believed these soils to be the artifact of repeated, intense, aboriginal burning — as also stated later by Cooper (1961) in *Scientific American*.

As can be seen from page 205 of Jenny’s (1941) vegetation classification, a key part of the argument for prairies being Amerind-made is the fact that trees generally grow into drier climate than do the grasses of the prairie. Trees did not grow in the prairie because the climate was too dry, but the climate was moist enough to provide enough fuel for the frequent aboriginal fires to kill the trees. As one approached the desert, trees appeared again because the climate became too dry to grow sufficient fuel for fire to kill the trees but not too dry to prevent the growth of trees, albeit stunted in stature (Jenny, 1941, p. 205).

Review of the literature shows that human activities prior to European settlement profoundly influenced the region around Illinois. Early explorers found that the prairie extended northward out of Illinois to cover southern Wisconsin whereas much of central and northern Wisconsin were mostly forested (Curtis, 1959). Comments follow regarding southern Wisconsin:

“‘A sea of grass’ was the universal metaphor.

“The constitution of the woods depended on the section of the state.... Often the woods’ floor was so open that it was recommended for horse racing and carriage driving, while the lack of underbrush offered ‘no impediment to the chase (of deer)....’

“The rapidity with which woods grew under protection was common knowledge, for though the prairie might be treeless when settled, trees set out for house protection and ornament or for woodlots grew thriftily, almost without exception. A striking example of this is described in the first annual report of the Wisconsin Geological Survey on a farm where grew ‘dense groves of young trees from six to ten inches in diameter, where, twenty-five years ago, not a single shrub could be found larger than a riding whip.’ This same process in various localities served to strengthen the conviction that if the prairies were given proper protection from fires for a few years, every farm upon them would have an adequate supply of timber. The source of the new timber would lie in the seeds, roots and stumps sending up new growth after the inhibiting or destructive forces of the prairie fires were removed.

“Apparently this phenomenon was the chief cause of a 60 percent decrease in the prairie area of southwestern Wisconsin, which occurred between 1829 when Chandler marked it as nine tenths prairie, and 1854 when the Geological Survey reported it to be only one third prairie, broken in part by groves and oak openings....

“A hundred and sixty years ago Jonathan Carver climbed one of the three limestone outliers in southern Wisconsin known as Blue Mounds and recorded that he ‘had an extensive view of the country (where) for many miles nothing was to be seen but lesser mountains which appeared at a distance like hay cocks, they being free from trees....’

“To-day one looks from the Blue Mounds over a sea of green trees broken by fields and pastures [Figures 6a-e] and probably never thinks that once it was all a treeless prairie.... The landscape rich in oak and hickory, maple and linden, is indeed a far cry to the time when the people who came to Wisconsin found one of the greatest drawbacks to travel was the lack of sufficient wood to build a campfire” (Chavannes, 1941).

Looking at Figures 6a-e, it is hard to believe that, when early European explorers first visited this land, it was treeless prairie in which Blue Mounds and other hills looked like giant haystacks in the distance. That this region is now eastern temperate forest (Figure 7) argues for something other than climate as being responsible for the change. Whereas climate change (to increasing dryness) is asserted to be the cause of what paleoecological study shows Wisconsin prairies coming into existence 5,000-6,000 years before present or BP (Hole, 1976, pp. 53-56), the climate was becoming even more favorable for forest growth and less favorable for prairie as the region started becoming cooler and wetter around 7200 BP (Knox, 1983; Grimm, 1984; Dean, 1997), when the warmth of the Holocene Climatic Optimum was replaced by the cool and wet of the present worldwide Holocene Neoglacial (Matthes, 1939; 1941; Porter and Denton, 1967; Denton and Porter, 1970; Davis, 1988; Matthews, 1991; Nesje et al., 1991).

Or, as Butzer (1992) concluded:

“Native American use of fire, clearance for cultivation, and other forms of manipulation or exploitation had left an unambiguous imprint: the forests of eastern North America were relatively open, the prairies of Indiana and Illinois were unable to return to a woodland-grass mosaic despite the shifts to moister climate during the later Holocene....”

It appears, therefore, that the development of Wisconsin, Indiana, and Illinois prairies at this time, and especially their maintenance during the ensuing millennia of cooler and wetter climate, was primarily due to humans — whose activity, when stopped in the early 1800s, enabled rapid reversion of fire-maintained prairie to eastern temperate forest.

a. Approach to entrance of
Blue Mounds State Park.

b. Picnic clearing at top
of Blue Mounds.

c. View midway up
observation tower.

Figure 6. Blue Mounds State Park, Wisconsin
(photos by Edward C. Krug, May 29, 1998).

d. View from top of observation tower.

e. View from top of observation tower.

Figure 6. Concluded.

Figure 7. Ecological regions of North America.
Source: Posted on www.epa.gov/ceisweb1/...tors/ ecoregions_of_the_united_ states.html. Use this EPA site's "Ecological Regions of North America" link to the Commission for Environmental Cooperation (www.cec.org/ecomaps/anglais/index.html) for a larger map and description of the eastern temperate forest ecoregion. Data accessed August 9, 1999.

Moving west across the Mississippi River from Wisconsin (where it is drier than in Wisconsin (Geraghty et al., 1973), there was more pre-settlement prairie. However, more than 100 miles west of the Mississippi River in southern Minnesota, there was a peninsula of forest which early Europeans called the "Big Woods." The Big Woods extended far south into the prairie:

"'The existence of this great spur of timber, shooting so far south from the boundary line separating the southern prairies from the northern forests, and its successful resistance against fires that formerly must have raged annually on both sides, is a phenomenon in the natural history of the State that challenges the scrutiny of all observers' (Winchell 1875)" (Grimm, 1984).

The geography of the Big Woods is that of a district rich in rivers and lakes that provided firebreaks against the enormous and frequently immensely destructive fires driven by predominantly southwest winds (Grimm, 1984). Nevertheless, to the east of the Big Woods the lakes and rivers diminish and the vegetation was again prairie with frequent fires. Looking across the Mississippi River from the top of Maiden Rock Bluff on the Wisconsin shore of Lake Pepin, Latrobe described the scene in 1833:

"As we looked upon the summit early in the morning, across the troubled surface of the lake...a dense column of smoke from the opposite gave us intimation that the Prairies were on fire. The spread of the conflagration on the low grounds opposite, which drew our attention at intervals during the day, continued unabated; and as evening approached, other columns of smoke springing up in all directions, both on the summit of the opposite range of mountains and in the valleys at their feet, showed us that the Indians had taken advantage of the driving wind to fire the country for a great many miles inland.... At sunset, the flame seemed to have gathered full strength, and to have reached a very long tract of level grassy prairie nearer the shore, upon which it then swiftly advanced, leaving a black path in its trail.... In one place the progress of the fire, effectively checked by a small river, died away or edged over the country with slower progress. In another, after being seemingly choked, it would burst forth with renewed fury, sending bring jets of flame far on the wind.... We calculated at this time that the fire spreads over a tract nearly twelve miles in length, while the distant glare upon the clouded horizon showed that it was raging far inland. The whole evening the lake, the Maiden's Rock, the clouds, and the recesses of the glen were illuminated by the flames, while, gaining in the rank growth on the borders of the lake and the brow of the distant mountains, the country opposite blazed like tinder in the wind: and from the summit of Maiden's Rock, which we had again ascended before we retired to rest, the scene was fearfully grand" (Curtis, 1959, pp. 296-297).

Again, Minnesota prairie reverted to forest when Native Americans were no longer present and Europeans moved in:

"Before settlement by white people, fires annually burned over immense areas in southern Minnesota. The narratives, journals, diaries, reminiscences, and travel books of early white explorers, settlers, and scientists contain abundant accounts of wildfires (Curtis 1959, Moore 1972, Grimm 1981, Pyne 1982). Very large proportions of the prairie burned annually.... This extract from Plumbe (1839:33) is typical: '...the timber will increase rapidly as soon as the country is sufficiently settled to prevent the fires running annually, and sometimes twice a year over its whole surface.' The fires burned mainly in the fall and spring, although in dry years, they occurred throughout the summer months (Moore 1972).

"The frequent and widespread fires exerted a powerful influence on the vegetation, which was immediately obvious to those who witnessed the annual conflagrations. For example, Upham (1888:155) wrote:

"'The absence of trees and shrubs upon large areas, called prairies, in this and neighboring states, is generally attributed correctly to the effect of fires. Through many centuries fires have almost annually swept over these areas, generally destroying all seedling trees and shrubs.... Late in autumn and again in spring the dead grass of the prairie burns very rapidly, so that formerly a fire within a few days sometimes spread fifty or a hundred miles. The groves that remain in the prairie region are usually in a more or less sheltered position, being on the border of lakes and streams and sometimes nearly surrounded by them; while areas that can not be reached by fires, as islands, are almost always wooded.'

"The ability of trees to invade prairie following the cessation of prairie fires was widely observed (e.g., Phillips 1840, Winchell 1875, 1884:278-279, Rosendahl and Butters 1918, Curtis 1959). Winchell (1875) observed in Faribault and Freeborn counties in the south of the Big Woods:

"'In those counties, as the suppression of the prairie fires is rendered more complete by the farming of the soil, the scattered shrubs of oak and the aspens, that are the avant couriers of encroaching forests, bring on more and more the character and aspect of a wooded country. Other species then gradually venture out from the sheltered valleys, and flourish in the open tracts'"(Grimm, 1984).

Moving south and east into Illinois itself, the Native Americans encountered by some of the early priests and explorers were referred to as "Fire People" (Strong, 1926).

Regarding the nature of the Illinois landscape:

"In a previous paper (1912), referring to the location of certain isolated groves in central Illinois, it was shown that they were uniformly situated on the eastern side of prairie sloughs, and the conclusion was advanced that their existence in these places was due to the protection against prairie fires furnished by the water barrier. Since the publication of this paper, a number of similar facts have come to hand, all serving to indicate the efficiency of ponds and streams in protecting forests from the incursions and destructive effects of prairie fires. In general it may be said that the location of forests throughout central and northern Illinois, and also through the adjacent states, is closely correlated with prairie fires.

"It is well known that the prevailing winds throughout most of the Middle West come from the west, varying from northwest to southwest. Prairie fires would, therefore, in most cases travel toward the east, and would attack the forest on the west side....

"Copies of the original surveys have been examined and tracings made for eight adjacent counties in central Illinois, Champaign, Coles, De Witt, Douglas, Macon, Moultrie, Piatt, and Shelby. They indicate over twenty such isolated groves, of various shapes and sizes, and located in various habitats. Every one of these which has been visited by the writer, except two referred to under the next general effect of fires, is in some way connected with a stream or a series of sloughs" (Gleason, 1913).

In the next section, the writer explains that these two apparent exception sites were protected by waters that have since been drained (Gleason, 1913):

"...it is doubtful if mature trees were ever killed by a single fire. But the seedlings must certainly have been destroyed in large numbers, and the repeated charring of the bark of the larger trees led after a few years to their death. Statements to this effect may be found in several of the older books of travel. Loomis (1825) states: '...the heat and fury of the flames driven by a westerly wind far into the timbered land...destroying the undergrowth of timber, and every year increasing the extent of prairie in that direction, has no doubt, for many centuries added to the quantity of open land found throughout this part of America.' Brackenridge (1814, p. 109) makes a similar statement..."' (Gleason, 1913).

Regarding reference conditions available today for Illinois prairie, only about 5 square miles (~2,000 acres) of prairie is reported to still exist in Illinois. The little undisturbed land has grown up in trees, and the rest has been converted to agriculture and urban land (Betz, 1986; Samson and Knopf, 1994; Illinois Natural History Survey, 1999). Virtually none of this tiny remnant is of the once vast moist, tallgrass prairie on heavy textured soil (Betz, 1986; Betz and Lamp, 1989). Much of remnant prairie is actually railroad right-of-way; prairie was favored by deliberate disturbance plus, until recent decades, the high frequency of fires accidentally ignited by sparks from passing trains (Vestal, 1918; Harrington and Leach, 1989; Leach and Givnish, 1996). Remnants of prairie also exist on poor (sandy) soil and on what remains of heavy textured soil (silt loams) in old cemeteries located on swells rather than in the previously common large wet flat and swale locations of the original prairies (Betz and Lamp, 1989). Thus, we see that even the remnants of the "virgin" prairie are not in the condition they were prior to European settlement.

Furthermore, because of the absence of even a remnant of true native, moist, tallgrass prairie, in the early 1940s the University of Illinois converted part of the Trelease Woods into the Trelease Grassland so as to have a research prairie site in Champaign County, Illinois. The University maintained its research prairie as prairie (prevented reversion to forest) by burning. Old (1969) summarized the switch from Native American to European land-use practices as follows:

"Aboriginal man has long used fire as a means of land clearance for primitive agriculture and as a hunting technique. With an end to nomadic existence, uncontrolled forest and grassland fire became a threat to urban and rural settlements, pastoral occupations and silviculture."

In regions of Illinois with landscape features that were more fire protective — such as southern Illinois' Shawnee Hills — forest composition and ecology were still significantly shaped by fire: in terms of tree species, density of trees, creation of an herbaceous groundcover, and the animals that lived in the forest (Fralish et al., 1991). In central states, such as Illinois, preservation of forest areas as remnants of our natural heritage in the absence of frequent fire is actually destroying them:

"In the central states region, forested areas often preserved as an example of our natural heritage may be ecosystems developed since fires and other disturbances ceased less than 150 yr ago.

"Frequently, present land management activities in oak-hickory forest usually do not include the use of fire, either before or after cutting, to maintain oak; yet on mesic sites, many stands dominated by *Quercus alba* or *Q. veltina* are rapidly changing to *Acer saccarum* and other mesophytic species not only in southern Illinois but throughout the Midwest. In Illinois, from 1962 to 1985, there was a 4119 percent increase in the area occupied by the beech-maple cover type (Iverson, 1989). Given this rate of change, oak forest with its complement of animals and understory plants may be classified as a rare ecosystem in another 100 yr. We have observed that dense groves of *A. saccharum* stems exclude herbaceous plants adapted to and normally found under an oak canopy. To maintain oak with its normal herbaceous understory in natural or wilderness areas, disturbance at the level found in pre-settlement forest may be necessary" (Fralish et al., 1991).

It is thus apparent that people have to deliberately set fires to maintain even the heavily forested regions of the State to keep them in a resemblance of the reference/background condition first seen by Europeans.

The states east of Illinois, while being wetter (Geraghty et al., 1973), also had much pre-European-settlement prairie:

“Many of the middle western Indians, as La Salle had already found out [in Illinois], followed the custom of the plains Indians, burned off the country occasionally to keep it open enough for game. Otherwise the eastern forests would have gone on moving even farther west until they covered the country, without a break, as far as the Mississippi.

“Early white settlers in Michigan, adapting the Indian custom, sometimes burned the meadows to make the grass ‘tender.’ When they got out of hand, prairie fires were a terrible danger. ‘These fires,’ wrote an early eastern visitor to Michigan, ‘traveling far over the country, seize upon the large prairies, and consuming every tree in the woods, except the hardiest, cause the often-mentioned ‘oak openings,’ characteristic of Michigan scenery. It is a beautiful sight to see the fire shooting in every direction over these broad expanses of land which are kindled at a variety of points. The flame at one moment curls along the ground, and seems to lick up its fuel from below, while at the next it tumbles over like breakers of the sea upon the dried grass, and sweeps it like a wave of fire from the ground.’

“A traveler in Illinois describes riding along a roadside near Peoria with a ‘wall of fire as high as our horses’ ears’ not far away. ‘The prairie presented exactly the appearance of a broad burning pool,’ and as the fire rolled past ‘like the waves of the sea itself, when they break upon the shore, a thousand forked tongues of flame would project themselves far beyond the broken mass, and greedily lick up the dry aliment that lay before them.’

“‘It was the most glorious and most awful sight I ever beheld,’ wrote Elias Pym Fordham, an English settler in Indiana. ‘A thousand acres of Prairie were in flames at once; the sun was obscured, and the day was dark before the night came. The moon rose, and looked dim and red through the smoke, and the stars were hidden entirely. Yet it was still light upon the earth, which appeared covered with fire. The flames reached the forests, and rushed like torrents through. Some of the trees fell immediately, others stood like pillars of fire, casting forth sparkles of light. Their branches are strewed in smoking ruins around them.’ That night five large fires were blazing, some of them miles away but still visible.

“The glow could sometimes be seen for forty miles and the advancing prairie fire might be preceded by a shower of ‘flakes and cinders’ for about the same distance. In the autumn, when grass and woods were dry, there was usually a fire blazing somewhere on each bank of the Mississippi, until rain, damp ground, or a broad stream extinguished it.

“It was perhaps one of these fires which touched off an exposed vein of coal on the Muskingum River, in Ohio. The coal burned for a full year. In Illinois a prairie fire kindled a stump which set off the coal bed above which it stood. This burned for several months, until falling earth put it out. But these fires were trivial compared with those in the lignite beds in the Canadian Far North, which the explorer Alexander Mackenzie, saw burning in 1799 and which were still burning in the twentieth century.

“The forest fires, however terrible, had one advantage. They decreased the density of the forests and thus encouraged the deer, so that the Indians were likely to kindle fires and let them run whenever they wanted more deer — which, as one warrior explained, were their cattle. As a result, the animals were everywhere. Christopher Gist, exploring the Middle West, notes casually: ‘Being in Want of Provisions, I went out and killed a Deer.’ It was as simple as telephoning the butcher. Hunters rarely took anything but the haunches, the choicest meat” (Bakeless, 1961, pp. 308-309).

Undoubtedly, the great number of large grazing animals living in the park-like forests also helped keep the forests in a more open condition.

Moving on, south of Illinois, western Kentucky, now forested, also had a large amount of prairie when Europeans first visited:

"Geologically this formerly treeless meadow has been rather closely identified by Prof. A.M. Miller with the portion of the Mammoth Cave limestone series...lying between the Green River and Tennessee....

"These barrens doubtless owed their origin to fires. Michaux records that it was the custom of the Indians to burn the Barrens during the early spring to facilitate the chase of game, prior to the settlement of the state by whites...which would account for the presence of great treeless prairies in the midst of forests where there seem to be no edaphic nor climatic factors to maintain such conditions....

"The transformation which has occurred in these regions has gone so far that the barrens are only a memory. The regions still go by the name but it has no significance now. In recent years the forests have become so diversified that they differ in no important particular from other upland forest regions. Most recent estimates show that over 800,000 acres of forest exist in Michaux's Barrens, with *Q. velutina* the dominant tree. The monotonous grassland now has approximately five hundred million board feet of black oak alone standing on it, with beech, post oak, and white oak as important members of the forest" (Shull, 1921).

Shaler (1891, pp. 186-187) noted that, in the mid-1800s, some 5,000 square miles of western Kentucky were still in prairie.

Going west across the Mississippi River, Iowa and Missouri, which once held huge expanses of prairie, were by the second half of the 19th century becoming forested (Christy, 1892).

Going further south, Arkansas was largely prairie. Even the Mississippi River alluvial plain of the east and the Ozarks, now forested, were grassy savannah at the time of European settlement (Harper, 1914; Beilmann and Brenner, 1951).

Apparently, there was appreciable prairie-like savannah in both Mississippi and Alabama (Harper, 1914). And even the pine forests of the deep south were called savannah-like, or as Hilgard (1860) is quoted as observing:

"The herbaceous vegetation and undergrowth of the Longleaf Pine Region is hardly less characteristic than the timber...the pine forest is almost destitute of shrubby undergrowth, and during the growing season appears like a park, where long grass is often very beautifully interspersed with brilliantly tinted flowers....

"In their natural state, as received from the hands of the Indians, the Pine Woods were one great pasture...." (Malin, 1953).

Going to the eastern extremes of the MRB, the aboriginal fire/buffalo culture had breached the Appalachians, so that early explorers found that the Shenandoah River Valley was prairie with herds of buffalo, elk, and deer grazing on it (Maxwell, 1910). And:

"Grassland corridors such as the Shenandoah Valley were maintained by fire and provided major thoroughfares for the dispersal of settlers. The lush wildlife that provided subsistence to early vanguards of frontiersmen depended on a habitat created and sustained by the Indian pattern of broadcast fire....

"The habitat that supported so rich a natural population of grazers and browsers was ideally suited for the domestic stock introduced by Europeans and upon which their agrarian economy was so heavily dependent. In the same way that herders of domesticated stock occupied the openings previously maintained for the harvest of wild game, immigrant farmers moved into the former fields of the aborigines cleared and fertilized with fire" (Pyne, 1983).

Native Americans had literally created the “fruited plain” of which Americans now patriotically sing.

The prairie in Canada was impacted by European influences appreciably later than that of the United States — the progressive extermination of buffalo for robes, and even the passage of settlers, began after 1870 (Roe, 1951, pp. 467-469). Thus, much later and more quantitatively extensive scientific observations were made of the intact Plains Native Americans between 1850 and 1870. It was seen that their burning activities were truly prodigious:

“...the only conditions required for fire to run over hundreds of miles — or around the world, for the matter of that — are a more or less strong wind behind and a level stretch of grass in front. I myself saw a fire which I had reason to believe was 40 miles in length; while Professor H.Y. Hind says: ‘From beyond the south branch of the Saskatchewan to the Red River, all the prairies were burned last autumn [1857] — a vast conflagration extending for 1000 miles in length and several hundred in breadth. The dry season had so withered the grass that the whole country of Saskatchewan was in flames. The Rev. Henry Budd, a native missionary of the Nepowewin, on the north branch of the Saskatchewan, told me that, in whatever direction he turned in September last, the country seemed to be in a blaze. We traced the fire from the 49th parallel to the 53rd, and from the 98th to the 108th degree of longitude. It extended, no doubt, to the Rocky Mountains’” (Christy, 1892).

Between 1850 and 1870, the prairie fires were documented as greatly expanding the area of prairie at the expense of forest (Christy, 1892). Since the 1870s, some 200 million acres of Canadian prairie have reverted back to forest (e.g., Archibold and Wilson, 1980; Campbell et al., 1994).

Similar prairie advancement and subsequent retreat were hypothesized to have occurred some centuries earlier in the eastern United States. This is the condition that the early explorers reportedly found in the mountains of Virginia:

“‘They found large level plains, and fine savannahs three or four miles wide, in which infinite quantities of turkeys, deer, elks, and buffaloes, so gentle and undisturbed that they had no fear of the appearance of men but would suffer them to come almost within reach of their hands’” (Maxwell, 1910).

Buffalo were found in Virginia until 1825 and elk until 1856. Prairie and savanna extended into southern Pennsylvania. While prairies closed up quickly in the eastern forests, some prairies were so large that vast stretches of prairie lasted for at least a century beyond the removal of their Native American inhabitants, as is recorded by the deeded lands of George Washington, among others (Maxwell, 1910).

The extension of prairies so far into the humid east was truly a remarkable achievement of whole ecosystem manipulation, given that such extension had to work against the increasing moisture gradient, which increasingly favored trees over grasses, plus other advantages that the canopy gives trees both physically and chemically over grasses in such environs.

By the 1870s, N.S. Shaler had already hypothesized that Native Americans were responsible for the creation of the prairies east of the Mississippi River. Furthermore, his archeological studies found earlier, highly advanced agricultural peoples who did not know buffalo, but who had been supplanted by buffalo hunter/gatherers. Shaler’s studies also showed the expansion of prairie eastward by fire was later aided by buffalo which, along with other grazing animals, would exert their effect on the forest as well. Shaler believed that, at the past rate of human-induced prairie expansion, if European settlement of the New World had been delayed by 500 years, the prairies would have extended solidly to the Appalachian Mountains (e.g., Shaler, 1891, pp. 184-188; Maxwell, 1910; Roe, 1951, pp. 27-28, 86-88, 846, 850-851; Malin, 1953).

The extension of the aboriginal/buffalo culture is supported by the finding that buffalo did not exist in large number east of the Mississippi River until several centuries prior to European settlement (Griffin and Wray, 1945; Smith, 1965). During this period, herds of these grazing animals would have imposed their effect on top of the prairie-promoting effect of fire:

"The buffalo, for example, crossed the Mississippi from the west about A.D. 1000. By the sixteenth century the buffalo entered the south; by the seventeenth, its range extended into Pennsylvania and Massachusetts" (Pyne, 1983).

As noted earlier by Shaler (1891), the extension of the buffalo eastward of the Mississippi River coincided with the puzzling decline of the major Native American civilization east of the Mississippi River. This earlier civilization, which rivaled the higher classical civilizations of Central and South America, was replaced by a much smaller population of hunter-gatherers (Griffin, 1961; Williams and Stallman, 1965).

Indeed, according to a BBC/Learning Channel (1998) documentary, which extensively interviewed Illinois scientists, one of the Illinois cities of this lost civilization, Cahokia, had a population greater than its contemporary Medieval cities of Rome and London in Europe.

The scientific literature shows that the relatively large population of this earlier Cahokian civilization also relied heavily on the wetland bottomlands bordering rivers to produce crops like corn (Butzer, 1978; Milner, 1986; Emerson and Lewis, 1991). Outside of the cities, towns, and villages, the widely scattered bottomland farmsteads of this earlier civilization gave these bottomlands an estimated rural population density of about 100 people per square mile at its height (Milner, 1986).

However, about 100 years before Columbus, this earlier Midwestern Mississippian Native American civilization had gone into decline and was being replaced by yet another Native American civilization.

Thus, with the later ecological change, as indicated by the successions of Native American civilizations and the introduction of the buffalo, more than one pre-settlement reference/background condition needs to be considered. And it is these various pre-European-settlement, N-saturated conditions which we use as the reference/background conditions against which to scientifically assess the effects of post-European settlement agriculture.

Some Effects of Fire on the Nitrogen Cycle

"SUMMARY

"Nitrogen is essential for all living things, and it has often been the major limiting factor in crop production throughout the centuries" (National Research Council, 1972, p. 90).

"The riverine ecosystem response to higher nutrient loading is consistent with the nitrogen-saturation hypothesis described for northern forests by Aber et al. (1989)" (Turner and Rabalais, 1991).

The standing N-cycle paradigm advertises the Aber et al. (1989) N-saturation hypothesis as a new and exciting discovery. Having apparently forgotten that N saturation was old news under the previous well-established paradigm, the rediscovery of N-saturated soils is reported as the discovery of something new under the sun — a problem created by new and unique man-made phenomena, like acid rain (e.g., Aber et al., 1989) and chemical-N fertilizer (e.g., Turner and Rabalais, 1991).

However, the N-saturation problem is so old that, as the following quote from the USDA's *Soils & Men: Yearbook of Agriculture 1938* shows that Old World peasant farmers figured out how to transform the N-saturation problem created by livestock wastes into an asset:

"BUILDING SOIL ORGANIC MATTER LARGELY A NITROGEN PROBLEM

"Soil bacteria, the agents of decomposition, use carbon mainly as fuel and nitrogen as building material for their bodies.... Fresh organic matter is characterized as a rule by a large amount of carbon in relation to nitrogen. It has a wide carbon-nitrogen ratio, in other words; or so far as the bacteria are concerned, a wide ratio of fuel to building material. Such fresh material — straw, for example, — may have a ratio that is too wide.... The carbon will then be rapidly used up as fuel while the nitrogen is held or treasured without appreciable loss.... Thus when decay has proceeded to the point where the carbon-to-nitrogen ratio is significantly decreased, a residue of a more stable nature is produced. Thereafter the carbon-nitrogen ratio is narrower and remains more constant. This corresponds more nearly to the condition that holds in the case of the organic matter in virgin soils. Its further decay...liberates nitrogen in place of storing it or preserving it" (Albrecht, 1938).

Scientists operating under the previous, well-founded, N-cycle paradigm took pleasure in sharing admiration of the old peasant wisdom. In the absence of the periodic table, C:N ratios, and the science of microbiology, Old World farmers empirically figured out how to transform excessively N-rich and rapidly decomposable (very labile) animal wastes into the highest quality, N-releasing fertilizer. For example, continuing on where we left off with Albrecht:

"Small amounts of added nitrogen may in this way make possible the use of large amounts of carbonaceous matter in restoring the soil. Thus the European farmer first 'makes' his manure by composting the fresh straw-dung mixture from the barn and then treats it intermittently with the nitrogen-bearing liquid manure or urine from the same source and the nitrogen-rich leachings from the manure pit. He does not consider the fresh, strawy barn waste manure in the strictest sense until the surplus carbon has been removed through the heating process, and the less active manure compounds become similar to those of the soil organic matter.... The manure making of the Old World farmer turns the miscellaneous straw-dung-urine mixture, of highly variable value, into a standardized fertilizer for specific use" (Albrecht, 1938).

More than 60 years ago, soils scientists had already equated N saturating a plowed field with chemical N fertilizer as being in the same category as pre-scientific-era Old World N saturation, e.g.,

"Commercial nitrogen used as treatment on straw for the production of artificial manure in compost piles, or when plowing under straw in the field after a combine, may be considered in the same category" (Albrecht, 1938).

Or, to describe the N-saturation hypothesis in the words of Aldrich, which also predate the Aber et al. (1989) N-saturation hypothesis:

"When plant residues contain more than about 2.6 percent N, nitrates become available (are *mineralized* or *mobilized*) [emphasis his] as soon as the residue begins to decay. When the residue contains less than 1.2 percent N, nitrates are taken from the soil...(immobilized). Between 1.2 and 2.6 percent N there is a temporary immobilization of nitrate followed later by a release of nitrogen in nitrate form" (Aldrich, 1970).

Or we can go further back to the USDA's *Soil: Yearbook of Agriculture 1957* to paraphrase Aldrich's (1970) statement:

"If the carbon-nitrogen ratio is greater than about 30:1, any ammonia that is produced [by decomposition of organic N] will be rapidly reassimilated and be converted into microbial protein....

"When the C-N ratio of protein-containing organic residues becomes narrower than about 15:1 (so that considerable nitrogen in excess of microbial needs is present), the ammonia resulting from protein breakdown enters another phase, nitrification....

"Leaching also may take nitrate out of the soil cycle" (Broadbent, 1957).

Thus, be it the addition of N from animal waste, acid rain, chemical fertilizer, or other narrowings of the C:N ratio, we are talking about the same thing — after a certain threshold value of N is achieved, N begins to be released in solution as NO_3-N to the hydrosphere. As Viets and Hageman (1971) reminded us in the USDA's *Agriculture Handbook No. 413*, the NO_3-N "problem" is not a new problem. By restoring the concept of N saturation to its rightful place in the whole of the N cycle, like the scientists of old, we too can now appreciate Old World peasants' manipulation of the N-saturation problem in the barnyard.

Furthermore, we can now be amazed at the grander scale with which the indigenous Native American civilizations developed and used fire and animal management, and land-use techniques of whole ecosystem manipulation to modify the environment for their benefit. They did so by N saturating the landscape to increase productivity of plant and animal resources.

The effect of Native American use of fire to sustain the land as prairie, rather than have it grow up into forest, had an especially large effect on the size of N reservoirs and the transfers of N between them. As Figure 8 shows, undisturbed prairie soils of the humid Midwest in the early 20th century had about twice the N content of their undisturbed forest soil counterparts.

First, Native American land-use practices increased the soil N reservoir by promoting and maintaining the growth of grasses and legumes over trees. By doing so, Native Americans N saturated the landscape by greatly narrowing the C:N ratio of the soil-forming plant litter. As Table 7 shows, the effect of Native American land use was enormous in terms of the N cycle, as the N concentration of grassland litter is at least three-fold greater than that of forest litter.

Even the forested land that resisted from becoming prairie became more prairie-like. As documented above, such forests more resembled treed pastures with low tree-stand density and a forest floor covered with grasses, herbs, and legumes than the forests occupying the very same locations today. Clearly, by this difference, pre-European land-use practices simultaneously increased the size of the N reservoir, and the rates of N transfers, thereby increasing the overall N cycle, e.g.,

"Burning of prairies increases biomass production and nutrients, affects bacteria and fungi, and serves as a nutrient recycling pathway, accomplishing rapidly what the decomposers may take several seasons to do" (Dhillion et al., 1987).

There are a number of mechanisms, direct and indirect, by which fire increased the size of the terrestrial N reservoir and rates of N transfer from it. One way that fire did this was by making soils wetter. Equivalent soils under grasses are wetter than those under trees, as trees transpire more water than do grasses. And the equivalent grassland watersheds have higher water tables which manifest themselves in increased N content of soil. The fantastic fertility and naturally high N content of the dark colored agricultural soils of Illinois are in no small part due to the fact that these heavy textured soils were intermittently waterlogged.

The above average moisture enabled tallgrass prairie to grow as high as an elephant's eye:

"The original prairie consisted chiefly of big bluestem (*Andropogan furcatus*) with an admixture of a considerable number of other grasses, legumes, and various other forbs. The

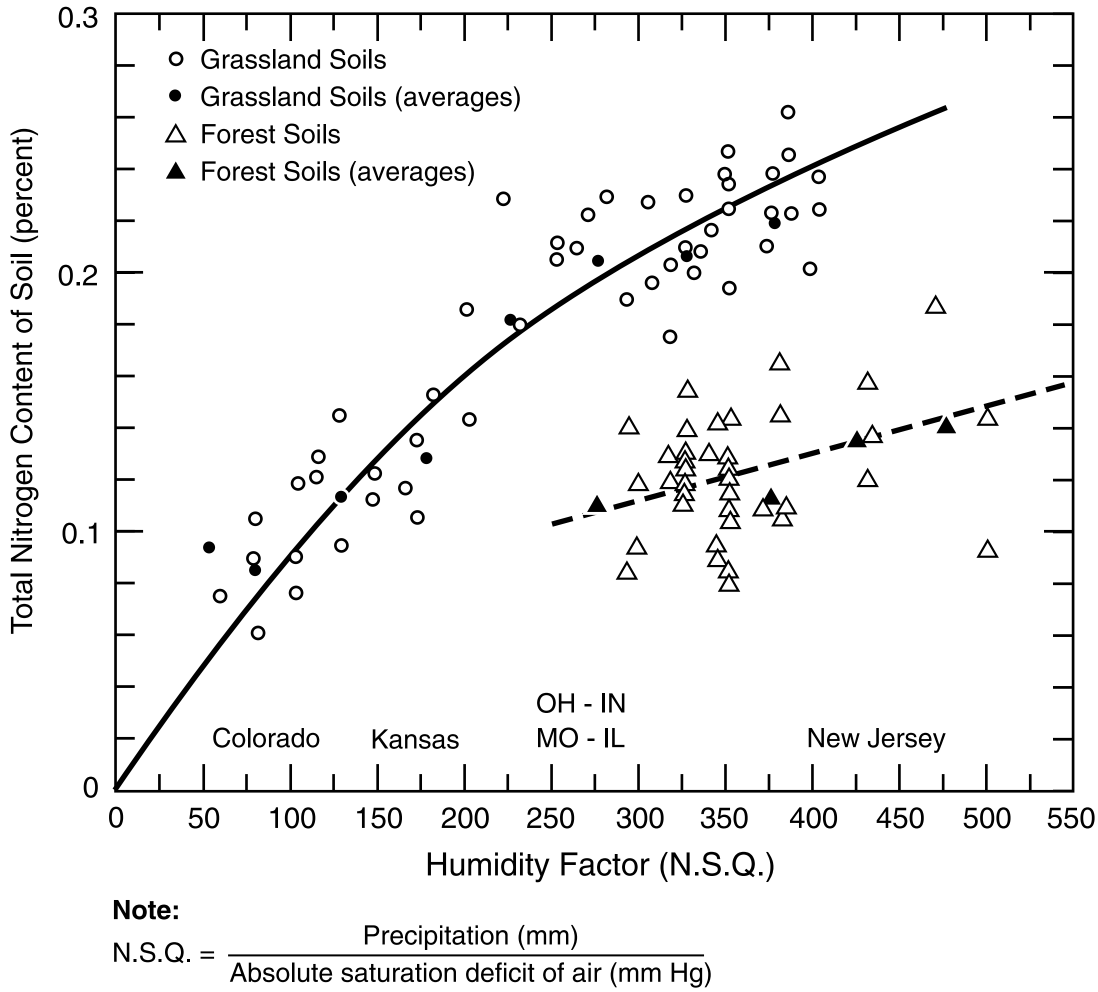

Figure 8. Soil nitrogen humidity relationship for prairie and forest soils of the central and eastern United States along the annual 11°C isotherm. **Source**: Adapted from Figure 56 of Jenny (1941).

Table 7. Typical C:N Ratios of Some Organic Materials

Material	*C:N*
Microbial biomass	6-12
Sewage sludge	5-14
Soil humus	10-12
Animal manures	13-25
Legume residues	13-25
Cereal residues and straw	60-80
Forest wastes	150-500

Source: Modified from Table 5.3 of Stevenson (1986).

grasses commonly reached a height of 6 to 8 feet, and formed a very tough sod" (Smith, Allaway, and Riecken, 1950).

Moist tallgrass prairie produced an extraordinary amount of litter. However, when combined with the less-than-complete oxidative destruction of litter — due to intermittent waterlogging (Aldrich, 1970; Viets and Hageman, 1971) during the period of highest flow [when precipitation exceeds evapotranspiration (Kofoid, 1903; Palmer, 1903; see "Water-Quality Reference/ Background Conditions")] — it produced black colored, heavy textured soils with somewhat elevated C and N content compared to their better drained, lighter colored counterparts (Table 8).

The Native American land-use practice of firing the landscape, which contributed to the waterlogging of soils, compounded the N-saturation "problem" by enhancing microbial N fixation. Table 9 shows litter typical of grasslands enhanced tenfold or more by waterlogging, and enhanced even further by the addition of yet more grassland litter (straw).

Brouzes, Lasik, and Knowles (1969) conducted similar experiments on the effect of addition of straw and other easily decomposable (labile) organic matter (glucose), and waterlogging on N fixation in agricultural and forest soils. Nitrogen fixation was greatly stimulated by waterlogging and by addition of a labile organic matter for agricultural soils; however, there was relatively little effect on N fixation in forest soils:

"Generally speaking, however, there was no consistent effect of litter addition in the forest soils" (Brouzes, Lasik, and Knowles, 1969).

Overall:

"Rough calculations showed that the nitrogen incorporation data represented a fixation of commonly 10-50 kg N/ha per year and occasionally as much as 200 kg N/ha per year. This paper thus provides further evidence that in many natural and other ecosystems the accretion of nitrogen through non-symbiotic fixation can be of considerable significance" (Brouzes, Lasik, and Knowles, 1969).

Review of N fixation in the wetlands of the world agree with the reported results of the above experiments. Wetlands in what ecologists would call an early stage of succession are nonforested and have very high rates of N fixation. But after wetland succession carries them from a grassy state into a forested state, N fixation drops off sharply (Waughman and Bellamy, 1980).

Table 8. Quantity of Nitrogen Found in the Top 40 Inches of Some Virgin, Common North Central States' Soil Types

Soil type	*Kg N/ha*
Black clay loams	16,490
Brown silt loams	13,370
Brown sandy loams	10,270
Yellow silt loams	5,980
Sands	6,090

Source: Modified from Table 3 (Schreiner and Brown,1938).

Table 9. Measurements of Asymbiotic Nitrogen Fixation Using ^{15}N or C_2H_2 Methodology

Methodology	*Experimental Conditions*	*N fixed (µg/g soil/28 days)*
^{15}N	Soil aliquots given laboratory incubation	
	(a) At field capacity, plus 1 percent straw	19
	(b) At field capacity, plus 5 percent straw	150
	(c) Waterlogged, plus 1 percent straw	67
	(d) Waterlogged, plus 5 percent straw	240
C_2H_2	Jordan Fertility Plots (Pennsylvania, U.S.A.)	
	(a) No fertilizer added, 0-15 cm depth	33.9
	(b) 27 kg/ha of N added, plus P and K	22.4
	(c) 81 kg/ha of N added, plus P and K	11.8

Source: Modified from Table 1 of Clark and Paul (1970). Methodologies based on measurement of the fixation of ^{15}N isotope altered N_2 gas or the reduction of acetylene (C_2H_2) to ethylene (C_2H_4).

From this, we can conclude that fire, by providing a regular disturbance, keeps the tallgrass prairie wetlands in an early stage of succession. With this, fire prevents tallgrass prairie wetlands from becoming forested. By doing this, fire keeps N fixation elevated far above what it would be otherwise.

Fire-enhanced waterlogging also increased N fixation within the soil itself. Microbial ecologists know that the most prolific N-fixing microorganisms — as well as the greatest number of known N-fixing species — are those of oxygen-deficient environs. The reported advantage of low-oxygen environs for N-fixing microorganisms is the fact that N-fixing organisms need to protect the N-fixing enzyme (nitrogenase) from O_2. In waterlogged, organic-rich environs, the investment needed to protect nitrogenase is low (Sprent, 1987).

Thus, Native American land-use practices appear to have further enhanced N saturation in precisely the landscape elements which most rapidly and directly transport N to surface waters (see "Clearing and Draining").

We see this because, not only do grasslands have higher N content than equivalent forest lands, grasslands yield greater amounts of runoff than do their forested equivalents. And, the more open, park-like, pre-European-settlement forests would have also yielded more runoff than their post-European forest successors (Goodell, 1952; Love, 1955, 1970; Orr, 1963; Hewlett, 1967; Douglass and Swank, 1972; Patric, 1974), And, given that moist, tallgrass prairie processes amounts of runoff disproportionately large relative to its area, because of its hydrologic setting (Dunne and Black, 1970; Bache, 1984; Rush et al., 1985; Krug, 1989; 1991; Wood et al., 1990), leaching of copious amounts of N from high N content, moist, tallgrass vegetation and N-rich soil to surface waters is expected (see "Clearing and Draining").

In the pre-European-settlement Illinois landscape, given the timing and magnitude of runoff (Geraghty et al., 1973), this is expected to result in a pronounced seasonal (dormant season) N peak in surface waters, not only for NO_3-N, but also for organic-N. Indeed, waterlogging of such soils will solubilize high concentrations of humified soil organic matter and their accompanying forms of organic-N.

The review of Thurman (1986, p 153) shows that from 0.5 to 10 mg N/l as total dissolved amino acids will be so solubilized to soil water.

Whereas the above indirect effects of anthropogenic plus natural pre-European-settlement firing of the landscape resulted in great quantities of N to be leached from this waterlogged soil and its nutrient-enriched vegetation (e.g., Figures 4, 5; Table 7; and see "Clearing and Draining"), not all of the standing biomass was available for leaching, or for enhancing N fixation (Table 9). This is because the direct effects of prairie fires transferred much of biomass N and C to the atmosphere.

The prairie reportedly burned almost annually, usually during the fall and spring of the dormant season (Gleason, 1913; Sauer, 1916; Curtis, 1959, pp. 295-305: Old, 1969; Bragg and Hulbert, 1976; Grimm, 1984). To quote Sauer on the Illinois situation:

"As long as large areas of prairie grass remained, there was great danger of prairie fires. 'From the first frost until spring, the settler slept with on eye open, unless the ground was covered with snow'" (Sauer, 1916, p. 158).

Ecosystem analysis of the N cycle of tallgrass prairies has shown that about 90 percent of biomass N is released to the atmosphere by prairie fire (Risser and Parton, 1982). Furthermore, during their hot burning periods, the gaseous emissions of grass fires are like those of industrial fossil-fuel combustion: namely, much nitrogen oxides and other high-temperature gaseous emissions are produced (Boubel, Darley, and Schuck, 1969; Crutzen and Andreae, 1990).

With the above, plus some additional data and concepts, we attempt a first-cut estimate of N lost from the landscape, and how much fixed N was emitted and redeposited for the reference/background state of the MRB. These estimates will be compared to present estimates of anthropogenic N emission and deposition, and to the amount of chemical-N fertilizer applied in the MRB.

Annual anthropogenic U.S. N-combustion emissions to the atmosphere are estimated to be 6 million metric tons N/yr (United Nations Environment Programme, 1993), of which an estimated 2.7 million metric tons come from the MRB. Annual deposition of anthropogenic N-combustion emissions to the MRB are estimated to be 1.0 million metric tons (Lawrence et al., 2000).

Under the standing N-cycle paradigm, N-combustion emissions and deposition from other than industrial sources are considered to be so small that such N deposition is considered to be almost exclusively a creature of the Industrial Revolution (e.g., Clark, 1996; Goolsby et al., 1999; David and Gentry, 2000a).

As with other aspects of the N cycle, the romantic Rousseauian vision of combustion in the putative Perfect Natural State of the MRB prior to European settlement resists correction by the facts; namely, rates of deposition of combustion products preserved in lake sediments show that for much of the prairie region of the MRB deposition rates were often tenfold higher in the 0 to 1850 BP period than in the 20th century (Clark, 1996).

The following estimate shows that pre-European-settlement firing of the MRB alone was on the same order as total estimated anthropogenic combustion N emissions for the entire United States today.

We begin our estimate of pre-European-settlement combustion N emissions from MRB prairie fires starting with an estimate of current biomass N production in the MRB. About 10 million metric tons N/yr are estimated to be harvested from 58 percent of the MRB — 8.6 million tons (Goolsby et al., 1999) from the 208 million acres of cropland (Faber, 2000) — in which about another 3 millions tons N/yr are left on the field as unharvested stubble (Goolsby et al., 1999) — plus some 1.2 million tons (apparently principally harvested as meat) from the ~250 million acres of grazed land in the 800-million-acre MRB (Goolsby et al., 1999), with the predominance of N left on the grasslands.

Based on the above, prior to European settlement of the MRB, probably some 20 million metric tons biomass N/yr or more were left standing at the end of the growing season to be burned in the form of prairie biomass. Forest biomass would add yet more to this figure — averaging 75 percent N volatilization and 2,800 kg N/ha for forest fires of the Upper Midwest (Snyder, 1905, p. 93). Considering only prairie fires and assuming that half of this MRB prairie biomass was burned each year and 90 percent biomass N was released to the atmosphere, we calculate that 8 million metric tons N/yr were emitted from MRB prairie fires to the atmosphere.

However, spring fires should result in less than 90 percent of biomass N losses to the atmosphere, due to overwintered N leaching to the hydrosphere.

For moist tallgrass prairie on glaciated terrain of the Midwest, the following was found:

“Losses, however, are minimized in the spring at the time burning when soil conditions are cold and wet. Furthermore, by this time about 75 percent of the total nitrogen from its peak level of the preceding season has been leached from the standing crop prior to burning” (Koelling and Kucera, 1965).

By assuming half of the MRB prairie fires were spring fires, combustion-N emissions are reduced to 5 million metric tons N/yr.

Regarding how much of this biomass N remained as biologically available fixed N, it has been estimated that up to half of burned biomass N undergoes pyrodenitrification to N_2 gas (Crutzen and Andreae, 1990). This nearly 50 percent value applies to forest materials of high C:N ratio. The more N rich the plant material, the lower the percentage of the plant N that undergoes pyrodenitrification: 24 percent for C:N = 77 (savannah grasses); 19 percent for C:N = 33 (hay); and 5 percent pyrodenitrification for C:N = 11 (grass/clover) (Kuhlbusch et al., 1991).

Using a pyrodenitrification value of 20 percent, estimated pre-European prairie-biomass-burning emissions of fixed N for the MRB drops down to 4 million metric tons N/yr. Even though this value does not consider the additional load of N released from pre-European-settlement forest fires, it is appreciably higher than the 2.7 million metric ton N/yr modern-day MRB estimate of fixed N emissions (Lawrence et al., 2000).

Moving on to the estimation of pre-European-settlement N deposition resulting from MRB prairie fires, this estimation starts with the current estimate of anthropogenic N deposition and the principles used to derive it.

From this, we conclude that, in the pre-European-settlement period, more of fire-generated fixed N was deposited in the MRB than N combustion emissions are today. This appears to be so for a number of reasons.

First, the geographic distributions of pre- and post-European-settlement combustion emissions and prevailing westerly wind favor a greater proportion of deposition of the pre-European-settlement prairie N combustion emissions in the MRB than occurs for N combustion emissions today. Nitrogen-combustion emissions today are mostly in the eastern third of the United States (Goolsby et al., 1999). The greatest N emissions within the MRB are concentrated in the Basin's northeast quarter (Lawrence et al., 2000). On the other hand, prairies are concentrated in the central and western portions of the MRB. Thus, based on geography alone, more N emissions from prairie fires would have been deposited within the MRB than is the case for N combustion emissions today.

Second, the nature of pre-European combustion N emissions favored more local deposition than emissions from modern combustion sources. Namely, the smoky (particulate) nature of the pre-European-settlement biomass combustion more favored local deposition. The nature of today's less smoky fossil-fuel emissions, plus appreciable emissions deliberately made from tall stacks, have transformed combustion-related N deposition from being essentially a local deposition phenomenon to more of a long-range, continental-scale transport phenomenon, which crosses national boundaries (Likens and Bormann, 1974; Braekke, 1976; Likens et al., 1979; Overrein, Scip, and Tollan, 1980; Patrick, Binetti, and Halterman, 1981). Thus, based on the nature of the emissions themselves, more of the pre-European-settlement combustion emissions would have been locally deposited than is true for today's emissions.

Thus, pre-European-settlement combustion-related N deposition in the MRB is estimated to have been much higher than it is today. Conservatively, estimating a 50 percent deposition rate for pre-European N combustion emissions (compared to 37 percent for modern sources (Lawrence et al., 2000), we estimate that N combustion deposition in the MRB was 2 million metric tons N/yr. This is double the contemporary estimate of 1.0 million metric tons N/yr (Lawrence et al., 2000).

Clearly, the idea that today's 1.0 million metric tons N/yr deposition value represents a nearly 1.0 million metric tons N/yr increase over the reference/background N-deposition value for combustion N is wrong.

On the other side of the equation, we conservatively estimate that pre-European-settlement prairie biomass burning in the MRB caused a loss of at least 1 million metric tons fixed N/yr from the MRB due to pyrodenitrification. And up to another 2 million metric tons N/yr are estimated to have been lost due to atmospheric transport outside of the MRB.

That the prairie landscapes of the MRB could maintain its hugely elevated soil-N reservoir in the face of losing some 3 million metric tons N/yr from fire alone — about twice the N now being lost down the Mississippi River to the Gulf of Mexico (Goolsby et al, 1999) — can only be explained by massively elevated N fixation occurring within the prairie soils at levels heretofore not previously conceived of.

To explain this, we now further refine our understanding of how the Native American use of fire may have further increased N fixation in the prairie beyond what we have already considered.

As with the previous factors analyzed, we will see that the factors which increased the soil-N reservoir also enhanced transfer of N from that reservoir.

The fierce and frequent pre-European-settlement fires transformed the abundant litter of the tallgrass prairie. Not only did this burning of plant litter reduce the amount of C in fresh litter that would otherwise tie up N, fire ash created by the burning of plant material increased the N reservoirs in soil and water by enhancing N fixation in both soil and water by raising pH and by supplying concentrated amounts of nutrients, which stimulate both symbiotic and asymbiotic N fixation.

Regarding the enhancement of soil N fixation, pre-European-settlement fire did this by raising soil pH and by providing nutrients in concentrated form. Both increased pH and fire's concentration of nutrients enhanced N fixation by symbiotic and asymbiotic-fixing microorganisms. Fire, which promoted the growth of prairie over forest, acted to raise soil pH as high lignin, high C:N and low-nutrient-content forest litter promotes the development of highly-acidic soil humus relative to that produced by prairie vegetation (e.g., Figure 9; Marbut, 1951). Fire also reduced the tree density of the pre-European-settlement forest and promoted soil waterlogging, which increased soil pH and the amount of surface runoff (Goodell, 1952; Love, 1955, 1970; Orr, 1963; Hewlett, 1967; Douglass and Swank, 1972; Patric, 1974). For example:

"Hibbert (1966) summarized 30 forest cutting and poisoning experiments in the United States, Africa, and Japan, as well as nine additional cases in which streamflow increases were studied for some years following afforestation. The controlled experiments all showed significant changes in water yield, averaging about eight inches increase following elimination of fully stocked stands and about the same decrease 20 or 30 years after afforestation. Dozens of soil moisture studies have verified the fact that forest removal or conversion to other vegetation types reduces evaporative draft on soil water and increases the opportunity for these 'savings' to be delivered as streamflow" (Hewlett, 1967).

As the data in the Gulf of Mexico hypoxia literature show (Burkart et al., 1999; Goolsby et al., 1999; Mitsch et al., 1999; Wu and Babcock, 1999), the quantity of N exported from a watershed is heavily dependent upon the amount of water issuing from it, and, therefore, the amount of N leached to receiving waters (see also Viets, 1971; Viets and Hageman, 1971; National Research Council, 1972).

Returning to the effect of fire on soil pH, fire ash also acted directly to raise soil pH, because it is highly alkaline — lime has a pH of ~8 and fire ash has a pH of 12-13 (Unger and Fernandez, 1990; Ulery, Graham, and Amrhein, 1993; Someshwar, 1996; Vance, 1996; Chirenje and Ma, 1999).

Thus, the frequent and intense fires of the pre-European-settlement era, by their indirect and direct effects on raising soil pH, enhanced N fixation by both free-living and symbiotic microorganisms, the free-living N-fixers being especially pH sensitive (McHargue and Peter, 1921; Wakesman, 1937; Jenny, 1941; Thompson, Black, and Zoellner, 1954; Lodhi, 1977; 1982; Stark and Steele, 1977; Griffith, 1978; Cole and Heil, 1981; Schimel, Stillwell, and Woodmansee, 1985; Sprent, 1987, pp. 58-60; Mulder et al., 1997). Fire ash, unlike lime [the latter composed mostly of (Ca, Mg) CO_3], has its plant nutrients in even more highly soluble oxide form. The oxides of plant nutrients which make up fire ash (Unger and Fernandez, 1990; Ulery, Graham, and Amrhein, 1993; Someshwar, 1996; Chirenje and Ma, 1999) promote N fixation, with P long known as being especially effective in enhancing terrestrial N fixation (e.g, McHargue and Peter, 1921; Thompson, Black, and Zoellner, 1954; Griffith, 1978; Cole and Heil, 1981).

The old, pre-chemical N-fertilizer era literature directly recognized the importance of fire ash and similar materials in enhancing N fixation in grasslands, e.g.:

"Wood ashes make an excellent top dressing for grass lands, particularly where it is desired to encourage the growth of clover [a legume]" (Snyder, 1905, p. 185).

And:

"**309. Leguminous Crops.** For leguminous crops potash and lime fertilizers have been found to be of most value...as the results of growing leguminous crops...the soil is enriched with nitrogen and the phosphoric acid is changed to available form" (Snyder, 1905, p. 226).

Addition of fire ash-like materials to centuries old, undisturbed grassland over a period of two years resulted in the increase of legume plants from 8.01 percent to 23.06 percent of total plants growing in grassland. Quantity of legumes increased from 202 lb/acre/yr to 1,026 lb/acre/

yr. And while the percent of grasses plants declined (from 67.55 percent to 61.03 percent) the quantity of grass increased from 1,743 lb/acre-yr to 2,808 lb/acre/yr (Davenport, 1927, pp. 75-76).

In Minnesota, it was found that by including clover in the wheat/oats/corn crop rotation that instead of losing 146.5 lb N/acre/yr from the soil, the soil gained 61 lb N/acre/yr. The total improvement in N status when including N in harvested crops was 210 lb N/acre-yr by including the legume clover in the crop rotation (Snyder, 1905, pp. 112-114).

Turning to aquatic N fixation, scientific analysis indicates that the frequent, intense pre-European-settlement fires also increased aquatic N fixation to greater levels than those considered "natural" today. This is because some of the fire ash was washed off into receiving waters. The plant nutrients that comprise fire ash, especially P, promote the growth of noxious blooms of N-fixing algae and the N-fixing aquatic macrophyte azolla [N fixed by azolla's symbiont blue-green algae] (Cohn and Renlund, 1953; Fitzgerald, 1969; Moore, 1969; National Research Council, 1969; Rusness and Burris, 1970; Shapiro, 1973; Ruttner, 1974; Gerloff, 1975; Peters, 1977; Talley, Talley, and Rains, 1977; Watanabe et al., 1977; Horne, 1979; Kilham and Tilman, 1979; Leonardson and Ripl, 1980; Stewart et al., 1981; Smith, 1982; 1983; Wetzel, 1983).

Assessment of pre-European-settlement conditions indicates that appreciable amounts of this N-stimulating fire ash were washed off the land into surface waters. Fire ash, unlike agricultural fertilizer, is not tilled into the ground to prevent the nutrients from washing off the land and into lakes and streams. Unlike fertilizer, fire ash is deposited on the soil surface. That makes fire ash much more susceptible to being washed off the land and into receiving waters than applied agricultural fertilizer.

Furthermore, the propensity of fire ash to run off into receiving waters is exacerbated by the hydrological significance of the burned, moist, tallgrass prairie wetlands. Wetlands exert disproportionally great influence on surface-water chemistry because of their hydrologic proximity to receiving waters and their role as collectors and transmitters of water from more upland elements of the watershed (e.g., Dunne and Black, 1970; Bache, 1984; Wood et al., 1990). Moreover, the burning of the highly productive, high-nutrient-content, moist, tallgrass prairie deposited large amounts of highly soluble oxides of plant-nutrient ash in these prairie wetlands.

The propensity of ash to run off into receiving waters is exacerbated by the fact that these prairie fires occurred principally during the dormant season — the season of greatest runoff and highest water tables. These conditions facilitated rapid delivery of high volumes of high nutrient content water to surface waters, largely bypassing subsurface drainage in which dissolved nutrients undergo extensive biogeochemical processing and immobilization by within-soil processes (e.g., USDA, 1938, 1947; Jones, 1942; Krantz, Ohlrogge, and Scarseth, 1943; Scarseth et al. 1943; McColl and Grigal, 1975; Wright, 19776; Krejsl and Scanlon, 1996; Vance, 1996; Williams, Hollis, and Smith, 1996; Chirenje and Ma, 1999), as well as being immobilized by plant uptake.

These dormant-season prairie fires would have also affected stream-side forests — the principal forest type existing in the Illinois prairie (Gleason, 1913; Sauer, 1916; Forbes, 1919; Johnson and Bell, 1975) — in much the same manner.

With this, we see that "Mother Nature," applied fire-ash fertilizer contrary to today's recommended fertilizer-application practices, never plowing it in. After more-or-less clearing the land, Nature dumped the heaviest amounts on the surface in precisely the right location and at precisely the right time to maximize the washing of highly soluble nutrients into surface waters.

Such burnings also would have increased soil erosion. These predominately dormant season fires would have maximized soil erosion runoff, given the lack of plant growth to recover the soil and the elevated flow and water tables that maximized surface runoff. Such fire-induced, surface-water overfertilization helps explain why typical pre-settlement Illinois surface water was hypertrophic — overgrown with jungle-like masses of aquatic vegetation and algae — and not oligotrophic, almost distilled water as asserted by the standing paradigm. The flush of concentrated nutrients from prairie fire ash into surface waters promoted and further exacerbated eutrophication by inducing N fixation in aquatic ecosystems. Or, to quote the Gulf of Mexico Program (Turner and Rabalais, 1991) on the expected effect of the fire-induced pre-European-settlement condition:

"The riverine ecosystem response to higher nutrient loading is consistent with the nitrogen-saturation hypothesis described for northern forests by Aber et al. (1989)."

However, pre-European-settlement prairie fires were N saturating the environment long before the Industrial Era and its concomitants of acid rain and chemical N fertilizers. Humates, the principal component of soil humus, are solubilized by treatment with alkaline solution — this being the standard method employed for their identification. The pH 12-13 solutions produced by fire ash readily solubilized soil humus; and this solubilized humus also would have transported its appreciable content of organic N (Table 7) and sorbed NH_4-N in runoff to surface waters above and beyond that liberated by waterlogging itself.

The raising of soil pH (by fire) also increased loss of soil N to the atmosphere by converting a greater proportion of soil ionic ammonium (NH_4-N) to ammonia (NH_3-N) gas, thereby increasing the gaseous loss of ammonia N to the atmosphere (e.g., Sprent, 1987, p. 58).

Experiments show that much of this volatilized ammonia gas, with its high affinity for water, was apparently redeposited to nearby surface waters (Viets and Hageman, 1971).

As noted in reviews below, fire also increases the amount of NH_4-N in soil (Dhillion, Anderson, and Liberta, 1988; Niering and Dreyer, 1989), thereby compounding the amount of ammonia gas volatilized from soil to the atmosphere through the chemical law of mass action. Given that NH_4-N also solubilizes soil humus, pre-European-settlement fires also appear to have enhanced the transfer of humate-bound organic-N and NH_4-N to the hydrosphere.

The raising of soil pH by fire ash also appears to have increased loss of soil N to the hydrosphere by yet another mechanism — the enhancing of nitrification (conversion of NH_4-N to NO_3-N), e.g.,

"Grassland burning results in enhanced mineralization, especially nitrification due to increased numbers of soil bacteria (Black, 1957; Moore, 1960; Neuenschwander, 1976; Sharrow and Wright, 1977). Rice and Parenti (1978) also found that excessive litter can reduce nitrification and, following its removal by fire, nitrification is favored, thus further increasing nutrient availability" (Niering and Dreyer, 1989).

And:

"Higher N and P in plants and soils on burned sites than on unburned sites following fire (reported by some workers, e.g., Knapp 1985; Old 1969) apparently results from the stimulation of biological processes, such as nitrification and mineralization, by burning (Ahlgren 1960; Alhgren and Ahlgren 1965; Old 1969; Well 1971; Biswell 1972)" (Dhillion, Anderson, and Liberta, 1988).

Note that Old (1969) is the seminal research study of Illinois tallgrass prairie conducted at the University of Illinois' Trelease Grassland.

Of course, increased bioavailablity would be true for virtually all soil nutrients, not only N and P. A major factor for this was already recognized by the time of Snyder (1905) and Hopkins (1910). Namely, factors that enhance biogeochemical nutrient cycling increase the proportion of the nutrient reservoir in the form of fresh and labile organic matter. This reservoir of readily decomposable organic material readily gives up its nutrients and is, therefore, a ready source of calories (fuel) for the heterotrophic decomposers that release nutrients from the soil. Not only does this increase the size of the labile N and other labile nutrient reservoirs, but it also increases the transfers from these increased reservoirs.

From the above, it can be said that fire performs a type of alchemy — it consumes biomass which has long been characterized as "souring" soils, and by such transformation creates ashes which have long been characterized as "sweetening" soils.

Thus, fired prairie soils stand in sharp contrast to the Corn Belt soils that have come to replace them. The remnant organic matter and nutrient stores of the Corn Belt soils have survived largely because they are hard to decompose: they are the biogeochemical equivalent of tough old, Army boot leather.

Additionally, fire would have swept out of the prairie and into the pre-European-settlement forests of Illinois. Here too fire would have increased nitrification. Fire appears to enhance the leaching of NO_3-N by reducing the C:N ratio in the unburned residue and by the fire ash raising soil pH, which enhances microbial mineralization of organic-N to NH_4-N and stimulates the microbial nitrification of NH_4-N to NO_3-N (Fowells and Stephenson, 1934; Isaac and Hopkins, 1937; Viro, 1974), e.g.,

"Nitrification in forest soils is stimulated by burning and the liberation of the basic ash materials" (Fowells and Stephenson, 1934).

Of course, prior to the era of modern chemical fertilizers, the old scientific texts on soil fertility not only sang the praises of fire ashes for enhancing N fixation, but also of fire ash and/or lime for converting fixed N to NO_3-N via nitrification, e.g.,

"Ashes are valuable, too, because they add alkaline matter to the soil which corrects acidity and aids nitrification" (Snyder, 1905, p. 183). Fire ashes when applied to soil promote nitrification, provided there is a source of readily decomposable organic matter, O_2, and enough water. The release of NO_3-N was reported as stimulating the early growth of plants (Snyder, 1905, pp. 175-186).

The old texts not only sang the praises of fire ashes in making N more plant available, but also in making P more plant available:

"The neutralization of the organic acids of soils by application of lime and wood ashes hastens the bacterial action. During the process of nitrification, the bacterial action is not alone confined to the nitrogenous compounds of the soil, the nitrifying organisms require phosphates as food which are left after nitrification in a more available condition as plant food" (Snyder, 1905, pp. 252-253).

As previously discussed, increased bioavailability of P would also enhance N fixation. Similar assessments regarding the enhancement of symbiotic and asymbiotic N fixation, as well as nitrification of the fixed N to NO_3-N by fire ash and similar substances, can be seen throughout Hopkins (1910).

Limiting our assessment to the effect of fire on nitrification in Illinois prairie soils, and drawing on the more controlled scientific studies of the latter period of the well-founded N-cycle paradigm, we used Morrill and Dawson's (1967) study of 116 U.S. soil types, ranging in pH from 4.4 to 8.8, and selected a soil with physical and chemical properties resembling prairie soil common to Illinois (Figure 9) — a pH 5.5 silt loam. Figure 10 shows that adding lime greatly increases the nitrification of NH_4-N to NO_3-N, as well as the intermediate form of N — NO_2-N — in water leaching out of the soil.

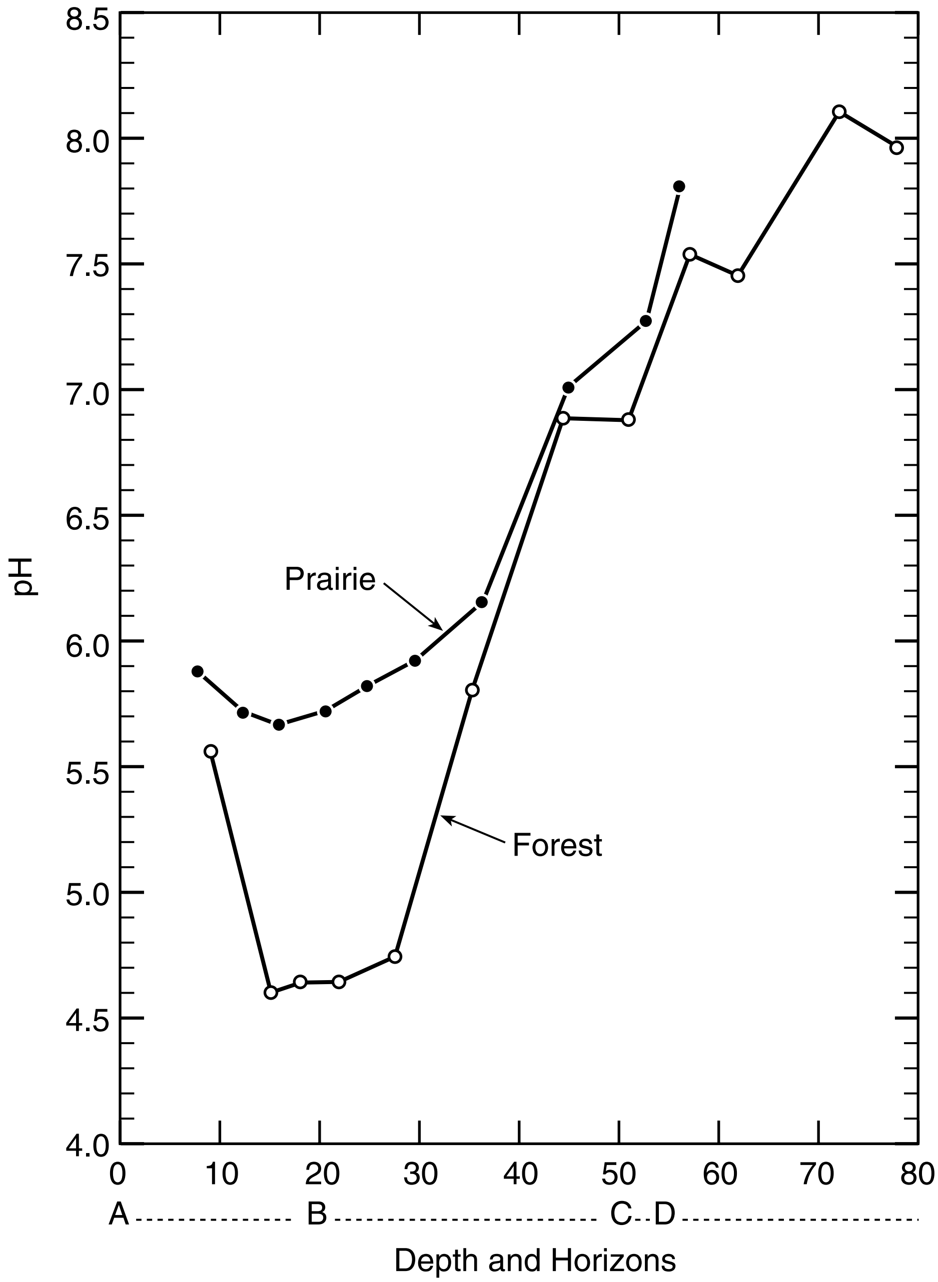

Figure 9. Comparison of the pH of forest and prairie soils of Illinois under identical soil-forming factors. **Source**: Adapted from Figure 110 of Jenny (1941).

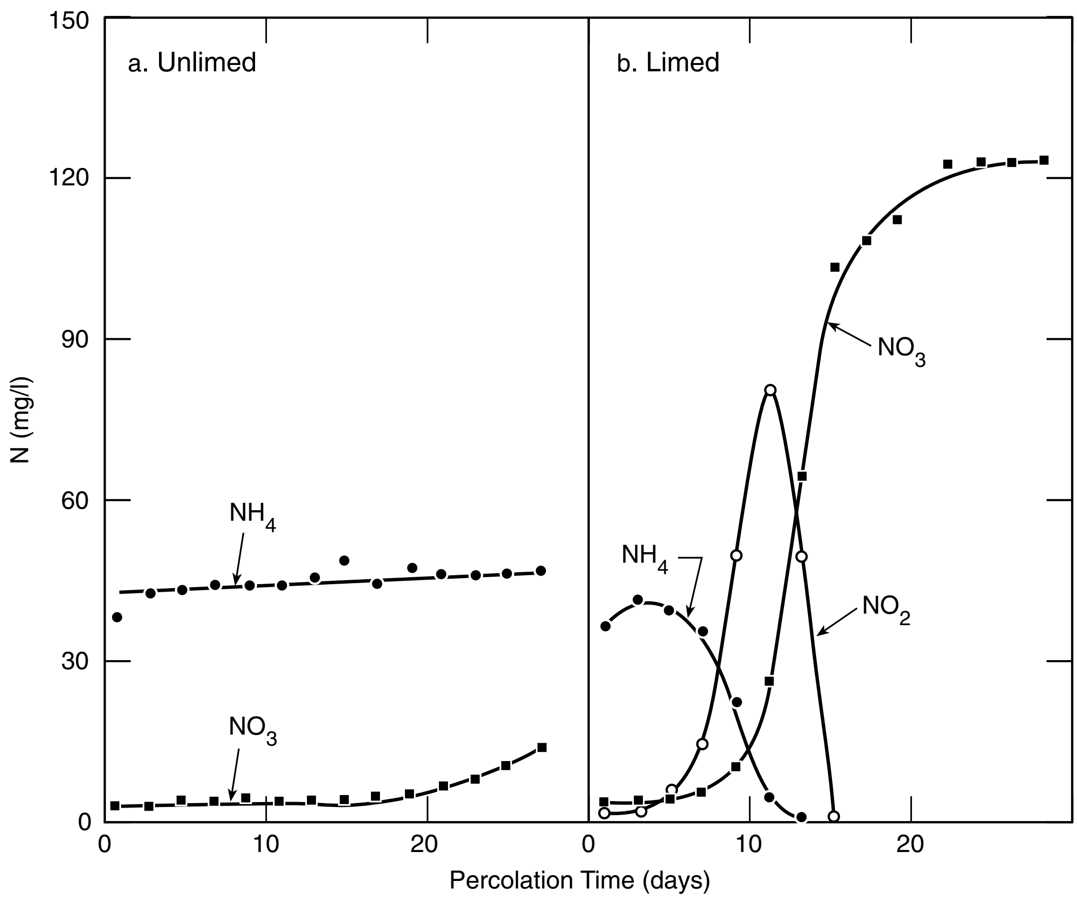

Figure 10. The effect of liming on nitrification in pH 5.5
Kibly Silt Loam: a) unlimed and b) limed.
Source: Adapted from Figure 3 of Morrill and Dawson (1967).

As mentioned above, fire also acts to increase the supply of NH_4-N, thereby compounding the amount of NO_2-N and NO_3-N available for leaching by increasing the supply of raw material (ammoniacal-N) available for nitrification. Again, this is predicted by the chemical law of mass action.

The majority of ash-producing fires occurred during the dormant season, when appreciable amounts of soil nitrification still occurred (e.g., Storer, 1897, p. 514; Snyder, 1905, pp. 114-117; Foster, Nicholson, and Hazlett, 1989; Hazlett, Englis, and Foster, 1992; "Plowing and Fertilizing"), when plants were not taking up this produced NH_4-N, NO_2-N, and NO_3-N, and when most runoff to surface waters occurred. Therefore, we concluded that, prior to European settlement, burned tallgrass prairies were leaching appreciable amounts of NO_2 -N and NO_3-N to receiving waters during the dormant season.

Fire, by enhancing nitrification, also greatly enhanced transfer to the atmosphere of gases produced by nitrification and denitrification. Both the nitrification (oxidation of ammoniacal-N to NO_2-N and/or NO_3-N) and denitrification (reduction of NO_3-N and/or NO_2-N to N_2 or N_2O gases) sides of the ~10 billion ($10x10^9$) metric tons N/yr biospheric N cycle produce gaseous oxides of N that are lost to the atmosphere. However, whereas the gaseous products of nitrification and denitrification released to the atmosphere are minor products in terms of the ~10 billion metric ton natural biospheric N cycle, these nitrogen gases are major when compared with the ~100 million metric ton anthropogenic N cycle and the ~100 million metric ton N/yr estimated background value for N fixation.

The estimates of two of the gaseous fixed-N byproducts, nitric oxide and nitrous oxide, are on the order of 100 million metric tons N/yr (Soderlund and Svensson, 1976; National Research Council, 1977, pp. 20-25). This does not include another important (often the most important) gaseous byproduct of denitrification: N gas (N_2) itself. With these facts, plus the other imbalances noted by Soderlund and Svensson (1976) in the atmospheric portion of the N cycle, it appears that the standing N-cycle paradigm significantly underestimates the amount of natural N fixation of atmospheric N_2 gas.

In regard to the pyrrhic pre-European-settlement condition, the literature shows that fire enhances the emissions of these two gaseous oxides of N by 2- to 10-fold over those of the unburned background condition grasslands. Enhanced emissions of N oxides occur both in the nitrification side of the N cycle (oxidation of NH_4-N to NO_3-N), due to the fire-stimulated increased nitrification, and in the denitrification side of the N cycle (reduction of NO_3-N to N_2 and N_2O gases), when the grassland soils are waterlogged. The more intense the fire, the greater the emissions (Levine et al., 1988).

Experiments plus review of the world's literature showed:

"The measurements reported here indicate that NO and N_2O emissions from burned areas equal or exceed those from fertilized agricultural areas and persist for much longer periods of time" (Anderson et al., 1988).

All of the above strongly suggest that the pre-European-settlement emissions of nitric oxide and nitrous oxide from the MRB were at least as great as the estimated 7 million metric tons chemical-N fertilizer added yearly to the MRB today. Given that N_2 gas is usually the principal product of denitrification, just for soils to maintain the status quo, annual pre-European-settlement terrestrial-N fixation in the MRB had to be at least several fold higher than the 7 million metric ton N fertilizer added value. Again, we have yet another factor that indicates that the standing N-cycle paradigm significantly underestimates natural N fixation of atmospheric N_2 gas.

When we include the estimated 3 million metric tons N/yr lost directly by biomass combustion, plus the greatly enhanced fire-induced loss of N to the hydrosphere — both ground water and surface water — MRB pre-settlement N fixation appears to be multiple times greater than the amount of fixed N added to the MRB today as fertilizer. Such values of gaseous losses to the atmosphere suggest that the estimate used for "natural" N fixation needs to be revised significantly upward to a value that exceeds the current estimate of both "natural" and anthropogenically induced N fixation.

This analysis of the pre-European-settlement condition of the N cycle indicates that the prairie landscape was appreciably different than that of undisturbed prairie today. It was also different than the undisturbed prairie condition used as reference/background conditions by soil scientists of the early 20th century (e.g., Schreiner and Brown, 1938; Jenny, 1941). Clearly, the terrestrial N reservoir and N transfers from it were larger than those of the undisturbed prairies of the early 20th century.

The conclusion of this analysis is supported by what is common knowledge in prairie, prairie restoration, and environmental literatures: namely, that the pre-European-settlement prairie was different than today's so-called, virgin, undisturbed prairies. e.g.;

"However, leaving the area alone will not satisfactorily reestablish the original prairie because the large herbivores, bison, elk, and antelope formerly present are absent, and because fire would rarely occur naturally" (Hulbert, 1973).

And:

"'Wildlife also benefit from fire,' Fuge said. 'Grasslands that are improved by burning provide better habitat than unburned areas for upland game, waterfowl and wading birds....'

"'Prairies are Minnesota's most endangered habitat,' Fuge said. 'If people were to compare the state's original 18 million acres of prairie to a dollar, they would realize that we have less than a penny's worth left. Burning helps us keep the little bit of prairie we have left healthy'" (Anonymous, 1997).

Scientific and environmental literatures on prairie restoration can help us further refine our assessment of the pre-European-settlement condition. How pre-European-settlement fires influenced the growth and species composition of native prairie plants is relevant to the issue of the N-saturation "problem" via the promotion of the growth of legumes:

"During the 1940s and 1950s, the great botanist John Curtis surveyed the plant species compositions of prairie remnants in Wisconsin, which has lost about 99.9 percent of its original prairie. Leach and Givnish built on this heritage by resampling 54 of Curtis's sites, originally chosen to control for differences in soil fertility. This important long-term study showed that about one-third of the plant species originally present at each of these 'undisturbed' sites had been lost during the intervening 40 to 50 years, that is, had gone locally extinct....

"The species lost from the prairie remnants were a highly biased subset, composed of smaller, shorter plant species and nitrogen-fixing legumes. Such species, Leach and Givnish suggest, are fire dependent, and their biased loss may be caused by an unexpected component of habitat fragmentation — the loss of a major landscape-level force, periodic fire. The disruption of natural fire cycles resulting from agriculture, roads, and other human activities, as well as from overt fire suppression, it seems, was the major force behind the unexpectedly high rate of species loss in these prairie remnants" (Tilman, 1996).

However, the 1940s and 1950s prairies studied by Curtis were already quite different from that developed under Native American stewardship. Not only were the vast numbers of buffalo and other animals missing, but also the frequent and intense dormant-season fires. As noted by Chavannes (1941) earlier, by the time Curtis viewed the prairie, it was profoundly changed from what Jonathan Carver observed in the 1780s. After clearing of Native Americans from the landscape to make way for European settlers, greatly decreased fire frequency and intensity had a major effect on Wisconsin prairies. By 1829, prairie was mapped as covering 90 percent of southern Wisconsin, but this had decreased to only 33 percent by 1854. By the time Curtis examined the prairies in the 1940s and 1950s, their extent was reduced to small specialized landscape elements, such as narrow segments of railroad right-of-ways (Leach and Givnish, 1996).

Regarding Illinois prairie, as stated in the introduction of Betz and Lamp (1989), even detailed plant surveys of Illinois prairies in the 1910s and 1920s (e.g., Sampson,1921) were no longer representative of the prairies encountered by the original settlers. Thus, the difference between pre- and post-European-settlement prairie legume content is probably even greater than reported by Leach and Givnish (1996). And, given that legume plant material is so N rich, its C:N ratio being close to that at which decomposition causes the release of NO_3 to soil water (e.g., Broadbent, 1957; Table 7), massive legume loss represents a very significant change in the level of N saturation of the landscape between pre- and post-European settlement. Further, given how quickly the soil system can readjust itself, especially in the early years after change, this significant decrease in legumes would probably have resulted in a significant and rapid decrease in the soil N reservoir.

For example, Niering and Dreyer (1989) state:

"In the southeastern United States leguminous species markedly increased following savanna grassland fires and after 8 years, total nitrogen increased 50 percent in the upper 15 cm of the soil (Garren, 1943)."

To quote the extensive review of Garren (1943) itself:

"Higher total nitrogen is also reported for these burned soils. Since more grass and legumes are found on burned-over longleaf areas, one possible source of this additional nitrogen is obvious. The main soil changes as a result of fire, however, seem to be due to the return of mineral materials to the soil in ashes....

"Considerable reduction in the area and quantity of grasses and other herbs results from complete fire protection in longleaf forest grazing areas. In six years grazing areas decreased twice as rapidly on fire-protected range as on adjacent winter-burned range. Over twice as many green-weight pounds of grass can be found per acre on burned areas as can be found on comparable unburned areas....

"Grasses growing on areas subjected to burning for ten years show slightly higher percentages of protein, lime, phosphate, ash, and fat than the same species growing on unburned areas. Grass from unburned areas has a greater bulk and crude fiber content, but the green dry weight is much lower....

"Other herbs also respond to burning-over of the longleaf forest floor. A tally revealed 11 species of legumes on unburned and grazed areas in Mississippi, while adjacent burned-grazed areas showed 16 species of legumes" (Garren, 1943).

What this legume-induced increase in soil N would mean to the amount of NO_3-N leaking out of the legume nitrogen-saturated soil are indicated by experimental removal of N-fixing alder. Water leaching out from under alder averaged 4.4 mg NO_3-N/l. After removal of alder and replacement with non-N-fixing vegetation, the concentration of NO_3-N in water leaching through the soil decreased sharply. After just four years, average concentration of NO_3-N dropped from

4.4 mg NO_3-N/l to 0.02 mg/l NO_3-N/l – the concentration typically found under the replacing type of non-N-fixing vegetation (Van Miegroet, Cole, and Foster, 1992, pp. 194-195).

Relaxing of the Native American land-use practices with the decline of their civilizations would, therefore, have resulted in rapid and profound decreases in soil and water N content and fertility. With this, the early settlers did not experience the full fertility of the Illinois landscape as it would have been when the landscape was firmly under the stewardship of Native Americans. This will become even more apparent as our assessment progresses.

Returning to the effects of fire, in addition to mechanisms already discussed, fire increased N fixation and N mineralization-nitrification by other mechanisms related to fire's removal of thick, smothering litter layers.

Changes in surface environmental conditions following fire, removal of the thick blanket of smothering litter, early warming of the surface due to blackening, plus other more subtle changes in the landscape's surface, promote certain types of vegetation. These changes also enhance the ability of such vegetation to stimulate N fixation, mineralization, and nitrification by providing complex root exudates of carbohydrate and hormone-like substances, which stimulate microbial N fixation, and the growth of worms and other soil animals. Their mucus, wastes, and other excretions promote N fixation, mineralization, and nitrification, and the direct transfer of nutrients between plants through hyphae development in the root zone (Seastedt, Hayes, and Petersen, 1986; Sprent, 1987; Niering and Dreyer, 1989; Polsinelli, Materassi, and Vincenzini, 1991). Again, these are all subtle and complex ecological effects that work in concert to increase the reservoir of labile N and the increase the rates of transfers from such enlarged reservoirs.

Additionally, fire's destruction of the smothering litter layer also destroys chemical compounds present in the litter, that poison N fixation, N mineralization, and nitrification. This chemical warfare waged by plants on each other and on microorganisms involved in the N cycle is known as allelopathy.

Plant allelopathy was first discovered by agronomists. Many natural grassland plants are considered weeds, because they compete with crops for nutrients, water, and light. They also release allelopathic chemical agents, which accumulate in soil to the point that these chemicals stunt, kill, and/or prevent seed germination of crops, and kill essential soil microorganisms. Indeed, many crop species poison themselves by poisoning the soil through the release of allelopathic substances (Schreiner and Sullivan, 1909; Rice, 1967; Tukey, 1969; Zimdahl, 1999).

Reviews of the literature shows that allelopathic inhibition of soil microorganisms involved in the N cycle is a common occurrence (e.g, Clark and Paul, 1970; Rice, 1984). Regarding Illinois tallgrass prairie, Old (1969) suggested that the effect of fire in improving prairie vegetation and plant and soil nutrient status due to removal of litter may be due to both improved microclimate, removal of N-sequestering litter, and the elimination of allelopathic inhibition from substances contained within the prairie litter.

The litter of many plant species contain numerous water-soluble organic allelopathic substances, such as tannins, phenolics, and other compounds that chemically inhibit the germination and growth of grasses, legumes, and other grassland herbs. Furthermore, common substances, such as tannins, chemically combine with organic-N to inhibit mineralization. Tannins and many other organic substances inhibit the growth of N fixing, N decomposing, and nitrifying microorganisms. Because of the difficulty of distinguishing the effects of the removal of allelopathic substances by fire, it is difficult to distinguish and quantify from the myriad other concomitant growth-promoting effects of fire, as well as various competitive interactions. Studies of allelopathy have, therefore, heavily relied on biological assays performed in the laboratory

(Schreiner and Sullivan, 1909; Wakesman, 1937; Basaraba, 1964; Rice 1964, 1984, Risser, 1969; Tukey, 1969; McPherson and Thompson, 1972; Lodhi, 1975, 1976, 1977, 1978a, 1978b; Grant, 1976; Rice and Parenti, 1978; Jobidon and Thibault, 1982).

In summary, the fire regime of the pre-European-settlement Illinois prairie and forest put into play a vast array of complex and interactive factors that enhanced terrestrial and aquatic N reservoirs and the transfers of N from such reservoirs over what is considered "normal" today for undisturbed "natural" watersheds. This made pre-European-settlement surface waters hyper-trophic — more eutrophic than waters are today. Similarly, the transfer of N from the terrestrial N reservoir to the atmosphere and hydrosphere was much greater than is considered normal today for undisturbed "natural" watersheds.

Overall, assessment of fire's effects indicates that the pre-European, prairie soil N reservoir was probably more than twice the size of the soil N reservoir of today's Corn Belt soils. Pre-European prairie N fixation was many times greater than the rate that chemical-N fertilizer is now added to Corn Belt soils.

An Animal-Populated Landscape: Some Effects on the Nitrogen Cycle

"They started down the river at the end of February, 1680. The Illinois broadened and deepened as they descended, flowing in that flat land.... 'The soil,' Hennepin noted, 'looks as if it had already been manur'd.' It was, in fact, the result of centuries of the slow rotting of prairie vegetation, made still more fertile by the 'chips' dropped through the ages by millions of buffalo, and fertilized at last with their bones. The constant moisture had favored decomposition. The country was, in fact, one vast compost heap. No wonder that it includes today some of the best farm land of the nation" (Bakeless, 1961, p. 297).

"A considerable portion of the above ground biomass of a prairie was consumed each year by the grazing of a wide range of grazing animals, such as bison, elk, deer, rabbits and grasshoppers. This grazing was an integral part of the prairie ecosystem.... Grazing increased growth in prairies, recycles nitrogen through urine and feces, and the trampling opens up habitat for plant species that prefer some disturbance of the soil" (Illinois Natural History Survey, 1999).

Animal manure has long been regarded as an N-saturation problem (e.g., Albrecht, 1938; Viets and Hageman, 1971). The animal kingdom creates the N-saturation problem by eating the plant kingdom. Most of the C in the food plants supports respiration and as such is burned up as fuel (and passed into the atmosphere as CO_2 gas). This leaves a residue of easily decomposable (labile) N-rich animal waste (urine and feces) and N rich animal biomass. Because of this, the decay of animal waste and the bodies of the animals themselves readily leak large amounts of soluble organic N and NO_3-N to the hydrosphere. In this regard, animal manure (urine plus feces) is considered to be an important source of N contributing to the N-saturation pollution problem of the Corn Belt (the animal bodies are exported, thereby, becoming an urban, N-point-source problem).

The National Gulf Hypoxia Program reports that manure N generation in the MRB is quite large — officially reported as 3.5 to 5.9 million metric tons N/yr by different methods of estimation (Goolsby et al., 1999). However, unlike chemical N fertilizer, which has increased greatly in recent decades (Table 2), manure N generation is reported as having remained unchanged over the last 40 years (Goolsby et al., 1999); the number of animal units having remained at around 32 million animal units for the entire MRB (converting all types of domesticated agricultural animals to 1,000 pound animal units: the animal unit being roughly the equivalent of a cow (Doering et al., 1999; Goolsby et al., 1999) or an American buffalo (Haugen and Shult, 1973).

And we need to put this in perspective: "one cow equals the sewage equivalent of 10 to 12 people" (Viets and Hageman, 1971, p. 17). Thus, 32 million animal units represent a lot of pollution. Since these are domesticated animals, the manure they generate is implicitly assumed, and, by this, concluded to be an additional source of anthropogenic source of problem N to Illinois and the MRB (e.g., Goolsby et al., 1999).

However, with this, the same mistake is made with chemical-N fertilizer and combustion N — it assumes that long-established, animal-barren corn and soybean fields represent the "natural" state. But the vista which greeted early European explorers was not an animal-barren, fire-free view of long-established corn and soybean fields stretching out farther than the eye could see. As noted above by the Illinois Natural History Survey (1999), the vista that greeted the pre-European explorers was an animal-rich, tallgrass prairie. Or, to quote the prairie-restoration literature:

"Shelford (1963:329) depicts a 'common morning scene' on the prairie before the coming of the white man as 'a herd of bison or pronghorns in the distance, jack rabbits returning to their forms, a wolf or coyote trotting to its den, several small birds flying overhead and singing, and locally a prairie dog or a ground squirrel sitting upright at its burrow....'

"Today, when one looks out over the prairie lands of this country, he sees a different scene. We have traveled well over a century through time since the temperate grasslands of North America carried vast herds of bison and pronghorn. The burrowing animals such as prairie dog have been effectively removed" (Haugen and Shult, 1973).

There are estimates available that can be used to estimate how many of the largest herbivores lived on the pre-European-settlement prairie. Best estimates are that prior to European settlement there were 10-20 million buffalo east of the Mississippi River (Roe, 1951, pp. 492-493). Extensive analysis shows that almost all of these buffalo were living in Illinois, southern Wisconsin, and the Ohio River Valley (Roe, 1951).

In comparison, contemporary statistics on the number of cows and cattle for the same region plus Missouri and Iowa (east-central United States) is around 10 million (White et al., 1981). Thus, the landscape in and around Illinois was more animal-rich prior to European settlement than it is now at the height of European agriculture.

The total pre-European-settlement herd of buffalo and pronghorn has also been estimated in the prairie-restoration literature:

"THE HERBIVORES

"There can be little doubt that the two major prairie dominants among large herbivores was the bison and the pronghorn. Estimates vary, but at least 60 million bison once roamed over North America, with at least 45 million occurring in all parts of the grasslands except California (Shelford 1963). Pronghorn populations have been estimated at between 20 and 100 million (Seton 1929)....

"Bison feed primarily on grass. In terms of animal units, they are considered nearly equal to domestic cattle. That is, stocking rates on good range are two-thirds to 1 animal unit. One animal unit is taken as the forage consumed by a domestic cow with a calf. The pronghorn has been rated at 9.6 animals per unit (Stoddard and Smith 1955). With the pronghorn, however, food habits vary more with location and season than with bison. As a general statement, range evaluation for pronghorns should be made in terms of forbs and browse rather than grass....

“Although the bison and pronghorn were the dominant large herbivores, two other influents in the prairie were elk and deer. These species probably were more typical of areas where stream courses with associated browse species were found. We do know, however, that the elk is a species that utilizes grass more than deer. In this respect, elk can compete directly with bison and should be considered when establishing stocking rates for an area. In terms of animal units, elk generally are placed at two animals per animal unit (Stoddart and Smith 1966). Here again, however, the local and seasonal food habits must be considered in establishing stocking rates” (Haugen and Shult, 1973).

A summary of detailed analyses shows that most of these more than 60 million buffalo lived within the MRB (Roe, 1951). Just on the basis of the major large herbivores alone, the pre-European-settlement landscape of Illinois and the MRB was much more animal rich than in today’s agricultural setting. As noted from Hennepin’s 1680 observations of manure on the Illinois landscape, vast amounts of manure are not a unique and new problem created by European agriculture. Neither can the concentration of large amounts of manure be considered a new and unique problem, when the size of the average cow or cattle herd ranges from 41 to 106 animals (Doering et al., 1999, Appendix 1-1), and a herd of 4 million buffalo was deemed “inconspicuous” (Roe, 1951, pp. 335-336).

To these major, large herbivores — buffalo, elk, pronghorn, and various deer — must be added the innumerable prairie dogs, ground squirrels, and other rodents as well as water fowl and other birds whose flocks were so large that they could block out the sun.

We now move on to assess the effect of pre-European-settlement animals on the terrestrial N reservoir and the transfers of N to the atmosphere and hydrosphere.

The following analysis indicates that the effect of animals on the landscape is akin to the “alchemy” produced by fire. In both cases, biomass is transformed into material that “sweetens” the soil. With animals transferring plant biomass into manure, urine, and animal biomass, the reservoir of easily decomposable, nutrient-rich organic matter is increased, as are the transfers of nutrients from that reservoir — the nutrient of most interest to this assessment being N.

Regarding the effect of herds of large grazing ungulates on the soil N reservoir, observers and scientists dating back to Darwin and earlier have attributed the unquestionably superior initial fertility of the prairie “party to be traced to the heavy and constant manuring and the trampling of the same content into the soil. This automatic process of ‘scientific farming,’ which most certainly went far toward returning to the soil what it had taken from it, may have distilled a richer nutritive capacity into the pasturage than can be conferred solely by climatic agencies” (Roe, 1951, p. 497).

Keeping on with the studies and observations of the early European scientists, the famous Lawes and Gilbert experiments at Rothamstead in the 19th century came up with the remarkable finding that while cultivated land lost N, pastured land gained an average of 44 lb N/acre/yr (Snyder, 1905, pp. 111-112).

Turning to the more recent studies conducted on the American prairie, analysis of paired ungrazed and grazed tallgrass prairie shows higher N content in tallgrass prairie vegetation and higher concentrations of total soil N, soil NO_3-N, and NH_4-N in spite of grazing-increased N lost to ammonia volatilization and N lost to harvesting of the cattle themselves (Risser and Parton, 1982). These two forms of N loss are significant. The harvesting of cattle from the land represents some 25 percent of the total N eaten by the cattle (Aldrich, 1980, Figure 4.4). And dairy manure has been determined to lose anywhere from 61 to 99 percent of its NH_4-N within 5 to 25 days after being on the surface (Lauer, Bouldin, and Klausner, 1976).

In the only long-term comparison of its kind known, comparison of grazed versus ungrazed, virgin North Dakota prairie showed that over a period of 75 years the grazed (but otherwise unmodified) prairie had accumulated 1,630 kg soil N/ha (1,830 lb N/acre) more than its ungrazed counterpart (Bauer, Cole, and Black, 1987). Thus, it appears that, even though grazing increases the transfer of N from the terrestrial N reservoir to other components of the N cycle (including the to-be-discussed transfers to the hydrosphere), grazing prior to European settlement appears to have increased the soil N reservoir by aiding in the fixing of N in greater amounts than grazing enhanced its transfer of out of the soil reservoir.

As asserted above, soil studies show that grazing also increases the transfer of N to the hydrosphere. This is done by greatly N oversaturating the landscape in a patchy manner:

"Uneven deposition of excretal N by grazing livestock can lead to spot application rates equivalent to 400 to 2000 kg N ha-1 (Jarvis et al., 1997)" (Watson et al., 2000).

In regard to leaching of N from feces, most of the N leached is organic, at least in the short run. This is illustrated by dairy manure/sawdust mix, soil-lysimeter experiments conducted by the USDA's Soil and Water Conservation Research Laboratory in West Virginia. Over a period of 10 weeks, the lysimeters were treated with 40 inches of water. The average concentration of organic C in lysimeter water was 763 mg/l. Average concentration of N was 181 mg/l, of which 98.5 percent was organic-N. This gives a C:N ratio of 4.2 for the organic matter, that water dissolved out of the manure. Organic-N concentration started out at 600 mg N/l in the first week of treatment and dropped to 100 mg N/l at five weeks (Elrashidi et al., 1999).

Another set of soil-lysimeter experiments conducted by the USDA's Pasture Systems and Watershed Management Research Laboratory in Pennsylvania examined the amount of NO_3-N leaching out of cow fecal matter versus cow urine. Natural rainfall, averaging 23.1 cm/yr (spring through fall) passed through the soil. This value can be compared to 29.9 cm/yr of runoff draining the IRB (Goolsby et al., 1999, Table 2.3's 34.8 cm/yr value adjusted downward to subtract water artificially draining from Lake Michigan into the Illinois River).

The NO_3-N draining out from under fecal matter in this relatively short-term experiment was no different from that draining out of the grassland. On the other hand, the concentration of NO_3-N draining out from urine patches was greatly elevated — from 52 to 176 mg NO_3-N/l, depending upon year and season (Stout et al., 1997).

Stout et al. (1997) stated that the disproportionately large effect of urine on elevating NO_3-N concentrations in water appeared to be due to two factors:

"Urine immediately infiltrates into the soil where the urea is readily hydrolyzed to NH_3, nitrified, and becomes more subject to leaching than volatilization. In contrast, feces remains on the surface where organically bound N is subject to volatilization as NH_3 is produced during the mineralization process."

Stout et al. (1997) calculated the NO_3-N leaching out from under pasture that 2.2 cows/ha would graze for 180 days (cows and cattle are typically moved off grassland during the winter). Such grazing was determined to result in an average annual concentration of 15.0 mg NO_3-N/l to ground water. Not counting organic-N leaching to the ground-water or surface-runoff, this value of NO_3-N leaching translates to 34.65 kg NO_3-N/ha/yr.

Additional N was probably also mobilized by urine, because urea, like NH_4-N, dissolves organic matter from soils (Kelly, 1981). However, organic-N was not analyzed.

Considering the condition prior to pre-European settlement, the vast herds of large herbivores were not moved off the prairie in the winter. Nor were their feces and urine stored over-winter in manure tanks to keep these wastes from accumulating and then fouling surface waters during heavy periods of dormant season runoff (e.g., Minshall et al., 1970) when such pollution problems would be especially severe, e.g.:

"Pollution problems may arise, however, when cattle occupy a pasture longer than the normal summer grazing season and into the winter-feeding period, especially in a humid climate. While grazing animal density is rarely that in a feedlot, waste does become more concentrated than with the summer-grazing system at a time when climatic conditions favor excess water movement and, hence, greater chemical transport" (Chichester, Van Kauren, and McGuinness, 1979).

To study of effect of winter versus summer grazing on water quality, a number of scientists from a collection of USDA laboratories researched four rotationally grazed summer pastures in Ohio with winter feeding on one of the pastures. The summer-grazed pastures lost 0.4 N/ha/yr in surface runoff and 18.4 kg N/ha/yr in subsurface runoff — for a total loss of 18.8 kg N/ha/yr to the hydrosphere (Chichester, Van Keuran, and McGuinness, 1979).

However, when the animals were kept outdoors to graze over the winter — as would naturally occur in nature — the winter-grazed pasture lost from 24.8 kg N/ha/yr in surface runoff to 35.0 kg N/ha/yr in subsurface runoff — for a total loss of 59.8 kg N/ha/yr to the hydrosphere (Chichester, Van Keuran, and McGuinness, 1979).

The findings of Chichester, Van Keuran, and McGuinness (1979) supported the conventional wisdom that had been put into practice, namely: not to keep cows and cattle out overwinter in a temperate, humid, continental climate such as in Illinois.

However, as with the land application of fertilizing, nutrient-rich fire ash, so "Mother Nature" did with the disposal of animal manure — Nature did not adhere to the conservation techniques of keeping the animals in barns overwinter and constructing manure tanks to keep the wastes off the land when such wastes would create the biggest pollution problems.

We now examine animal behavior within the landscape to further assess how the numerous animals of the pre-European-settlement landscape may have influenced water quality.

Detailed analysis of observed buffalo behavior indicates that buffalo herds spent much time in and around bodies of surface water (Roe, 1951). To quote an 1814 account of a tallgrass prairie scene:

"Herds of light-limbed antelopes, and heavy colossal buffalo...all these champaign beauties reflected and doubled as it were, by the waters of the river" (Shay, 1986).

Animals need water. This is an important reason why the majority of small U.S. dairy and cattle operations were initially located along small streams (Middlebrooks, 1974). Otherwise, special care and effort would have been required to provide water for the animals. However, today, even livestock operations along streams and rivers typically artificially supply their livestock with water to keep livestock from fouling the water and from greatly increasing streambank erosion.

However, Mother Nature did not fence off the streams and rivers to keep great herds of large herbivores from trampling and compacting the banks, and from polluting the water. Not only did the numerous large animals void directly into the water and on the trampled banks, their dead carcasses also littered the water (Roe, 1951). In Illinois, after grazing all summer on the tallgrass prairie, buffalo congregated in winter along the Illinois River: especially along the stretch from Peoria and south to be near open, potable water. Native Americans overwintered with the buffalo along the Illinois River (Roe, 1951, pp. 73-75).

As with animal wastes, bird wastes are high in N — their wastes (guano) have been used extensively in the past commercially for N fertilizer. Bird wastes are also notorious for creating

N water-pollution problems (Viets and Hageman, 1971). In regard to the vast flocks of waterfowl, which in the past flew down the Illinois River flyway, waterfowl selectively eat N-rich materials (harvest the watershed) and defecate directly into the water. Up until the 1930s, the Illinois River still remained one of North America's richest waterfowl areas (Talkington, 1991, p. 20), and the birds must have contributed to the large N load in the river.

In summary, terrestrial animals, waterfowl, as well as the plentiful aquatic animals and fish used the surface waters of the IRB as open sewers.

Continuing with assessment of animal behavior within the landscape, other activities of the numerous animals of the pre-European-settlement landscape also may have influenced water quality. Buffalo engaged in both dust (Roe, 1951, pp. 104-105) and mud wallowing. Wallowing, along with eating and voiding wastes exerted selective pressure on plants, soils, and microorganisms, as well as altered physical and hydrological characteristics of the land so disturbed (e.g., Polley and Collins, 1984; Gibson, 1989; Davis et al., 1991; Vinton et al., 1993; Steinauer and Collins, 1995).

Wet tallgrass prairie areas, known as "hay marshes," were where wallowing in the mud, the most characteristic of buffalo summer activities, occurred. These prairie-marsh hay sloughs were often miles in length and of considerable width. The rich and thick grass surrounding these areas would later be mown by farmers prior to the machine age of agriculture (it took until 1955 for tractors to outnumber horses and mules on U.S. farms (Rasmussen, 1960, p. 239), prairie-marsh hay being highly valued as animal feed (Roe, 1951, pp. 101-103). A large center of such wet prairie from which such hay was mown, before these areas disappeared due to draining in the 20th century, was the Grand Prairie of Illinois, which covered most of the IRB and extended into Indiana (Hewes, 1951).

Not surprisingly, the soils of these hay marshes were exceedingly N-rich — nearly 10-fold more N-rich than surrounding prairie soils, averaging some 2.2 percent N (Snyder, 1905, p. 127).

Given their disproportionately large influence on water chemistry and hydrology, these wetland, N-enriched buffalo wallow areas appear to have greatly enriched the N chemistry of water. They apparently accounted for the unpalatability of wallow waters which, among other things, appeared to have NO_3-N concentrations so high so as to exert pharmacological properties on human physiology (e.g., Viets, 1970; Viets and Hageman, 1971, p. 5).

In regard to dust wallowing by buffalo:

"Bison are attracted to prairie dog towns, particularly during the summer months. The dog mounds provide excellent dusting sites for the bison along with other bare areas found in the towns....

"Wallowing is the most obvious grooming activity of bison. This activity consists of an animal dropping to its knees and then lowering itself with its hind legs to a position of sternal recumbency. The animal then rolls over onto one side as its legs rake the ground, raising a cloud of dust and throwing dirt and dust over its body. Sometimes the animal sniffs, horns, or paws the ground before wallowing....

"This activity results in the formation of traditional wallowing sites, which are created and maintained through repeated use. These sites historically are termed wallows and are shallow dish-shaped depressions varying in size and frequency of use. These depressions are denuded of vegetation and occur wherever bison are present" (Haugen and Shult, 1973).

Given the reported size of buffalo herds, such denudation could be significant. Apparently, the massive buffalo herds were in ecological relation with massive towns of burrowing animals. Indeed, the number of burrowing animals even may have been in excess of the needs of the buffalo, at least at times and in some places. For example, to quote from a journal kept by an officer in an 1846 military expedition passing through tallgrass prairie:

"'Whenever we rode to the side of the road we noticed that our horses would frequently sink to the fetlock, and saw on the ground little piles of loose earth...formed by the sand rats, or gophers...[Four days later he added]: The mounds of the gophers...were more abundant than heretofore, and in several places a number of these mounds were so close together that the distinctness of each was completely lost in the mass, covering an area of five or six feet'" (Malin, 1953).

These bare prairie dog/buffalo wallowing areas would have enhanced transfer of ammonia-N to the atmosphere and loss of N to the hydrosphere via nitrification of soil N and erosion of soil N. The burrowing animals would also have created tunnels — massive macropores – which would have significantly short-circuited the hydrologic cycle. The short-circuiting of plant uptake and within-soil processing thereby facilitated delivery of N-rich runoff from animal feces, urine, and decaying bodies — buffalo, prairie dog, and others — into surface waters and ground waters.

Thus, we conclude that the animal-manure, N-saturation problem is not new to Illinois and the MRB. Prior to European settlement, more manure was generated than today, and its method and location of deposition were done in ways that today violate standard practices of conservation and water-pollution control.

As with fire, the effect of animals on the landscape was both to increase the N content of vegetation and soil, and to increase the transfer of N in solid, liquid, and gaseous forms from the land to the atmosphere and hydrosphere and, thereby, also increased the reservoirs of fixed N in all four spheres – geosphere, biosphere, hydrosphere, and atmosphere.

Soil Erosion: Some Effects on the Nitrogen Cycle

To start this section, we note in "Title 35, Illinois Administrative Code, Environmental Protection Subtitle C: Water Pollution" that numerical effluent standards dictate that it is illegal to raise the concentration of suspended solids in a receiving water more than 15 mg/l above its background concentration (1999, Section 304.103; Section 304.124).

As previously documented, the dogma illuminating the contemporary view of the pre-European-settlement condition is that of nondisturbance — water was slowly and universally filtered by vegetation and percolated through porous and stable soils. Based on this perception, rates of runoff and erosion have been asserted to be much lower in pre-European-settlement times than they are today: rivers draining prairie such as the Illinois, Missouri, and Mississippi Rivers were described as clear water streams prior to European settlement (e.g., Bennett, 1939; Leopold, 1949; Gunter, 1952; Mills et al., 1966; Commoner, 1970; Dodds et al., 1996).

This can be shown again using the following introductory quote from the prestigious 1939 textbook, *Soil Conservation*, written by H.H. Bennett, the Father of the Soil Conservation Service. Bennett asserted that both the Missouri and Lower Mississippi Rivers were naturally clear-water streams before settlement by European man:

"CHAPTER I. THE PROBLEM OF THE UNITED STATES.

"The Virgin Land

"The earliest settlers arriving on North American continent found a land richly endowed by nature and virtually unexploited by man. Except in an inconsequential way, the aborigines had done little to cultivate this land or change its virgin character....

"Rains fell on the land, and snows melted with the changing seasons; but water tended to move slowly over the ground surface, checked and kept clear by the tangled canopy of vegetative growth. The deep, humus-charged, granular topsoil, perforated even into the subsoil by decaying plant roots and burrowing earthworms, insects, and animals, soaked up the raindrops, which filtered down to nourish the growth of vegetation or to replenish underground reservoirs and springs. Rivers ran clear, except in flood, when abrasive rushing waters tore soil from banks, sometimes muddying even the Missouri and the Mississippi. Generally speaking, however, the natural circulation of waters was a uniform and orderly process. Flood heights and silt-laden streams were the spasmodic exceptions in a land of prevailing harmony and balance" (Bennett, 1939, p. 1).

However, geology, soil science, archeology, and the historic and scientific records all disagree with this widely held view of the pre-European-settlement condition of the MRB.

In the last 5,000 years, since sea level and climate have roughly achieved their present states, the Mississippi River has delivered an estimated 8,000 cubic miles of sediment to form the present Mississippi delta. These sediments were delivered principally as silt and clay (Fisk, 1952; Fisk and McFarlan, 1955). Over the last 5,000 years, the rate of sediment delivery appears to have been at least equal to that measured in the 19th century (Fisk, 1952; Kesel,1988), and much higher than currently being experienced in the 20th century (e.g., Kesel, 1988).

In addition to what the geology of the Mississippi River delta tells us, the geology of the Mississippi River itself also provides information about the state of erosion prior to European settlement. The width and depth of the stream channel are determined by the interplay between the quality and quantity of sediment load and flow, as are the nature and rate of meander, deposited sediments, and capture of the main channel of the Mississippi River by its distributaries. All of these river features inform geologists of past flows and sediment loads:

"Each of the Mississippi River courses in the southern part of the alluvial valley is marked by well-developed meander belts.... The Maringouin-Mississippi started to develop approximately 3,000 years ago; the Teche-Mississippi started to develop 2,000 years ago; the Lafourche-Mississippi River 1,600 years ago and the present course of the Mississippi River south of Donaldsville was first occupied approximately 800 years ago.

"<u>Earlier meandering courses compared with the modern course</u>

"The meander belts of the earlier Mississippi River courses give every indication that they were produced by a stream of the same size and characteristics as the modern one. Virtually all of the characteristics of the modern Mississippi River are duplicated in the abandoned meander belts. For example, the variation in size of meander loops and the height and width of natural levees along the ancient channels are the size of the modern Mississippi River features; natural levee slopes are comparable; and all of the courses, ancient and modern, have channels of the same width and depth. These relationships clearly show that the poised character of the river has been maintained throughout a period of meander belt formation which has probably existed since sea level reached its stand. The maintenance of the poised condition over a long period of time furnishes perhaps the best key to an understanding of the factors involved in Mississippi River diversion" (Fisk, 1952, pp. 52-53).

Thus, over the last several thousand years, the geology of the Mississippi River itself indicates that the Mississippi River had a remarkably high and consistently high sediment load.

Regarding what Fisk (1952) means by Mississippi River diversion is also a problem related to the Mississippi River being a muddy river of great sediment load. The problem of the diversion (capture) of the Mississippi River by the Atchafalaya River, as is plainly indicated by the title of his quoted publication, *Geological Investigation of the Atchafalaya Basin and the Problem of Mississippi River Diversion* (Fisk, 1952).

The problem is that the high sediment load that the Mississippi River has had over the last 5,000 years is that the Mississippi River rapidly builds a land extension into the Gulf of Mexico, thereby reducing its rate of drop per mile (sea level does not change, whereas the number of miles the river must travel to reach sea level increases). When rate of drop is reduced enough, the Mississippi River switches its flow down a steeper slope — as is the present case where the Mississippi River would have completely switched its flow down the three-fold steeper course of the Atchafalaya River were it not for the U.S. Army Corps of Engineers.

Transport of unusually large amounts of eroding soil in the several hundred years prior to European settlement down the current mainstem of the Mississippi River have built a delta clear across the continental shelf:

"The topography of the sea floor around the Mississippi...differs somewhat in character from that found off most other large rivers which enter directly into the sea because, unlike all other rivers, the Mississippi has built a delta across the entire continental shelf (Fig. 1)" (Shepard, 1956).

And:

"...the bird-foot delta of the Mississippi which has built a pier of mud and silt 60 miles seaward in a few hundred years, right into the teeth of Gulf Coast hurricanes" (Lowman, 1951).

Thus, the geologic record does not support the popular perception that the MRB was a low-erosion environment, or that the Mississippi River was a clear water stream prior to settlement by Europeans.

Neither does the scientific and historic record support this popular belief. For example, Charles Dickens, traveled along a stretch of the Mississippi River between Illinois and Missouri during the summer of 1842 — when this area was the frontier. Dickens described the Mississippi River along Illinois in 1842 as follows:

"But what words shall describe the Mississippi, great father of rivers, who (praise be to Heaven) has no young children like him! An enormous ditch, sometimes two to three miles wide, running liquid mud, six miles an hour: its strong and frothy current choked and obstructed everywhere by huge logs and whole forest trees: now twining themselves together in great rafts, from the interstices of which a sedgy lazy foam works up, to float upon the water's to float upon the water's top.... The banks low, the trees dwarfish, like marshes swarming with frogs, the wretched cabins few and far apart, their inmates hollow-cheeked and pale, the weather very hot, mosquitoes penetrating into every crack and crevice of the boat, mud and slime on everything: nothing pleasant in its aspect, but the harmless lightning which flickers every night upon the dark horizon....

"We drank the muddy water of this river while we were upon it. It is considered wholesome by the natives, and it is something more opaque than gruel. I have seen water like it at the Filter-shops, but nowhere else" (Dickens, 1996, pp. 171-172).

Study was made of the sediment load of Mississippi River in 1843 and 1846 by the Association of American Geologists and Naturalists with the collaboration of England's Lyell, the Father of modern geology (Riddell, 1846). The average concentration of suspended solids for the Mississippi River at New Orleans was reported to be 866 mg/l for 1843 and 863 for 1846 (Riddell, 1846).

Forshey (1878, p. 18) reported that, "The waters of the Mississippi River are always turbid" carrying, on average, 556 mg/l of suspended mineral matter.

While the Mississippi River today is considered muddy with its contemporary (1963-1982) load of ~140 million metric tons/yr (Kesel, 1988), in 1843 and 1846 the Mississippi River is estimated to have been carrying ~600 million metric tons/yr of suspended sediment (Riddell, 1846), assuming that flow for these years were the same as today's average (Goolsby et al., 1999, Table 2.2).

The Riddell (1846) study found a relationship between flow and suspended solids with the lowest concentration during the lowest flow. However, the lowest concentration of suspended solids found was 390 mg/l. If this clearest of Mississippi River water (390 mg/l of suspended solids) were the average, it would mean that annual suspended load was some 270 million metric tons/yr — almost twice the sediment load of today's "muddy" Mississippi River (Kesel, 1988).

Professor Lyell, in his review of the research study, concluded that the sediment load of the Mississippi River was appreciably underestimated, because it did not take into consideration the considerable organic debris load (Riddell, 1846).

At that time, the Mississippi River and its tributaries were not leveed as they are today. Thus with the annual high-water cycle, the fast-moving water blasted accumulated debris out of the river and out of the backwaters and floodplain. Kofoid (1903) describes this for the Illinois River from the time prior to its being leveed throughout his report. This can also be seen from the description of the Mississippi River along Illinois by Dickens and by the general description of the MRB given by Riddell himself.

Riddell (1846) noted that the floodplain "consists of vast swamps, covered with trees, the tops alone are visible in the time of floods." Inhabitants along the Mississippi River and its major tributaries, "after making a large raft, on which they prepare to bring all the produce of the year, for 1800 or 2000 miles, to the market of New Orleans, find themselves near the termination of some two months, entire weeks of which may have been passed by them aground, waiting for a flood to float them off again, suddenly hurried through one of the openings which the river makes in its banks, at a rate of 10 or 12 miles an hour, and left aground in the midst of a vast morass; where they are obliged to climb a tree for safety, and await the chance of a boat coming to their rescue."

Unlike today's situation where the floodplains are protected by levees, in the past the rivers of the MRB blasted clogging amounts of debris out of the watershed. In the early 1850s, the U.S. Army Corps of Engineers conducted analysis of the sediment load of the Mississippi River at New Orleans (Humphreys and Abbot, 1876). This study missed an appreciable amount of the Mississippi River's flow as New Orleans is far enough into the delta to have significant amounts of the Mississippi River water diverted down numerous side rivers and crevasses, which have since been sealed up. The Humphries and Abbott (1876) data are of such high quality that the scientific community compares these data directly with those of modern studies (Kesel, 1988).

Humphries and Abbott (1876) determined that some 400 million metric tons of suspended solids (not counting debris) were being carried past New Orleans every year. Based on the Humphries and Abbott (1876) and subsequent data, it has been determined that:

"Since 1850, there has been an overall decrease in excess of 70 percent in the sediment load transported by the Lower Mississippi River. A decrease of 25 percent between the earliest measurements and 1950 may be partly the result of a decline in discharge and partly the result of a change in land use practices" (Kesel, 1988).

The data of Humphreys and Abbot (1876) show that the Mississippi River and Missouri Rivers ran muddy even at low flows. And floods were as extreme in the previous two centuries (and even earlier) as they are now: perhaps even more so, as noted by Kesel (1988). And as Table 10 shows, even as late as 1850, the MRB was but lightly settled, particularly the Missouri River Basin, from which some half of the Mississippi River's sediment load was and is still derived. Nevertheless, the extreme floods and the high sediment loads of the Mississippi River and its tributaries recorded in the 1800s suggest that the basin was vastly more disturbed than could be accounted for by the meager European settlement of the time (Table 10).

Indeed, as the MRB was being put to the plow in the 1800s, rates of erosion within the MRB as indicated by sediment load were not increasing. The great decrease of sediment load in the 20th century, and particularly after 1950, appear related to the creating of the lock-and-dam and levee system (Kesel, 1988).

Regarding the Illinois River, as with the Mississippi River, research indicates that the popular perception of a pre-settlement, low-erosion, clear-water stream may not be true for the Illinois River either. It appears from study of a 70-km-long segment of the Illinois River Valley that the river became silt-chocked some 5,000 years ago from high rates of erosion:

"...during the first millennia of the Holocene the Illinois flowed over a valley floor a minimum of 12 m below the present flood basins.... It appears that prior to 5,000 B.P. the river was sandier than today, lacking backswamps. Thereafter, as the river stabilized near its present level, the key stages of its channel evolution can be approximated as follows (see Figure 1):

"Macoupin Substage. High-sinuosity river with multiple channels...some alluviation (slightly coarser than today).... Probable age, ca. 5000-2100 B.P.

"Long Lake Substage. Higher sinuosity than today, with some major alternative channels, now abandoned; flood silt and basin regime much the same as at present. Probable age, ca. 2000-1000 B.P." (Butzer, 1978).

Overall, the possible reported causes for the high flow and high rates of erosion within the MRB are numerous, complex, and possibly interrelated. Using the Illinois Valley and the Butzer (1978) study just cited, it becomes apparent that Native Americans lived on the slopes of the river valley. Archeological analysis of the Butzer's Koster site indicated that:

"The Holocene sedimentary sequence indicates periodic soil erosion upslope, with redistribution of this sediment downslope. Until ca. 8500 B.P., net sediment accretion on the Koster site probably averaged 20-25 cm per century, then increased to 25-50 cm per century ca. 8500-7700 B.P. Slope erosion was reduced ca. 7700-5500 B.P., when accretion rates declined to 9 cm per century, increasing again to 18 cm per century from 5500-5000 B.P. These rates are generally well in excess of erosion and deposition in the wake of intensive Anglo-American land use and disturbance. They also represent a major departure from the predictable model of dynamic slope equilibrium under the mesic hillside forests that mantled the Koster watershed during the early nineteenth century (Figure 3). Opening up of the hillslope vegetation must be postulated in order to allow for persistent, vigorous erosion....

"Following upon an erosional break ca. 5000 B.P., slope erosion rapidly diminished and...the hillsides were probably forested, with parkland on the valley floor, much as they were during the early nineteenth century. This pattern of equilibrium was disrupted ca. 2100-1900 B.P. and again 1200-950 B.P. in response to brief dry spells and reduced vegetation that favored gullying or slope stripping upstream and fan alluviation along the margins of the Illinois Valley....

"Finally, the Koster geomorphic evidence provides some suggestions that Archaic occupance may have temporarily accelerated geomorphic trends.... The potential role of Archaic disturbance on the vegetation cover and soil mantle during the coarse of food and fuel-procurement, as

Table 10. Population and Estimated Acres of Improved or Cultivated Land by State in the Mississippi River Basin, 1800 to 1850

	1800		*1810*		*1820*		*1830*		*1840*		*1850*	
State	*Pop*	*Land*	*Pop*	*Land*	*Pop*	*Land*	*Pop*	*Land*	*Pop*	*Land*	*Pop*	*Land*
PA	201	749	270	1,008	350	1,306	416	1,553	574	2,124	771	2,876
VA*	330	2,405	366	2,663	400	2,911	454	3,310	465	3,888	533	3,885
KY	221	1,342	406	2,470	564	3,428	688	4,179	780	4,738	982	5,968
TN	106	545	262	1,351	423	2,182	682	3,519	829	4,280	1,003	5,175
OH	36	181	185	918	465	2,315	750	3,733	1,216	6,047	1,584	7,881
IN	5	24	25	126	147	751	343	1,751	686	3,486	988	5,047
MI	4	25	20	115	38	214	68	388	188	1,066	303	1,722
IL			12	73	55	325	157	932	476	2,818	851	5,040
LA			37	113	76	234	108	356	176	541	259	795
MO			21	90	67	287	140	605	384	1,653	682	2,938
AR					14	53	30	113	98	363	210	782
IA									43	185	192	825
WI									26	88	254	871
MN											6	5
Total	903	5,273	1,603	8,926	2,599	14,006	3,838	20,441	5,940	31,297	12,926	63,167

Source: Adapted from Humphreys and Abbot (1876, p. 438). Data are in thousands of people (*Pop*) and thousands of acres (*Land*).
Notes: Mississippi River Basin is ~ 800,000,000 acres.
*Today West Virginia plus Virginia.

well as on-site manipulation and habitation activities, remains to be objectively reassessed" (Butzer, 1978).

Note that many of these periods when rates of erosion were greater than experienced after European settlement were of longer duration than total time of European settlement.

Also note that during the early 1800s rates of erosion were exceptionally low. Subsequent analysis will show that this time period fits Denevan's (1992a, b) generalized observation, namely, at this time Illinois was essentially depopulated — this being a period of minimal human influence by both Native American and European civilizations.

Regarding Native American influence, the University of Illinois published a book (Emerson and Lewis, 1991), in cooperation with the Illinois Historic Preservation Agency, that sheds further light on the subject of aboriginal occupancy and land use effects in Illinois. For example, archeological analysis of the Illinois side of the Mississippi River between the Illinois and Kaskaskia Rivers for the period 1000-1400 A.D. reported:

"Coupled with these pan-regional [climatic] changes are hypothesized anthropogenic changes to local hydrology. Overexploitation of wood resources as well as agricultural field clearing in the watersheds bordering the American Bottom (Lopinot and Woods 1988) would have resulted in increased rates of erosion and runoff, filling in of stream channels, and extensive flooding during heavy summer rainstorms. Evidence for these changes derives from shifts in habitation to higher ground for late Mississippi Riveran occupations in the southern bottomlands (Emerson and Milner 1982; Milner 1984; Milner and Williams 1983, 1984) and at the Cahokia site (Brown et al. 1986), and abandonment of occupation at the Goshen site in the northern American Bottom during the Mississippi Riveran period (Brown et al. 1988; Polley and Brown 1988). Similar conditions of flooding associated with deforestation were noted historically in the American Bottom before emplacement of levees (Bowman 1907). The results of the hypothesized summer flooding would have been catastrophic for bottomland maize fields associated with Cahokia (Woods and Meyer 1988). These conditions probably contributed to a reoccupation of the interior upland during the Moorehead phase, coupled with the decline in population in the American Bottom (Milner 1986b)" (Woods and Polley, 1991).

On the other side of the Mississippi River in northeastern Iowa, review of a large number of soils and archeological studies showed a landscape disturbance and erosion history (Ruhe, 1983) like that of Illinois (e.g., Butzer, 1978; Emerson and Lewis, 1991; Woods and Polley, 1991). Researched sites in Iowa showed intermittent periods of intense erosion during the Holocene whose dates and durations vary from site to site. Erosional events do not correspond to climatic changes:

"The numerous episodes of erosion have resulted in the formation of a widespread erosion surface that covers 18,500 km^2 in northeastern Iowa. Wisconsin loess has been almost completely stripped from that region. It occurs only as thick caps on isolated hills, or paha (Scholtes, 1955). The paha are loess-mantled erosion remnants that stand above the erosion surface at interstream divides (Ruhe et al., 1968). The erosion surface is generally marked by thin loam sediments above a stone line on glacial till, and the surface ranges in age from 12,700 to less than 2900 years....

"The episodes of hillslope erosion and sedimentation and the cutting of the widespread erosion surface in Iowa indicate that the Holocene was a time of numerous episodes of instability in the landscape. The results of the detailed soil-geomorphic studies do not agree with the simple tripartite history of gradual changes shown by the pollen records of the region" (Ruhe, 1983).

The extra-climatic agency of disturbance can be explained as follows:

"The Indians who were largely dependent upon the buffalo followed these random wanderings as best they could. Thus the number of buffalo that might occupy a particular spot could be enormous, and damage to vegetation disastrous, but the incidence was not continuous...it is in this context that we learn that surface erosion by wind and water was present and upon occasion severe under aboriginal conditions — recurring droughts, fires, overgrazing, and trampling by animals, especially buffalo, as well as the wearing of innumerable paths to watering places. Dust storms upon a large scale were not caused by the 'plow that broke the plains'" (Malin, 1953).

The prairie restoration literature notes:

"Kofoid (1958) states that, before the white man invaded the plains, there was a reciprocal ecological relation between bison and prairie dogs, with each tending to maintain the short grass interspersed with patches of forbs and bare ground, which was ideal habitat for the other" (Haugen and Shult, 1973).

Further, a general archeological observation can be made for the flatter interfluvial sites protected from extreme water erosion show signs of great wind erosion:

"According to the archaeological evidence, the thickness of the wind-blown material that interlayers successive aboriginal village sites would indicate greater dust storms by far than occurred during the decade of the 1930s" (Malin, 1952).

Overall, the IRB and the MRB prior to European settlement were not "a land of prevailing harmony and balance" (Bennett, 1939, p. 1), as the standing paradigm asserts. Illinois and the MRB appear to have experienced disturbance by animals, human habitation, fires, and climate — all of which varied in intensity and form with time and space before European settlement.

In establishing a reference/background, pre-European-settlement state to compare with the present, scientists must not only define a pre-European-settlement climatic/landscape unit equivalent of our own, but must also deal with the fact that aboriginal civilizations rose and fell; and with them their differing land-use practices and concomitant effects on the pre-European-settlement N cycle and rates of watershed erosion. For example, as seen above, as the more agrarian Mississippian civilization was in decline, the more mobile buffalo culture was in ascendance (e.g., Shaler, 1891, pp. 184-188; Griffin and Wray, 1945; Griffin, 1961; Smith, 1965; Williams and Stallman, 1965; Pyne, 1983; Emerson and Lewis, 1991; Woods and Polley, 1991).

But even this successor civilization went into decline just prior to European settlement. As noted by Denevan (1992a), the landscape observed by the early settlers was in its most undisturbed state — less disturbed than it was under the previous intact occupying Native American civilizations. For example:

"It appears probable that early writers saw only a small part of the agricultural clearing in the Northeast. Fields were abandoned as they wore out or as the white settlements came close. These abandoned fields grew up to forests. Occasionally expeditions striking at centers of Indian population saw Indian agriculture as it was, as when General Wayne reached the village of the Miamis and their allies in 1792 and found a continuous planting the length of the Maumee River from the present site of Fort Wayne [Indiana] to Lake Erie (Mooney and Thomas, 1906)" (Day, 1953).

And:

"In Ontario their fields were so extensive that when the missionary Sagard (1632) travelled from village to village, he lost his way in the fields more often than in the woods. Champlain (1613-32) traversed 60 to 90 miles of this region and called it 'a well-cleared country.' The peninsula between Lake Huron and Georgian Bay was mostly cleared" (Day, 1953).

The land and water being settled was in its most undisturbed state because Old World diseases preceded the Old World colonists, leaving on average only 10 percent of the original population alive (Denevan, 1992a, b). Also, as alluded to in Day (1953), many of those surviving the onslaught of disease were killed or moved off by military expeditions sent in to prepare the way for European settlement. Introduction of European weapons further disrupted the status quo and enabled some groups to completely exterminate competing groups — as happened with the complete extermination of the very high West Virginia civilization and its inhabitants in the 1680s by their woodland rivals from the north, the latter having acquired the killing edge in the form of English rifles (e.g., Maxwell, 1910).

Later, a similar scenario would be replayed further west in Illinois. By the 1680s, the buffalo were already in decline in Illinois. As quoted from La Salle's, *The Illinois Country, 1680*:

"'The buffalo are becoming scarce here since the Illinois are at war with their neighbors; both kill and hunt them continually'" (Sutton, 1976, p. 21).

Tribes moving in advance of European settlers clashed with the Illiniwek and all but wiped them out. Apparently, the interaction was not favorable for the buffalo either, which left Illinois by around 1800, even though Illinois at the time had a population of only 2,458 people (Roe, 1951; Buck, 1967; Starrett, 1972). The buffalo chips and bones that littered the Illinois prairie in 1680 would be absent from the landscape descriptions of the early 1800s (e.g., Buck, 1912, 1967; Schoolcraft, 1918). Like the bare, eroded land created by innumerable animal tramplings and diggings, the chips and bones of buffalo would disappear from sight within 20 years after their removal, even in areas where 20 years earlier a herd of 4 million buffalo would have been considered "inconspicuous" (Roe, 1951, pp. 335-336).

Thus, the decreasing suspended-sediment load experienced in the MRB since 1850 appears to have been in part due to an unusual interim period of low landscape disturbance prior to and during the early stages of European settlement in much of the basin. In regard to rates of erosion, the MRB consistently appears to have experienced rates of watershed erosion as high or higher than that produced during post-European settlement.

In the IRB, unlike the overall MRB, this interim period of low landscape disturbance occurred too early in Illinois for scientific quantification of its effects on suspended sediment in the River. However, archaeological, soil, and geologic evidence all indicate that, prior to European settlement, the IRB had an appreciable sediment load which, at times, may have approximated or even exceeded present conditions.

This is an important finding, because soil erosion is reported to be the most important source of N delivery to surface waters from agricultural lands in the United States (e.g., Stevenson, 1986, p. 148).

However, before moving on, we address yet one more problem regarding erosion – the problem of subjectivity of observation as discussed in the section, "Reference/Background Pre-European Settlement Conditions" and by Simkin et al. (1981).

The contemporary literature takes on face value the words of some that the Illinois River prior to the twentieth century was a clear-water river with nominal erosion (e.g., Mills et al., 1966; Talkington, 1991), the secchi depth data of Kofoid (1903) being used as substantiation.

However examining Kofoid's observations and secchi depth data in context with 20th century perception of what clear water is we see the following:

"The effect of varying sky conditions lies primarily in their relation to the temperature of the water, but is due to a less degree to the influence of light upon the multiplication of chlorophyll-bearing organisms — the primal food supply of the plankton — upon which the movements of these and other plankton organisms. The abundant silt in suspension in waters of the [Illinois] river and most of the adjacent lakes doubtless hinders the penetration of the sunlight, but modifies to a much slighter extent its effect upon temperatures. Wind and sky conditions combine to favor or prevent the appearance of the 'water-bloom.' This is a characteristic green scum which coats the surface of the [Illinois] river, and occasionally of the lakes, on still, warm days in midsummer. On cloudy or windy days the minute organisms Euglena, Chlamydomous, etc.) which form the bloom do not rise to the surface" (Kofoid, 1903, p. 178).

Regarding secchi depths, Kofoid noted:

"In the [Illinois] river the great majority, about two thirds, of the records lie between 20 and 50 cm. [8 in. - 20 in.], while the extreme range is from 2 cm. [0.8 in.], in the flood of May 1897 to 115 cm. [45 in.] in the declining waters of July, 1896. The clearer waters appear, as a rule, with declining floods and stable low stages, especially under the ice" (Kofoid, 1903, p. 179).

By 20th century standards, the Illinois River of the good old days, which scientists insist on calling a clear water, would be considered filthy – not one secchi depth met the 4-foot minimum secchi depth transparency standard for bathing set by the Illinois Department of Health (Sefton et al., 1980, p. 32). [A 4-foot secchi depth generally means that a 6-foot tall man standing chest deep in water will be able to see the bright white secchi disc lying on the bottom at his feet even though he will have trouble seeing his swim trunks through the murky water. A 4-foot secchi depth is what many people today would consider quite dirty water.]

We believe that the Illinois River of the good old days — which on a good day was covered by green scum and (after managing somehow to keep aside the scum) had a secchi depth of less than 20 inches — was not a nice clear water, oligotrophic stream of running Perrier.

Also, we believe that what people during the 19th century Illinois called clear water was subjectively different from what people living in the 20th century would call clear water.

Continuing with Kofoid's description of the waters of the previous century:

"The turbidity of the [Illinois] river is due to both plankton and silt, the later being as varied as the character of its tributaries, with the added contamination from the cities along its banks" (Kofoid, 1903, p. 179).

By examining the Spoon River, the most pristine of all of the Illinois' tributaries at the time (Kofoid, 1903; Palmer, 1903), we may be able to gain insight into the nature and quantity of the natural suspended sediment and nutrient load entering into and being transported down the Illinois River:

"In Spoon River the extremes are even more marked than in the main stream, varying from 1.3 cm. [0.5 in. secchi depth], in flood conditions, to 165 cm. [5 ft., 5 in. secchi depth] at low water under the ice. The turbidity here is almost entirely due to silt, that at flood being largely composed of earth and clay, giving a black or yellow tinge to the water. The amount of comminuted vegetable debris found in the waters is considerable" (Kofoid, 1903, pp. 179-180).

And:

"In Spoon River the solids in suspension are highest (274.3 [mg/l]) and those in solution least [of the waters tested] (167.1 [mg/l]), a condition due to the recent origin of its water and to the large amount of silt which it carries. The organic origin of some of this silt is shown by the large loss on ignition (41.9 [percent]), the oxygen consumed (14.1 [mg/l]), the albuminoid ammonia (.604 [mg/l]), and the total organic nitrogen (1.292 [mg/l]), all of which are in excess in its waters. The freedom from sewage is evidenced by the low chlorine (3.8 [mg/l]), while the considerable amounts of free ammonia (.245 [mg/l]), nitrites (.039 [mg/l]), and nitrates (1.01

[mg/l]), indicate organic decomposition in progress or completed. In the absence of any considerable contamination by sewage it seems probable that these substances have their origin in the organic silt and the soil waters of the very fertile catchment-basin of the stream. The water of Spoon River, in so far as the nitrogenous substances (2.586 [mg/l]) are concerned, could support a much more abundant plankton than it produces (.384 [cm^3/m^3]). As in the case of the main stream, the explanation of the slight production lies in the recent origin of the tributary water. Impound Spoon River water in Thompson's lake, and it produces an abundant plankton" (Kofoid, 1903, pp. 204-205).

Palmer (1903, p. ix) concluded that the tributaries of the Illinois River contain organic matter in proportion to that of the Illinois River itself.

Palmer (1903, p. 35) noted that mercuric chloride ($HgCl_2$) was added to collected water samples to sterilize the water and thereby preserve water chemistry and inhibit organic decomposition, "The waters of the Illinois river and its tributaries and those of the Mississippi contain a great deal of organic matter which is easily susceptible to the influence of dissolved oxygen."

In summary, we conclude that the reference/background condition of soil erosion in the IRB was appreciable. And, with this appreciable erosion of organic-rich, nutrient-rich soil, vegetable matter and animal matter, appreciable amounts of biologically available N and other nutrients entered the system of lakes, streams, and rivers.

Such erosion-related nutrient enrichment would have been especially true at the height of the Native American presence some centuries earlier. At this time, fierce fires annually laid bare the earth and herds of millions of buffalo and other animals tore up the landscape, including the banks of the surface waters and wallows which they frequented and into which they freely defecated. Masses of nutrient-rich and highly decomposable wetland and aquatic vegetation also grew in and around the surface waters, and were transported in great quantity throughout the surface waters of the IRB.

WATER-QUALITY REFERENCE/BACKGROUND CONDITIONS

The establishment of reference/background (pre-European settlement) water-quality conditions poses a number of challenges. One major challenge is that there is no one reference/ background state, but we select one. A succession of Native American civilizations and climate changes could provide a suite of reference/background states. However, neither the Cahokian Native American civilization, its Native American successor, nor the early explorers who witnessed the latter civilization intact, left us with any written records of chemical water quality.

Thus, early water-quality conditions were assessed in light of changes which have occurred in the landscape — both anthropogenically induced and naturally induced changes — prior to the first water-quality records.

The earliest comprehensive chemical water-quality records we were able to find for the IRB are from the 1880s. In the 1890s, chemically comprehensive, chemical water-quality sampling was done frequently and consistently enough to enable compilation of arithmetic average monthly, multi-year concentrations for 1894-1899 for the Lower Illinois River (above where it empties into the Mississippi River (Figure 11; Table 11). These records pre-date the diversion of large quantitites of water into the Illinois River from Lake Michigan starting in 1900. It is interesting to note that these early data are more comprehensive than most modern data, whose N analyses are often limited to the collective measurement of NO_2-N plus NO_3-N.

Direct examination of the data in Figure 11 and Table 11 show that, even after passing through the jungle-like growth of aquatic vegetation and algae, which removes an enormous amount of N from the field of these analyses, the 1890s water-quality NO_3-N and total-N data are still well above the 0.3 mg/l "natural" value asserted to leach from the land. Indeed, even after passing through this dense living N filter, total-N concentration was not much different than that of today (Table 11).

These data will now be refined by assessing them in the light of anthropogenic and natural factors, as well as the understanding produced by the standing N-cycle paradigm.

About 0.42 mg/l of the 1.10 mg/l total organic N measured in 1894-1899 was plankton (particulate N). However, in the course of the study, it was found that the then-standard net missed an amount of plankton 3.3 times greater than that collected (e.g., Kofoid, 1903, p. 574).

With this discovered shortcoming, and assuming the modern organic-N data are correct, the 1894-1899 organic-N value was adjusted upward by the authors of this report to 2.49 mg N/l. The organic-N-corrected total N value for the 1894-1899 period now becomes 5.07 mg N/l, slightly higher than the 1993-1998 average of 4.82 mg N/l.

We also know that the concentration of N in rivers and streams is precipitation and flow dependent. Figure 12 shows a statistically significant relationship between statewide precipitation and concentration of NO_2-N plus NO_3-N in Illinois rivers and streams in 1978-1998. The 1890s was a period of extended drought, which devastated American agriculture and sent the United States into depression. For the 1890s the natural flow of the Illinois River was equivalent to only 3.7 in./yr of runoff from the IRB (Leighton, 1907, p. 159). In the 1900s, the drought broke, and for the 1900-1903 period the normal flow of the Illinois River (normal now having to be corrected for appreciable diversion of Lake Michigan water into the IRB) was the equivalent of 8.6 in./yr of runoff (Leighton, 1907, p. 159) — returning to about what it was before the 1890s: when the flow of the Illinois River was equivalent to 8.88 in./yr runoff for the IRB over the 1879-1889 period (Leverett, 1896, p. 739). Moving into the present, and using USGS flow data, the 1980-1996 period was exceptionally wet — normal flow (adjusting for 3,200 cfs of

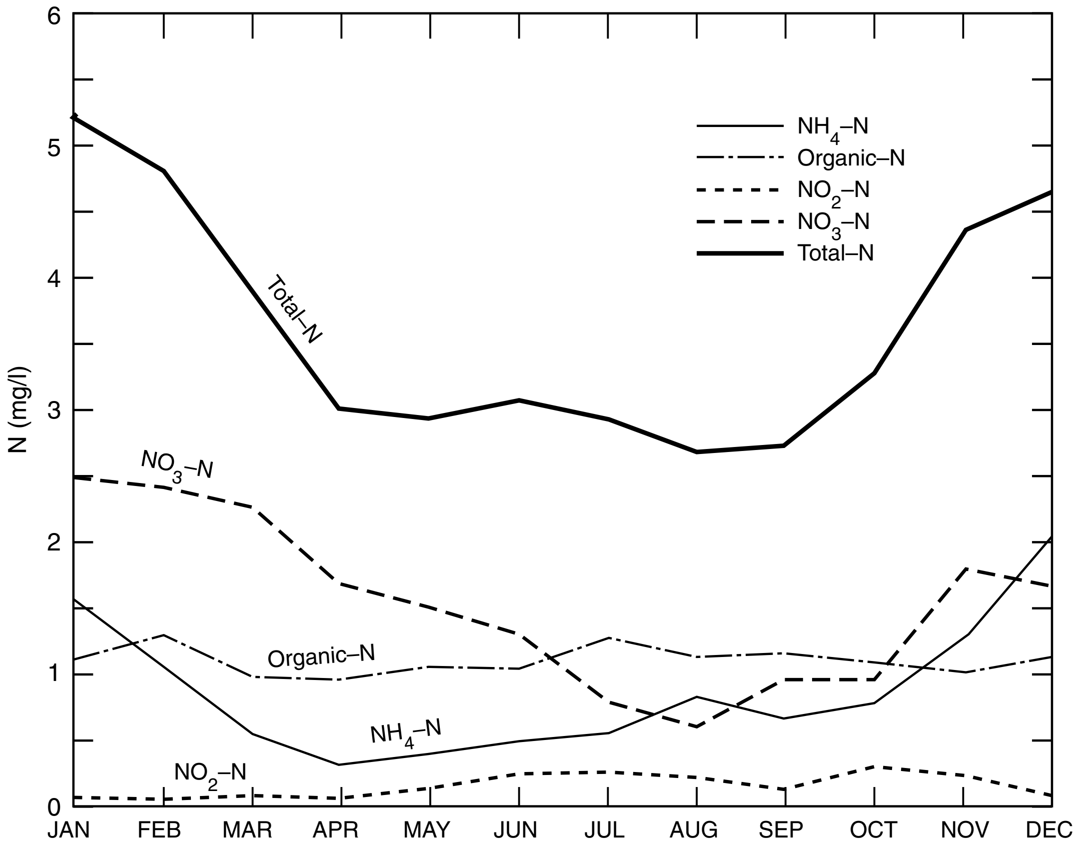

Figure 11. Average monthly concentrations of nitrogen for the Lower Illinois River, 1894-1899.
Source: Data from Kofoid (1903) and Palmer (1903).

Table 11. Comparison of Average 1894-1899 and 1993-1998 Concentration of Nitrogen for the Lower Illinois River

Period	*NO_3-N*	*NO_2-N*	*NH_4-N*	*Organic-N*	*Total*
1894-1899	1.54	0.16	0.88	1.10	3.68
1993-1998	—— 3.77 ——		0.16	0.89	4.82

Sources: Arithmetic average data compiled from 1894-1899 data of Kofoid (1903) and Palmer (1903). Arithmetic average 1993-1998 data from Dave Soballe, USGS, La Crosse, WI, personal communication, March 1999.

Lake Michigan water) was the equivalent of 13.7 in./yr for the IRB — this being higher than even the 1939-1996 average value of 11.5 in./yr.

To compensate for the lower rainfall and much lower runoff in the1890s, Figure 12 suggests that the combined concentration of NO_2-N plus NO_3-N for the 1890s should be increased by some 25 percent for meaningful comparison with the 1990s data. With this flow correction, average NO_2-N plus NO_3-N concentration rises from 1.70 mg N/l to 2.13 mg N/l.

The flow-corrected average total N value for the 1894-1899 period now becomes 5.50 mg N/l — higher than the 1993-1998 average of 4.82 mg N/l.

However, there is still yet another correction to make for the 1890s data.

The jungle-like growth of aquatic vegetation that removed an enormous amount of N from the field of these 1890s analyses also participated to some degree in the transport of biologically available N down the river in the form of debris. Unfortunately, measurement of transported debris appears to have escaped both the analyses of the past and the present — to the chagrin of discerning and concerned scientists from the time of Lyell to the present.

Whereas we have been unable to discover any existing quantification of the transport of such debris, prior to development and leveeing of the floodplain, and the construction of the lock-and-dam navigation system, huge amounts of N-rich debris were flushed down the river.

About 220 miles of the 259-mile-long mainstem of the Illinois River was bordered by significant floodplain (from $1^1/_2$ to 6 miles wide on either side) containing numerous lakes, pools, bayous, swamps, and sloughs which, along with extensive organic-rich bottomland, were flushed out every year during the flood season (Palmer, 1903, p. 59). Whereas analyses of wetlands under the standing N-cycle paradigm have them removing soluble forms of N from water, these analyses do not consider the fact that, in the natural state, much of this N would be transported down the river in the form of particulate organic-N, including large quantities of debris. Descriptions of the flowing water of the Illinois River almost universally cited the observance of notable amounts of visible debris (Kofoid, 1903).

Considering the above facts, it is not surprising that the late 1800s description of the main channel of the Illinois River was like that of Schoolcraft's 1821 description — for most of its length, the main river was chocked by decaying vegetation, e.g., "in times of low water, a large abundance of aquatic vegetation [lay in the river channel] which frequently gave off foul odors...." (Leighton, 1907, p. 175).

In addition to the blinkering of perspective imposed by the standing N-cycle paradigm, these massive amounts of debris were, in fact, also physically removed from the field of analysis as well as from the experience of modern scientists by the drainage and leveeing of the surrounding highly fertile floodplain, by the later development of the lock-and-dam navigation system, and by the effects of sedimentation.

It can be said that the development of the Illinois River and its floodplain has resulted in corn being exported down the Illinois and Mississippi Rivers in the place of the export of massive amounts of exceptionally N-rich plant litter for, as Wetzel (1979) characterized:
"It is well known that, among the plant communities of the biosphere, the productivity of emergent freshwater macrophytes exceeds all others."

Given that debris is a new perspective heretofore unconsidered in the N budgets of the IRB and the MRB, this point has yet to be researched.

Nevertheless, at this point, assessment of the old water-chemistry data and the circumstances surrounding them suggest that the concentration of N in the Illinois River system prior to the 20th century was higher than today in the era of chemical-N fertilizer.

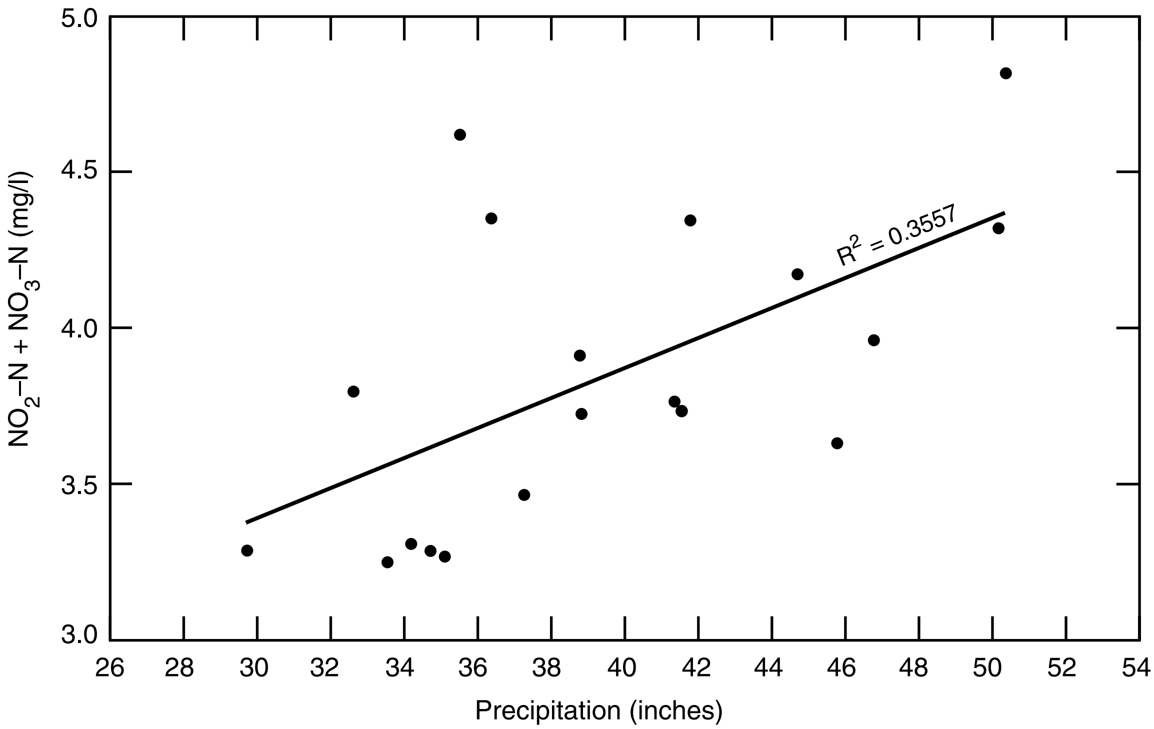

Figure 12. Relationship between annual 1978-1998 statewide precipitation for Illinois and 1978-1998 annual mean statewide, NO_2-N + NO_3-N concentrations for all Illinois rivers.
Sources: Illinois river and stream data from Matt Short,IEPA, personal communication, November 1999.
Illinois precipitation data from Jim Angel, ISWS, personal communication, November 1999.

Assessment of the old water-quality data and the circumstances surrounding them enable us to make additional statements — definitively and with scientific certainty.

First, the consensus produced by the standing N-cycle paradigm is that prior to the widespread and intensive use of chemical N fertilizer, the landscape was not sufficiently N saturated to yield a pronounced (two-fold) seasonal NO_3-N peak (Turner and Rabalais, 1991; Rabalais et al., 1996; Goolsby et al., 1999; Rabalais et al., 1999). This consensus produced by the standing N-cycle paradigm is the exact opposite of our previous analysis on the effects of fire on the N cycle. The previous analysis of the pre-European-settlement condition concluded, largely based on fundamental scientific principles, that there should be a significant natural, seasonal N peak in runoff. For the consensus to say that in the unobserved past there was no such seasonal peak is logically the same as rejecting the fundamental principles of physics to assert that a tree falling unobserved makes no sound.

Nevertheless, this new consensus is reported to be supported by observation itself, namely, analyses of water-quality data from the MRB are reported as showing that, before the era of chemical N fertilizer, "There was no pronounced peak [seasonal two-fold increase] in nitrate concentration....' (Rabalais et al., 1996). Because of the importance of these reportedly hard scientific facts, additional quotes to this effect follow. To quote an executive summary of the national Gulf Hypoxia Assessment:

"There was no pronounced seasonal peak in nitrate concentration prior to 1960, whereas there was a spring peak from 1975 to 1985. Prior to the 1960s, nitrogen flux closely paralleled river discharge, a pattern that still holds but the load of nitrogen per volume discharge is greater than historically. There is no doubt that the concentration and flux of nitrogen (per unit volume discharge) has increased from the 1950s to 1960s, especially in the spring" (Rabalais et al., 1999; "Executive Summary").

To quote the seminal article that discovered the reportedly unnatural, pronounced, two-fold seasonal peak in concentration of NO_3-N:

"There was no pronounced peak in nitrate concentration earlier this century, whereas there was a spring peak from 1975 to 1985, we think due to fertilizer application....

"Water quality changes are coincident with increased nitrogen fertilizer use...the nitrogen loading doubled when fertilizer applications increased after World War II.... The rise in nitrate in recent decades is evidence that the ability of watershed land to store the mostly ammonia-based nitrogen fertilizers was exceeded....

"The riverine ecosystem response to higher nutrient loading is consistent with the nitrogen-saturation hypothesis described for northern forests by Aber et al. (1989)" (Turner and Rabalais, 1991).

Similar claims are also made today for Illinois using comparisons of the Illinois State Water Survey water-quality data of Palmer (1903) as the reference/background condition and comparing these old data with USGS water-quality data from 1989-1991 (e.g, Hey, 1999).

Thus, these MRB and IRB data are reported as supporting the new scientific consensus that the two-fold seasonal NO_3-N peak is a recent phenomenon, which is the consequence of anthropogenic inputs of N from fertilizer and atmospheric deposition (produced by greatly elevated combustion of fossil fuels) overwhelming nature's N-assimilatory capacity.

But the data do not show what it is asserted they show. These cited data actually show that well before the era of chemical N fertilizer and the rain of nitric acid (HNO_3-N) from coal-fired electric plants and many millions of vehicles, scientists of the Illinois Natural History

Survey and the Illinois State Water Survey documented that a pronounced seasonal NO_3-N peak occurred naturally in the soils and waters of Illinois. For example:

"The cycle of seasonal fluctuations (see Pl. XLIII.-L) in the chemical condition is, in the most general terms, an increase in the nitrogenous compounds during the colder months and a decrease during the warmer ones.... This fluctuation is somewhat similar to that found in soil waters....

"These maximum and minimum pulses in the Illinois River in 1896 (Pl. XLIII.) are most evident in the nitrates and free ammonia, though traces of their influence can be detected in the curve of the albuminoid ammonia....

"The coincidence of the spring plankton maximum and the decline of nitrogenous matters in the river water has its parallel in the decline of nitrates in soil waters with the pulse of spring vegetation. In both cases the decline of nitrogenous matters seems to be due to utilization by growing vegetation, by chlorophyll-bearing organisms....

"The nitrates, the final products of decomposition, exhibit the maximum-minimum cycle most clearly, as, for example, in Pl. XLV., XLIX., and L" (Kofoid, 1903; pp. 207, 209, 213).

And:

"In Plate XXXIV there are also shown lines representing the quantities of nitrogen in the form of nitrates.... The decrease at the coming of warmer weather, in May and June, results from the partial cessation of the leaching, from the partial exhaustion of the supply of nitrates in the soil, and from the assimilation of nitrates by the vegetation, especially that of the plankton which at this season of the year increases in abundance with very great rapidity" (Palmer, 1903, p. iv).

Thus, the examination (Hey, 1999) of Palmer's (1903) data regarding the NO_3 peak is reported incorrectly. Therefore, the conclusion derived from the erroneous reporting of Palmer's data is also wrong — as is the more general assertion of a pronounced (two-fold) seasonal NO_3 peak being an unnatural post-1950s phenomenon.

Because of the importance of seasonal N concentration to our analysis, seasonal soil and water NO_3 data contemporary and independent of Kofoid (1903) and Palmer (1903) were sought for comparison.

Regarding seasonal changes in soil NO_3, the natural seasonal fluctuation of concentration of NO_3 in water leaching out of unfertilized, turn-of-the-century soil is shown by University of Wisconsin research illustrated in Figure 13. This shows a four-fold seasonal increase in the concentration of NO_3 (King and Whitson, 1902).

Table 12 shows the natural, seasonal, more-than-four-fold fluctuation of average concentration of NO_3 in water leaching out of unfertilized California soil continuously cropped for nine years.

As we see for both Wisconsin and California soils, and as both Kofoid (1903) and Palmer (1903) report for Illinois, during the dormant season mineralization of organic soil N continues with a resultant increase in the amount of NO_3. Indeed, King and Whitson (1902) report that NO_3 continued to accumulate in Wisconsin soils during the time that these soils were frozen. For nine soil plots during the period in which these soils were frozen (between November 29, 1900 and April 9, 1901), an average of 62.9 lb NO_3/acre (13.1 kg NO_3-N/ha) accumulated in the top 4 feet of these soils.

Even under forests whose N-poor litter is not conducive to the release of NO_3-N, in-situ bag experiments in Ontario show that 3.4 kg NO_3-N/ha is generated overwinter in the forest floor (Foster, Nicholson, and Hazlett, 1989), 6.2 kg NO_3-N/ha in the underlying 6 inches of mineral soil (Hazlett, Englis, and Foster, 1992), and about 5 to 15 kg NO_3-N/ha is reported to be

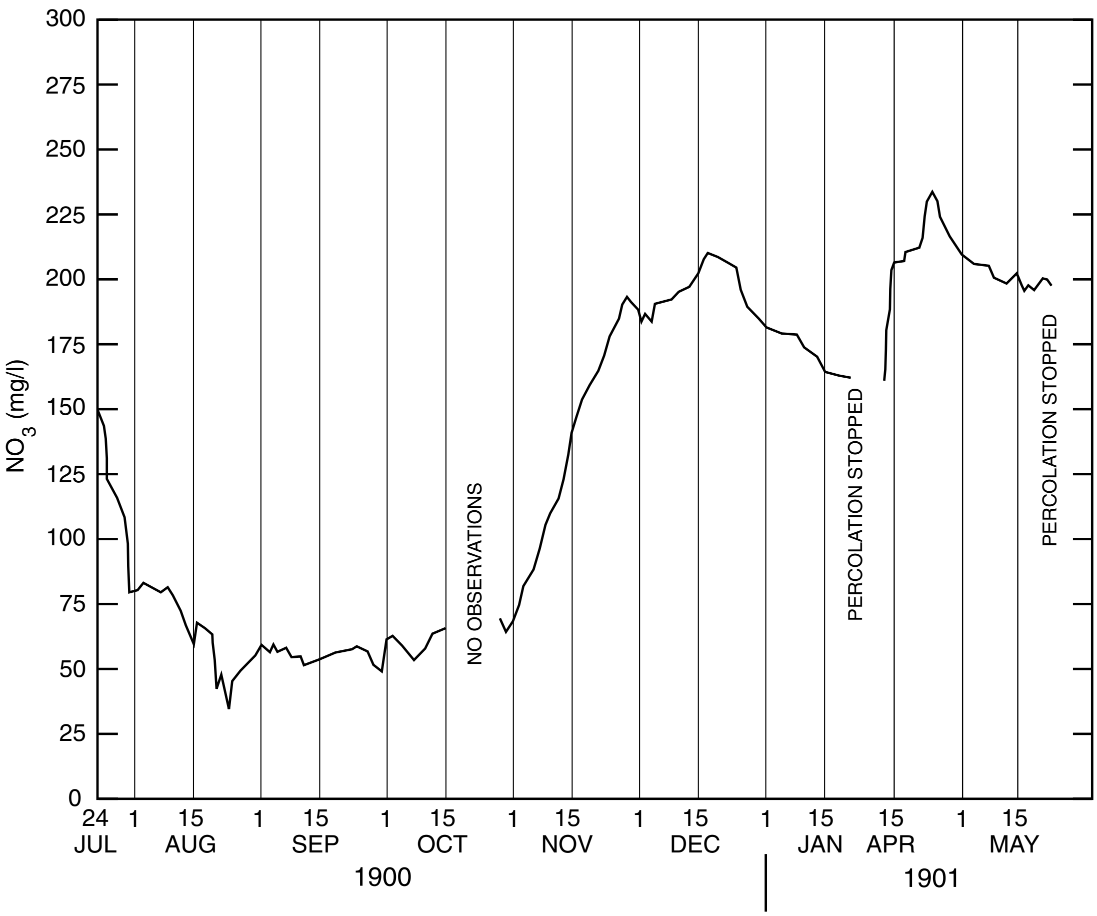

Figure 13. Variation in the concentration of NO_3 leaching from Wisconsin soil between July 24, 1900, and May 20, 1901. **Source**: Adapted from Figure 6 of King and Whitson (1902). Data in mg NO_3/l.

Table 12. Concentrations of NO_3 in Water Extracted from Unfertilized California Soils at the Beginning and End of the 1923 Growing Season and at the Beginning of the 1924 Growing Season

Soil number	*April 30, 1923*	*September 4, 1923*	*April 28, 1924*
7	174	58	222
8	274	88	227
9	160	43	182
10	230	40	200
11	166	16	286
12	115	50	156
13	146	13	167

Source: Adapted from Table 4 of Burd and Martin (1924). Data in mg NO_3/l.

generated during the winter in such mineral soil under forest in Wisconsin (Foster, Nicholson, and Hazlett, 1989).

It should also be considered that the early settlers found the soils of central and southern Illinois unfrozen most of the time (e.g., Buck, 1912), unlike those of Ontario and Wisconsin. Therefore, over winter NO_3-N formation (nitrification) of pre-European-settlement soils and early agricultural soils of Illinois would, for this reason, be expected to be greater than that observed in Ontario and Wisconsin.

To give perspective as to whether such amounts of leachable NO_3-N generated during the winter and available for leaching in snowmelt and runoff from rain during the ensuing dormant season are significant relative to the high amounts of NO_3-N being reported as leaching from fertilized cropland of the region, the average amount of NO_3-N annually lost to surface water and ground water from fertilized Wisconsin croplands is estimated to be 5 kg NO_3-N/ha, for the central United States as a whole 8 kg NO_3-N/ha, for the eastern Corn Belt states 12 kg NO_3-N/ha, and 13 kg NO_3-N/ha for Illinois (Wu and Babcock, 1999).

Thus, the average 13.1 kg NO_3-N/ha generated in frozen, unfertilized agricultural Wisconsin soils well before the advent of chemical-N fertilizer and post-World War II acid rain generated over winter alone amounts of NO_3-N equal to or larger than total annual amounts generated from heavily N-fertilized soils. Similarly, undisturbed natural soils whose physical, chemical, and biological conditions are not conducive for the formation of NO_3-N, like the old Wisconsin soils, produced amounts of NO_3-N that would be considered quite alarming, that is, if such NO_3-N was coming from "heavily N fertilized" agricultural soils of the Corn Belt.

Relating seasonal changes in soil NO_3-N to surface-water chemistry, Figure 14 is a graphic compilation of United States Geological Survey (USGS) water-quality data (Collins, 1910), which shows pronounced (two-fold) seasonal fluctuation in NO_3 concentration in Illinois rivers and lakes well before the era of chemical N fertilizer and post-World War II acid rain. Interestingly, Collins (1910) was part of the turn-of-the-century national USGS water-quality survey cited by Gulf hypoxia scientists as showing no pronounced seasonal NO_3 peak prior to the curent era of chemical-N fertilizer (Turner and Rabalais, 1991).

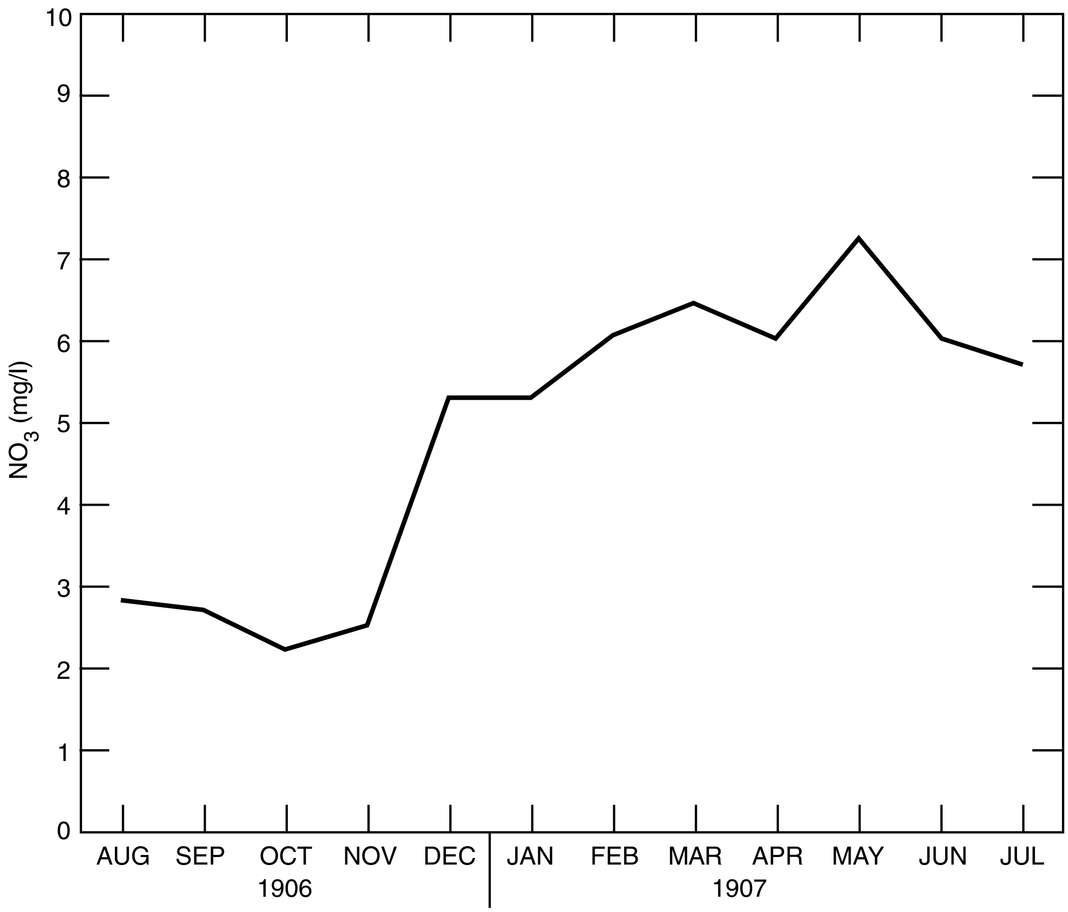

Figure 14. Average monthly concentration of NO_3 at 27 sites (13 rivers and 4 reservoirs) in Illinois from August 1906 to July 1907.
Source: Data from Collins (1910). Data in mg NO_3/l.

Whereas these USGS data (Collins, 1910) do not support the conclusion that the adherents of the standing N-cycle paradigm derive from them, these USGS data do support the above-mentioned observations and conclusions of the Illinois State Water Survey (Palmer, 1903), the Illinois Natural History Survey (Kofoid, 1903), and others about pronounced seasonal fluctuations in the concentrations of NO_3 in soil and surface waters well before the era of chemical N fertilizer and acid rain.

For these turn-of-the-century Illinois waters, it is interesting to note that the sampling site described by the USGS as being representative of the river reported to be the most undisturbed and natural of the Illinois rivers sampled, the Sangamon (whose watershed was described as being "mainly rolling prairie" (Collins, 1910, p. 31), then had a reported seasonal amplitude of NO_3 ranging from 0.9 to 20.0 mg NO_3/l — 0.2 to 4.6 mg NO_3-N/l. Thus, this most natural of Illinois Rivers, in 1906-1907 had a 20-fold seasonal NO_3-N peak whose seasonal high value was as great as the 1996 average NO_2-N + NO_3-N concentration for Illinois rivers, and whose seasonal low value was less than the average 1996 low for all Illinois rivers (Figure 15).

Figure 15. Monthly average NO_2-N + NO_3-N for all Illinois rivers in 1996.
Source: Personal communication from Matt Short,
IEPA (November 24, 1998).

These data show that the standing N-cycle paradigm that NO_3-N leaking out of soils is an unnatural and recent phenomenon resulting from recent manmade N saturation of watersheds by chemical-N fertilizer and post-WW II acid rain is scientifically invalid. This is also suggested by Figure 16, which shows no statistically significant relationship between annual statewide N-fertilizer use and the annual concentration of NO_2-N + NO_3-N in Illinois' rivers.

Nevertheless, the appearance of scientific validity is bequeathed upon it by what appears to be independent validation by the following consensus geographic analyses.

In the western reaches of the MRB, there are still some "virgin" prairie watersheds. These western prairie watersheds are used as reference/background watersheds against which Illinois and other more eastern Corn Belt watersheds are compared. From the fact that the quantities of N delivered to surface waters in Illinois are much larger than those in the more western prairie watersheds, it is concluded that these higher amounts of N are unnatural and due to heavy fertilization of Illinois fields with chemical-N fertilizer (e.g., David et al., 1997; Goolsby et al., 1999).

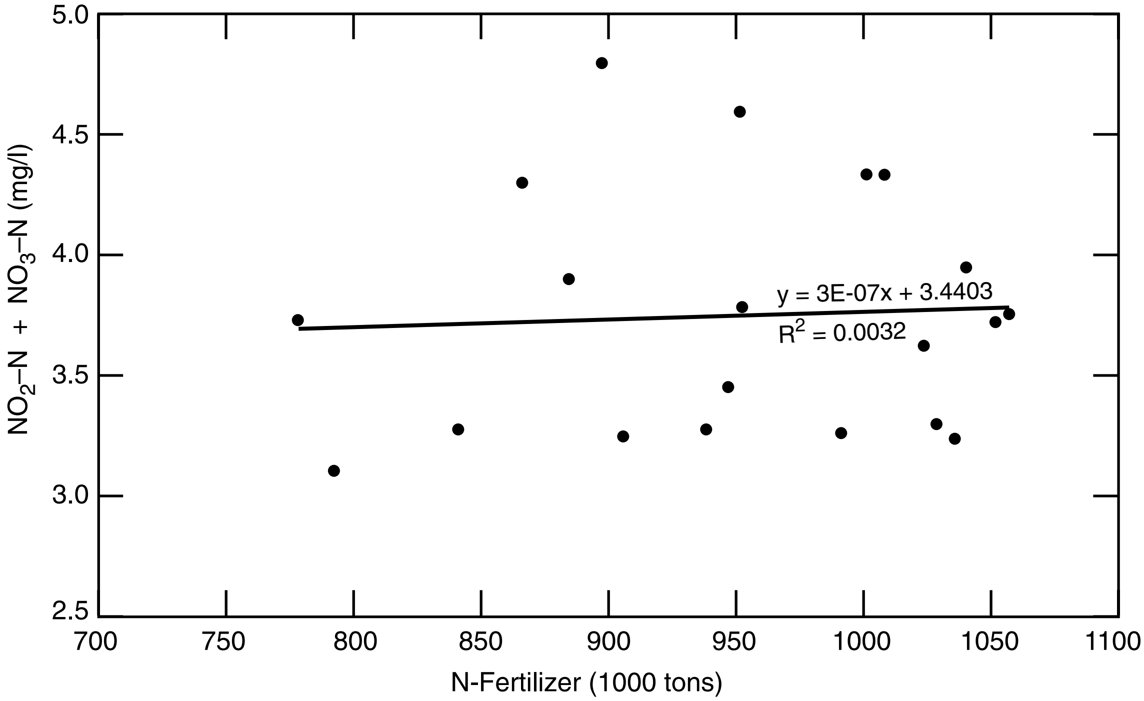

Figure 16. Relationship between 1978-1998 annual statewide nitrogen-fertilizer use in Illinois and 1978-1998 annual statewide NO_2-N + NO_3-N concentrations for all Illinois rivers.
Sources: Illinois nitrogen fertilizer use data from Alan Gulso, IDOA. Illinois river and stream data from Matt Short, IEPA.

Unfortunately, this "factual" support for the standing N-cycle paradigm did not use the scientific method to scientifically prove that the application of chemical-N fertilizer is the cause of more N leaching out of cultivated eastern MRB prairie watersheds relative to uncultivated western MRB prairie watersheds. This geographic correlation is given a causal interpretation without seriously attempt to falsify it through the use of multiple working hypotheses (e.g., Chamberlain, 1965) to evaluate if any other factors are responsible for the geographic differences in NO_3-N leaching from prairie soils of the MRB. Or, stated another way, it was not determined if the correlation is causal or spurious, as the science of statistics requires, e.g.,

"To test whether a correlation between two variables is genuine or spurious, additional variables and equations must be introduced, and sufficient assumptions must be made to identify the parameters of this wider system. If the two original variables are causally related in the wider system, the correlation is 'genuine'" (Simon, 1954).

Thus, this assessment widened and increased the number of parameters in the geographic definition of the MRB to see if the correlation is "genuine." This was done by examining the effects of four geographic factors which the geographic fertilizer hypothesis of natural east-west equality of N cycle of MRB prairie soil watersheds presumes to be equal.

The first geographic factor considered in testing the geographic fertilizer-leaching hypothesis was geographic variation in the annual quantity of runoff. Figure 17 shows that the presumed geographic equality of quantity of runoff across the MRB is false. The amount of runoff from eastern Corn Belt watersheds is much higher than that of western MRB watersheds. For Illinois, for the period analyzed, runoff was nearly 10 in./yr, whereas for the same period west of the north-south line running roughly along the Minnesota-Dakota border, runoff was less than 1 in./yr (Figure 17).

Thus, on the basis of amount of runoff alone, eastern Corn Belt watersheds will naturally have greater amounts of NO_3-N leaching into surface waters and ground waters. This invalidates the presumed equality of N cycle of prairie-soil watersheds across the MRB.

Interestingly, research on agricultural watersheds across the wetness gradient of the MRB has found that increasing runoff, in and of itself, increases the amount of NO_3-N lost to the hydrosphere: often by increasing both concentration and amount of runoff (Burkart et al., 1999; Goolsby et al., 1999; Mitsch et al., 1999; Wu and Babcock, 1999) — as did our analysis for Illinois (Figures 12, 16). Nevertheless, the MRB research has not been applied to falsify the presumed equality of watersheds across the MRB. What this says about the standing N-cycle paradigm was succinctly stated in *Science*:

"A scientific theory must be tentative and always subject to revision or abandonment in light of facts that are inconsistent with, or falsify, the theory. A theory that is by its own terms dogmatic, absolutist and never subject to revision is not a scientific theory" (Overton, 1982).

The second geographic factor used to test the standing geographic hypothesis was geographic variation in the timing of runoff across the MRB. Timing of runoff is important because, as discussed above, all else being equal, more N and other nutrients naturally leak out of the land during the dormant season than during the growing season.

Figure 18 shows that the presumed geographic equality of timing of runoff across the MRB is false.

The season of lowest runoff for western MRB watersheds is generally during winter and early spring (Figure 18) — the time when concentration of N in runoff is naturally high.

The season of lowest runoff in the eastern Corn Belt is during late summer and fall (Figure 18) — a fact reinforced by Figure 19, which shows the temporal relationship between amounts of precipitation, evapotranspiration, and runoff to the hydrosphere.

The season of lowest runoff for the eastern Corn Belt is during the late summer and fall — the time when concentration of N in runoff is naturally low. Thus, on the basis of timing of runoff alone, eastern Corn Belt watersheds will naturally have greater amounts of NO_3-N and total N leaching into surface waters and ground waters. This further invalidates the presumed equality of N cycle of prairie-soil watersheds across the MRB.

The third geographic factor we considered in testing the geographic fertilizer-leaching hypothesis was geographic variation in quantity of soil N across the moisture gradient of the MRB.

The presumed geographic equality of soil N across the MRB is false. As Figure 8 shows, as one moves east through the MRB, increasing moisture correlates with naturally increasing N content of prairie watersheds. As previously discussed, improving moisture conditions naturally promotes the increase in both symbiotic and asymbiotic N fixation, e.g., "the increased water in the soil must aid in symbiotic as well as ordinary nitrogen fixing activities" (Buckman, 1910). Thus, on the basis of natural watershed N content alone, eastern Corn Belt watersheds will have naturally greater amounts of N leaching into surface waters. This again invalidates the presumed equality of N cycle of prairie soil watersheds across the MRB.

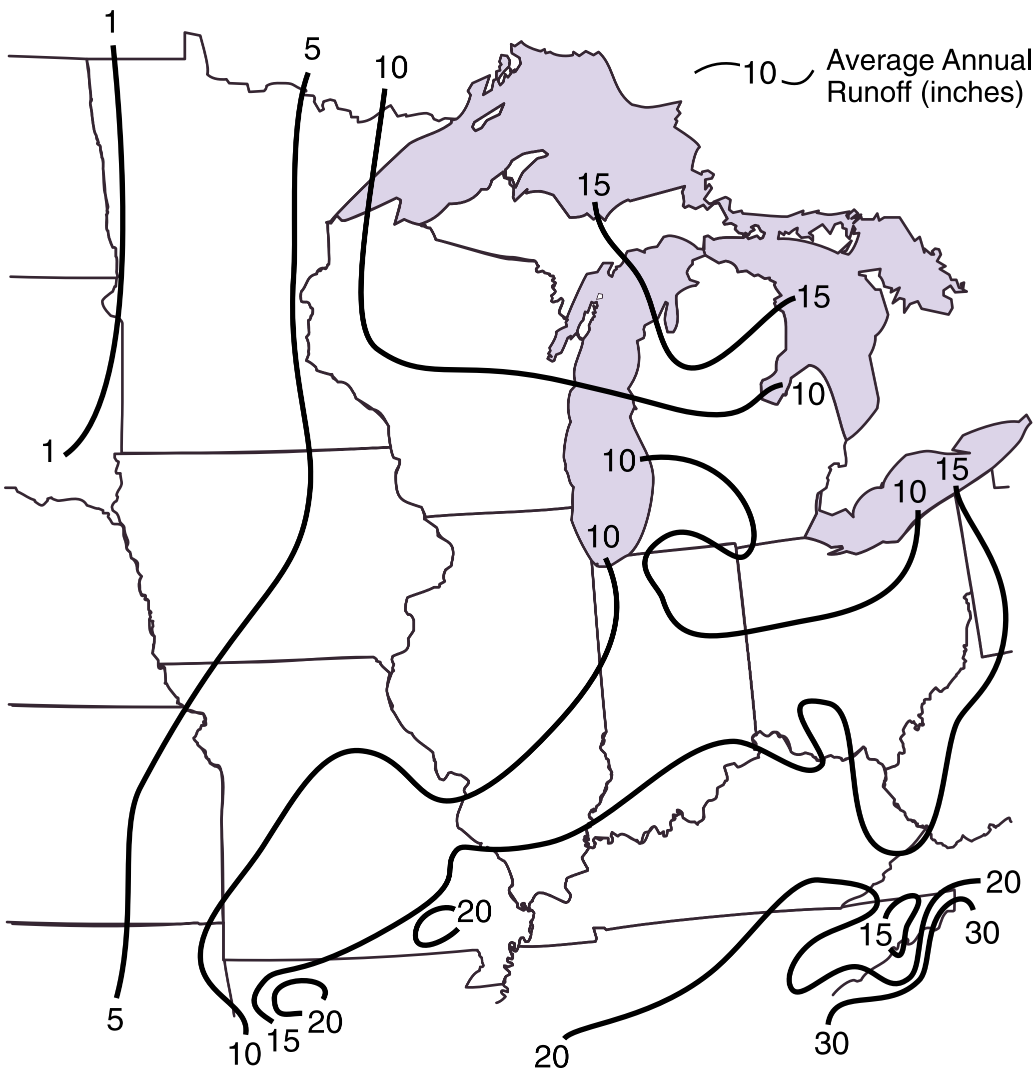

Figure 17. Annual average central United States surface-water runoff.
Source: From Plate 21 of Geraghty et al. (1973). Data in inches.

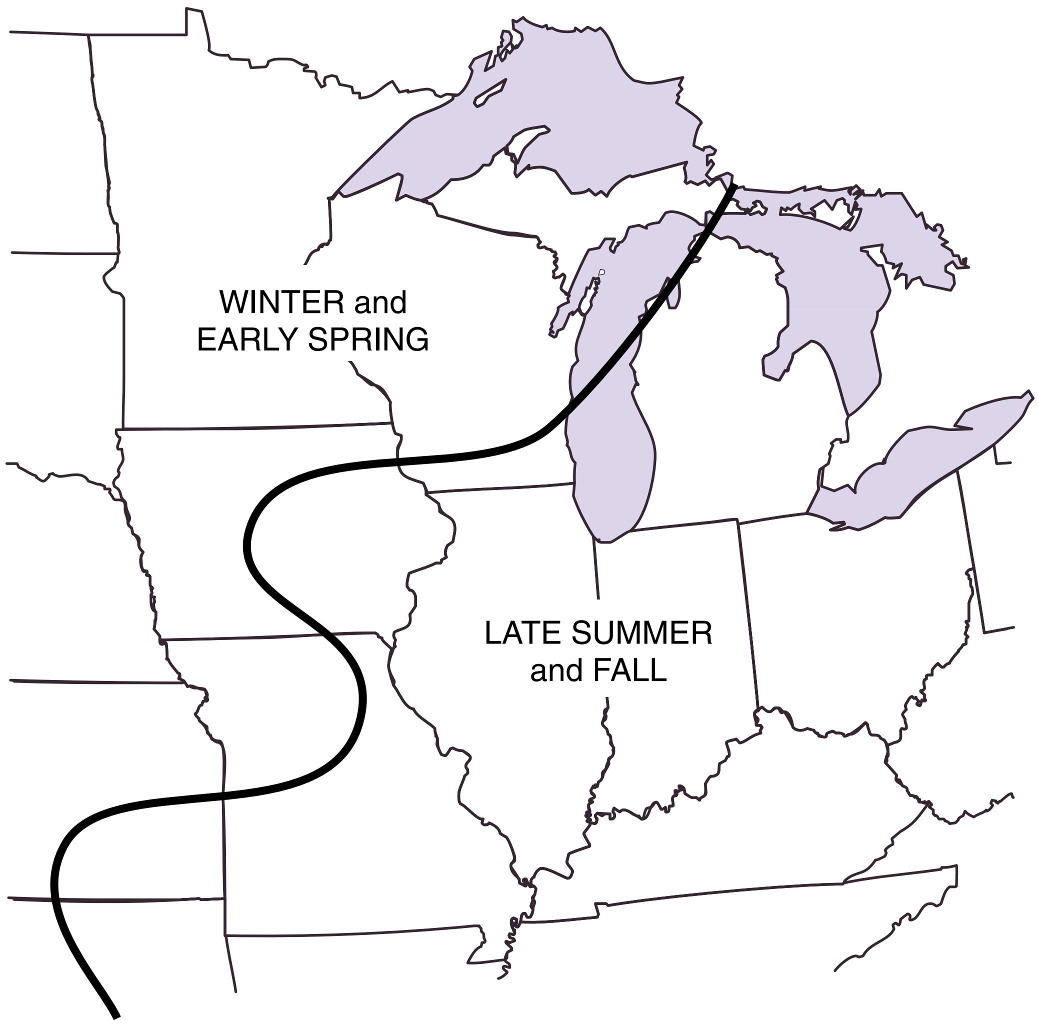

Figure 18. Seasons of lowest central United States stream flow.
Source: From Plate 24 of Geraghty et al. (1973).

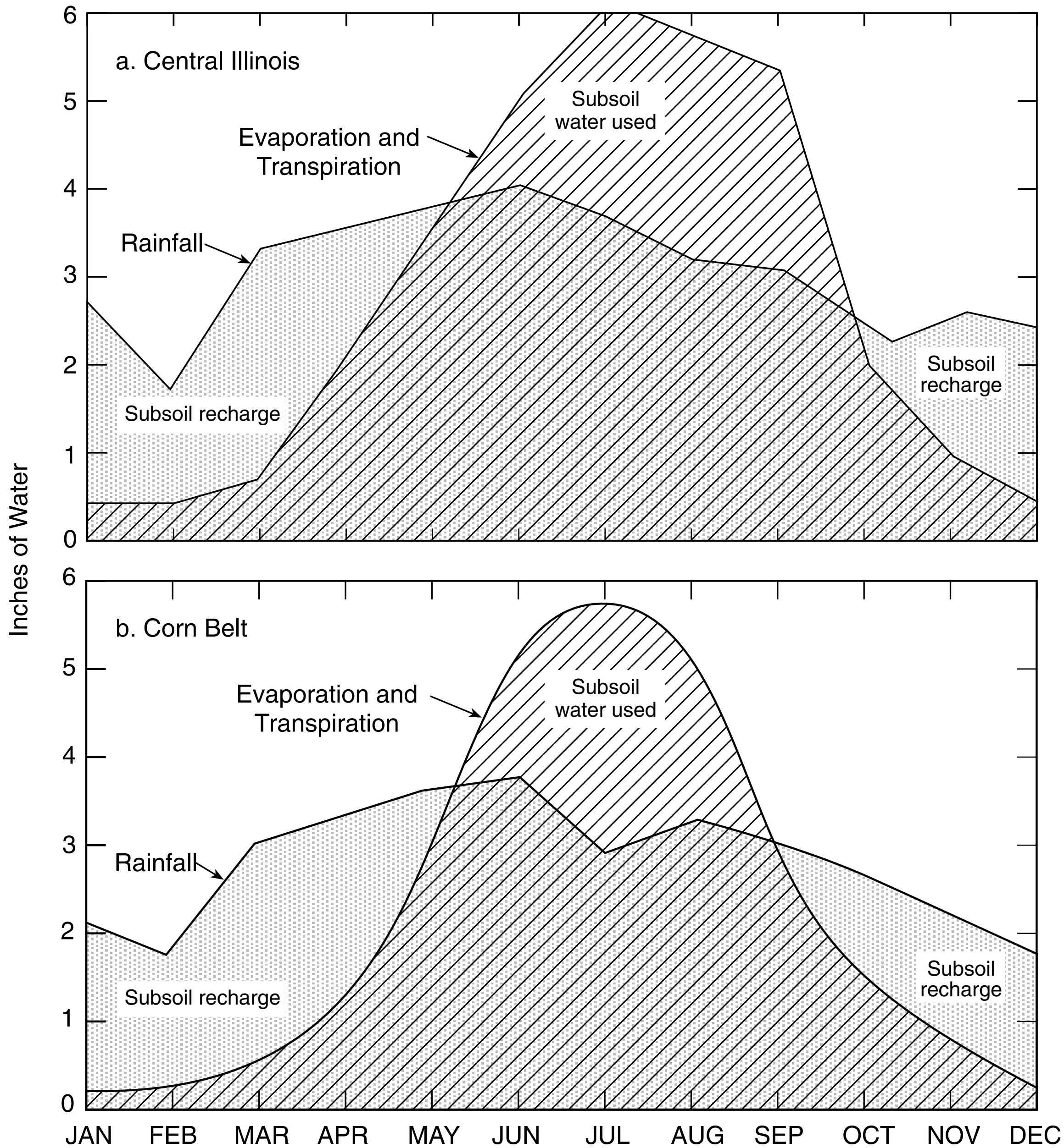

Figure 19. Temporal relationships between amounts of precipitation, evapotranspiration, and runoff: a) in central Illinois and b) in the Corn Belt.
Sources: Figure 19a from Figure 3 of Aldrich (1970).
Figure 19b from Figure 2.8 of Aldrich (1980).

The fourth geographic factor considered in testing the standing geographic hypothesis was geographic variation in mineralization of soil N across the moisture gradient of the MRB. As Mayo's (1895) quote noted (e.g., "'There was a large amount of organic nitrogen on and in the soil; there was sufficient moisture much of the time to permit nitrification and seldom so much moisture as to check it....'") it has been long known for that increasing soil moisture (short of waterlogging) increases N mineralization and conversion to NO_3-N (e.g., Buckman, 1910; Brady, 1974, p. 430; Bouwman et al., 1993).

The increasing moisture gradient across the MRB thus creates a double contradiction for the standing N-cycle paradigm. Not only does the increasing moisture gradient result in an ever-increasing soil N reservoir across the MRB, it also results in an increasing rate of mineralization and oxidation of this ever-increasing amount of soil N to NO_3-N.

Thus, eastern Corn Belt watersheds naturally have greater amounts of NO_3-N to leach into surface waters. Yet again, the presumed equality of N cycle of prairie-soil watersheds across the MRB is found to be invalid.

In summary, there are at least four natural factors that work together (enhance each other's ability) naturally to make more N leach out of eastern prairie MRB watersheds than from their western counterparts. More water leaches out of the soils of the eastern prairie watersheds, and this greater volume of water is leaching these soils at the very time when soil NO_3-N levels are naturally at their greatest. Furthermore, these eastern prairie soils have more N to leach, which is compounded by this greater amount of soil N naturally undergoing greater rates of conversion to NO_3-N.

This analysis scientifically invalidates the basis for the consensus assertion that the seasonal peak in N (especially NO_3-N) is an unnatural phenomenon caused by the recent N saturation of Illinois and MRB landscapes by the post World War II problems of chemical-N fertilizer and acid rain.

Our assessment shows that the analysis of the historic water-quality data is erroneous. The consensus geographic analyses, which appear to provide independent validation of the erroneous analysis of the historic data, are not independent.

Having said this, in order to improve our understanding and to provide direction for new research needed to scientifically resolve our environmental concerns, we now revisit the old Illinois water-chemistry data.

We can see that there are still yet more issues to be resolved in determining how much of what we have seen is natural or anthropogenic pollution caused by agriculture and urban pollution — issues previously obscured from scientific consideration by the false certainty imposed by the consensus of the standing N-cycle paradigm.

Data from Palmer (1903) and Leighton (1907) can be used to ascertain the relative importance of urban pollution of the IRB around the turn of the century. At this time, the Basin had a population of 385,000 people exclusive of the Chicago Sanitary District, which serviced 1,900,000 people (Leighton, 1907, pp. 116-117, 147).

In 1900, the Sanitary and Ship Canal opened using Lake Michigan water to flush the untreated sewage of 1,300,000 people (and a proportionate amount of untreated stockyard and other waste) from the Chicago Sanitary District down the Illinois River (Palmer, 1903, p. x). To do this, the amount of water diverted was large — equivalent to ~80 percent of the average annual flow of the Illinois River at Peoria (Mills et al., 1966, p. 8). The pollution diverted from Chicago was enormous relative to anything ever seen before. St. Louis, which is about 400 miles downstream, was so concerned about Chicago sewage polluting the greater volume of the Mississippi River from which St. Louis drew its drinking water that:

"On the day that the Chicago Drainage Canal was formerly opened, January 17, 1900, the State of Missouri instituted proceedings in the courts, asking for an injunction against the State of Illinois and the sanitary district of Chicago to the end that the St. Louis water supply should not be polluted.... This legal struggle between the two great cities attracted much attention.... The Illinois River had become known to the multitudes" (Purdy, 1930, p. 2).

Nevertheless, in spite of the inherently high N content of untreated human and animal wastes and the byproducts from animal slaughterhouses (Table 7), Figure 20 shows that the amount of N coming from the Chicago Sanitary District amounted to only a small fraction of the N load imposed on the Lower Illinois River from the rest of its drainage basin.

A far greater N load was being delivered to the waters of the IRB from a watershed that had yet to see chemical-N fertilizer. The watershed had become less N rich because Illinois had been losing its legume-rich vegetative cover for more than a century and had lost its vast herds of buffalo and related wildlife. It had also lost its N-stimulating effects on soil and water of vast and intense annual burnings. In short, the watershed's natural N load was greater prior to European settlement than it was at turn of the century.

In summary, the water-quality reference/background conditions of the IRB was that of hypertrophic surface waters set in a landscape more N saturated than today. Nitrogen loading and organic loading of the Illinois River appear to have been greater than they are today.

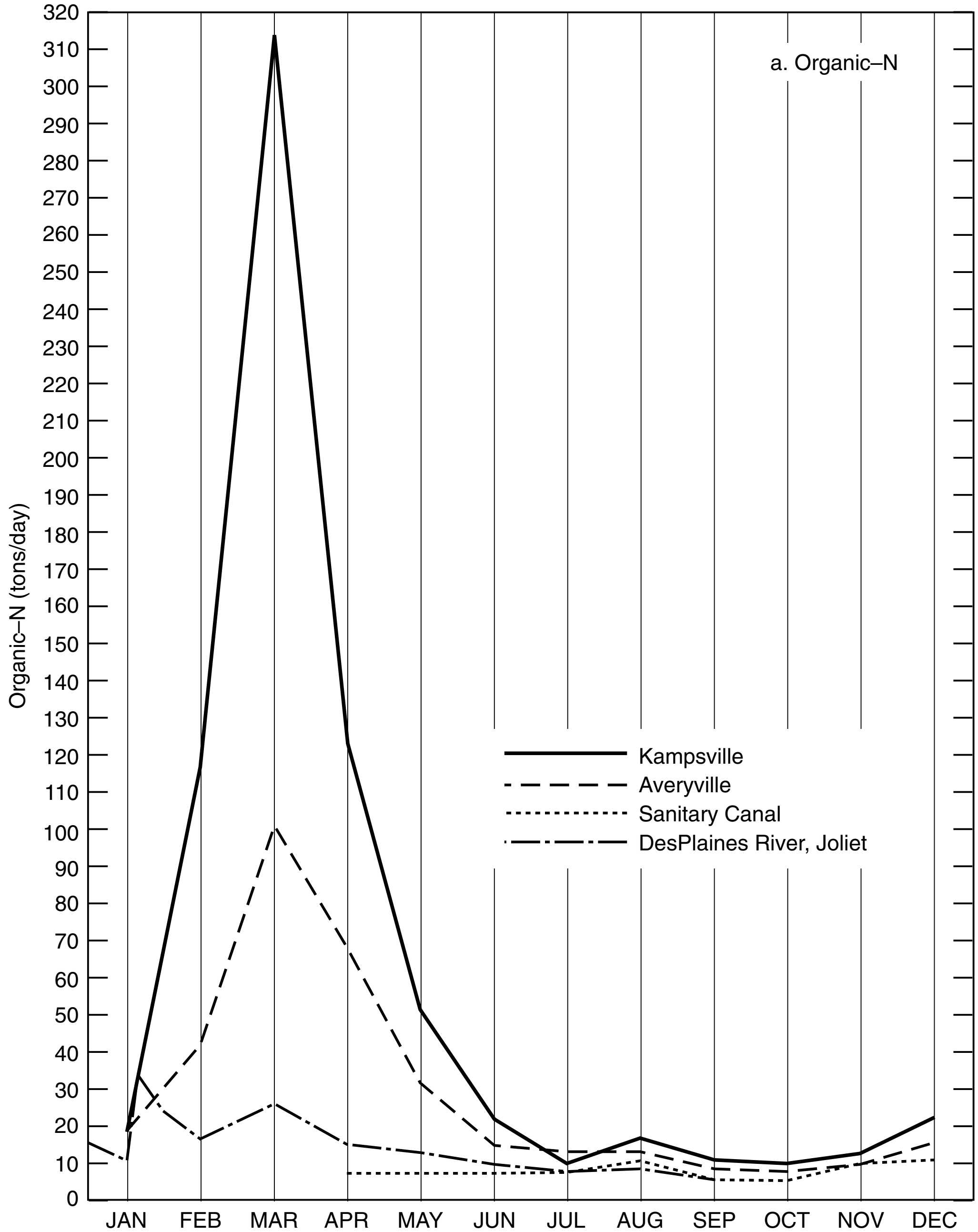

Figure 20. Quantity of measured nitrogen transported down the Illinois River in 1900: a) organic-N; b) NO_3-N, and c) NH_4-N. **Source**: Adapted from Plates 34 and 36 of Palmer (1903).

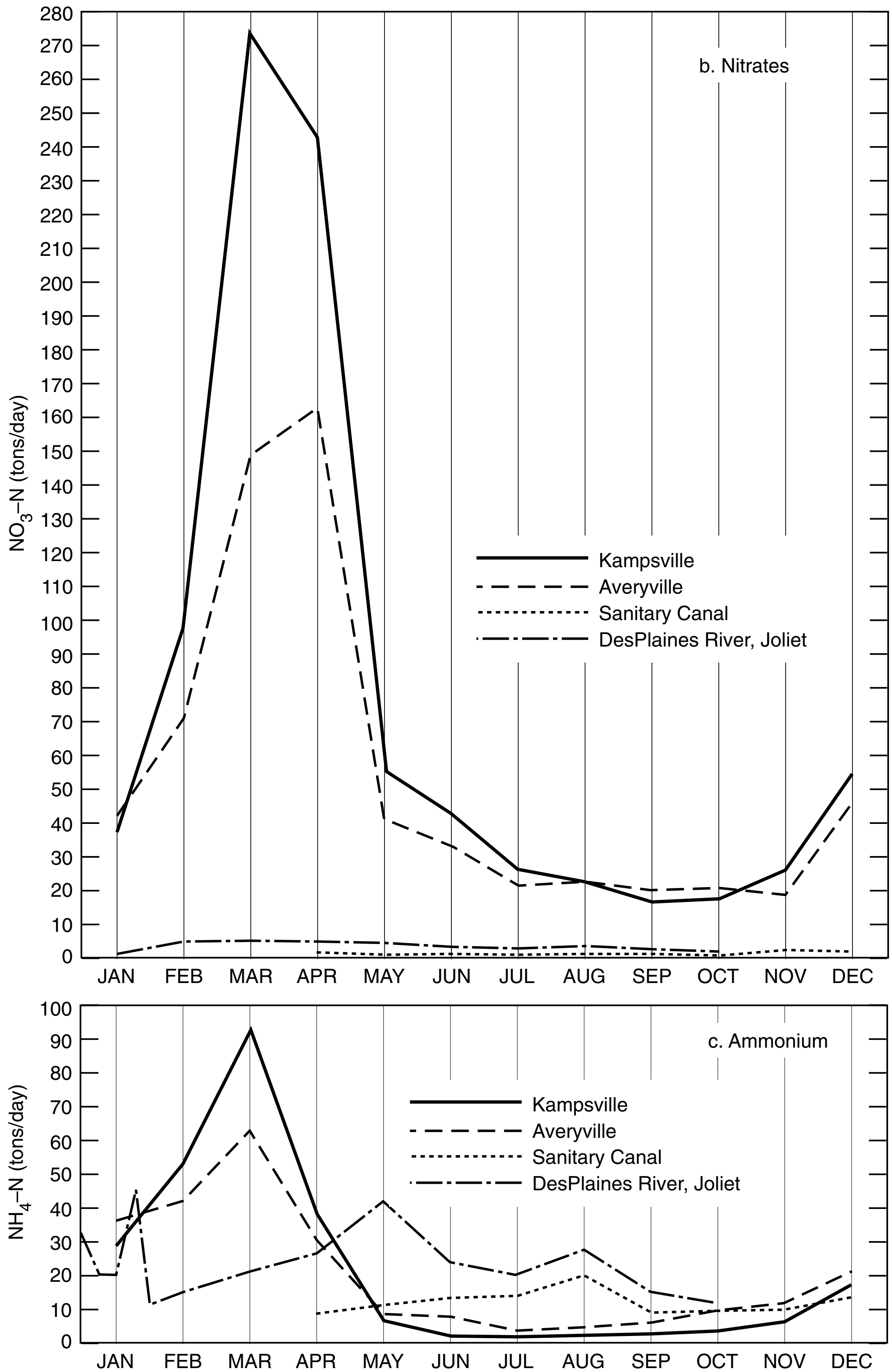

Figure 20. Concluded.

SOME EFFECTS OF AGRICULTURE ON WATERSHEDS

"Virgin Soils.

"To most Americans it is a fact familiar through personal experience, as well as from tradition and history, that when the forests and prairies of this country were first brought into cultivation, the land was, generally speaking, found to be much more fertile than it is now....

"The explanation of the matter is not far to seek now that it has been made plain that forests and prairies in their natural state have the power to bring up plant-food from the soil below, and to bring in nitrogen from the air above.... All this has long been plain to observation. It was illustrated by Voelcker's analyses of prairie soils, brought to England from America by Caird, which were found to be extremely rich in nitrogen, and is explained by Hellbriegel's discovery of the nitrogen-bringing power of certain micro-organisms which live in the roots of plants" (Storer, 1905, pp. 340-341).

As discussed in the "Introduction," new concerns about water quality have generated intense renewed interest in assessing how agricultural activities influence Illinois' nutrient cycles, especially the N cycle. This renewed interest in understanding agriculture's impact on the N cycle, unfortunately, coincides with a standing N-cycle paradigm that is less able to generate scientific understanding than the paradigm it replaced.

On the other hand, this rejuvenated environmental interest rationally coincides with the widespread historic use of N as a measure of water pollution and as a measure of soil and water fertility developed under the previous, better-founded N-cycle paradigm.

Our assessment used this older, better-founded N-cycle paradigm, updated with new data and concepts, to evaluate some ways in which agricultural activities may have affected the surface-water quality of Illinois. As will be discussed in "Some Other Anthropogenic Effects on Nitrogen Water Chemistry," other human activities also affected water quality, but the focus in this section is agriculture.

In 1900, as previously discussed ("Introduction"), some 10 million of the 23 million acres of Illinois cropland had already been cleared. Palmer (1903, p. iv) had already discerned that such agricultural activity was influencing N water chemistry.

Regarding the history of such land use in Illinois, the settlement pattern was to first occupy the woodland fringe bordering the streams and major tributary rivers — these woodlands were extensively and intensively used for wood and animal husbandry well into the 20th century. Well-drained prairie lands were also used and represented the principal cropland type around the turn of the century. With increasing pressure for more farmland coinciding with the steam-powered machinery to accomplish the task, the draining of wet prairie soils and the floodplain of the Illinois River began in earnest after 1900, until ~10 million acres were drained (Borah, 1998; Zucker and Brown, 1998, p. 7). Overall, in the MRB, 2 million acres of land were reportedly drained by 1900, compared to 70 million acres drained today (White House, 2000, Figure 2.3). In Illinois, draining, which occurred mostly in the 20th century, added nearly another 10 million acres of prime farmland to Illinois' current total of 23 million acres.

Draining of wet Illinois soils affected the main stem of the Illinois River and the streams and rivers of the IRB by eliminating the aquatic and emergent wetland vegetation from their shores and surrounding wetlands and pools, and also eliminating much of the stream- and river-channel epiphytic algae, mosses, and other N-rich aquatic vegetation (Buck, 1912, 1967; Hansen, 1914, pp. 296-297; Sauer, 1916, pp. 141-203; Quaife, 1918; Forbes, 1919; Telford, 1919; Thompson and Hunt, 1930; Bardolph, 1948; Hewes, 1950, 1951; Larimore and Smith, 1963; Boggess and Geis, 1967; Johnson and Bell, 1975; Thompson, 1989; 1994; 1996; Dickens, 1996; Borah, 1998; Davis, 1998; Esarey, 2000).

Thus, the various effects that agriculture had on water quality in Illinois were most significant from around the start of the 20th century onward.

Some Effects on Terrestrial-Nitrogen Reservoirs and Transfers within the Nitrogen Cycle

"It did not seem possible to the sons and the son's sons that these rich lands could ever reach the point of exhaustion, or that the time would come when they must be farmed and treated in a different manner than when they were first planted, yet that very time has come to millions of acres of American soils.

"Millions of acres of our land that once produced from seventy-five to one hundred bushels of corn per acre will not now produce twenty bushels to the acre. These acres have gone into 'agricultural bankruptcy.'

"Nitrogen is 'the element soonest-farmed out of fertile soils'" (Smith, 1913).

The global and national effects of agriculture on water quality were assessed to place this Illinois situation into perspective.

As discussed in the "Introduction," the effect of agriculture on the world's terrestrial soil N reservoir has been estimated to be a 13 billion metric ton loss of soil N over the first 60-70 years of the 20th century. Such loss of soil N has necessitated the addition of large amounts of chemical-N fertilizer to help maintain crop yields (Rosswall, 1976).

This estimated 13 billion metric ton loss of soil N prior to, and during, the early years of the era of chemical N fertilizer gives an average annual loss of 200 million tons of natural soil N/yr due to world agriculture. This annual average soil N loss value can be compared to the some 80 million metric tons of chemical N fertilizer now added each year to the world's agricultural soils (Table 1).

The amount of chemical-N fertilizer applied (Table 1) can also be compared to the change in the decline in the annual supply of mineralized (NH_4-N + NO_3-N) N this 13 billion metric tons in the soil N reservoir represents. Given the 1 to 3 percent per year range of values reported for mineralization of soil organic N (Rosswall, 1976), this loss from the soil N reservoir represents a 150 to 450 million metric ton/yr decline in the supply of mineralized N to the world's agricultural soils.

This estimated anthropogenically induced decline in mineralized N supply is now being partially compensated for by the anthropogenic addition of 80 million metric tons of chemical N fertilizer (Table 1). Most of this fertilizer is removed at harvest (National Research Council, 2000, pp. 25, 98, and 107).

Agriculture's effect on the transfer of mineralized N from the soil to the hydrosphere can also be compared for the pre- and post-chemical-N fertilizer eras. Given that from 20 to 30 percent of this lost 13 billion metric tons of natural soil N (200 million metric tons per year average loss of soil N) is estimated to have been lost as NO_3-N in water leaching to the hydrosphere (Viets and Hageman, 1971; Rosswall, 1976; Stevenson, 1986, pp. 145-149) — an average of 40 to 60 million metric tons NO_3-N/yr is estimated to have been transferred to the hydrosphere due to pre-chemical-N fertilizer agricultural practices.

By applying this 20 to 30 percent loss to the hydrosphere value to the 150 to 450 million metric ton/yr decline in mineralized N supply, the decline in transfer of mineralized N from the soil N reservoir to the hydrosphere ranges from 30 to 135 million metric tons/yr.

This range of values can be compared to the 16 to 24 million metric tons NO_3-N/yr estimated to be leached to the hydrosphere from the annual use of ~80 million metric tons of chemical N fertilizer/yr globally at the height of the era of chemical N fertilizer (Table 1). Globally, early in the 20th century there appears to have been more NO_3-N leaching into the hydrosphere from agricultural soils than is occurring now at the height of the era of chemical N fertilizer.

However, the rate of loss of these 13 billion metric tons of soil N was not uniform over time. Such soil N loss has been determined to be exponential over time: on average, rate of soil N loss declined three-fold per 60-year period. Rate of leaching loss of soil-N as NO_3-N also underwent change with time: generation of NO_3-N and its leaching losses appear to drop about two-fold more quickly than rate of N loss from the soil N reservoir (e.g., Albrecht, 1938; Jenny, 1941, pp. 251-257; Stevenson, 1986, pp. 55-56; and see "Plowing and Fertilizing").

Given the above rates of loss the global transfer rate of natural soil NO_3-N to the hydrosphere from the loss of N from the soil N reservoir of agricultural soils can be estimated for the period 1900 to 1960-1970. This estimate is simplified by assuming no N losses in the absence of agriculture. As seen in our previous analyses of pre-European agricultural landscapes this is not true. Thus, the following calculations are conservative.

For 1900, the estimated loss of soil N as NO_3-N to the global hydrosphere was 160 to 240 million metric tons NO_3-N/yr to receiving waters from agricultural soils not receiving any chemical N fertilizer. For 1930, the estimated loss of soil N as NO_3-N was the average of the 60- to 70-year period: 40 to 60 million metric tons NO_3-N/yr. For 1960, the estimated loss of soil N as NO_3-N was 27 to 40 to million metric tons NO_3-N/yr.

Regarding the effects of U.S. agriculture on the soil-N reservoir and its concomitant effect of transfer of soil N to the hydrosphere, the USDA estimates that agricultural activities have reduced the store of soil N in the conterminous United States by 1.75 billion tons over a 100-year period — 1860s to 1960s (Viets and Hageman, 1971, p. 14). The overall rate of soil-N loss is reported to have exponentially declined three-fold per 60 years (Jenny, 1941, pp. 251-257; Stevenson, 1986, pp. 55-56; and see "Plowing and Fertilizing").

Using the 2 percent annual soil-N mineralization rate currently employed for U.S. agricultural soils (e.g., Burkart and James, 1999; Goolsby et al., 1999), agricultural land-use practices have decreased the supply of mineralized N from the N reservoir of U.S. agricultural soils by 35 million metric tons/yr. This value can be compared to a high of ~11 million tons N/yr of chemical-N fertilizer added to U.S. agricultural soils in recent years (Table 2), most of which is removed at harvest (Hoeft, 1998; Goolsby et al., 1999; National Research Council, 2000, pp. 25, 98, 107).

Using the 20 to 30 percent value of this lost natural soilN as having been lost as NO_3-N in runoff, given that 1.75 billion tons soil N have been reportedly lost over 100 years, this represents an average of 3.5 to 5.25 million metric tons NO_3^--N/yr of this N lost from the soil-N reservoir of U.S. agricultural soils being lost as NO_3-N to the hydrosphere.

Making the same calculation based on the net loss in the supply of mineralized soil N (decline of 35 million metric tons/yr of mineralized soil N), the net decline of NO_3-N from agricultural soils has been 7.0 to 10.5 million metric tons NO_3-N from the first year to the 100th year of the period.

This range of values of values in the decline of NO_3-N supplied to the hydrosphere by the declining soil N reservoir of U.S. agricultural soils in the absence of chemical-N fertilizer can be compared to the 2.2 to 3.3 million metric tons $N0_3$-N/yr estimated to be leached to the hydrosphere from the annual use of 11 million metric of chemical-N fertilizer/yr in the United States (Table 2).

These ranges of values can also be compared to the reported measured value of 1 million metric ton NO_3-N/yr being discharged from the MRB— America's breadbasket — which reportedly receives 7 million of the 11 million metric tons chemical-N fertilizer/yr used in the United States (Goolsby et al., 1999; Table 2).

Further calculations were made for the United States to account for the facts that the rate of loss of N from soil-N reservoir and the rate that such N loss is converted to NO_3-N are not uniform over time. And because the research on which these calculations were based were themselves based on total soil-N loss, our analysis was limited to this basis.

As with the global estimate of NO_3-N losses from the natural soil-N reservoir, our model predicts that U.S. NO_3-N losses of natural soil N exceeded the 3.5 to 5.25 million metric ton/yr average in the early years of the period. Leaching losses declined exponentially over time. After the mid-1920s, leaching losses are modeled as having dropped below average and, from then on, rates of NO_3-N leaching declined relatively slowly.

Available U.S. soils and water data enable some further refinement of the above U.S. estimates. The area of harvested cropland approximately doubled in the second half of the 19th century, reaching a peak of ~400 million acres around the turn of the century. Area of harvested cropland remained essentially constant into the 1950s, with some trading going on between less fertile eastern cropland being retired and more fertile western wild lands being converted to cropland (U.S. Department of Agriculture, 1869, pp. 25-34; U.S. Department of Agriculture, 1876, pp. 20-33; Beach, 1912, p. 30; Brown, 1936; Olsen, Clark, and O'Donnell, 1955; Rasmussen, 1960, pp. 282-283; Viets, 1971). Such regional cropland trading within the United States is illustrated by the more than doubling of the acreage of Illinois cropland from 10 million acres in 1900 to 23 million acres in recent years.

Since the majority of the 1.75 billion metric ton decline in U.S. soil-N content appears to have come after 1900, our model can be simplified and made to conform to the world soil model by assuming that the 1.75 billion ton loss of U.S. soil N occurred in the 60 years after 1900.

Based on these simplifying assumptions, for 1900, NO_3-N leaching from U.S. agricultural soils to the hydrosphere would have been 14 to 21 million metric tons NO_3-N/yr. The average leaching year becomes 1930 — with an estimated value of 3.5 to 5.25 million metric tons NO_3-N/yr. For 1960, NO_3-N leaching is estimated to have been 2.3 to 3.5 million metric tons NO_3-N/yr.

These estimates of soil N leaching can be compared to actual measurements and estimates made for the entire United States by scientists working under the earlier, well-founded N-cycle paradigm. As previously noted, prior to the establishment of the current standing N-cycle paradigm in the 1970s, the U.S. Department of Agriculture estimated that 100,000 research experiments had been conducted just on the leaching of NO_3-N in soil water alone (Viets and Hageman, 1971).

Stevenson (1986, pp. 145-148) summarized the published studies of soil- N-leaching values for the United States. Nitrogen leaching from U.S. soils to the hydrosphere in 1930 was determined to be 3.7 million tons/yr. For 1947, leaching was determined to be 3.0 million metric tons NO_3-N/yr. For 1967, leaching was determined to be 2.0 million metric tons NO_3-N/yr (Stevenson, 1986, pp. 145-148).

Overall, the U.S. NO_3-N leaching values derived from the voluminous NO_3-N leaching studies conducted under the previous, well-founded N-cycle paradigm show a general fit of the data with the simplified model — the reported data in Stevenson being on the low side of our calculated range of values.

Note that the above measurement-derived estimates of NO_3-N leaching differ markedly from those produced under the current standing N-cycle paradigm. Under the current paradigm — which does not recognize agriculture's effect of diminishing the soil-N reservoir — NO_3-N leaching should have risen sharply between 1930 and 1967, since the use of chemical-N fertilizer rose to 5.5 million metric tons N/yr by 1967 (Table 2) from ~0.0 million metric tons N/yr in 1930. The standing N-cycle paradigm predicts a net increase in NO_3-N leaching of 1.1 to 1.65 million metric tons N/yr between 1930 and 1967, not a net decline of 1.7 million metric tons N/yr as reported by the various studies (Stevenson, 1986, pp. 145-148).

Returning to our model, we now apply it to estimate NO_3-N leaching from Illinois cropland in 1900. Assuming the 10 million acres of Illinois cropland had the same average properties as the rest of the 400 million acres of U.S. cropland in 1900, the NO_3-N leaching from Illinois cropland in 1900 would have been 1/40th that leached from all U.S. cropland — 350,000 to 525,000 metric tons N/yr (86 to 130 kg/ha-yr). The amount of NO_3-N estimated to have been leached from the 10 million acres of Illinois cropland soils in 1900 is markedly larger than the amount of NO_3-N reported to be leaching from all of Illinois with its 23 million acres of heavily, N-fertilized 23 million acres of cropland. Namely, the amount of NO_3-N leaching from today's heavily N-fertilized soils of Illinois is metamodeled as an amount equal to 16 percent of total applied fertilizer — 13 kg NO_3-N/ha/yr (Wu and Babcock, 1999). And the most recent available N budgets developed for Illinois have surface-water N flux out of state at 0.5 billion lb N/yr (227,000 metric tons N/yr) and 244,000 metric tons total N/yr (David and Gentry, 2000a, b).

Regarding N loss from the Illinois Corn Belt, Illinois appears to have been different from the national average in that the area of cropland more than doubled since 1900 rather than staying the same. Thus, as more land was plowed under and converted to crops, the amount of NO_3-N leaching to the hydrosphere from Illinois cropland would have been increasing, probably reaching its maximum around 1930.

Nevertheless, returning to our 1900 agricultural soil-NO_3-N leaching estimate — which was arrived at by means independent of our other assessments — this agrees with these other assessments that the flux of soil/plant N to Illinois' hydrosphere was higher around the turn of the century than it is now. Moreover, given our assessment of the very large size of the pre-European-settlement, soil-N reservoirs, and the very elevated rates of N transfer from the frequently and highly disturbed soils and vegetation of the pre-European-settlement landscape to the hydrosphere, we cannot say that agriculture in 1900 had elevated the flux of N to the hydrosphere relative to the various animal-rich, pyrrhic, pre-European-settlement-landscape conditions.

All the collective results of our qualitative and quantitative analyses tell us that the present flux of N in solution to the hydrosphere of Illinois is appreciably less now than it was around the turn of the century and prior to European settlement. Quantitatively, the flux of N from Illinois cropland to the hydrosphere has been estimated to be 13 kg NO_3-N/ha/yr, whereas our estimated flux is ~100 kg NO_3-N/ha/yr from the same land around the turn of the century and prior to European settlement.

This assessment also considers how agriculture has influenced the soil-N reservoir and the transfer of N from it. Soils lose N to the hydrosphere not only in dissolved form, but also in particulate form, via soil erosion. With erosion, N and other nutrients are carried, not in solution with water, but attached to soil particles. In this way, soil erosion depletes the soil-N reservoir via transfer to other components of the N cycle. Indeed, statistics indicate that soil erosion is the most important source of agricultural N to surface waters (Stevenson, 1986, p. 148). As with the loss of NO_3-N to the hydrosphere, there have been changes over time in the amount of N transferred to the hydrosphere surface-water component by soil erosion.

In a summary of U.S. soil conservation data, Stevenson (1986) noted that improving soil conservation has been reducing the amounts of particulate N lost through soil erosion: from 4.5 million metric tons N/yr in 1930; 4.0 million tons/yr in 1947, and; 3.0 million tons/yr in 1967 (Stevenson, 1986, p. 148). A significant part of the 1947 - 1967 decrease also was probably due to the fact that the area of U.S. cropland was reduced to about 320 million acres at the end of this period (Viets, 1971; Avery, 1991, p. 224).

Undoubtedly, the amount of particulate N that croplands contribute to surface waters has continued to drop since 1967 due to improved soil conservation techniques on the 280 million acres of remaining U.S. cropland. Furthermore, to quote the Clinton Administration's Department of Agriculture on the results of the fallowing of cropland under the Conservation Reserve Program (CRP):

"Since 1986, more than 36 million acres of erodible and environmentally fragile cropland have been converted to grasses and trees.... We estimate that the CRP has:

"Kept 90 million tons of sediment from cropland from entering streams" (Rominger, 1995).

In summary, U.S. soil-leaching and erosion data indicate that the net effect of U.S. agriculture on the transfer of terrestrial N to the hydrosphere has been to decrease this transfer 3.2 million metric tons N/yr between 1930 and 1967: from a total of 8.2 million metric tons N/yr in 1930 to 5.0 million metric tons N/yr in 1967.

These findings are opposite those produced by the standing N-cycle paradigm, because the standing N-cycle paradigm is a one-way street — it considers only how agricultural activities have added N to the soil and not how agriculture has also depleted to an even larger extent the soil-N reservoir and, thereby, how agricultural activities have produced a net decreased in the transfer of soil-N to the hydrosphere.

The overall effect of 20th century agricultural N additions and subtractions has been to decrease the soil-N reservoir and the transfer of N form the soil reservoir to the hydrosphere.

Plowing and Fertilizing

"The conclusion that virtually all the organic matter (and N) might eventually be lost from soil by cropping caused considerable alarm in agronomic circles. It was feared that unless drastic measures were taken to maintain organic matter reserves, many soils would become unproductive....

"For soils of the corn belt, about 25 percent of the N was found to be lost the first 20 years, 10 percent the second 20 years, and 7 percent the third 20 years." (Stevenson, 1986, p. 55).

As previously discussed, the standing N-cycle paradigm does not recognize that any changes have occurred to the soil's natural N reservoir and transfers. Such changes are implicitly assumed not to have occurred. What is recognized as changing, however, are increases imposed by modern cultural practices such as N-fertilizer addition and N deposition from acid rain. Thus, those operating under the standing N-cycle paradigm have concluded that agricultural practices have created a uniquely "modern problem" — the N saturation of the landscape. This uniquely "modern problem" is asserted to have increased the transfer of N from the soil in quantities that degrade water quality as well as pose health threats to humans and animals eating and drinking NO_3-N-contaminated water and/or plant materials.

Our hypothesis contends that activities prior to the era of chemical-N fertilizer — including plowing and cropping — have diminished cropland soil-N reservoirs. We contend that a thorough scientific assessment must consider ways that agriculture has both added to and subtracted from soil-N reservoirs and transfers.

While our hypothesis about previous subtractions from soil-N reservoirs and transfers is inconsistent with the standing N-cycle paradigm, it is supportable. As the above quote of Stevenson (1986) shows, a major driving force behind the development of scientific agriculture, and the conservation movement itself, was declining soil N of Corn Belt croplands, e.g.:

"While the soils of the mid-west may be ideally situated for greatest efficiency in regard to nitrogen supply, there is no question but that greater efforts must be put forth to replenish and conserve nitrogen....

"Except on those soils which still have a large portion of unexhausted nitrogen left, the nitrogen problem is the most important soil fertility problem before the corn belt farmer...and the time has arrived when the lack of nitrogen is seriously reducing yields" (Conner, 1922).

After having removed the ecology and the land-use management system that created and sustained all that N, agriculture then began mining the store of N and other nutrients from the soils of the Midwest. The mined nutrients were exported in food and additional nutrients were lost (wasted) in erosion and leaching to the hydrosphere. Denied its previously great level of N fixation, as the land was progressively agronomically mined, it progressively lost value.

Under the previous, well-founded N-cycle paradigm, this loss of value was widely recognized by scientific experts, farmers, and real estate agents. For example, to quote Missouri's Dr. William Albrecht from the USDA's *Soils & Men: Yearbook of Agriculture 1938*:

"Nitrogen, as the largest single item in plant growth, has been found to control crop-production levels, so that in the corn belt crop yields roughly parallel the content of organic matter in the soil.... With declining organic matter go declining corn yields and therefore lower earnings on the farmer's investment. Thus the stock of organic matter in the soil, particularly as measured by nitrogen, is a rough index of the land value when applied to soils under comparable conditions. According to studies in Missouri, for example, the lower the content of organic matter of upland soil the lower the average market value of the land" (Albrecht, 1938).

Thus, the assumption that the soil's natural N reservoir, rates of N fixation, and rates of N transfers (sans fertilizers and other modern additions) is today unchanged from what it was is erroneous. Also, as indicated by the above quotes regarding declines in the supply of N to plants, the transfers of N from soil-N reservoirs appear to have declined significantly in the period prior to the era of chemical-N fertilizer.

As previously discussed, agronomists and historians noted that in the earliest years, Illinois croplands were supplying N in excess of that needed for optimal crop yields (e.g., Buck, 1912; 1967; Welch, 1979, p. 10; Figures 4, 5). As discussed earlier, this is an unheard of condition today — even for highly fertile soils which scientists deliberately, massively overfertilize (e.g., Viets and Hageman, 1971; Sabey, Agbim, and Markstrom, 1975; Motavalli, Kelling, and Converse, 1989). As Conner (1922) and others observed, in the decades following the excess N supply problem years, the transfer of soil N remained so high that fertilizer additions were not needed to sustain luxuriant crop growth but were low enough in N to finally also sustain significant grain yields (Smith, 1913). For example, prior to 1860, a traveler passing through Illinois noted:

“I saw fields of maize in which grain had been grown for 30 years and that, too, without any fertilizer. They left nothing to be desired for the stalks grow luxuriantly to the height of 15 feet” (Sutton, 1976, p. 202).

Indeed, for some time the transfer of soil N appears to have exceeded the amount that could be taken up by the luxuriant growth of N-rich, highly productive crops. This is indicated by observations of free NO_3-N accumulations in Midwest Corn Belt soils of the late 1800s and early 1900s. Back then there was so much free nitrate in cropland soils that accumulations of NO_3-N salt crusts on and near the surface during dry periods was not considered to be something remarkable (e.g., King and Whitson, 1901; Scarseth et al., 1943).

Even in the decades after the early years of N transfer being so high as to exceed optimal crop yield, concentrations of NO_3-N in crops were all too often so high that NO_3-N poisoning of livestock was a widespread problem in the Corn Belt (Mayo, 1895; Davidson, Doughty, and Bolton, 1941; Wright and Davidson, 1964; Deeb and Sloan, 1975). For example, during the 1800s, when drought killed plants like corn in mid-season (preventing soil NO_3-N taken up by the plants from being converted to organic forms), the amounts of plant NO_3-N could be so great that plant stalks burned like fuses, e.g.,

“A casual examination of the samples of corn stalks received, revealed the presence of large quantities of nitrate of potash (saltpetre).... If a stalk was cut in two and tapped lightly upon a table, the crystals of potassium nitrate would be jarred loose and fall as a fine powder upon the table. Upon splitting a corn stalk, the crystals in the pith of the stalk could easily be seen with the unaided eye.... On lighting a bit of stalk with a match, it would deflagrate, burning rapidly like the fuse of a fire cracker. A chemical examination of a quantity of stalks gave 18.8 per cent of dry weight of the stalk nitrate of potash” (Mayo, 1895).

In noting that the situation he analyzed was not unique, Mayo (1895) cited a previous example of the same thing analyzed by two other professors:

“‘In November, 1888, a Mr. Williams, near Grainfield, Gove county, this state, sustained a serious loss from a herd of 120 head of cattle.... The corn fodder of a portion of the field was so impregnated with the nitrate that many of the stalks would burn like a fuse, sometimes flashing into a blaze. On the outside of the stalks and just under the cuticle a white deposit of the nitre was visible on many stalks. An analysis of one stalk that may have been more than commonly charged with the salt, showed that one-fourth of the total weight of the stalk was saltpetre.... There was a large amount of organic nitrogen on and in the soil; there was sufficient moisture much of the time to permit nitrification and seldom so much moisture as to check it; the high temperature was favorable; there was not enough rainfall to leach the soil of the nitrate formed. So there was every opportunity for nitrate to accumulate in the soil, and from the soil to pass into the corn plants.... We have previously mentioned that in a portion of the field conditions favored the production of nitrate in the soil while lack of drainage prevented its loss in this way’” (Mayo, 1895).

The USDA analysis reported that NO_3-N plant values in the pre-N-fertilizer era NO_3-N were at least three-fold higher than the highest values seen under the highest rates of N fertilization (Viets and Hageman, 1971, pp. 50-51).

To help us understand the changes that have occurred in the supply of mineralized N in cropland soils, we turn to long-term soil studies. These studies were started in the 1800s and continued well into the 20th century. They were conducted at various agricultural experiment stations in the Corn Belt, and elsewhere. Although different agricultural practices affected the soil-N reservoir differently (e.g., Figure 21), overall comparison of undisturbed prairie soils and their early 20th century Corn Belt counterparts indicate that the agricultural practices of the time

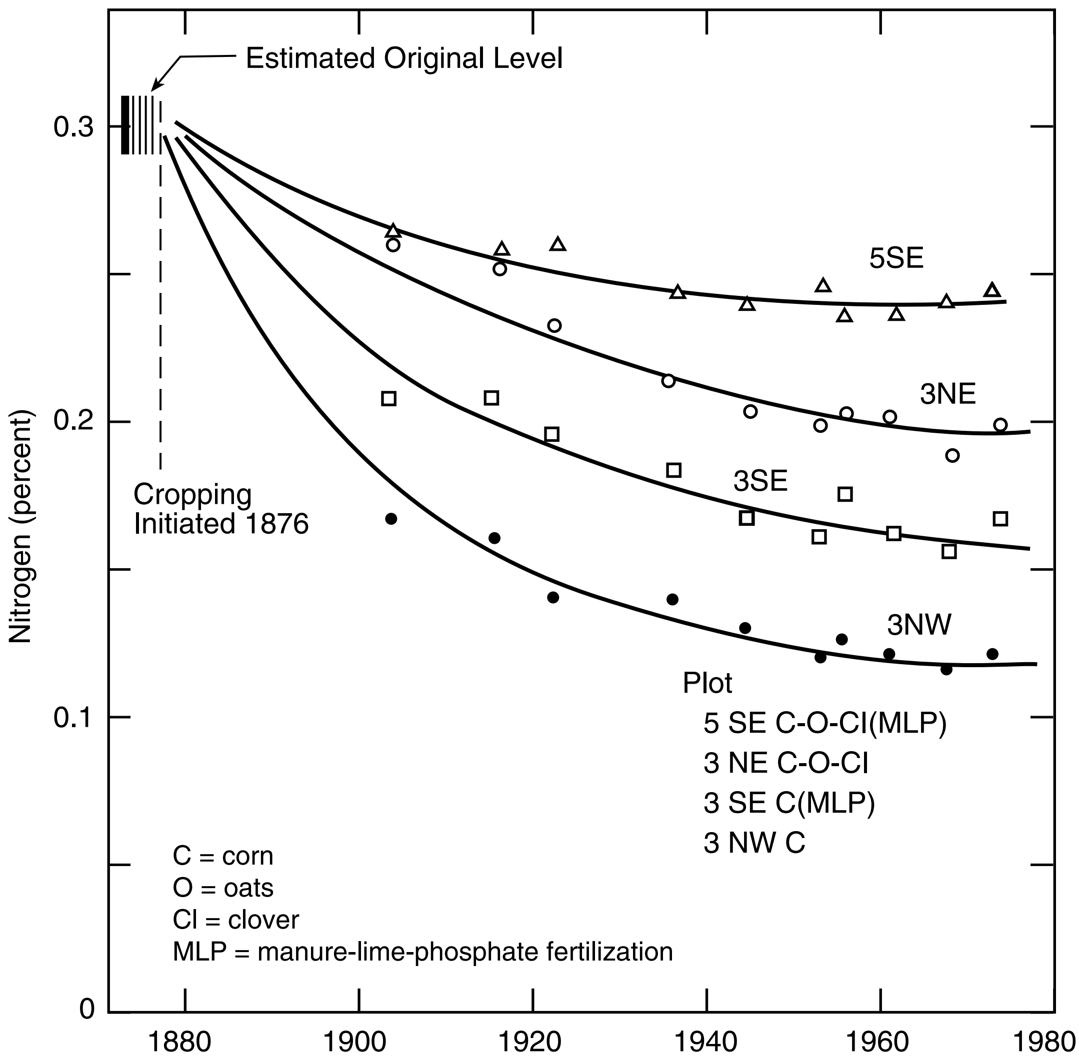

Figure 21. The effect of crop rotation and fertilization practices on the nitrogen content of select soils from the University of Illinois' Morrow Plots at Urbana, Illinois.
Source: From Figure 2.10 of Stevenson (1986).

had, on average, about halved the soil-N reservoir (Jenny, 1941, pp. 251-257; Commoner, 1970; Stevenson, 1986, p. 55). As previously discussed, the soil-N reservoir originally must have been even larger, as these undisturbed 20th century prairies had been missing for about a century the N-stimulating activities of the pre-European-settlement fire-and-grazing regimes.

Even in Illinois' intensively studied, world-famous Morrow Plots, and the Sanborn Field in Missouri, soil N was not measured when the plots were first established. The Morrow Plots were established in 1876, but soil C and N were reported as being first determined in 1904. Original soil characteristics were taken to be that of 20th century grass fringe around the edge of the plots (Odell et al., 1984; Stevenson, 1986, p. 56). Missouri's prestigious Sanborn Field was established in 1888, but soil N values were first determined in 1915. As with the Morrow Plots, so-called virgin conditions were estimated from grassy areas bordering the field (Woodruff, 1949).

Keeping the above caveats in mind, we can now use the USDA's method (Viets and Hageman, 1971) to estimate the quantity of NO_3-N transferred from the soil-N reservoir to the hydrosphere prior to the era of chemical-N fertilizer. For example, conversion of 0.25 percent of soil N in the top foot of soil to NO_3 over a hundred years will result in 28.6 mg NO_3-N/l in 12.6 in./yr of soil water over these hundred years (Viets and Hageman, 1971, p. 14). The same calculation can be applied to Illinois tallgrass prairie soils using Morrow Plots soil data.

Morrow Plots soil is estimated to have been 0.314 percent N prior to European settlement (Stevenson, 1986, p. 56). Using a steady-state turnover rate of 175 years for soil N (Stevenson, 1986, p. 112) as the measure of soil N being mineralized to NO_3-N, the N being mineralized in just the top foot of soil would impart 10 mg NO_3-N/l to 10 inches of runoff/yr, if but 0.00004 (1/25,000th) of the soil N being mineralized annually was lost as NO_3-N to the hydrosphere.

From the above calculations, we see that prior to European settlement, but a minuscule leakage of N from the soil's internal N cycle would result in transfer to the hydrosphere of what are considered today exceedingly high concentrations of soil NO_3-N.

The effect of tillage on the loss of soil N to the hydrosphere can also be examined by such calculation. For example, if plowing and hoeing caused the loss of 0.25 percent soil organic-N from the top foot of Morrow Plots soil over 100 years, this will impart on average 36 mg NO_3-N/l to 10 inches of water over those 100 years, if but only one percent of this NO_3 is transferred to the hydrosphere.

As with the above estimated reference/background nutrient flux, this estimation of the effect of early agriculture appears conservative, given that the scientific estimation of the proportion of this soil N which is lost as NO_3-N to runoff is on the order of 20-30 percent, not one percent as assumed here.

The changes in the supply of NO_3-N that would occur during the early years of agriculture can be seen from the following:

"Soil organic matter is the source of nitrogen. In the later stages of decay of most kinds of organic matter, nitrogen is liberated as ammonia and subsequently converted into the soluble or nitrate form....

"A study of the nitrate levels under corn in a Missouri silt loam during 13 years reveals a gradual decline in the production of nitrates. During the first 5 years of the test this soil increased its nitrates in the spring to the maximum of more than 20 pounds per acre as early as May. During a similar period only 2 years later, this maximum had been reduced to 18 pounds, and it was not attained until June; 3 years later the maximum was less than 16 pounds, attained in July; and 3 years after that, the maximum of 13 pounds was not reached until August (fig.1) [our Figure 22]. During continuous cropping to corn without the addition of organic matter, the

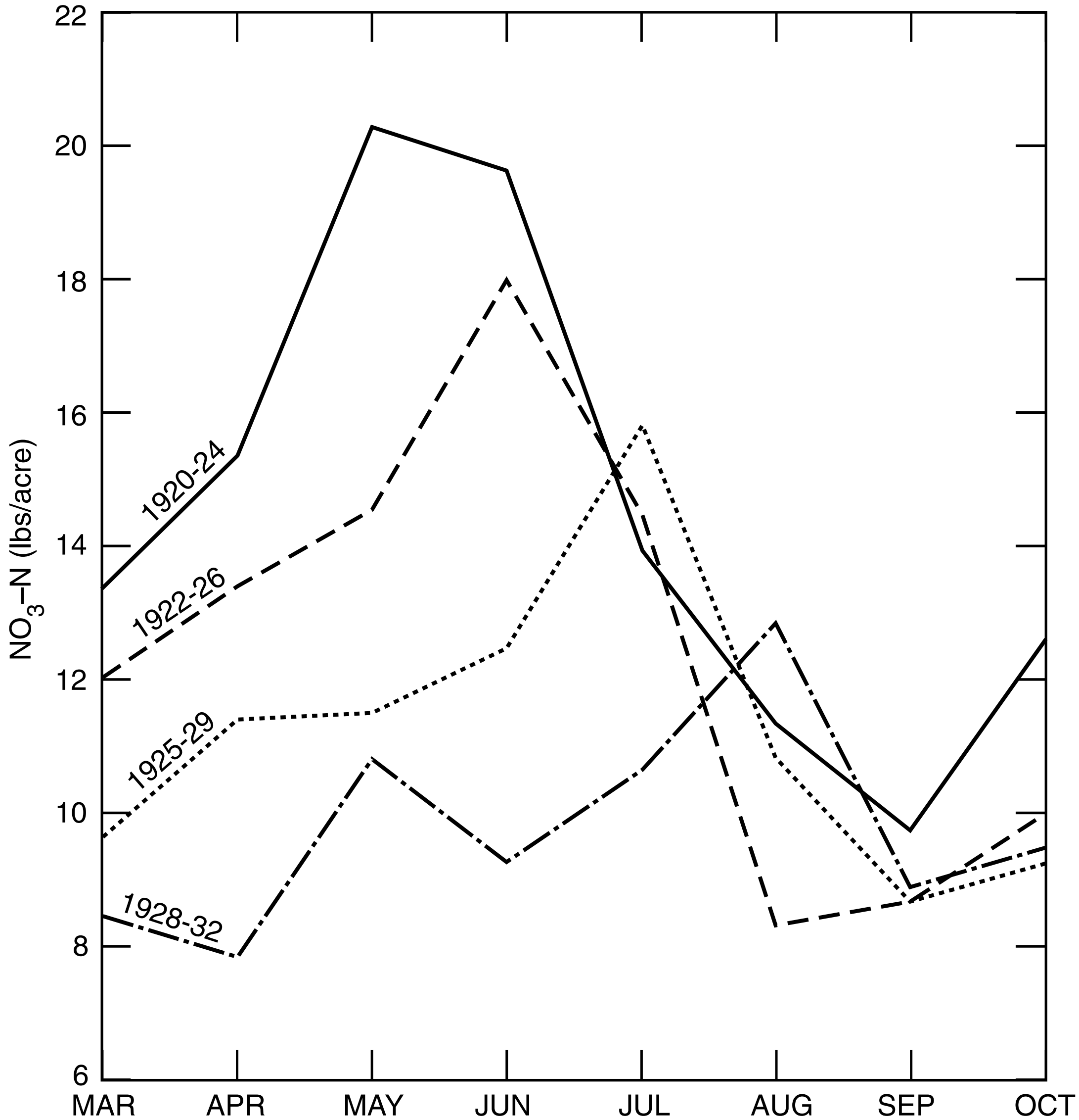

Figure 22. Changes in quantity and timing of NO_3–N release in soil water of Missouri soil in the early years of cultivation. **Source**: From Figure 1 of Albrecht (1938).

maximum nitrate accumulation dropped to 65 percent of that in the initial period, when the land had been in sod for some time" (Albrecht, 1938).

Having removed the previous high N-fixing ability, continued harvest resulted in a diminishing supply of mineralized N (including NO_3-N) and a diminishing supply of N-bearing organic matter (decreased stover — leftover plant material after harvest) for soil microorganisms to process into the fresh and easily decomposable (labile) organic soil N pool.

This, in turn, resulted in further decreases — next year there would be still less mineralized N (including NO_3-N) to stimulate plant and microbial growth, and even less stover to transform into the easily decomposable (labile) soil-N pool. And so on.

Review of the literature shows that:

"The proportion of soil N as amino acid N generally decreases with cultivation....

"Results obtained for the Morrow Plots also indicate that when soils are subject to intensive cultivation, those compounds intimately bound to clay minerals are selectively preserved.... Nitrogen compounds held within the lattice structures of clay minerals would be particularly resistant to attack by microorganisms" (Stevenson, 1982b).

And with this disproportionate loss of labile soil N over refractory soil N, it is expected that creation of mineralized soil N, including the formation of NO_3-N, would drop more quickly than would the size of the overall soil-N reservoir.

And, indeed, this is exactly what is seen as happening.

While the farming of Corn Belt soils had, on average, reduced the soil-N reservoir 25 percent in the first 20 years, the amount of NO_3-N in solution appears to have been halved in just 8 years (Figure 22). That the amount of NO_3-N leaching from soil decreases more rapidly than the decrease in total soil N itself was shown by the famous long-term experiments initiated by Lawes and Gilbert in 1870 at the Rothamstead Experimental Station in England. Whereas soil N decreased 32 percent in the plow layer (from 3500 lb/acre to 2380 lb/acre), soil NO_3-N leaching decreased 48 percent — from 44.25 lb/acre/yr to 25.82 lb/acre/yr (Russell and Richards, 1920).

Not only does the rate of NO_3-N supply to soil water decrease at a disproportionately large rate with decreasing soil-N reservoir, the seasonal timing of the release of NO_3-N to soil water also changes. As seen earlier with our analysis of winter and dormant season soil nitrification, production of soil water NO_3-N, and, as also reported by early scientists in Illinois (e.g., Kofoid, 1903; Palmer, 1903), the soil water NO_3-N peak occurs in the winter and during the dormant season. However as seen with Albrecht's experiment conducted in the 1920s and 1930s, as agriculture depleted the soil-N reservoir, the timing of the NO_3-N peak became progressively delayed by 3 months after only 8 years (Figure 22), as the more easily mineralized organic-N was depleted. This left behind a smaller amount of soil N, which became progressively more difficult to decompose.

Research on paired, virgin prairie and cropland soils in states ranging from North Dakota to Oklahoma validate these findings made in Illinois, Missouri, Wisconsin, and elsewhere around the world:

"The relationship between total nitrogen in the soil and nitrate production during a 6-week incubation period was determined on a total of 214 samples from 13 locations.... In addition to the 6-week incubation period, 1 high- [virgin grassland] and 1 low-nitrogen soil [its paired cropland soil] from each location was incubated for 12, 18, and 24 weeks. The high-nitrogen soils not only produced more nitrate during the first 6-week period but were able to maintain a higher rate of nitrification during longer periods of incubation" (Haas et al., 1957).

These findings have profound significance for both the pre-European-settlement reference/background condition and today's cropland soils. Regarding the reference/background condition, the dormant season of native plants of the Illinois prairie appears to have been long ("came up late in spring and failed early in the fall") relative to that of domesticated grasses, which came to replace them, and to some other crops (Bardolph, 1948, p. 136). Thus natural vegetation was leakier in regard to conserving NO_3-N in soil water than may be generally supposed. Leibig's Law says that such leakiness would tend to the whole suite of essential nutrients, as the robust primary productivity of the Illinois River system does not indicate limitation by the other nutrients essential to plant growth.

That N could be used as a surrogate for other nutrients is also supported by the research done by scientists operating under the earlier, well-founded N-cycle paradigm. Under the previous paradigm, soil scientists compared Corn Belt cropland with nearby "virgin" lands to determine the effect of agriculture on nutrient status. They found concomitant losses of N, P, K, S, Ca, and Mg. And often these concomitant nutrient losses were roughly of the same order as N loss, especially for S (e.g., Conner, 1922; DeTurk, 1938; Whiteside and Smith, 1941).

These findings on the effect of the changing quantity and quality of the cropland soil-N reservoir have major significance in regard to present day Corn Belt cropland. First, the decline in the soil N has to be made up; scientists operating under the earlier, well-founded N-cycle paradigm realized that chemical N fertilizer additions were becoming necessary to make up for the decreased release of mineralized N from the cropland soils, e.g.:

"These losses mean that one source of nitrate is becoming less important and that the deficit needed for good crop yields must be made up with fertilizer N and increased cycling of N in crop residues and animal wastes" (Viets and Hageman, 1971, p. 51).

Second, these scientists also realized that "Mother Nature's" N-fertilizer practices were quite wasteful from the perspective of the agronomist — too much of the N being released from the soil's natural store of N was going to things other than crops:

"Crops use nitrogen in greater quantities than they do any other plant food element. In cultivated soils large amounts of nitrogen are lost in the drainage waters, also considerable quantities escape into the air" (Conner, 1922).

Not only were these earlier scientists aware of the issue of the quantity of the release of mineralized N, they were also aware of the importance of timing in order not to waste so much of it, as Mother Nature had done when the soil-N reservoir was fuller.

The 100,000 soil NO_3-N leaching research studies conducted by these scientists under the previous, well-founded N-cycle paradigm were now forgotten under the new standing N-cycle paradigm. The memory of the N-saturation issue under the new, standing N-cycle paradigm seems to date back only to the 1989 — the date of the so-called discovery of N saturation by Aber et al. (1989).

In spite of today's popular perception, great concern and effort to deal with NO_3-N leaching (and nutrient conservation in general) goes back into the organic/animal-based era of the First Agricultural Revolution, predating the chemical fertilizer/machine-based era of the Second Agricultural Revolution. Before the 1950s — way back in the pre-chemical-N fertilizer era — agronomists were concerned with efficiently and scientifically maintaining, if not boosting, soil fertility. They extensively researched how to enhance N fixation in soils and plants in a number of ways: by addition of P, K, lime, and N-fixing crops; by raising N content (and that of other nutrients) by direct additions of nutrients in green manures (N-rich plant materials), animal manures, and fertilizers mostly in the form of natural organics (basically N-rich industrial by-products); and by crop rotations.

Having maximized this as best they could, they were next concerned about the various balances of nature: how to keep N in soil in a biologically useful form and not lose it to air or water. They were then concerned about applying N and other nutrients in ways that would maximize the feeding of crops, rather than weeds.

The old scientific literature of the previous, well-founded N-cycle paradigm shows that farmers and agronomists only wanted to add nutrients where and when they were needed. They wanted to add only as much as was needed, and then have the nutrients delivered in a form and at times most readily and efficiently used by crops (e.g., McHargue and Peter, 1921; Conner, 1922; USDA, 1938; 1947; Jones, 1942; Rubins and Bear, 1942; Scarseth et al., 1943). For example, they were aware of the problem of the various balances that influenced N leaching from plant residues:

"Summer legumes used as green manure crops did not increase the yield of the following crop as much as might be expected from the amount of nitrogen which was added....

"It is evident from these results that some of the nitrogen supplied by the summer legumes was either lost from the soil or remained in a form unavailable to the following crop. Various investigators have reported that large amounts of nitrogen are leached from sandy soils when summer legumes are turned under as green manure....

"*Norfolk sandy loam.* - The amount of [NO_3-N] nitrogen leached from Norfolk sandy loam was twice as great when the legumes were turned under in the fall as when they were turned under in the spring. It is evident from Table 3 that considerable leaching of nitrogen occurred when the legumes were left on top of the soil during the winter months. This loss was reduced from approximately 38 percent to 23 percent, a difference of 15 percent, by storing the plants until time for spring turning....

"*Decatur clay loam.*- The results given in Table 3 for Decatur clay loam are quite different from those obtained on the sandy soils.... Recovery of nitrogen was higher on this soil when the legumes were turned in the fall rather than in the spring due to the slow rate of decomposition of the plant material" (Jones, 1942).

Well before the current standing N-cycle paradigm, agronomists were also aware of the problem of the various balances that influenced N leaching by the addition of fertilizing N-rich substances. For example, review of the literature by the article, "Movement of Nitrogen in Soils," published by the Soil Science Society of America, noted that by 1911 agricultural scientists had recognized the need to minimize losses of NO_3-N by deep placement of nitrogenous materials within the soil (Krantz, Ohlrogge, and Scarseth, 1943). Long ago, agricultural scientists also knew that mixing in the N-rich fertilizing substances with materials like straw helped immobilize the added N in labile form near where it was plowed under. This N-retaining effect was further enhanced by plowing under lime and rock phosphate (Krantz, Ohlrogge, and Scarseth, 1943).

Looking at standard fertilizer recommendations in the eastern Corn Belt, in 1943 in Indiana, the standard recommendation was to maximize the efficiency of added fertilizing substances by applying only a small amount under the soil near the seeds during spring planting. The "heavy applications" were to be applied after the plants were growing, however, "There are serious objections to placing a heavy application of fertilizer near or on the surface....

"In some instances farmers may need to use the less desirable method of broadcasting the fertilizer containing nitrogen on the ground and plowing it under. In this case use a grain drill with a fertilizer attachment and apply the fertilizer in drill bands. Since there is an advantage in having the nitrogen that is plowed under in an ammonium form, it is important where ammonium sulphate or cyanamid is used, to plow *immediately* [emphasis his] after the material is put on the ground. If the nitrogen-containing fertilizers are not plowed under at once, the ammonium nitrogen will be converted to nitrate forms. This is objectionable, for the nitrates are easily moved to the surface in dry periods. There is, of course, greater danger of loss of nitrates by leaching and in run-off waters. Nitrogen-carrying fertilizers applied long before plowing under will be used up to a large extend by grasses and weeds, and thus be less effective in feeding the corn" (Scarseth et al., 1943).

An example of the national perspective contemporary to that of the 1943 example in Indiana is obtained from the USDA's *Science in Farming. 1943-1947 Yearbook of Agriculture*:

"Both ammonium and nitrate nitrogen are readily absorbed by plants in the early as well as later stages of growth. Nitrate nitrogen moves with the soil water and may be leached from the soil by heavy rainfall. Ammonium and related forms of nitrogen are not readily leached from the soil....

"The time when the crop needs nitrogen corresponds with its rate of growth. Little nitrogen is needed in the seedling stage, but that little is highly essential. The demand is greater when the growth is quite rapid. Usually this is in midsummer for spring-planted crops. Corn planted on May 22 in Ohio needed only 12 pounds of nitrogen before July 1. Between July 10 and August 10 the crop absorbed 81 pounds of nitrogen — almost 60 percent of the nitrogen required for the 117-bushel crop. These figures indicate the corn crop needs most of its nitrogen during the 1 month of maximum growth....

"Details of fertilization vary so much with soil, crop, and climatic conditions that it is advisable for farmers to consult local and State authorities for specific recommendations" (Parker, 1947).

And:

"...the chemical soil tests have been shown to be of great value as a guide to fertilizer recommendations.... Many States render this service free of charge to resident farmers, growers, and public agencies of the State. Special soil containers with detailed instructions for collecting the soil sample printed on the container are provided..." (Peech and Platenius, 1947).

But testing soil nutritional status was not the only weapon in the agronomist's soil fertility arsenal. By 1947, soil tests, plant tissue tests, and plant deficiency symptoms were all being used in concert with climatic and other local factors in order to guide fertilizer recommendations (Peech and Platenius, 1947).

Thus, long before the current standing N-cycle paradigm, agronomists and farmers were intensely concerned about NO_3-N leaching and the overall "wasting" of N and other nutrients and had developed a considerable body of truly scientific knowledge and expertise in dealing with the problem.

Moving forward in time to the Second Agricultural Revolution and the growing reliance on machine and chemical-N fertilizer, by 1960, 2.5 million metric tons of chemical-N fertilizer/yr were used in the United States (Table 2) and 150,000 tons in Illinois (Hoeft, 1998). Today about 11 million metric tons of chemical-N fertilizer/yr are used in the United States (Table 2) and nearly 1 million tons in Illinois (Hoeft, 1998).

Nevertheless, as seen from the above, from the beginning of the era of chemical-N fertilizer, additions of chemical N-fertilizer were being made largely in ways to minimize the wastage of fertilizer through leaching as NO_3-N or losses to the atmosphere via denitrification and volatilization of ammonia. Back then, in the northern half of the United States, the generalized recommendation was to use non-NO_3-N fertilizers at times (and cold temperatures) that minimize microbial conversion to NO_3-N. The recommendation, all else being equal, was to apply N fertilizer when it is needed for optimum growth (Aldrich, 1970). Or, to quote from the USDA's *Agriculture Handbook No. 413*:

"Nelson and Uhland (1955)...constructed a map of the eastern half of the United States showing the hazard in four zones of applying fertilizers in the fall. The parameters were fall and winter precipitation and time when the average minimum air temperature of 40° F was reached, the latter being significant since the nitrification of injected NH_3 and ammonium salts depends on temperature.

"Allison (1965) stressed the importance of curves of precipitation and evapotranspiration plotted on a monthly basis and the soil storage capacity for water in evaluating the potential for nitrate leaching. Presumably, runoff would also have to be considered. Allison stated: "'Probably the first fact that needs to be emphasized is that leaching of available nitrogen beyond the root zone usually does not occur to any marked extent in cultivated, medium-textured humid soils in the United States during the main growing season, unless the annual rainfall is above 50 inches. Most of the leaching occurs in the late fall, in the winter if the soil is not frozen, and in the early spring'" (Viets and Hageman, 1971, p. 23).

And so, a major consideration of the benefits and debits of "natural" N versus "anthropogenic" N is akin to that of using "natural" pesticides contained in the plant (breeding fruits to be pest-resistant by containing that pesticide) versus "anthropogenic" pesticides applied to the plant. With applied pesticide, the farmer can control the application so that little or none of the pesticide remains at time of harvest. With plant-contained pesticide, the consumer cannot avoid the pesticide. With applied chemical-N fertilizer, farmers have control over the leaching of NO_3-N.

Relying on nature to provide bountiful yields from humus N, eliminates control over the wasting of NO_3-N and other forms of N by leaching to the hydrosphere and volatilization to the atmosphere. Contrary to today's dogma of the Perfect Natural State, researchers of old were quite excited about the fact that chemical fertilizers represented new and greater control of the N cycle, which allowed the farmer to manage a crop-sustaining N cycle more efficiently than the natural N cycle of the fertile wildlands. And, unlike the natural system, the 10 million metric tons of harvested N would not lay on the land during the dormant season to be leached by runoff and/or incorporated into a labile soil N pool that is readily mineralized. With this harvesting, both the soil and the plant sources of leachable N were reduced relative to that of the reference/background condition.

But today, under the standing N-cycle paradigm, everything is viewed as a one-way street — people can only make things worse. According to the N-saturation hypothesis, nature is perfect in its efficient and balanced use of N: little NO_3-N existed in soil; plants had to work hard to extract it; and even less of this little residual NO_3-N leached into the water. This hypothesis asserts that human activities have doubled the biospheric N cycle and the seasonal NO_3-N peak is "scientific proof" of humanity's wasteful and excessive use of N fertilizer.

Nevertheless, research indicates agricultural activities of the past have at least halved the soil-N reservoir of Corn Belt cropland soils. And the rate that N is mineralized and converted to NO_3-N from this diminished reservoir of more refractory soil N is also reduced. Similarly, the amount of N mineralized from this reduced soil-N reservoir has been reduced even more, and the timing of the release of mineralized N from this diminished soil-N reservoir now occurs more during the growing season, when plants more efficiently use it and when there is less runoff to leach it to the hydrosphere. Clearly, not all N mineralization can be made to occur mid-summer as there is crop production. And with crop production there will be conversion of mineralized N and N-bearing stover to labile soil N, which will mineralize and convert to some degree to NO_3-N throughout the rest of the year. Similarly, there is some conversion (immobilization) of applied chemical-N fertilizer or legume crop rotation-supplied N into a labile organic-N pool that carries over as well (e.g., Odell et al., 1982; Hoeft, personal communication, May 2000).

Nevertheless, this reduction in the supply of naturally plant-available N has been partially made up by anthropogenic N additions, cropping techniques, and conservation techniques which result in less transfer of N to the hydrosphere than would occur naturally. Furthermore, this more efficiently plant-used N became less susceptible to leaching than that of the reference/background state, given that agriculture removes (harvests) this N from the system.

For the MRB, it is reported that 7 million metric tons/yr of N fertilizer are used, whereas agriculture removes 10 million metric tons N/yr (Goolsby et al., 1999). For Illinois in the 1990s, agriculture removed nearly 50 percent more N than was applied as N fertilizer (Hoeft, 1998).

Finally, before moving on, we must more fully assess what fertilizer addition is doing to the reduced "natural" remnant of what Stevenson (1986) called the "internal cycle of nitrogen in soil." We have demonstrated that cultivation has reduced the magnitude of the natural component of the internal N cycle, but we must also look inside the "black box" and see how fertilizer additions are changing what is going on inside it.

Under the standing N-cycle paradigm, attention is steadfastly focused on showing how additions of N fertilizer enhance transfers of N to the atmosphere and hydrosphere. However, estimates and models also need to consider the other aspects of the N cycle that compensate for N additions. For example, research indicates the need to seriously consider the fact that fertilizer addition reduces the amount of N fixed in the remnant of the natural internal N cycle by legumes and nonsymbiotic microorganisms (e.g., Table 8; Aldrich, 1970; National Research Council, 1972; Stevenson, 1986, pp. 122, 128; Polsinelli, Materassi, and Vincenzini, 1991). As Stevenson (1986, p. 178) observed, given that all methods of investigation of the N cycle (even isotopic methods) involves balancing of input and output from "black boxes" of various sizes and definitions, numerous complex transformations that interact with each other over time are missed. Therefore:

"Only limited success has been achieved in obtaining a balance for total N in the soil-plant system. Errors in N balances are accumulative" (Stevenson, 1986, p. 179).

Agricultural practices have diminished the cropland soil-N reservoir and transfers of N from this reservoir. The errors produced by the standing N-cycle paradigm that have been examined so far are accumulating large error on the side of overestimating the influence of agricultural practices on increasing the N cycle.

Clearing and Draining

"Originally, Champaign County had much wet, marshy land. Cattle raising was the primary early industry. In the late 1800s, many drainage districts were formed to drain the land by dredging ditches. This drainage system allowed for the cultivation of the level wet areas. As a result, the major land use changed from cattle raising to grain farming.

"In 1867, a land grant college, later to become the University of Illinois, was established in the Champaign-Urbana area" (Mount et al., 1982).

As previously discussed, the fantastic fertility and naturally high N content of the dark colored agricultural soils of Illinois is in part due to the fact that these heavy-textured soils were previously intermittently waterlogged [malarial moist grassland (Ackerknecht, 1945)], because of their location on flat terrain in a humid temperate climate.

Such above average moisture enabled tallgrass prairie to grow prolifically:

"The original prairie consisted chiefly of big bluestem (*Andropogan furcatus*) with an admixture of a considerable number of other grasses, legumes, and various other forbs. The grasses commonly reached a height of 6 to 8 feet, and formed a very tough sod" (Smith, Allaway, and Riecken, 1950).

And:

"'The bottom Prairies are covered with Weeds of different kinds of grass about 8 feet high. The high Prairies are also thickly covered with grass but finer & not so tall'" (Sutton, 1976, p. 141).

Furthermore, these tallgrass prairies process an amount of runoff disproportionately large relative to their area, because of their hydrologic setting (Dunne and Black, 1970; Bache, 1984; Rush et al., 1985; Krug, 1989, 1991; Wood et al., 1990).

This assessment agrees with the consensus that wetlands are especially important landscape elements in regard to their influence on surface-water quality. Unfortunately, research on the effect of draining of imperfectly drained, tallgrass prairie soils to create cropland considers only how such human activities have influenced elements of the N cycle to (or are hypothetically construed to) increase the flux of N from the soil. It particularly focuses on how drainage enhances decomposition of resident soil organic matter by oxidation and the concomitant liberation of soil N and its subsurface transport in drain tiles and ditches as NO_3-N to receiving waters. Indeed, such research has been so tightly focused that even the experts who were able to transcend the framing of the paradigm in some areas were unable to do it in this area (e.g., Aldrich, 1970, 1980; Viets and Hageman, 1971).

What has been overlooked is the positive feedback system (the multiplying of coincident factors) discussed in "Reference/Background Pre-European-settlement Conditions" and "Effects of Fire on the Nitrogen Cycle." This system naturally results in massive, relatively rapid and direct injection of N into surface waters from mature, natural tallgrass prairie growing on intermittent wetlands.

First, clearing and draining greatly diminished the amount of natural N fixation in these soils which previous analysis has shown to be in the tens to hundreds of kg N/ha/yr — the highest known rates of N fixation of any known so-called natural wetland type in the world. This is quite a profound statement, given that microbial ecologists know that the most prolific N-fixing microorganisms — as well as the greatest number of known N-fixing species — are those of oxygen-deficient environs. The reported advantage of low-oxygen environs for N-fixing microorganisms is that N-fixing organisms need to protect the N-fixing enzyme (nitrogenase) from O_2. In waterlogged, organic-rich environs, the investment needed to protect nitrogenase is low (Sprent, 1987).

A second factor not considered is that the dormant season — the high flow, high N concentration time for Illinois' waters — is when the prairie landscape loses most of its N to surface runoff. During the dormant season, prairie plant material loses much of its N and other nutrients. The plant material loses it's N principally as organic N due to leaching losses of plant protein, losses, which can average up to 75 percent of total prairie plant N content lost over the winter (Watkins, 1943; Koelling and Kucera, 1965; White, 1973a, b; Timmons and Holt, 1977). As the dormant leaves and stalks become progressively more damaged the bleeding of nutrients increases markedly (Tukey, 1966).

Unfortunately, researchers have tightly focused their attention on the leaching of dissolved NO_3-N, thereby missing the principal form of N leaching from plant materials (Thurman, 1986, pp. 76-80, 151-180; Northrup et al., 1995).

Scientists operating under the standing N-cycle paradigm also have concentrated on growing-season runoff to the virtual exclusion of dormant season runoff. Perspective is further distorted by the fact that there is essentially no moist, tallgrass prairie surviving in the tiny 2,000 acre scattered remnant of Illinois prairie (Betz, 1986; Betz and Lamp, 1989).

However, agricultural research has been found which, in combination with the prairie-litter nutrition studies cited above, is useful in understanding the effect of conversion of prairie to cropland on dormant and growing-season runoff chemistries. The effect of conversion of grassland can be seen by comparing the runoff chemistry of harvested grassland (hay fields) with those of harvested corn and oat fields in western Minnesota (Tables 13, 14). Annual runoff from these fields was 2 to 3 inches (Timmons, Burwell, and Holt, 1968).

Most dissolved nutrients in runoff from these Minnesota fields was in runoff from snowmelt; and that the highest concentrations of N, P, and K were in runoff from the harvested hay fields (Tables 13, 14). Hay fields had by far the greatest loss of dissolved N. And, unlike the harvested corn and oat fields, which lost appreciable amounts of their N as NO_3-N, 97 percent of the dissolved N lost from the hay fields was lost as organic-N runoff during the dormant season as snowmelt runoff (Table 13). The 5 kg dissolved organic-N/ha lost yearly in snowmelt from harvested hay fields can be compared to what is today considered excessive amounts of N runoff — the average of 4 kg estimated total N (NO_3-N)/ha lost in total yearly surface runoff from the heavily fertilized croplands of Minnesota today. The heavily fertilized croplands of Illinois (with nearly 10 inches of total runoff) lose an estimated NO_3-N of 7 kg/ha/yr in surface runoff (Wu and Babcock, 1999).

Note that the greatly elevated N in snowmelt (Table 13) from this surrogate grassland (harvested hay fields) is accompanied by greatly increased amounts of the other nutrients (P and K) in snowmelt runoff compared to equivalent runoff runoff from corn and oat fields (Table 14).

Table 13. Annual Nitrogen (N) Loss in Runoff Water from Snowmelt and Rainfall for Minnesota Crops in 1967

	Snowmelt N			*Rainfall N*			
Crop	*Organic-N*	*NH_4-N*	*NO_3 -N*	*Organic-N*	*NH_4-N*	*NO_3-N*	*Total N*
Corn	0.61	0.00	0.31	0.11	0.00	0.05	1.08
Oats	0.27	0.00	0.61	0.01	0.00	0.20	1.09
Hay	5.18	0.00	0.12	0.02	0.00	0.03	5.35

Source: Data in kg N/ha adapted from Table 2 (Timmons, Burwell, and Holt, 1968). From 1961 on, corn rotation was fertilized with 46 kg N/ha/yr; oats, 15 kg N/ha/yr; and hay, 0 kg N/ha/yr.

Table 14. Annual Phosphorus (P) and Potassium (K) Loss in Runoff Water from Snowmelt and Rainfall for Minnesota Crop Rotations in 1967

	Phosphorus (P)			*Potassium (K)*		
Crop	*Snowmelt*	*Rainfall*	*Total*	*Snowmelt*	*Rainfall*	*Total*
Corn	0.04	0.02	0.06	0.30	0.06	0.36
Oats	0.01	0.01	0.02	0.16	0.03	0.19
Hay	0.31	0.01	0.32	4.70	0.01	4.71

Source: Data in kg/ha adapted from Table 3 (Timmons, Burwell, and Holt, 1968). From 1961 on, corn rotation was fertilized with 24 kg P/ha/yr; oats, 25 kg P/ha/yr; and hay, 0 kg P/ha/yr. None of the crop rotations were fertilized with potassium (K).

As discussed earlier, N is a useful surrogate for loss of soil nutrients in converting prairie to Corn Belt. The data in Tables 13 and 14 indicate that N also appears to be a useful surrogate for the effect of converting prairie to Corn Belt on plant nutrients lost in surface runoff.

Whereas harvested Minnesota hay fields are a useful surrogate for the nature and direction of the effect of conversion of prairie to Corn Belt on nutrients in surface runoff, this surrogate significantly underestimates the magnitude of the effect. Leaching of plant nutrients from harvested hay fields will not be as great as the amounts of nutrients leached from copious tallgrass prairie plants. Nor will 2 to 3 inches of runoff in western Minnesota leach as much nutrients as the nearly 10 inches of runoff in Illinois — runoff that occurs mostly during the dormant season (Figures 17-19).

The extraordinary amount of litter produced by moist tallgrass prairie made soils of elevated C, N, and other nutrient content. This litter also produced runoff much richer in N and other nutrients than runoff from cropland.

A third factor not considered is related to the effect of lowering the level of the water table by draining the moist tallgrass prairie. Lowering of water table changed the pattern of runoff in a manner that further reduced the loss of nutrients in surface runoff relative that of reference/background condition surface runoff. Water tends to run off wetlands like water runs off the back of a duck. Conversely, runoff in drained fields becomes subsurface flow as it is forced to move downward through heavy textured soils whose internal drainage is quite slow — typically well below 1 in./hr (e.g., Mount, 1982). These long-known conditions enable nutrients contained in runoff appreciable time and opportunity to be sequestered by within-soil biogeochemical processing (e.g., USDA, 1938, 1947; Jones, 1942; Krantz et al., 1943; Scarseth et al., 1942; McColl and Grigal, 1975).

Regarding the original undrained situation where the water table was at times above the surface of the land (Mount, 1982), research on the experimental watersheds of the USGS support the water-running-off-a-duck's-back analogy:

"...the major portion of storm runoff seems to be produced as overland flow on small saturated areas close to streams.... Runoff from these wet areas...is essentially an expanded stream system... Where the water table intersected the ground surface before and during a storm, water escaped from the soil surface and ran quickly to the stream at velocities 100 to 500 times those of the subsurface system. Direct precipitation onto the saturated area was another major contributor of storm flow" (Dunne and Black, 1970).

And:

"As more soil becomes saturated, the water table appears at the surface in hollows and depressions or emerges as a spring line. Flow then occurs over the land surface much faster than within soil, and this tends to be most common at the base of slopes. In heavy storms, overland flow is the main source of most of the water contributing to the sharp hydrograph peak. Its major component is **return flow** [emphasis his] consisting of water that has initially entered the soil on high land, and has returned to the surface at lower levels. **Direct precipitation** [emphasis his] onto saturated areas also contributes to saturated overland flow" (Bache, 1984).

And to quote a fundamental of the science of hydrology:

"Perhaps the most widely used model in engineering hydrology remains the unit hydrograph concept, developed by **Sherman** (1932) [emphasis his] and often combined with Horton's concept that storm response is due primarily to surface runoff generated when rainfall rates exceed the infiltration capacity of the soil.... During any particular storm... [s]urface runoff from these (partial) contributing areas may be generated by either the infiltration excess mechanism on low-permeability soils, or from rainfall on areas of soil saturated by a rising water table even in highly-permeable soils (referred to as saturation excess runoff generation). These saturated contributing areas expand and contract during and between storm events" (Wood, et al., 1990).

Thus, the above average moisture that stimulated growth of tallgrass prairie provided not only large amounts of nutrient-rich litter to be leached, but also leached these huge amounts of nutrient-rich litter with above average amounts of runoff, because of the additional contributions of water from the more upland landscape positions. Furthermore, these large amounts of litter became N-fixing factories upon moistening. And because of their tendency to be adjacent to receiving waters, runoff from moist tallgrass prairie had an immediate influence on the chemistries of receiving waters even greater than indicated by the disproportionately large volume of nutrient-rich runoff as N-fixing litter being leached.

We have been able to discern yet additional elements of the wetlands, which the perception generated by the standing N-cycle paradigm exclude. The fundamentals of hydrology quoted above, and the early descriptions of moist prairie wetlands and surface waters themselves indicate no clear-cut boundary between land and water. During high flow periods a portion of the land becomes water. And at normal flows — and even during low-flow periods — there is a vegetational gradient that goes from the upland grading into and through wetland. The vegetational gradient continues its extension into the surface waters themselves (e.g., Wetzel, 1983).

Compilation of early descriptions of the streams and tributary rivers, ponds and lakes — as well as the mainstem of the Illinois River itself — depict the banks and pools of these surface waters as generally having been rich in aquatic and wetland vegetation. The bottoms of riffles and more swift-flowing sections of the numerous tributary streams were shallow enough, as were portions of the larger rivers themselves [including the Illinois River itself (e.g., Schoolcraft, 1918)], to have been coated with epiphytic algae, mosses, and/or have N-rich aquatic vegetation growing out of the bottom and/or on the surface of the waters (Kofoid, 1903; Schoolcraft, 1918; Larimore and Smith, 1963).

From this, we see that not only do we have to deal with N in solution, but also with N carried along in plant debris. As previously discussed in "Reference/Background Pre-European-

Settlement Conditions," the amount of such plant debris being carried in the waters of MRB and the IRB was truly enormous, albeit, unmeasured.

The draining, ditching, and leveeing of the land made the land/water boundary much more distinct. Annual floods no longer blasted an enormous load of N-rich aquatic and wetland vegetation down sloughs, streams, and rivers. Draining and clearing of the land has diminished the amount of N transferred to and by surface waters from what is often reported as being the most productive ecosystem unit of planet earth (e.g., Wetzel, 1979, 1983). Draining and clearing the land has most literally resulted in corn being transported down the river in place of copious amounts of N-rich debris.

Yet another factor which has altered the relative proportions of nutrients in solution versus that tied up in biomass of Illinois' surface waters — forestry land-use-induced changes in the amount of light falling on surface waters.

The amount of light that Illinois' surface waters receive is very important to water chemistry because, as previously discussed in the "*Two Great Landscape Elements*" section of "*Nature and Scope of Report*," light, rather than nutrients, is typically the environmental factor limiting primary productivity (e.g., Forbes, 1887; Kofoid, 1903; Palmer, 1903; Thompson and Hunt, 1930; Bellrose, 1941; Larimore and Smith, 1963; Sefton et al., 1980; Munn, Osborne, and Wiley, 1989; Wiley, Osborne, and Larimore, 1990; Sorenson et al., 1999).

The amount of light the water receives will determine the degree that a surface water is autotrophic (net photosynthesis exceeds net respiration) and, thus, the degree that soluble and other nutrients are taken out of the water and stored and transported as biomass. With enough shading, a water switches from being autotrophic to becoming heterotrophic (net respiration exceeds net photosynthesis). This switch causes the surface water to produce a net release of soluble nutrients from nutrients stored and transported as biomass, rather than diminishing concentrations of soluble nutrients.

Wiley, Osborne, and Larimore (1990) noted the importance of stream-side shading on soluble nutrient concentrations. They observed that for equivalent reaches of river in east-central Illinois, the rate of photosynthesis was two-fold different, depending on whether the river was heavily shaded by tree gallery or in the open.

Given the high rate of photosynthesis in these Illinois prairie rivers, the effect of stream-side shading is exceedingly important in regard to the solution-measured nutrient status of Illinois' rivers and lakes. For example, Wiley, Osborne, and Larimore (1990) found primary productivity > 15 g C/m^2/day to be characteristic of Illinois' prairie rivers. This can be compared to what is characterized as the deadly high rate of photosynthesis in the "dead zone" of the Gulf of Mexico off the Mississippi River — its "deadly" rate being 0.33 g C/m^2/day (Justic, Rabalais, and Turner, 1997).

Thus, a change in shading that will induce a 2 percent change in the rate of photosynthesis in the drainage system of the IRB will induce a change in nutrient status equivalent to the total rate of plant nutrient uptake in the Gulf of Mexico's highly productive "dead zone."

Changes in stream-side shading appear very important in Illinois. As noted by Gleason (1913), because of the role of fire in creating the pre-European-settlement Illinois prairie, forested areas occur alongside water — although the most headwaters regions are typically treeless moist prairie (Larimore and Smith, 1963; Wiley, Osborne, and Larimore, 1990). This is the same view held today (e.g., Iverson et al., 1989). Thus, what impacts the water-side forest also impacts the surface water embedded within it. To use the nearly century-old words of Stephen A. Forbes, then Chief of the Illinois Natural History Survey:

"Stream and forest are so frequently associated here in Illinois that where we see a forest we naturally look for a stream somewhere within its heart, and where we see a river we expect to see a forest bordering or embedding it. And yet, the two are in many respects at quite opposite extremes. A forest is stable, stolid, and old. An old tree is, I suppose, the oldest living thing in the world....

"A flowing stream, on the other hand, is the immediate product of its immediate environment.... Its material substance is rarely more than a few weeks, perhaps only a few days old....

"So, when I speak of the study of a river or of a forest survey I must ask you to think of them as a survey, a study, of this kind of forest, of a river in this sense of the word" (Forbes, 1919).

Forbes (1919) noted that, at the time, only about one-third of Illinois was forested. The remaining waterside forests little resemble the pre-European condition, being in poor shape because of the cutting, burning, and grazing activities of post-European land-use practices. This is understandable, given, as discussed in "Water Quality Reference/Background Conditions," the European settlement pattern was to first occupy the woodland fringe bordering the streams and major tributary rivers. This not only greatly reduced the forested area, it also greatly reduced the size and basal density of the remaining forests (Buck, 1912, 1967; Hansen, 1914, pp. 296-297; Sauer, 1916, pp. 141-203; Quaife, 1918; Forbes, 1919; Telford, 1919; Thompson and Hunt, 1930; Bardolph, 1948; Hewes, 1950, 1951; Larimore and Smith, 1963; Boggess and Geis, 1967; Johnson and Bell, 1975; Wiley, Osborne, and Larimore, 1990; Dickens, 1996; Davis, 1998; Esarey, 2000) for reasons, in part, described below:

"Nearly all of the early settlers of the prairies came here from sections of the country where timber is abundant, and the great study in regard of it had been how the most cheaply to get rid of it. They were, therefore, as a general thing, tree destroyers, not culturists, and, as a natural consequence, plied vigorously their former vocation on our native groves. The first settlers made their homes near the groves and timber belts of our streams..." (Edwards, 1863).

And so, we now have less waterside forest than was determined to exist prior to European settlement.

However, the surviving streamside forests are not being intensively used as they were before, i.e., the remaining waterside forest is growing up and recovering from earlier heavy and abusive usage (e.g., Larimore and Smith, 1963; Boggess and Geis, 1967; Johnson and Bell, 1975; Iverson et al., 1989; Wiley, Osborne, and Larimore, 1990). Not only is streamside forest not being intensively burned, cut, grazed, and deliberately destroyed as it was in the past, over the last several decades considerable effort has been made to replant and restore the waterside forest that was removed.

What this means is that the streams, rivers, and other surface waters are now being more shaded than they were when the early water chemical quality measurements were made around the turn of the century.

The more open, waterside forests at the turn of the century acted to depress the amounts of N and other nutrients in solution relative to what would occur in the same water today.

On the other hand, all else being equal, the greater extent and greater shade of the pre-European-settlement waterside forests acted to elevate soluble nutrient concentrations greater than at any time since European settlement.

In summary, the standing N-cycle paradigm ignores factors by which clearing and draining decrease the rate of N fixation, decrease the size of the soil/plant-N reservoir, and decrease the rates of transfer of those reservoirs to surface waters. The standing N-cycle paradigm also ignores land-use changes, particularly those that affect the amount of light received by surface waters and how such changes in light alter the quantity of the most commonly measured forms of N.

The errors in the treatment of the effects of clearing and draining on surface-water chemistry are not random. They all work in the same direction — to overestimate the effect of agricultural practices on surface-water chemistry. Statistically, such consistent pattern of error is not called error; it is called bias.

SOME OTHER ANTHROPOGENIC EFFECTS ON NITROGEN WATER CHEMISTRY

Many profound changes in Illinois landscapes and rivers have influenced water chemistry. It is perhaps because human influence has been so pervasive and complex that a thorough analysis of the many aspects of human activities on water chemistry has not been conducted to date. Most analyses have focused, rather narrowly, on just one or a few human activities and their impacts on one or a few aspects of water chemistry. Below are some examples of how the construction of levees, drainage systems, locks and dams, and the direct addition of N have influenced water chemistry. A comprehensive analysis of the impacts of human activities on water chemistry needs to be researched.

Some Effects of Levee/Drainage and Lock-and-Dam Navigation Systems on Nitrogen in the Illinois River

"Today, the appearance of the Illinois Valley is a far cry from its appearance in the early 1900s. A glimpse of its near-pristine condition is available in sketchy historical accounts, in old photographs, and in maps prepared by J.W. Woermann between 1902 and 1904 for the U.S. Army Corps of Engineers, Chicago Office" (Bellrose et al., 1983, p. 3).

"The lower river, extending from Beardstown to Grafton, was once rich with backwaters, but levees erected early in our century destroyed almost all of the lakes and wetlands along this stretch. Thus only about 53 [out of 300] backwater lakes now survive along the full length of the river, and the floodplain of the Illinois River is now little more than 200,000 acres, about half its size 100 years ago. Although the Illinois River Valley was once almost entirely wetlands, actual water surfaces now account for only 60 to 100 square miles (40,000 to 70,000 acres)" (Talkington, 1991, p. 3).

"Permit me to take, as a marked example, the largest river of the State, the one from which Illinois derives its name.... It is in many ways a remarkable stream, unlike any other in the country. 'It is peculiarly characteristic of the State of Illinois, and next to its prairies, was its leading natural feature. Its broad bottom-lands, the bed of a former outlet of the Great Lakes system; covered with huge trees, completely flooded when the river was highest and holding many marshes and shallow lakes at its lowest stage....'

"Now, the productivity of a river depends, other things being equal, upon the area of shallow water along its banks and draining freely into it from its border-lands, for it is in such shallow water that plant and animal life is, generally speaking, most abundant...

"By diking and draining operations it is being robbed of the haunts of its water birds and the principal breeding grounds and feeding grounds of its fishes, and corn will presently be growing every year on some 200,000 acres of forest, marsh, and lake over which its waters spread a few years ago in time of flood" (Forbes, 1919).

Figures 23-25 illustrate some changes made by the levee/drainage system of the Illinois River Valley have made. Prior to the levee/drainage system, the Illinois River was loaded with N- and nutrient-rich plant debris. During low flow, massive quantities of such plant debris filled its main channel making it a "reeking slough" (e.g., Sauer, 1916, p. 19). During high flow, the swift currents of the floods would blast huge amounts of N- and nutrient-rich debris out of the floodplain and sweep it down the river (e.g., Kofoid, 1903; Figure 23).

Today, this does not happen. First, ~50 percent of the floodplain is drained and leveed: mostly as fertile cropland (Figure 24). The result is a reduction of cross-sectional area and thus a

Figure 23. The Illinois River north of Chillicothe illustrates the levee/vegetation-rich backwater floodplain system existing along most of the Illinois River prior to 1900. **Source**: Illinois Natural History Survey photo reproduced in Talkington (1991).

Figure 24. The farmland/levee system existing along much of the Illinois River by 1930.
Source: Illinois State Water Survey photo taken by Tom Rice
and reproduced in Talkington (1991).

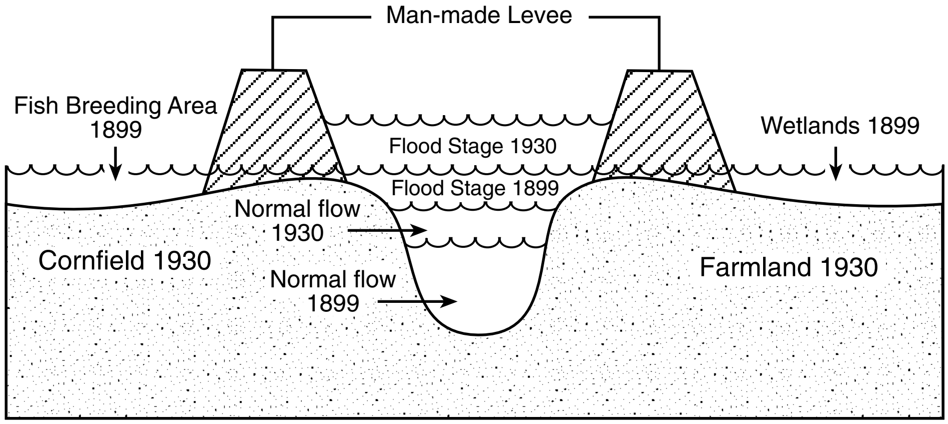

Figure 25. Cross-sectional diagram of changes in water level induced by leveeing and draining of the Illinois River floodplain.
Source: Adapted from Talkington (1991).

raised water level (Figure 25). Water level was also raised after 1900 by release of Lake Michigan water into the Illinois River system. In the 1930s, water level was raised even more, and depth of water further deepened, by the construction and completion of the 9-foot lock-and-dam navigation system:

"In the 1930's, 9-foot navigation channel projects were authorized by Congress for both the Mississippi River and Illinois Rivers. The 9-foot channel was achieved by the construction of locks and dams, wing dikes, and by dredging. Construction of the locks and dams was essentially completed by 1940" (Upper Mississippi River Basin Commission, 1982, p. 9).

A result of this was a great decrease in N- and nutrient-bearing debris. Another result was a switch from a more autotrophic to a more heterotrophic water. Increased depth of water would mean less uptake of soluble nutrients for conversion into biomass (solid) form. This, combined with the reduction in N-rich debris would mean an apparent increase in flux of N and other nutrients as more of the nutrients would now be in measured forms.

The increase in water level would also affect the remaining intact floodplain. As noted by Demissie (1997), this final elevation of the Illinois River's water level, in conjunction with the high sediment load of the river, profoundly altered the relationship of the Illinois River with the remaining half of its somewhat still intact floodplain.

The remaining nonleveed floodplain would no longer be a source of great amounts of N-rich and nutrient-rich plant debris; it would become a sink for sediment. By 1990, sedimentation had been determined to have reduced the total volume of the remaining floodplain lakes by 72 percent (Demissie, 1997).

This increased sedimentation, increased fetch of lakes in the direction of the prevailing wind, concentrated effects of bottom-feeding fish such as carp, extreme high and low water levels of the 1950s, along with perhaps subtle effects of 20th century pollution (20th century pollution being the topic of the next section) resulted in catastrophic loss of the aquatic vegetation in the remaining intact, non leveed floodplain (Bellrose, 1941, pp. 261-265; Mills et al., 1966, pp. 13-14; Talkington, 1991, pp. 4, 25, 36-37):

"Aquatic and marsh vegetation declined almost to the point of extinction during the middle years of the study period (1938-1976)" (Bellrose et al., 1979).

With this essentially came the demise of the last remnant of the jungle-like, luxuriant, nutrient-rich natural growth of the floodplain. Along with this came an end to the flood of nutrient-rich organic debris.

The overall effect of these anthropogenically induced changes was the transformation of the system from one of a great organic loading imposed on surface waters by the watershed to one of much lower organic loading.

Such a transformation in the state of organic loading had great influence on aquatic N chemistry through the interaction of the C, N, and oxygen (O) cycles. It resulted in the increase in the proportion of the N held and carried in soluble form, as well as an increase in the proportion of aquatic N in the form of NO_3-N, since there would be much more oxygen by which to convert organic-N ($R-NH_2$) to the NO_3-N form, as the following analysis shows. First:

"The nitrates are the final products of the oxidation of nitrogenous matters...the nitrates do, for the latter indicate mainly the unutilized portion of the nitrogenous plant food immediately available..." (Kofoid, 1903, pp. 196-197).

But, for this to happen, there has to be enough oxygen, as noted below by scientists of the Illinois State Water Survey:

"**Biochemical Oxygen Demand**

"Previous studies in the La Grange pool of the [Illinois River] waterway demonstrated the need for assessing both the carbonaceous and the nitrogenous oxygen demand...the sum of these demands was considered for the total dissolved biochemical oxygen demand [BOD] upon the dissolved oxygen resources in the waterway....

"The oxygen requirements for these fundamental oxidation processes are very different. For satisfying the carbonaceous demand one part of oxygen is required for each part of the substance oxidized; for the nitrogenous demand 4.57 parts of oxygen is required for one part ammonia-N oxidized. In effect, 1 mg/l NH_3-N has the potential oxygen demand equivalent to 4.57 mg/l" (Butts, Evans, and Lin, 1975, p. 13).

The nature and chemical composition of aquatic vegetation makes it more resemble sewage sludge than the more difficult to decompose, terrestrial vegetation with its much lower N content and much greater lignin and wax contents. Aquatic vegetation, thereby, imposes a great oxygen demand on surface waters (Allgeier, Peterson, and Juday, 1934; Jacobs and Elderfield, 1934; Misra, 1938; Boyd, 1968; Moore, 1969; Jewell, 1971; May, 1973; Hutchinson, 1975, pp. 371-405; Reddy, 1983; Ostrofsky and Zettler, 1986; Table 7).

The enormous oxygen demand imposed on surface waters by aquatic vegetation has been long recognized, e.g.,

"The proportion of organic nitrogen in the volatile solids of river muds is not unlike that of sewage solids. Dissolution of organic nitrogen, therefore, appears to be of the same order of magnitude as that of the remaining organic substances" (Fair et al., 1941).

And:

"The decomposition dynamics of river water whose BOD mainly derives from primary production, corresponds to the decomposition dynamics of domestic waste water (Imhoff, 1976)" (Muller and Kirchesch, 1980).

And:

"Although a river or stream that has dense weed growth seems rather harmless, the application of the kinetics of decay indicates the severe load that may be imposed on the oxygen resources. Consider a section of stream 1,000 m in length and 10 m wide with an average accumulation of plants amounting to 500 g ISS/sq m. If these plants are killed and remain in the water, the initial rate of DO [dissolved oxygen] demand would be equivalent to the discharge of untreated domestic wastewater from 24,000 people" (Jewell, 1971).

Small wonder then that the opening of the of the Chicago Sanitary and Ship Canal in 1900 with its untreated sewage from 1.3 million people, the Chicago stockyards, and other wastes amounted to only a small portion of the N load imposed on the Illinois River by some 220-mile-long, 3 to 12 mile-wide luxuriant growth of N-rich vegetation within its floodplain.

Elimination of the massive amounts of aquatic vegetation that grew naturally in the floodplain of the Illinois River system (e.g., Kofoid, 1903; Palmer 1903; Sauer, 1916; Schoolcraft, 1918) between 1900 and the 1950s lifted an enormous oxygen demand from the river, which can be seen from the comparison of modern and pre-1900 observations.

The waters of the Illinois River are not as hypertrophic as when they were sampled by Schoolcraft in 1821. The water in 1821 was so loaded with natural decaying organic matter that water samples could not be kept because the intense fermentation kept blowing off the corks on the collection bottles (Schoolcraft, 1918).

As noted by Sauer (1916), in its natural (reference/background) state the Illinois River would take on the characteristic of a "reeking slough" during periods of drought (p. 19). Such poor water quality was well observed and documented as being due to “a large abundance of aquatic vegetation which frequently gave off foul odors...” (Leighton, 1907, p. 143). Indeed, the natural organic loading was so severe that even prior to the opening of the Chicago Sanitary and Ship Canal in 1900 fish such as carp, catfish, and buffalo — coarse fish characteristic of hypertrophic waters and best able to survive high organic loads and its consequence of putrification/ oxygen depletion — these most durable fish would naturally be periodically all but wiped out: “fish life was occasionally decimated by extreme drought, stagnation and prolonged ice cover which exhausted the oxygen content of the water” (Cooley, 1913, p. 44; see also Greenbank, 1945).

Remarkably, prior to 1900, even the essentially pristine Quiver Lake, with atypically high water quality, would naturally undergo oxygen depletion events so severe as to not only kill fish and aquatic insects on a massive scale, but also dramatically result in the “practical extinction of the plankton” (Needham and Hart, 1903, pp. 11, 87; Kofoid, 1903, p. 176; see also Greenbank, 1945).

Today, the Illinois River is a more vibrant sport-fishing river with species of sport fish that require much higher levels of dissolved oxygen than do carp and catfish (e.g., Raibley et al., 1997; Heidinger and Brooks, 1998; Wildlife Forever, 1999). The present condition of the river and its system of tributaries and lakes stand in stark contrast to the reference/background state whose observed and reported natural water quality would periodically kill even the hardiest hypertrophic fish and generally reduce the palatability of the survivors.

Indeed, today the Masters Walleye Circuit (MWC) starts off the World Walleye Championship tournament every year on the Illinois River. The MWC founded professional walleye fishing in North America in 1984, and the MWC is reported to still be the world’s premier walleye angling event (Wildlife Forever, 1999).

Having established a difference in oxygen status, we now assess how the masses of decaying vegetation acted to influence the aquatic N cycle. The depletion of oxygen from overlying water and the bottom deposits themselves by decaying vegetation would hinder their own decomposition into soluble forms of N.

Furthermore, the N released into solution from the decaying biomass would not easily be oxidized to NO_3-N. This oxygen-limitation bottleneck to the formation of NO_3-N is also a bottleneck to loss of N from the aquatic N cycle — biologically available N must first be oxidized to NO_3-N before it can be denitrified and lost to the atmosphere, principally as N_2 gas, e.g.,

“BIOLOGICAL NITRIFICATION-DENITRIFICATION

“Probably the most common method of removing nitrogen from wastewater is the biological nitrification and denitrification process. The process basically consists of oxidizing all the ammonia to nitrates (nitrification) and then reducing the nitrates to nitrogen gas (denitrification) which is released to the atmosphere.

“Nitrification alone will remove ammonia nitrogen, but the resulting nitrite and nitrates nitrogen normally will not be removed [in wastewater treatment] and can serve as nutrients for undesirable algal growths in streams and lakes...With proper control of wastewater treatment processes, both nitrification and denitrification can be made to occur, thus removing not only the ammonia nitrogen but nitrite and nitrate as well. True biological denitrification, or nonassimilative removal of nitrogen, is performed only on the oxidized forms of nitrogen. The oxidation of ammonia, or biological nitrification, is thus essential to nitrogen removal. To assure complete denitrification, nitrification must also be complete” (Reeves, 1972).

Or, to use words describing the sequence in nature:

"Nitrifying bacteria connect the oxidized and reduced sides of the N-cycle by nitrification, the conversion of ammonium to nitrogen oxides.... By serving as a conduit between ammonium regeneration and denitrification, nitrification links N regeneration and N loss..." (Joye and Hollibaugh, 1995).

Therefore, the internal N cycle induced by such oxygen depletion in the originally vegetation-rich IRB was much more of a conservative, closed system than the more oxidized Illinois River system of streams and lakes today with its higher proportion of NO_3-N. The reference/background condition of the Illinois River system was one which conserved its N relative to what is seen today in its better-oxygenated condition.

Early survey sampling and analysis of the what researchers then considered to be unpolluted bottoms of the Illinois River and lake system likened the bottom survey sampling to being "'Essentially a soil survey of these aquatic properties...'" (Purdy, 1930, p. 16). Early survey sampling and analysis found the bottom fauna to be plentiful and N rich and the sediment N content to be quite high:

"Analysis of the bottom muds and estimate of the nitrogen content of the total bottom fauna per acre seemed to indicate that the sediment contained nitrogen several hundredfold greater than that represented by the flesh of the small-animal population therein. Similar chemical analyses show that the bottom sediments of the lakes are richer in organic matter than are the sediments of the adjacent river" (Purdy, 1930, p. 17).

However, the residual NO_3-N delivered from the watershed to the surface waters and which managed to evade assimilation by the luxuriant vegetation would have undergone enhanced denitrification when the water became anoxic, e.g.,

"The value of nitrates in polluted streams for preventing bad smells is now well recognized...if the stream is heavily polluted and denuded of dissolved oxygen, then the combined oxygen supplied by nitrates can be of very great importance....

"In the U.S.A. there are several reports of the deliberate addition of nitrates to polluted streams in order to prevent or eliminate odour nuisance. Thus Lawrance states that sodium nitrate was added successfully to stop bad smells due to hydrogen sulphite.... Todd reports the case of a stagnant creek (B.O.D. = 35 p.p.m.) Containing sewage...Pollution of the San Antonio River by brewery wastes..." (Klein, 1962, p. 81).

Similarly, even when the overlying water is well oxygenated, denitrification will be enhanced by NO_3-N diffusing into these organic-enriched, oxygen-depleted bottom deposits (Keeney, Chen, and Gratez, 1971; Vanderborght and Billen, 1975; Ripl, 1976; van Kessel, 1977; 1978; Sain et al., 1977; Beer and Wang, 1978; Triska and Oremland, 1981; Christensen et al., 1990; Lloyd, 1993).

Conversely, as previously discussed, this waterlogged, organic-rich, oxygen-depleted plant debris became N-fixing "factories." But, as with the N contained in the waterlogged, oxygen-depleted plant material itself, this microbially fixed N tended to be more conserved within the system, because the deficit of oxygen represents a roadblock to the nitrification that must first occur before this fixed N could be denitrified and lost from the system.

And this within-system-generated fixed N would also be transported by the Illinois River system as floods would readily scour and pick up this new fixed-N material and transport it.

In summary, whereas the above changes in the Illinois River Valley and its system of tributary streams and lakes are well recognized, how such changes have affected the aquatic C, O, and N cycles has not been assessed previously, let alone how such watershed change would have affected the nature and quantity of aquatic N, as well as the internal N cycle itself. We have been the first to do this.

Needless to say, these changes in the internal aquatic N cycle and the change in the nature of N held in surface waters need to be researched.

Some Effects of Direct Anthropogenic Additions on Nitrogen in the Illinois River

"On the day that the Chicago Drainage Canal was formally opened, January 17, 1900, the State of Missouri instituted proceedings in the courts, asking for an injunction against the State of Illinois and the sanitary district of Chicago to the end that the St. Louis water supply should not be polluted.... This legal struggle between the two great cities attracted much attention.... The Illinois River had become known to the multitudes" (Purdy, 1930, p. 2).

"In Illinois, Dawes et al. (1969) analyzed the NO_3^- data for Illinois rivers dating back to 1945. The median concentrations of some selected rivers are shown in table 14. They stated that since 1945 the NO_3^- concentration has almost doubled. They blame the 129-fold increase in use of commercial N fertilizers...[however] no information is given on other stream parameters such as BOD, NH_4^+-N, or total N in solution needed to determine the extent that installation of sewage treatment facilities, during the period of study, had on NO_3 concentrations or loads in the rivers. Viets (1970b) has indicated that the increase in NO_3^-concentration in Illinois rivers 'may be the first symptoms of stream recovery from organic pollution by raw sewage'" (Viets and Hageman, 1971. p. 32).

The *USDA Agriculture Handbook No. 413 Factors Affecting the Accumulation of Nitrate in Soil, Water, and Plants* (Viets and Hageman, 1971), noted some 29 years ago that reports of increasing concentrations of NO_3-N in water were considered proof in and of themselves of increasing pollution.

Such reasoning was also reported by Illinois State Water Survey scientists:

"Commercial inorganic fertilizers are also certainly implicated as a significant source of nitrogen; largely because their increasing use corresponds to increasing concentrations found in surface water. Since 1945 the tonnage of fertilizer nitrogen used in Illinois has increased over 100 times, and median nitrate levels in surface waters have doubled or tripled" (Harmeson and Larson, 1970).

And, as previously discussed, such reasoning still persists, as we can see from the Gulf hypoxia literature, e.g.,

"Water quality changes are coincident with increased nitrogen fertilizer use...the nitrogen loading doubled when fertilizer applications increased after World War II.... The rise in nitrate in recent decades is evidence that the ability of watershed land to store the mostly ammonia-based nitrogen fertilizers was exceeded.... Average nitrate concentration in the lower Mississippi River [at St.Francisville] and nitrogen fertilizer use in the United States is strongly related after 1960 ($R^2 = 0.74$), when nitrogen fertilizer use increased beyond 2 million mt per year....

"The riverine ecosystem response to higher nutrient loading is consistent with the nitrogen-saturation hypothesis described for northern forests by Aber et al. (1989)" (Turner and Rabalais, 1991).

The face of Gulf hypoxia is one of unequivocal scientific confidence. The November 1997 issue of *Scientific American* confidently reports "that the cause of the phenomenon is no mystery" — the scientific consensus is that the problem is runoff from principally an N fertilizer problem:

“The biggest contributor...is the Upper Midwest, especially the Illinois basin” (Beardsley, 1997).

As the 16 October 1996 issue of *Science* reports:

“The tough part, says NOAA’s Terry Nelson, will be convincing Midwest farmers that they’re part of the problem. ‘Most people don’t couple the middle continent and the ocean,’ he says” (Kaiser, 1996).

However, as the authors of the *USDA Agriculture Handbook No. 413* observed, even if such correlation exists, correlation does not prove cause, because the method of multiple working hypotheses has not been applied.

And another hypothetical cause does exist, namely:

“Whether there is a trend toward higher nitrate concentration in surface waters is impossible to evaluate because of the biological reactions in which it is involved. Increases in nitrate in lakes and streams may simply be a manifestation of better supplies of dissolved oxygen because of progressively lower inflows of raw or partly treated sewage. For these reasons, the authors of this paper cannot conclude that there is any trend in nitrate in surface waters, although they would not deny that the total N and total soluble N in many lakes and rivers may have increased significantly” (Viets and Hageman, 1971, p. 51).

Accordingly, the reported consensus about the correlation between concentration of NO_3-N and use of chemical-N fertilizer being causal was assessed. The correlation between NO_3-N concentration in the major rivers of the MRB and fertilizer use holds for only a select short segment of time. The relationship breaks down when the whole time frame is examined (Figure 26).

Similarly, the correlation between annual NO_3-N concentration in the Lower Illinois River draining the IRB and the rate of annual statewide fertilizer application only holds for a select, short period of time. This relationship also breaks down when we look at the whole time frame (Figure 27).

These data (Figure 27) are consistent with the previous analysis of 200 Illinois stream and rivers that showed no statistically significant relationship between annual concentration of NO_2-N plus NO_3-N and annual statewide use of N fertilizer (Figure 16). Of course, we recognize that some fertilizer may be retained in the soil to be leached out by heavy rainfall at a later date.

By disproving a constant association between the use of chemical-N fertilizer and concentration of NO_3-N in surface waters, we have also disproved the causality that this correlation is asserted to have.

We now test the alternative hypothesis of Viets and Hageman (1971) for the IRB. Their hypothesis is that 20th century anthropogenic perturbations of the aquatic C, O, and N cycles by waste disposal are the principal factor behind the post-World War II increase in NO_3-N concentration, e.g.,

“Increases in nitrate in lakes and streams may simply be a manifestation of better supplies of dissolved oxygen because of progressively lower inflows of raw or partly treated sewage” (Viets and Hageman, 1971, p. 51).

In the past, rivers were used as open sewers to carry away vast amounts of untreated human and industrial wastes. This is common knowledge.

The subsequent cleaning up of our rivers by the instituting primary, secondary, tertiary (and other advanced) treatment processes to reduce the load of oxygen-consuming organic C and N materials is one of the great environmental accomplishments of the century (e.g., Wolman, 1971). This too is common knowledge.

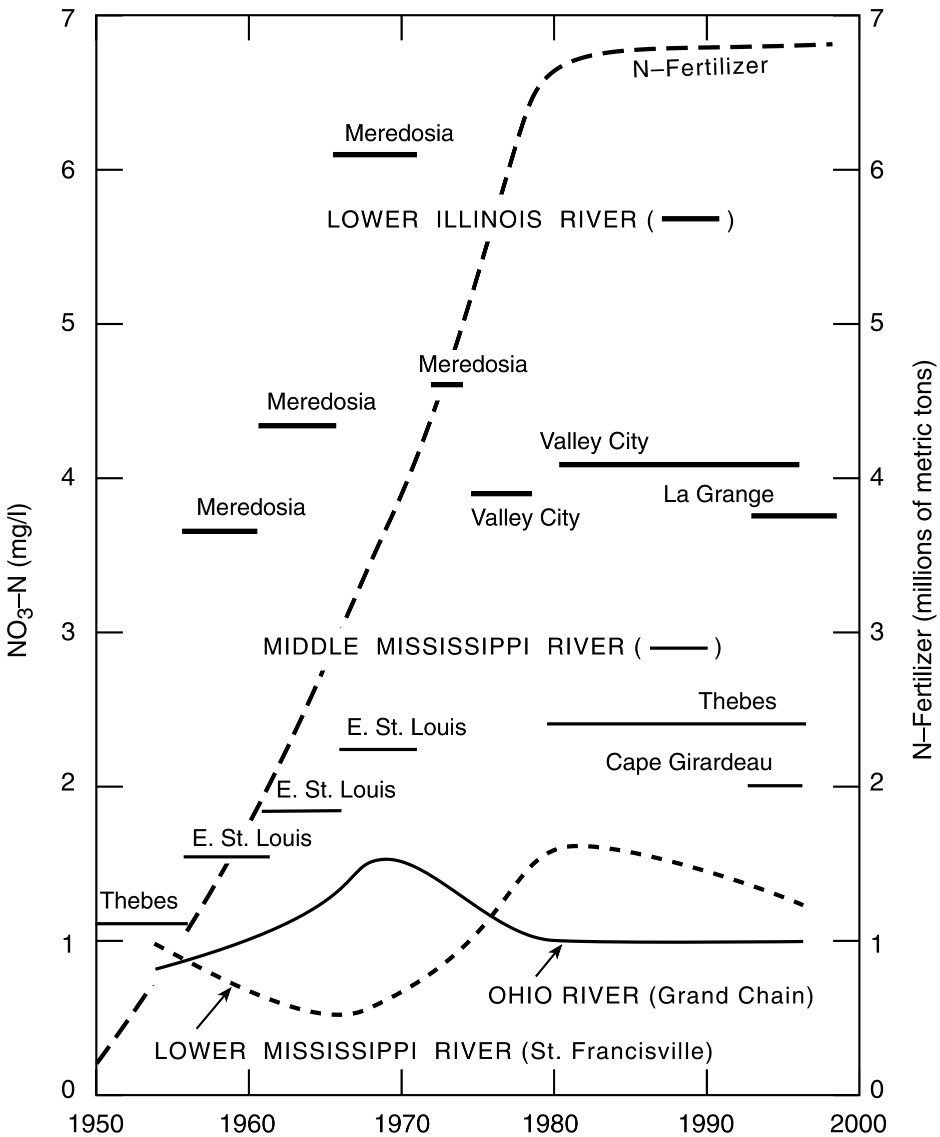

Figure 26. Relationship between nitrogen fertilizer use in the Mississippi River Basin (MRB) and annual NO_3-N concentrations in major rivers of the MRB. **Sources**: Data from Ackerman et al., 1970; Goolsby et al., 1999; Harmeson and Larson, 1969, 1970; Harmeson et al., 1973; Larson and Larson, 1957; STORET, 1999; USDHEW, 1963; USGS, 1996, 1999a and 1999b.

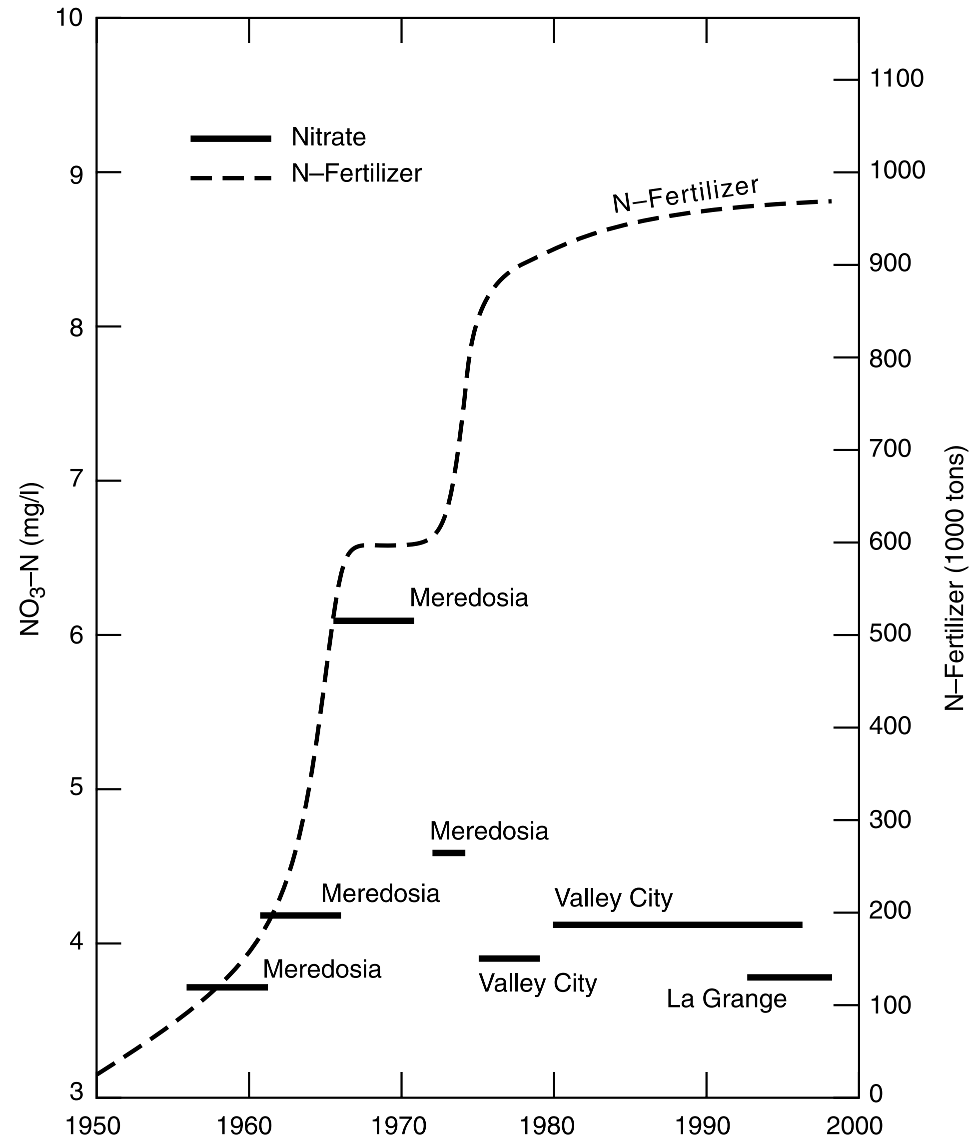

Figure 27. Relationship between nitrogen fertilizer use in Illinois and annual NO_3-N concentrations in the Lower Illinois River.
Sources: Data from Goolsby et al., 1999; Harmeson and Larson, 1969, 1970; Harmeson et al., 1973; Healy and Toler, 1978; Larson and Larson, 1957; STORET, 1999; USDHEW, 1963.

That such cleanup would also result in the type of change in water quality hypothesized by Viets and Hageman (1971) is consistent with the results and the understanding of water pollution and its abatement. One of the authors, having been a licensed sewage treatment plant operator, was taught that increasing NO_3-N represents improving water quality. This has been seen and known since the results and knowledge gained from the earliest comprehensive water surveys of Illinois (e.g., Kofoid, 1903; Palmer, 1903; Leighton, 1907). These and similar results and knowledge has been preserved ever since in the water sanitation, quality, and water treatment literature (e.g., Allgeier, Peterson, and Juday, 1934; Wisely and Klassen, 1938; Hood, 1948; Klein, 1962; Feth, 1966; Weinberger, Stephan, and Middleton, 1966; O'Connor, 1967; National Research Council, 1969; Sawyer, 1970; Fillos and Molof, 1972; Reeves, 1972; Ruttner, 1974; Butts, Evans, and Lin, 1975, 1978; Baxter, 1977; Happ, Grosselink, and Day, 1977; Sefton et al., 1980; Wetzel, 1983; Velz, 1984; Snodgrass and Klapwijk, 1986; Thomann and Mueller, 1987; Seitzinger, 1988; Cambardella et al., 1999).

And such results relating to water pollution and its subsequent cleanup have been documented for watersheds and rivers even bigger than the Illinois. For example, Table 15 shows that getting such water pollution under better control increased NO_3-N concentration for the water of the Rhine River:

"In the last decade, reductions in the discharge of untreated domestic and industrial wastewaters have improved the oxygenation of the [Rhine's] river water..." (Admiraals and Botermans, 1989).

The data in Table 15 show increasing concentration of NO_3-N and and decreasing concentration of total N. These opposite trends could come from decreased pollution loading and from the improved assimilatory capacity of the river enabling the Rhine River to better remove N from its system.

Given all of the above — including the fact that the Illinois River became nationally renowned for its being used as an open sewer by the ever-growing sanitary district of Chicago, the Viets and Hageman (1971) hypothesis was tested for the Illinois River.

As previously discussed, after the opening of the Chicago Sanitary and Ship Canal in 1900, Chicago's sewage problem appeared to present relatively little problem for the Illinois River. However, as the number of people and the activities within the sanitary district of Chicago continued to grow, the growing influence of its pollution was felt progressively further down the Illinois River.

Table 15. Some Changes in Rhine River Water Chemistry, 1974 to 1985

Year	*NO_3-N*	*NH_4-N*	*Organic-N*	*Total N*	*Dissolved oxygen (percent saturation)*
	mg/l				
1974	3.3	1.7	2.1	7.1	55
1985	4.3	0.7	0.8	5.8	80

Source: Admiraals and Botermans (1989).

To quote Forbes (1919):

"A careful survey, chemical and biological, made last August and September, showed us that the fouling of the waters was extending steadily down stream at an average rate, during the last six years, of five to ten miles a year* [* footnote describing data showing downriver extension of the hypoxic zone of dissolved oxygen less than 2 mg/l], ninety three miles down, is now nearly deserted by fishes.... Its oxygen is nearly all gone; its carbon dioxide rises to the maximum; its sediments become substantially like the sludge of a septic tank; its surface bubbles with the gases of decomposition escaping from the sludge banks on its bottom; its odor is offensive; and its color is gray with suspended specks and larger clusters of sewage organisms carried down from the Stony floor of the Des Plaines, or swept from their attachments along the banks of the Illinois. On its surface are also floating masses of decaying debris borne up by the gases developing within them, and covered and fringed with the 'sewage fungus' and the bell animalcule usually associated in these waters. The vegetation and drift at the edge of the stream are also everywhere slimy with these foul-water plants and minute filth-loving animals....

"The sewage load of the stream is steadily increasing year by year, however, and how long it may be before this frail barrier is broken through we may not say" (Forbes, 1919).

Subsequent determinations of the effect of Chicago pollution on reducing the dissolved oxygen of the Illinois River found:

"Urban pollution began to be a problem in the upper river by 1911 (Mills et al. 1966:8-9) and ballooned in scope during World War I. Between 1915 and 1920, the zone of pollution moved downstream from the Chicago area at a rate of 26 km (16) miles per year (Mills et al. 1966:9); by 1923 the river was almost devoid of free oxygen as far south as Chillicothe (Greenfield 1925:24-25) [160 miles downstream and just north of Peoria]" (Bellrose et al., 1983).

Even the hearty carp could not survive and was wiped out almost all the way down to Peoria (Mills et al., 1966).

The time trend in concentration of dissolved oxygen for the Upper Illinois River is shown in Figure 28. However, loss of dissolved oxygen from surface water was not the only major ecological consequence of dumping increasingly massive amounts of raw sewage into rivers — the suspended solids in raw sewage laid down a smothering putrid blanket on the bottom:

"The stream, on receiving the sewage effluent, lays down a 'pollution carpet,' or false bottom, consisting largely of precipitated organic and mineral matter" (Purdy, 1930, p. 7).

Whereas Chicago pollution removed most of the dissolved oxygen from the 160-miles of river below it, bottom surveys of the length of the Illinois River reported in Purdy (1930) showed that the blanket of putrid sewage sludge on the river bottom extended well beyond the upper river — eventually extending to cover the bottom of the Illinois River creating an oxygen-depleted bottom that extended through the upper and lower reaches of the Illinois River and down to the Mississippi River:

"Growth of the City of Chicago, with heavy increase in amount of sewage and of stockyard waste...its organic matter is carried farther downstream, before the offensive organic content is sufficiently removed. A visible result of the downstream encroachment of this decomposing organic matter (estimated at 16 miles per year), the valuable fishery interests of the lower river have been seriously harmed and threatened with extinction" (Purdy, 1930, p. 2).

A similar history was occurring in parallel on the Upper Mississippi River, even though the Minneapolis/St/ Paul area did not produce as much pollution as Chicago. The Upper Mississippi River was also bigger and better able to assimilate this lesser pollution load.

Nevertheless, a 60-mile-long-stretch of the Mississippi River below Minneapolis was made hypoxic (Winstanley and Krug, 1999) eliminating fish (Wiebe, 1928). Only coarse, pollution-tolerant fish like catfish and carp could survive in the subsequent 60 mile stretch of Mississippi River 120 miles downstream to Winona (Table 16).

As with the Illinois River, the effect of pollution extended much further than the zone of oxygen-depleted surface water. The river bottoms of nearly the entire lengths of the Illinois and Upper Mississippi Rivers became hypoxic (Richardson, 1928; Ellis, 1931; Scarpino, 1985), e.g.,

"Separately, pollution and silt degraded water quality. Together, they produced synergistic results. Sewage combined with fine silt was carried farther downstream than it would have been in clear water. Thus a local problem became regional in scope....

"By the late 1920s, natural reproduction of commercial mussels had practically ceased in the upper Mississippi River and many of its tributaries" (Scarpino, 1985, p. 107).

The nature of such bottom pollution was researched by the U.S. Fisheries Service which reported:

"Bacteriological and chemical studies of the water of the Mississippi River, both in the vicinity of cities and towns and in the portions of the river less closely bounded by civilization, showed that the pollution of the river by municipal sewage and industrial waste has been accomplished to an alarming extent; this factor of pollution itself, regardless of other conditions in the river, is rapidly reducing the river fauna to such forms as carp and paper shells, which are tolerant of these conditions. The municipal-sewage problem is greatly complicated by the presence of soil-erosion material, since the sewage when incorporated with the erosion silt decomposes more slowly than when moving in clear water and consequently the effects of pollution from municipal sewage are being projected farther and farther downstream from the source of pollution" (Ellis, 1931).

Table 16. Mississippi River Fisheries: Minneapolis to Winona, 1903 and 1922

Fish	*1903 (lb)*	*1922 (lb)*
Walleye	35,380	0
Sauger	14,305	0
Bass	12,870	0
Sunfish	21,400	0
Pickeral	57,525	0
Sturgeon	14,585	7,753
Catfish	311,149	147,016
Carp	473,440	3,048,332

Source: Wiebe (1928).

In pools and lakes, this bottom pollution, which projected itself many hundreds of miles downstream, depleted oxygen from surface waters, e.g.,

"After construction of Keokuk dam, bass, crappie, and other game fish increased...sport fishing was generally recognized as much better than before the dam was built...."

By 1930 Lake Keokuk "was found to be producing relatively large quantities of carp, and fair quantities of sheepshead, catfish, and various other 'rough' fish....

"As this silt consists of erosion material mixed with incompletely decomposed organic waste, the bottom of Lake Keokuk has been reduced to those forms capable of withstanding low oxygen and tolerant of various conditions attendant upon the decomposition of organic waste.... Consequently, carp, buffalo, and catfish were the dominant fish found in Lake Keokuk.... This silting in with a mixture of erosion silt and organic waste becomes a serious factor since such a mixture has a high oxygen demand" (Ellis, 1931).

By 1930, the highest summertime dissolved oxygen values measured in Lake Keokuk would be 60 percent saturation under most favorable conditions — a sunny afternoon in aquatic vegetation in July (Ellis, 1931).

Figure 28 is consistent with the Viets and Hageman (1971) hypothesis of increasing anthropogenic pollution in the first several decades of the 20th century. It is also consistent with the Viets and Hageman (1971) hypothesis regarding subsequent cleanup.

In northeastern Illinois sprang up one of the world's great cities, Chicago, with a metropolitan population of over 7 million. Whereas the rate of improvement in wastewater treatment was not initially able to keep up with the growing pollution, eventually improvements were able to outstrip growth, e.g.,

"By 1922, the Illinois River carried waste equivalent to the volume that would be produced by 6.2 million people. By 1962, the waste had been reduced to 28 percent of the 1922 level. By 1971 volumes were cut to 13 percent. Another 32 percent reduction by 1982 brought the total waste load down to 9 percent of the original 1922 level — equivalent to the volume that would be produced by about half a million people" (Talkington, 1991, p. 28).

According to the Illinois Environmental Protection Agency (IEPA):

"During the 10-year period covered by this survey, nearly 900 wastewater improvement projects were completed. Oxygen demanding waste discharges for 1982 have been reduced to half their 1972 levels" (IEPA, 1984).

And:

"Despite continuing industrial expansion, a growing population, and the increasing amount of waste to be disposed of in Illinois, the survey indicates water pollution control management programs achieved general statewide improvement in the quality of our waters....

"Only ten percent of the state's waters could be considered of highest quality during 1972-74, but more than 50 percent have qualified for that category since 1975" (IEPA, 1985).

Figure 29 depicts the great improvement made in the water quality of the streams and rivers of the IRB between 1972 and 1990.

In summary, data collected over the previous century for the various major forms of N in solution (Figure 30) enabled us to assess the changes in N chemistry concomitant with the rise and decline of anthropogenic pollution, and the rise and decline of dissolved oxygen for the Middle Illinois River (Figure 28).

The pattern of the concentration of TN measured in the water of the Illinois River over the previous hundred years (Figure 30) fits the Viets and Hageman (1971) hypothesis, and does not correlate with the standing N-cycle paradigm. Concentration of measured TN was slightly

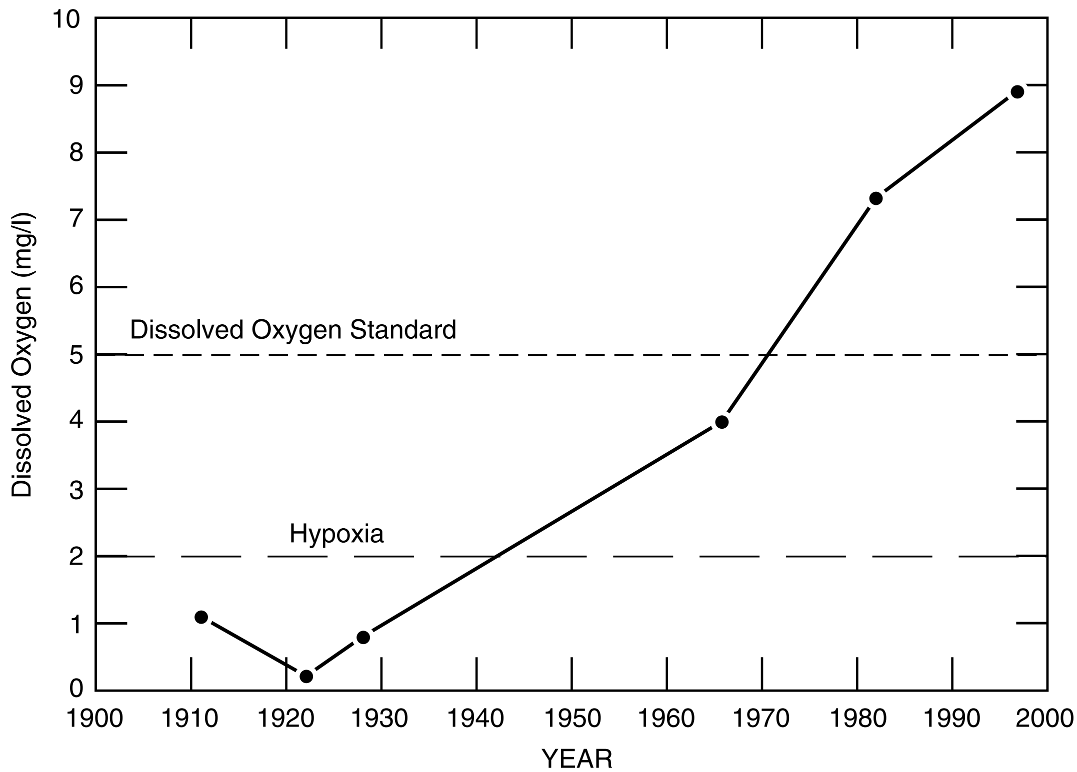

Figure 28. Summer values of dissolved oxygen in the Upper Illinois River.
Source: Adapted from Winstanley and Krug (1999).

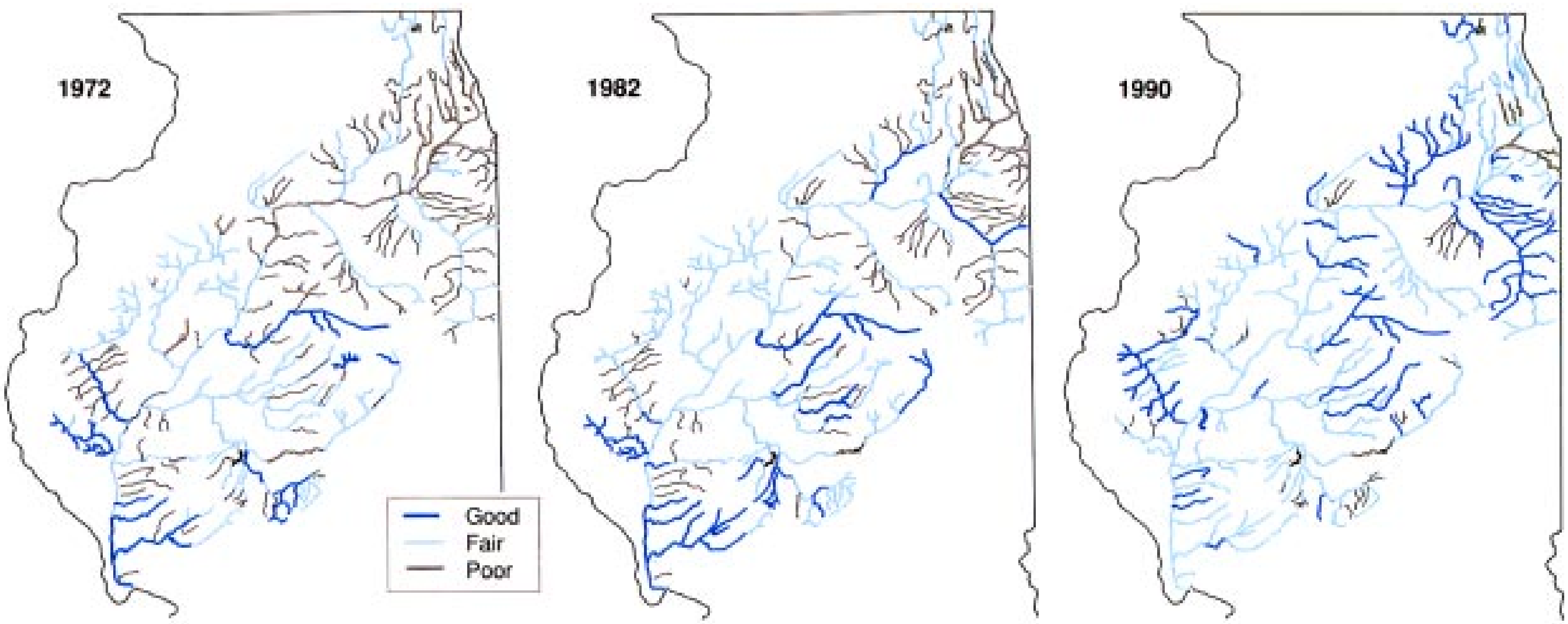

Figure 29. Water quality of Illinois River Basin streams and rivers, 1972, 1982, and 1990.
Source: Talkington (1991).

lower than today around the turn of the century — although corrections for flow and measurement techniques suggest that the reverse is, in fact, the case. The TN concentration in the early decades of this century then rose to about twice the current level before declining.

Figure 30 shows that the rise and decline in the relative proportions of reduced N (organic plus ammonia) relative to the oxidized forms (NO_2-N + NO_3- N) fit the Viets and Hageman (1971) hypothesis, but do not support the hypothesis that the application of N fertilizer is driving the N chemistry of the surface waters of the IRB.

Winstanley and Krug (1999) also found the same general trend for the stretch of the Mississippi River between St. Louis and Cairo. The pattern observed in the Illinois River also fits that measured in the Rhine River (Admiraals and Botermans, 1989).

In short, this assessment has disproved the N-fertilizer hypothesis.

This assessment has not disproved the Viets and Hageman (1971) hypothesis. As previously discussed, however, this assessment has discovered some factors for the IRB which confound the Viets and Hageman (1971) hypothesis and require further investigation.

One confounding factor is the decline of aquatic vegetation within the watershed of the Illinois River and its tributaries. This has probably contributed to some degree to the observed high N concentrations in mid-20th century.

Another confounding factor is the increase in agricultural cropland. This too would have would have increased the flux of N to the hydrosphere — this flux of N probably peaked around 1930. Interestingly, this flux of soil NO_3-N probably kept water quality from declining even more than it did by providing oxygen associated with the NO_3-N itself.

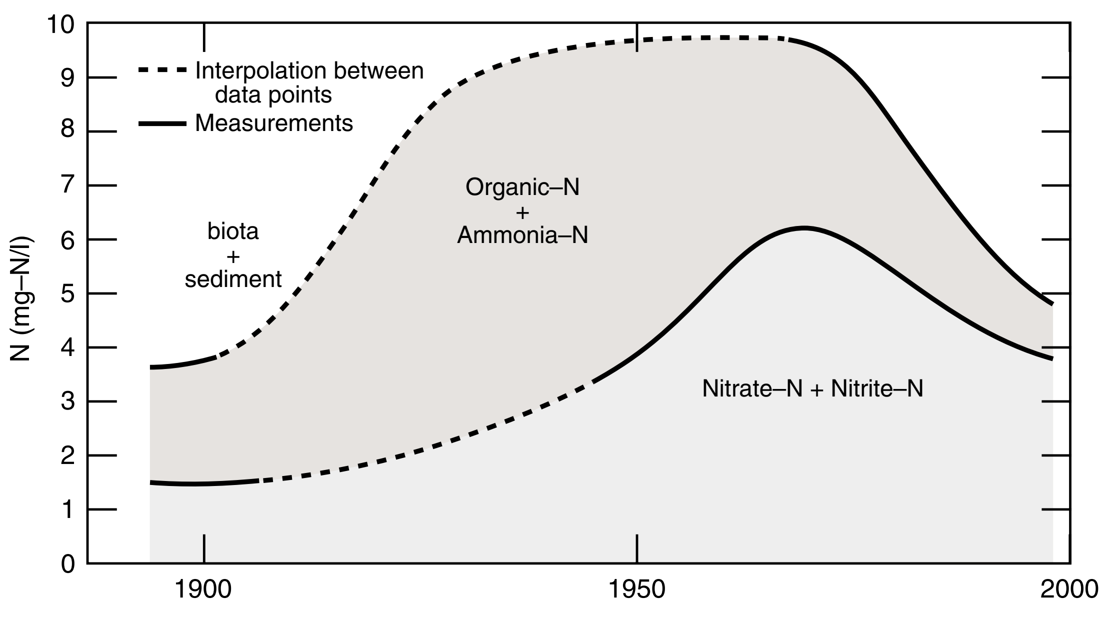

Figure 30. Concentration of nitrogen in the Lower Illinois River (Havana to Valley City), 1894-1998.
Source: Modified from Winstanley and Krug (1999).

And third, as documented earlier by Wolman (1971), biological recovery from oxygen stress lags behind improvement in measured surface-water dissolved oxygen and this is to be expected. This is so not only from the reasons derived from the observations of Muller and Kirschesch (1980) about the BOD of the products of primary production, but also for the obvious reason that waterlogged, aquatic sediments are the first to become anoxic and the last to recover:

"Past discharges of settleable and colloidal organic soils into natural waterways have resulted in appreciable accumulations of sludge in the bottoms of many lakes, estuaries, and river stretches over the years. Under such conditions sludge bottoms, when present, may become one of the most important factors influencing the quality of natural water" (Fillos and Molof, 1972).

Survey of the Illinois River prior to the construction of the lock-and-dam system in the 1930s showed the effect of oxygen stress on sediments and associated benthos was more widespread than that of dissolved oxygen in the water column (Purdy, 1930), as did a subsequent study that showed additional oxygen stress to incurred after completion of the Illinois River lock-and-dam system (Wisely and Klassen, 1938).

Recovery of the water will enhance decomposition of sewage sludge and other N-rich waste substances mixed in with bottom sediments causing ammoniacal N, which will then be readily oxidized to NO_3-N. Thus, this is yet another confounding factor that would elevate surface water NO_3-N- and TN concentrations beyond what they would otherwise be. That there is such sewage and other wastes in the sediments that release N to the hydrosphere is recognized in today's scientific literature in connection with aquatic biology not recovering as well as would be indicated by surface-water chemistry, e.g.,

"Pollution abatement in the last two decades has improved the dissolved oxygen levels of the river but not necessarily those of the adjacent bottomland lakes (Sparks and Starrett 1975:345-346). The reduction in oxygen content in the bottomland lakes is attributed to the resuspension of fine silts from the shallow lake bottoms by wave action. The resuspended material exerts an oxygen demand, removing dissolved oxygen from the water" (Butts, 1974, p. 12).

And:

"Fish life has not increased to the degree anticipated from the improvement of dissolved oxygen in the river (Mills et al. 1966; Sparks and Starrett 1975:345). A principal factor appears to be the sediments deposited in the bottomland lakes (Bellrose et al. 1977:IV-a)" (Bellrose et al., 1983).

Human and animal wastes have been determined to contaminate the sediments of the Illinois and Upper Mississippi River Rivers, thus creating extremely unnaturally elevated concentrations of ammonia too toxic for most bottom-dwelling organisms originally found in these rivers to re-establish themselves (e.g., Kelly and Hite, 1984; Sparks and Ross, 1992; Writer et al., 1995; Short, 1997; U.S. Geological Survey, 1999a).

The above are some additional confounding factors which complicate the Viets and Hageman (1971) hypothesis and need to be assessed to further test and refine their hypothesis.

In summary, the cleansing of the Illinois River from its polluted, organic-rich peak in mid-20th century is well under way. The reductions in the concentrations of all forms of N are attributable to both point- and nonpoint-source pollution control.

Restoration of water quality to conditions reported in the 1800s would necessitate an increase in unoxidized forms of N [organic-N and NH_4-N (ammoniacal N)], a reduction in oxidized forms of N (NO_2-N and NO_3-N), an increase inorganic loading, and a decrease in oxygen status of the surface waters of the IRB.

CONCLUSIONS

To provide a scientifically sound rationale for setting N criteria and standards, an appropriate analytical framework must be set. The concept of biogeochemical cycles provides such a framework.

Key questions relate to changes of N inputs to the N biogeochemical reservoirs, to changes in storage of N in these reservoirs, to changes in the fluxes and chemical forms of N within and among these reservoirs, and to fluxes of N from these reservoirs.

Understanding of the N cycle by most scientists today is restrictive in nature. The standing N-cycle paradigm does not adequately recognize the soil reservoir, or historical fluxes from this reservoir, as part of the N cycle. In fact, significant changes to the soil's natural N reservoirs and transfers are implicitly assumed not to have occurred prior to the 1950s. Pre-European-settlement conditions are described erroneously as being pristine and oligotrophic, with little N leaking out of the prairie landscape. Increases in N-fertilizer application and atmospheric deposition of N are recognized as changing, however, since the 1950s. These modern inputs of N are asserted to be the cause of N saturation of landscapes, increased transfer of N from the soil to surface waters and ground waters, and overall enhancement of the N cycle. Unlike the well-founded N-cycle paradigm it replaced, the current N-cycle paradigm incorrectly defines N gas (N_2) as the earth's dominant N reservoir and thus the source from which flows essentially all of our biologically useful N.

Changes in the Illinois River and its watershed are well recognized in the state. In this report, we have attempted for the first time, to assess in some detail and in a fairly comprehensive manner how such changes have affected the aquatic C, O, and especially N cycles. The changes in the nitrogen richness of the Illinois landscape over time are simplified and graphically presented in Figure 31.

We conclude that the landscape was N saturated prior to European settlement. During the first half of the 19th century, the landscape was less disturbed and less N saturated than in previous centuries. Nevertheless, in the 19th century the Illinois River was characterized by large amounts of plant material and debris, supported by large amounts of N and other nutrients. The river was hypertrophic. In the 1890s, the average measured concentration of TN in the Lower Illinois River was 3.68 mg N/l — flow and methods of measurement corrections indicate that it was more likely equivalent to about 5.5 mg N/l.

Expansion of population, industry, and agriculture changed the N cycle in Illinois. The disposal of large amounts of organic waste material and N directly into the rivers and streams, and the transfer of large amounts of organic material and N from agricultural lands to rivers and streams, caused the amount of N, especially organic-N and NH_4-N, to increase dramatically in the Illinois River. The concentration of TN in the Lower Illinois River increased to about 10 mg-N/l by mid-20th century. Much of the Illinois River was so depleted of dissolved oxygen in the first half of the 20th century that it was hypoxic.

Since mid-20th century, the Illinois River has been greatly cleansed. The input of organic material and N has decreased, the concentration of dissolved oxygen has increased, and the concentration of TN has decreased by about 50 percent. The measured concentration of TN in the Lower Illinois River in the 1890s was only about 25 percent lower than it is today; and the difference in N concentration becomes minimal or is reversed when plankton and differences in flow rates and methods of measurement are considered.

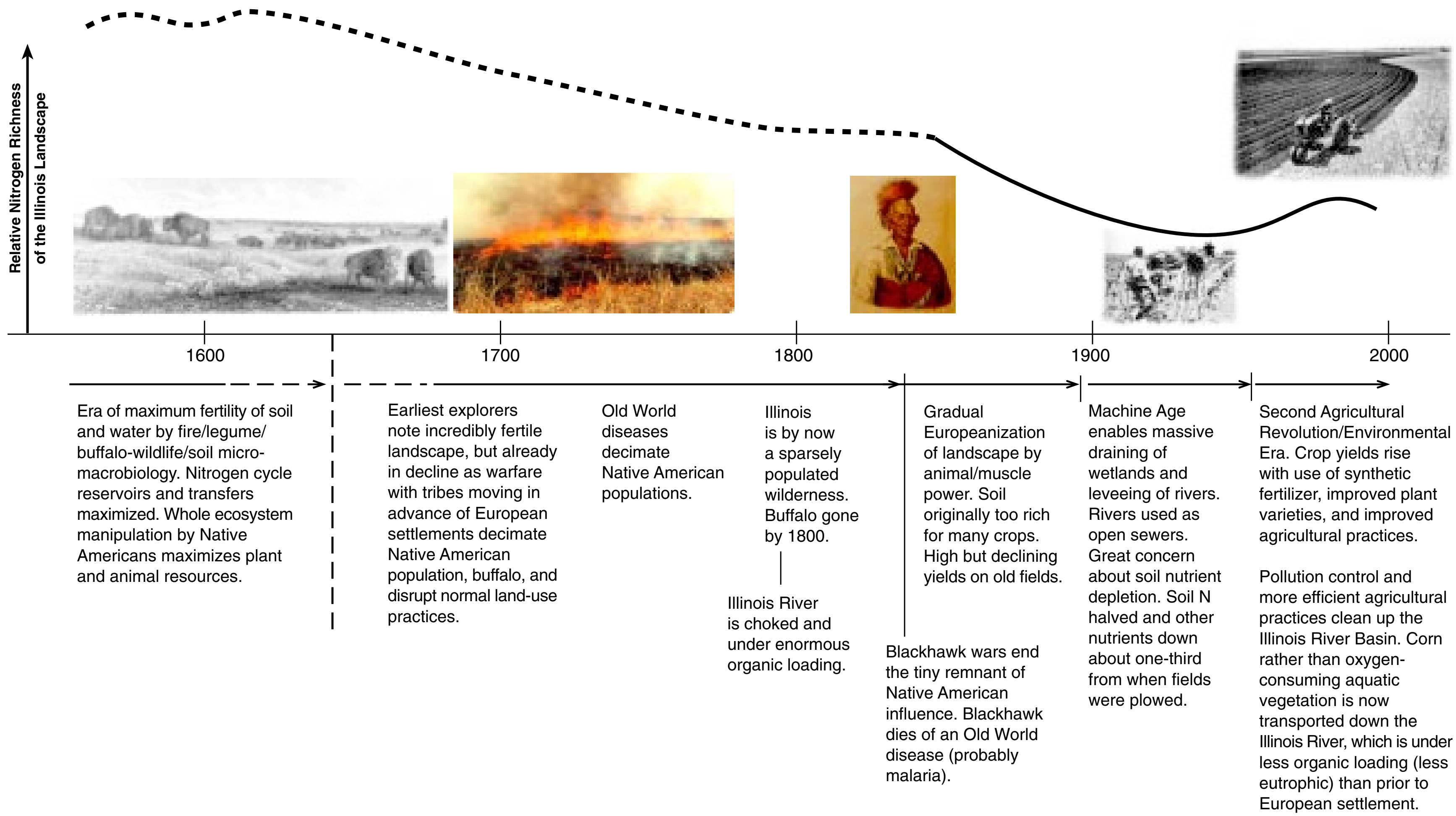

Figure 31. Relative nitrogen richness of the Illinois landscape before and after European settlement.

As part of this cleansing process, the concentration of NO_3-N in the Lower Illinois River initially increased, reaching a peak of about 6.2 mg NO_3-N/l in 1967-1971, but it subsequently decreased. Today, the concentration of NO_3-N in the Lower Illinois River is the same as it was around 1960, i.e., about 3.8 mg NO_3-N/l . These data, combined with the fact that N-fertilizer use continued to increase rapidly from 1970 to the 1980s, reveal the lack of a consistent relationship between N-fertilizer use and N concentration in the Illinois River.

The overall effect of these anthropogenically induced changes is assessed to be the transformation of the system from one of a great organic loading (hypertrophism) imposed on surface waters by the watershed to one of much lower organic loading.

Needless to say, these changes in N dynamics need to be researched. Focusing almost exclusively on changes in the concentration of dissolved inorganic-N in surface waters will never provide adequate scientific understanding of the natural N cycle, or human impacts on the N cycle.

To establish scientifically sound reference conditions, it is necessary i) to quantify in a common unit all forms of N [dissolved and particulate (micro- and macroparticles); and organic and inorganic] and all sources, reservoirs, transformations, and fluxes of N; and ii) to understand interactions between N and other biogeochemical cycles of, for example, H_2O, O_2, C, and P. Criteria for setting N standards must recognize the great complexity of the N cycle and its inter-dependence with other variables. They must also consider the ways that human activities have both added to and subtracted from natural soil-N reservoirs.

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