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Reconstructing Eutrophication and Phosphorus Loading for Lake Volney, Minnesota: Combining Lake Sediments and Land-Use History to Establish 'Natural' Baselines for Management and Restoration

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ABSTRACT

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Establishing management targets for lake nutrient inputs remains a major challenge to limnologists and resource managers concerned with the cultural eutrophication of lakes. In this study we used multiple sediment cores to reconstruct pre-Euroamerican (1650-1850) phosphorus (P) loading to Lake Volney, a hypereutrophic lake in Le Sueur County, Minnesota, and compared changes in P inputs to inferred changes in lake productivity based on biogenic silica (bSi). Euroamerican changes in land-use, as abstracted from census and tax records, were also compared with sedimentary proxies for soil erosion – loss-on-ignition and environmental magnetism. Whole-basin P accumulation in Lake Volney ranged from 0.31 - 0.39 $g \cdot m^{-2} \cdot yr^{-1}$ prior to the arrival of Euroamerican agriculture in the 1850s. Thereafter P accumulation rose nearly three-fold largely due to increased fluxes of organic and non-apatite inorganic P. P inputs were highest (3.9 $g \cdot m^{-2} \cdot yr^{-1}$) when organic, apatite and non-apatite P all peaked. Modern P accumulation rates of 1.3 $g \cdot m^{-2} \cdot yr^{-1}$ match closely P-loading estimates based on monitoring data and mass-balance calculations. Lake productivity showed little change until the early 1900s when bSi accumulation rose 5-10x over pre-1900 values. The initial increase in P loading observed in the 1850s corresponds closely to the arrival of Euroamericans in the Lake Volney watershed. Causes for the second increase in P inputs (1910-1930) seem related to an overall increase in large animal numbers (swine and cattle) that began in the 1910s. The methods combined in this study provide site-specific reconstructions of trophic change and its causes that can be used to guide lake management and restoration.

Key Words: eutrophication, Lake Volney, LOI, magnetics, paleolimnology, phosphorus, sediment, watershed.

Eutrophication of surface waters due to excessive inputs of phosphorus (P) continues to be a major concern, with P inputs to surface waters in the United States now estimated to exceed 1658 x 10^3 $Mg \cdot yr^{-1}$ (Carpenter et al. 1998). Non-point agricultural and urban sources are responsible for 84% of P inputs to surface water, largely through surface runoff, although subsurface movements of P are increasingly recognized as a major contributor (Tunney et al. 1997, Carpenter et al. 1998). Successful modeling and remediation of eutrophication will often depend upon site-specific understanding of P inputs, both modern and historical, as well as the dynamics of P within the water column and sediments (Carpenter et al. 1999).

Historical studies of lake sediments provide a means of assessing the timing and magnitude of cultural eutrophication (Engstrom and Wright 1984, Rippey and Anderson 1996, Anderson 1995, 1997) and – in combination with studies of land-use – may also provide decision-makers with information critical to evaluating different management strategies. A variety of sedimentary proxies has been used to reconstruct trophic change (Smol and Last 2002), with fossil diatoms, algal pigments, biogenic (diatom) silica, and sedimentary phosphorus being the most widely accepted.

Here we reconstruct historical changes in P-loading for Lake Volney, a hypereutrophic lake located in southeastern Minnesota. Sediment P (organic, apatite, and non-apatite fractions) was analyzed for a single ^{210}Pb dated core and five additional undated cores, and compared with current P loading as determined by monitoring and mass balance calculations (MPCA 1996). Trends in sediment P are then compared with changes in lake productivity (based on biogenic silica, bSi) and proxies for soil erosion (loss-on-ignition and environmental magnetism). Results from the sediment reconstructions are placed in the context of land-use change in the local watershed and surrounding county as documented in county tax records, U.S. Census data and Agriculture Department surveys, and aerial photographs.

Methods and Materials

Site Description

Lake Volney is an 89 ha, 22-m deep, hypereutrophic lake (170 ppb total-P in 1995; MPCA 1996) located in Le Sueur County in southeastern Minnesota (Fig. 1). Algal biomass is high (mid-summer chlorophyll a >10 $\mu g \cdot L^{-1}$) and the hypolimnion (below 16 m) is typically anoxic by the end of May.

The Lake Volney watershed is approximately 940 ha in area and is drained by several ditches and tile systems. A ditch to the south serves as the major outlet for the lake. Land-use is largely agricultural, although there are ca. 25 homes with septic systems on the north, west, and southern shores. Monitoring of the lake in 1995 found annual P inputs of 1382 kg and outflow of 325 kg, with the balance of 1057 kg retained (sedimented). Over 40% of the P load was contributed by a single ditch (MPCA 1996) that passes through a large wetland complex before entering the northeast corner of the lake (Fig. 1).

Sediment Sampling

Six sediment cores were collected from the lake in June 1995 (Fig. 1) using a piston corer equipped with a clear polycarbonate core barrel and operated by rigid drive rods from the lake surface. Maximum length of cores ranged from 0.8 to 2.2 m, as limited by the stiffness of the sediment or length of the coring tube. In all six cores the sediment-water interface was clearly visible and undisturbed. Eight gravity-core samples were taken near the south and west slopes at depths between 1 and 4 meters to help define the depositional area for soft sediment within the basin.

Cores were extruded vertically on shore and sectioned into 4-8 cm intervals. The entire central core (Core 1, 15.75 m depth, Fig. 1) was sectioned and transferred to polypropylene jars. For the other five cores only the surface interval and depths thought to be below the cultural horizon (based on field color and texture) were sectioned and saved. Sample jars were returned to the laboratory and stored at 4°C until processing.

Sediment Core Analyses

Lead-210 was used to date the central core (Core 1) based on analysis of 15 depth intervals by alpha spectrometry methods (Eakins and Morrison 1978) and the constant rate of supply (c.r.s.) model (Appleby and Oldfield 1978). The increase in *Ambrosia* (ragweed) pollen (a marker for onset of Euroamerican agriculture) was also identified for the central core based on pollen analysis at six sample depths. Pollen processing followed standard techniques used by the Limnological Research Center of the University of Minnesota. *Ambrosia* concentrations are expressed as a percentage of a total of 200 arboreal pollen grains/sample.

Moisture content, organic matter, calcium carbonate, and inorganic content were determined by loss-on-ignition (Dean 1974) for 1-cm^3 subsamples from all core intervals. Sediments were weighed wet, then dried at 100°C, and ignited at 550°C and 1000°C with weights taken after each step.

To better understand sediment properties, anhysteric remnant magnetization (ARM) and saturation isothermal remnant magnetization (SIRM) properties were analyzed for all intervals (5.3 cm^3 subsamples) of the central dated core at the Institute for Rock Magnetism, University of Minnesota. ARM, imparted by subjecting the samples to a peak alternating field of 100 mT in the presence of a 0.05 mT biasing field, provides a measure of the concentration of small ferromagnetic grains. SIRM, effected by briefly exposing samples to a 1T field, provides a measure of

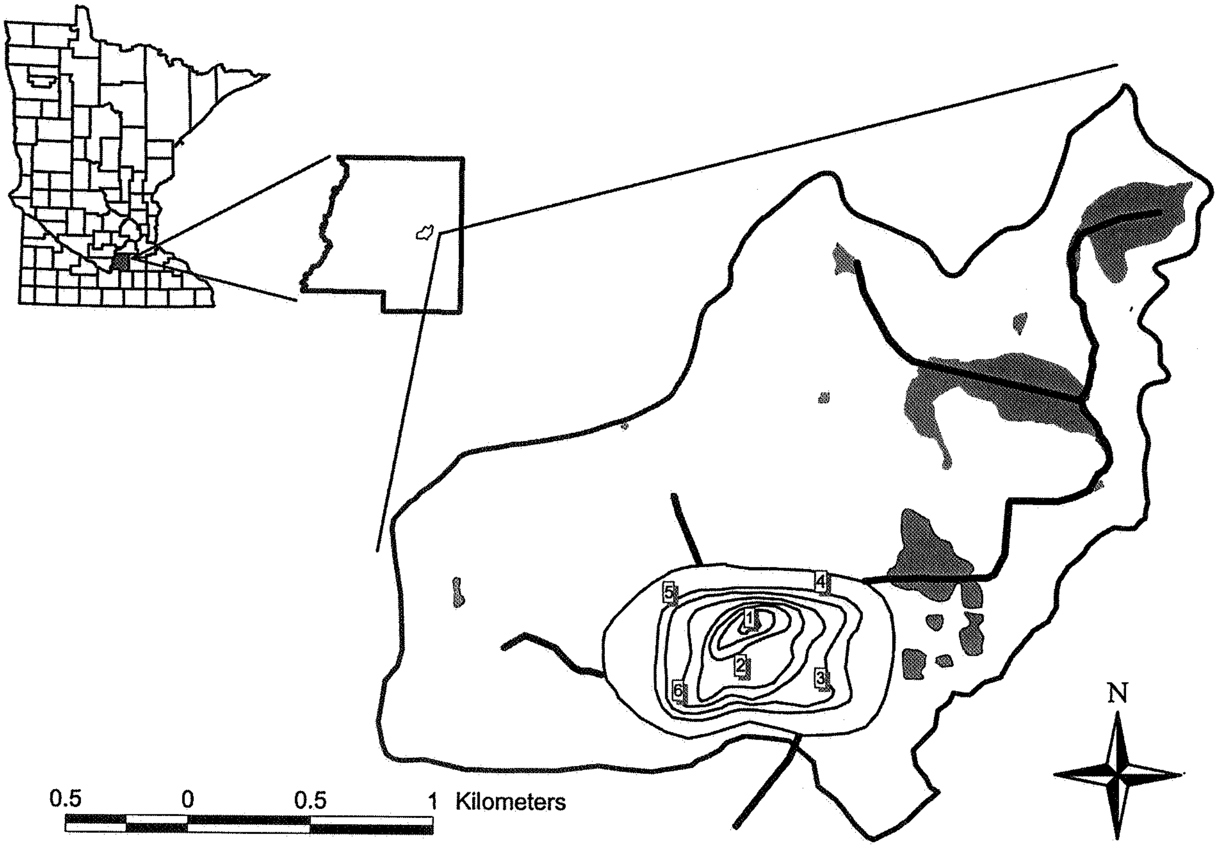

Figure 1.–Lake Volney and watershed, Le Sueur County, Minnesota. Core locations designated by number; depth contours = 3 m; wetlands denoted by shading in watershed.

total concentration of ferromagnetic materials. All measurements were made using a Superconducing Rock Magnetometer (SRM), and units are expressed as $m^3 \, kg^{-1}$ (dry weight).

Sediments subsamples for phosphorus analysis were dried for 24 h at 100 C and ground to a powder using a ceramic mortar and pestle. Total phosphorus (TP), organic-P, inorganic-P and non-apatite inorganic (NAI-P) were extracted using the procedures outlined by Brezonik and Engstrom (1998), and analyzed for orthophosphate by the ascorbic acid method (APHA 1985). Apatite-P was calculated as the difference between inorganic-P and NAI-P while organic-P was calculated as the difference between total-P and inorganic-P.

Additional sediments were freeze-dried in preparation for analysis of biogenic silica (bSi). bSi was extracted from 30 mg samples in 1% Na_2CO_3 for 3, 4 and 5 hours (Conley and Schelske 1993) and analyzed colorimetrically using an ascorbic acid technique (Wetzel and Likens 1991). Concentration of bSi were determined as the intercept of a line fit through the 3, 4, and 5 hour extractions (Conley and Schelske 1993).

Historical Data

Information about current and past land-use was collected from a variety of sources. Reconstruction of the pre-Euroamerican vegetation was based on the 1854 GLO bearing tree data and survey plats supplemented by Marschner's (1974) map of the *Original Vegetation of Minnesota*. While there is a wealth of information about the area following Euroamerican settlement, the records are not complete and the types of data collected have changed substantially through time. This necessitated describing trends at the county, township, and watershed level. Information on numbers of animals, land use, and land valuation within the Lake Volney watershed (or in the four townships containing the watershed) were taken from Le Sueur County personal and real property tax records. Some of these records were retained by the county but the bulk of the records were housed at the Minnesota Historical Society in St. Paul, Minnesota. This information was supplemented with U.S. Census agricultural information available by respondent for the 1860 and1880 census or else summarized for the entire county. In addition aerial photographs flown in 1937 were consulted and added to GIS data layers documenting current land use, National Wetlands Inventory data, and information gathered by the Minnesota Pollution Control Agency, and the Le Sueur County Clean Water Partnership Office.

Results

Sediment Composition and Dating

Surface sediments from all six cores were dominated by inorganic materials (54 - 68%) followed by $CaCO_3$ (21-32%) and organic matter (10-30%). Cores 3 and 4 from the east side of the lake had the highest percentages of inorganic matter. Percent $CaCO_3$ was consistently 1.5 - 2.0 times higher in the surface sediments than that observed for the pre-settlement samples within each core (Fig. 2A, 4B). Sediments in the gravity cores were characterized by sand and gravel, which led to the designation of the 5-m contour interval as the approximate boundary between depositional and non-depositional areas within the lake. Total depositional area was 72.1 ha.

The ^{210}Pb activity profile for the central core (Core 1) declines from surface values near 4 pCi g^{-1} to a near constant background (supported ^{210}Pb) of 1.0 pCi g^{-1} below 120 cm (Fig. 3). The down-core decrease is more or less exponential from the surface to about 48 cm and then fluctuates irregularly, indicating variable rates of sediment input. Dates calculated according to the constant rate of supply (c.r.s.) model have an uncertainty (based on counting precision – a minimum error) of less than ± 6 years for the last century; these errors rise substantially for the oldest three dated intervals, exceeding 40 years at 1845 (120 cm). The inventory of unsupported ^{210}Pb in the core (27.35 pCi cm^{-2}) is equivalent to a ^{210}Pb flux of 0.98 pCi $cm^{-2} \cdot yr^{-1}$. This value is about double the mean atmospheric flux of ^{210}Pb for the region (ca. 0.5 pCi $cm^{-2} \cdot yr^{-1}$), indicating higher sedimentation at the core-site than for the lake as a whole. That is, fine-grained sediment (and it's ^{210}Pb burden) is preferentially focused to this deep-water core site by wave and current action.

Lead-210 based sedimentation rates for the upper part of Core 1 (0-24 cm; 1970s -1990s) averaged 0.24 g $\cdot$ $cm^{-2} \cdot yr^{-1}$, four times higher than the 0.06 g $\cdot cm^{-2} \cdot yr^{-1}$ determined for the two lowest depth intervals (104-120 cm; 1840s-1880s) with unsupported activity (Fig. 3). Pre-Euroamerican sedimentation rates were extrapolated from this average for the two lowest depths. Sedimentation rates were highest in the late 1920s and again in the early 1950s, exceeding 0.85 g $\cdot cm^{-2} \cdot yr^{-1}$.

Based on the ^{210}Pb dating, sediments at 112-120 cm core depth correspond to the 1855–1860 arrival of Euroamerican agriculturists in the Volney watershed (Fig. 3). *Ambrosia* (ragweed) pollen – an indicator of disturbance associated with tillage agriculture – remained low (2.5-11.5%) until the 100 cm depth interval where it rose above 20% (Fig. 4B; 100 cm corresponds to a ^{210}Pb date of 1900).

ARM and SIRM declined together between 1850 and 1900 indicating an overall decrease in the concentration of magnetic materials in the sediments, concurrent with a rise in organic matter content (Fig. 4C). The ARM/SIRM ratio – a good indicators of magnetic mineral grain size (Banerjee et al. 1981) – declined only slightly from 1850 to 1900, indicating a slight shift to coarser grained materials. A more dramatic decline in

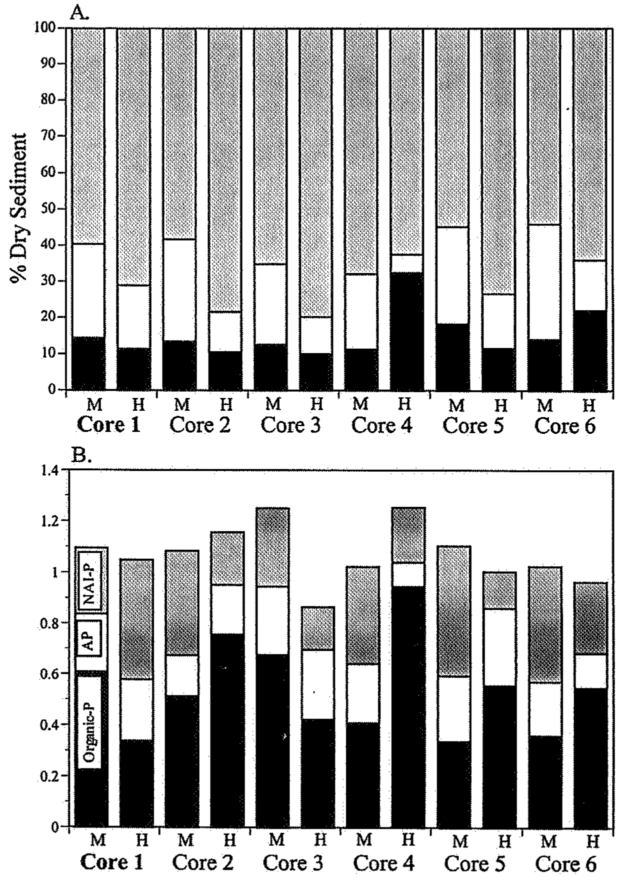

Figure 2.–Composition of modern (M) and pre-settlement (H) sediments in six cores from Lake Volney. Upper panel depicts percent organic matter, carbonate (Car), and inorganic matter as determined by loss on ignition; lower panel shows concentrations of total phosphorus and its fractions – organic-P (OP), apatite-P (AP), and non-apatite inorganic-P (NAI-P).

ARM/SIRM between 1900 and 1950 is driven by an increase in SIRM (Fig. 4), and indicates an influx of more coarse-grained magnetic materials.

Phosphorus and Biogenic Silica

Total phosphorus concentrations in the surface sediments of the six cores ranged from 1.02-1.25 mg·g^{-1} (‰) and were similar (Fig. 2B) to concentrations observed for the pre-Euroamerican sediments (0.86 - 1.25 ‰). Concentrations of NAI-P in the surface sediments were higher than those at depth for all but Core 1 (Fig. 2B).

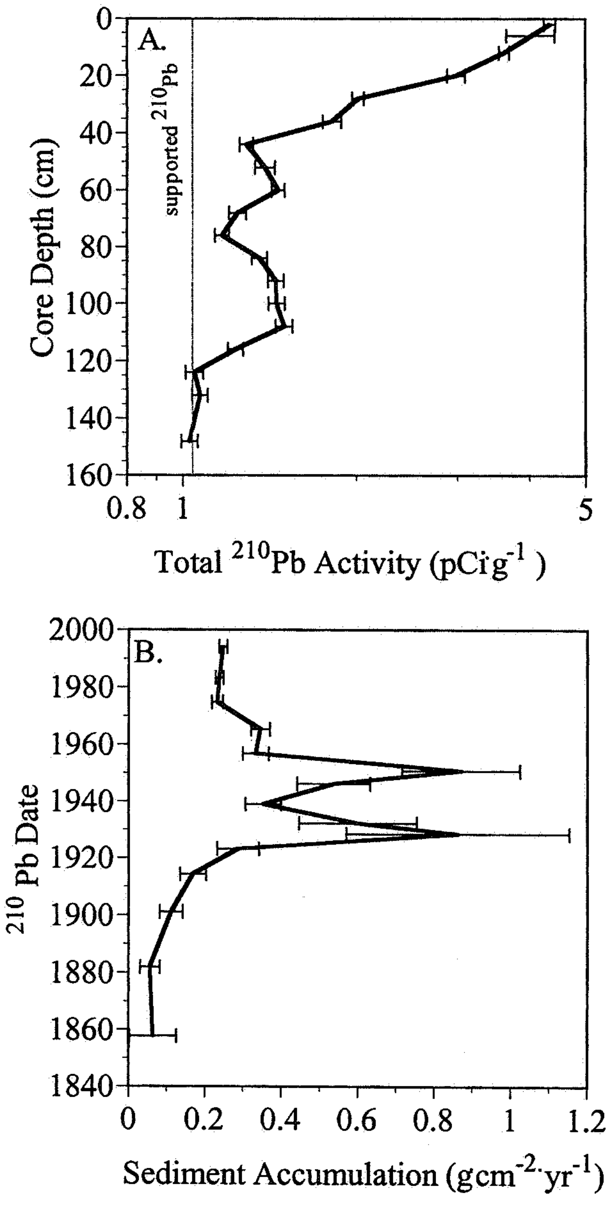

Figure 3.–Total ^{210}Pb activity profile for Core 1 (A) and sediment accumulation rates calculated according to the constant rate of supply (c.r.s.) model. Error bars represent ± 1 s.d. as propagated from counting uncertainty.

Whole basin fluxes were calculated for the central core based on the ^{210}Pb dating, a depositional area of 72.14 ha and a correction for sediment focusing (measured unsupported ^{210}Pb flux of 0.98pCi·cm^{-2}·yr^{-1} / atmospheric ^{210}Pb deposition of 0.50 pCi·cm^{-2}·yr^{-1}). The sediment based estimate of modern total-P flux (960 kg·yr^{-1}) is within 10% of the 1057 kg retained estimate of MPCA 1996). An area-based correction for focusing (not presented) yielded similar results.

Accumulation rates of P in the sediments, focusing corrected, were relatively constant (0.31 - 0.39 g·m^{-2}·yr^{-1}) until the 1850s (Fig. 4A); these values represent a lake-wide P-flux of 220-277 kg·yr^{-1}. From the 1850s to the early 1920s total-P accumulation tripled to 0.75 - 1.0 g·m^{-2}·yr^{-1} as a result of increases in organic-P and NAI-P, while apatite-P levels remained near their pre-1850s levels (Fig. 4A). P-accumulation doubled again in the 1920s, this time from increases in all three fractions including apatite-P (Fig. 4A). This final period (1920 - 1995) was characterized by considerable variation in total - P accumulation (0.9 - 3.9 g·m^{-2}·yr^{-1}) with 1930 and again 1950 being peak periods. Both of these times correspond with intervals of high sedimentation (Fig. 2B).

Flux rates for biogenic silica (bSi) showed little change (Fig. 4E) from 1650 until c. 1900, averaging 29 g·m^{-2}·yr^{-1}. bSi accumulation increased 5-10x in the 1910s averaging 178 g·m^{-2}·yr^{-1} between 1910 and 1995 with a high of 448 g·m^{-2}·yr^{-1} in 1930.

Land Use History

Pre-Euroamerican vegetation surrounding Lake Volney was a mixture of big woods (*Ulmus* spp., *Acer saccharum*, *Tilia americana*) forest (93% of land area) and wetlands (7%). By 1880 40% of the land in the Volney watershed had been converted to cropland, but this percentage remained relatively constant, and as late as 1920 37% of farmland was listed as cropland with 51% listed as undeveloped (Le Sueur County Real Property Tax Records; Fig. 5E). Undeveloped land included woodland and wetlands. The rapid early conversion to cropland and subsequent limited expansion was also evident for the surrounding townships and county (Fig. 5).

Early wetland drainage also occurred, but documenting timing is more problematic, as ditches and tiles in the watershed were private, and there is no record of their establishment. Public ditches were

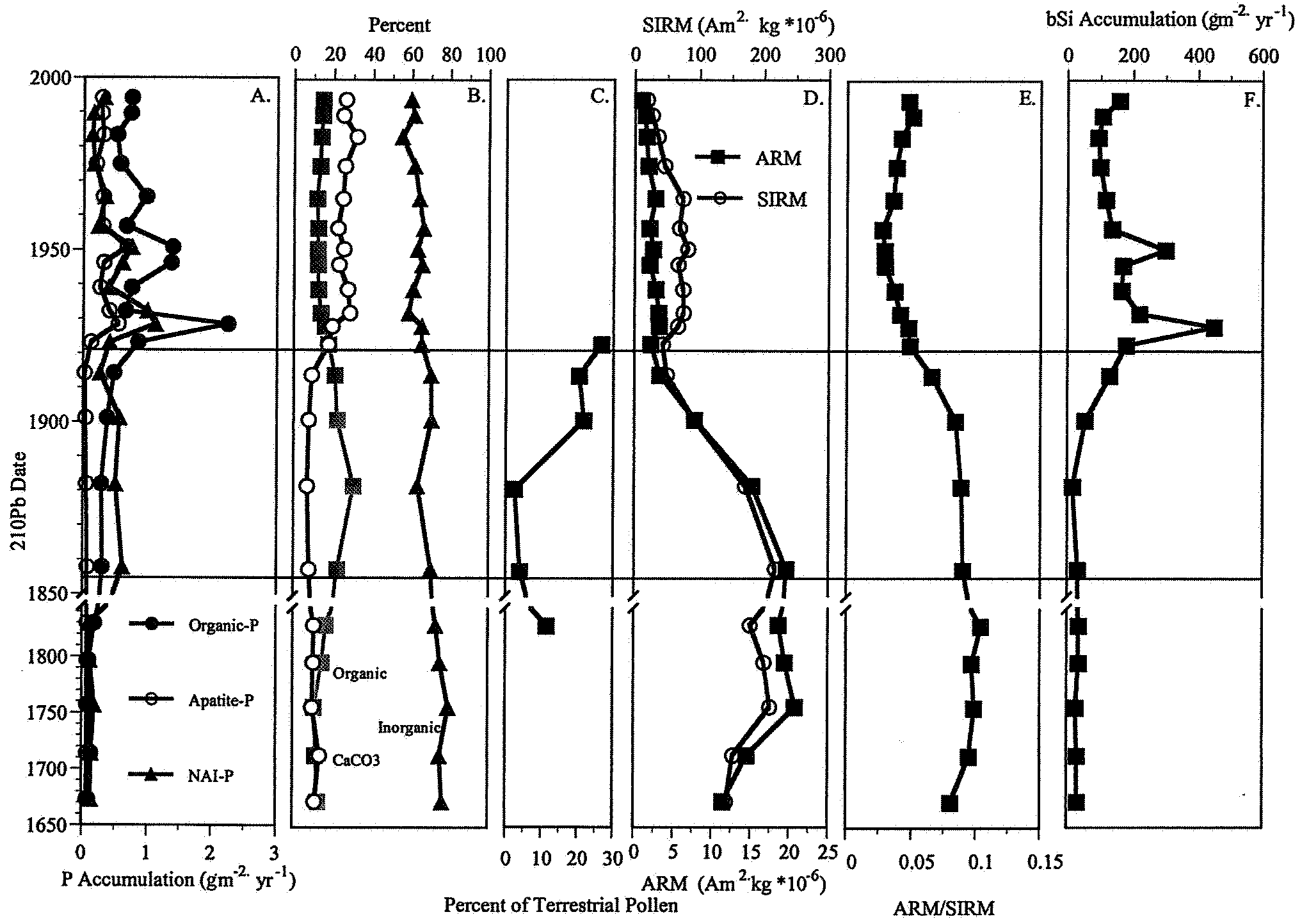

Figure 4.–Stratigraphic profiles from Core 1: (A) phosphorus accumulation, (B) loss-on-ignition, (C) Ambrosia ragweed pollen as a percent of terrestrial pollen grains, (D) mineral magnetics; anhysteric remnant magnetization (ARM) and saturation isothermal remnant magnetization (SIRM), (E) ratio of magnetic properties, and (F) biogenic silica (bSi) accumulation. Chronology determined by ^{210}Pb dating with dates prior to 1840 extrapolated from mean pre-1880 sedimentation rate (see text). Flux rates are focusing corrected.

already being constructed within Le Sueur County at the turn of the century, although the majority of drainage occurred in the mid 20th century (Fig. 5A). The ditch that drains the main wetland complexes within the Volney watershed and enters the NE corner of the lake (Fig. 1) is clearly visible in 1937 aerial photographs, and according to the present land owner, sections of this ditch were cleaned in the mid 1930s (Harry Gibbs, pers. comm.), implying an earlier establishment date. Success of these drainage efforts was limited, as these wetland basins were not cropped, although they were likely grazed. The early 1980s saw tiling and draining of the larger wetland complex immediately adjacent to the lake (Fig. 1).

For Le Sueur County as a whole, animal numbers rose rapidly in the late 19th century and then again after c. 1950s (Fig. 5). A rapid 20th-century increase in animal numbers also occurred in the four townships containing the Volney watershed, despite the virtual elimination of horses from farms between 1930 (average = 639 horses/ township) and 1940 (average = 6.9 horses/ township). Much of the recent increase in animal numbers has been due to greater numbers of hogs. Uncertainties regarding property tax records of animals within the watershed led to the calculation of animal densities for those farms reporting animal numbers (Fig. 5). Animal densities per farm increased five fold within the watershed, again led by increases in hogs, especially after 1910. Human populations in Le Sueur County increased during the 19th century from ~5300 in 1860 to ~20200 in 1900 to their current level of ~25000. Information on human populations within the watershed were not available, although lake-shore home-sites increased dramatically in the 1950s and 1960s with the platting of several developments and the construction of over 25 homes with septic systems.

Discussion and Conclusion

Lake Volney and its watershed have undergone dramatic changes over the past 150 years. Nearly all of the forests and wetlands present in 1855 (95% of watershed) were converted to agriculture fields and pastures, while the density of large domestic farm animals increased 400% (Fig. 5) from the 1850s to the 1950s. During this same time period, P inputs to

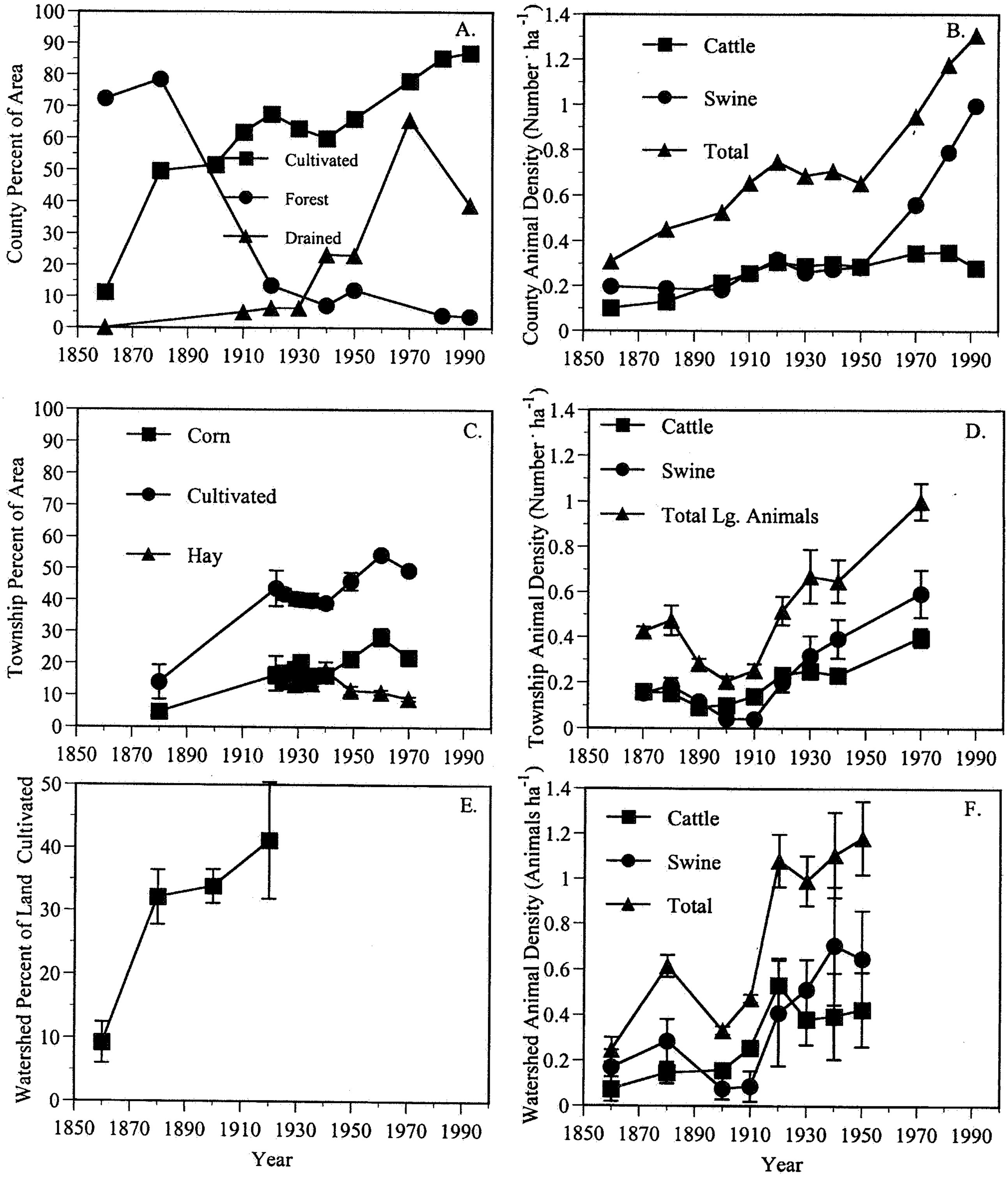

Figure 5.–Historical changes in land-use and animal numbers within Le Sueur Count (top panels), local townships (middle panels), and the Lake Volney watershed (lower panels).

the sediments increased five fold. This increase was not linear, and the late 1850s and 1920s were both periods of sustained increases in P accumulation that corresponded to shifts in biogenic silica, loss-on-ignition, mineral magnetics, and sedimentation rates (Fig. 4B-D). Changes in P inputs likely reflect land use shifts in the surrounding watershed as well as the oxygen regime of the lake and sediment-water interface.

Euroamerican agriculturalists arrived in the Volney watershed in 1855 and immediately began clearing trees and introducing domesticated animals. This activity was most likely the cause of the tripling in organic-P and NAI-P during the late 1800s. The rise in organic-P was most likely the result of increased productivity within the lake itself, which is also suggested by the rise in organic content and corresponding decline in magnetic material (Fig. 4). Soil erosion may have been the source of some of the additional P, but ARM/SIRM ratios – lower ratios indicate larger grain sizes (Banerjee et al. 1981) – declined only slightly, suggesting that overall erosion rates were low and/or the bulk of P entering the lake was dissolved-P. P-accumulation rates remained relatively constant until c. 1920 reflecting the relatively slow rise in domestic animal numbers within the watershed and adjacent townships and a nearly constant percent of land (40%) dedicated to tillage agriculture from 1880-1920. The relatively slow pace of clearing may also explain the delay of the *Ambrosia* pollen rise until 1900.

Accumulation rates for organic-P, NAI-P, and apatite-P all rose dramatically during the 1910s and 1920s (Fig. 4A). This rise in P and the sustained high levels within the lake most likely reflect a combination of factors. Increased apatite-P fluxes combined with a sharply lower ARM/SIRM ratio, and greatly accelerated sedimentation rates (Fig. 2) all point to higher soil erosion rates. However, there was no corresponding increase in the area of land devoted to cropland or decrease in hayfields or pasture within the four townships (Fig. 5). The increase in P accumulation is not due to the use of commercial fertilizers, which were introduced after WW II, but instead, manure and trampling from increased numbers of animals may have played a role. Animals are very inefficient users of P, and animal manure may be a major source of P loading (Sharpley and Rekolainen 1997).

Most (40%) of current P inputs to the lake come through a single ditch on the northeast side of the lake (Fig. 1). While it is known that this ditch was present in the 1930s, its date of establishment is uncertain, making it difficult to link ditch construction directly to the rise in P. Ditches and tiles may carry particulate P bound to organic or inorganic material, but as soils become P-saturated they may also carry significant amounts in dissolved form (Sharpley and Rekolainen 1997)

Eutrophication of the lake likely led to higher productivity and greater precipitation of carbonates – through photosynthetic uptake of CO_2 (Kelts and Hsu 1978, Hodell et al. 1998) – as well as organic matter, which in turn contributed to increased sedimentation. Greater eutrophication likely also led to an earlier onset of hypolimnetic anoxia (today typically in May, MPCA 1996). Anoxia is one of several factors that affect sediment-water exchange of P, and in general decreased oxygen levels result in greater internal P loading and lower P retention in the sediments. Higher productivity and positive feedbacks from anoxia and sediment P release may have caused an abrupt shift in trophic state, as suggested by the delayed response of biogenic silica to increases in P accumulation (Fig. 4).

Diatom-based reconstructions of lake-water P have shown that geochemical-based estimates of P accumulation can miss increases in release of P from sediment to the water column and so underestimate P loading to lakes (Anderson and Rippey 1994). Our estimates of modern P accumulation, however, match the MPCA (1996) mass-balance calculation of P sedimentation to within 10% (960 vs. 1060 kg$\cdot$yr^{-1}). The close match of our estimate is difficult to evaluate given its singular nature, but may indicate that anoxia is not a major control on P-release from sediments in this lake (Caraco et al. 1991).

If we assume that sediment P-retention has remained constant or was greater than present in pre-settlement times, then our results suggest a pre-1850s external load of 226-277 kg P$\cdot$yr^{-1}. Back-calculation of TP in the water column using the BATHTUB model (Walker 1986) results in a predicted average lake water concentration for TP of 33 ppb. These calculations assume an external load of 135 kg P$\cdot$yr^{-1} based on 117 kg$\cdot$yr^{-1} sediment-P accumulation, a retention coefficient of 0.85, and 10-50 kg$\cdot$yr^{-1} of soluble P. These estimates are within the range of pre-settlement total-P (34 ± 15 ppb) as reconstructed from sedimentary diatoms for 15 lakes in west central and southern Minnesota (Ramstack 1999). Such pre-disturbance levels are 4-5 times lower than the 1995 observed value of 170 ppb or the modeled value of 109 ppb (MPCA 1996), and are toward the lower end of the interquartile range (23-50 ppb) for reference lakes in the North Central Hardwoods Forest Ecoregion of Minnesota (MPCA 1999).

While based on only a single lake, our results in combination with the work of Ramstack (1999) suggest that Volney and other lakes in southern and south central Minnesota (especially those in the NCHF region) were not naturally eutrophic as often assumed, but were instead mesotrophic (see review by Anderson 1995). If a return to more "natural" condition is a reasonable management goal, then current objectives to reduce P concentrations to 60-80 ppb for Lake Volney (MPCA 1996) may not be aggressive enough. However, the actual goals for any specific lake will depend upon a host of economic, recreational, and ecological considerations (Carpenter et al. 1999). In general, our results point to the efficacy of a combination of historic approaches in understanding the impact of land-use on lake water quality and the development of management goals for lake improvement (Anderson 1995, Siver et al. 1999).

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