



Determination and Quantification of Factors Controlling Pollutant Delivery from Agricultural Land to Streams in the Lake Champlain Basin

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1. *A Research and Monitoring Agenda for Lake Champlain.* Proceedings of a Workshop, December 17-19, 1991, Burlington, VT. Lake Champlain Research Consortium. May, 1992.
2. *Design and Initial Implementation of a Comprehensive Agricultural Monitoring and Evaluation Network for the Lake Champlain Basin.* NY-VT Strategic Core Group. February, 1993.
3. (A) *GIS Management Plan for the Lake Champlain Basin Program.* Vermont Center for Geographic Information, Inc., and Associates in Rural Development. March, 1993.

(B) *Handbook of GIS Standards and Procedures for the Lake Champlain Basin Program.* Vermont Center for Geographic Information, Inc. March, 1993.

(C) *GIS Data Inventory for the Lake Champlain Basin Program.* Vermont Center for Geographic Information, Inc. March, 1993.
4. (A) *Lake Champlain Economic Database Project. Executive Summary.* Holmes & Associates. March 1993.

(B) *Socio-Economic Profile, Database, and Description of the Tourism Economy for the Lake Champlain Basin.* Holmes & Associates. March 1993

B) *Socio-Economic Profile, Database, and Description of the Tourism Economy for the Lake Champlain Basin. Appendices.* Holmes & Associates. March 1993

(C) *Potential Applications of Economic Instruments for Environmental Protection in the Lake Champlain Basin.* Anthony Artuso. March 1993.

(D) *Conceptual Framework for Evaluation of Pollution Control Strategies and Water Quality Standards for Lake Champlain.* Anthony Artuso. March 1993.
5. *Lake Champlain Sediment Toxics Assessment Program. An Assessment of Sediment - Associated Contaminants in Lake Champlain - Phase 1.* Alan McIntosh, Editor, UVM School of Natural Resources. February 1994.

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6. (A) *Lake Champlain Nonpoint Source Pollution Assessment.* Lenore Budd, Associates in Rural Development Inc. and Donald Meals, UVM School of Natural Resources. February 1994.

(B) *Lake Champlain Nonpoint Source Pollution Assessment. Appendices A-J.* Lenore Budd, Associates in Rural Development Inc. and Donald Meals, UVM School of Natural Resources. February 1994.

7. *Internal Phosphorus Loading Studies of St. Albans Bay. Executive Summary.* VT Dept of Environmental Conservation. March 1994.

(A) *Dynamic Mass Balance Model of Internal Phosphorus Loading in St. Albans Bay, Lake Champlain.* Eric Smeltzer, Neil Kamman, Karen Hyde and John C. Drake. March 1994.

(B) *History of Phosphorus Loading to St. Albans Bay, 1850 - 1990.* Karen Hyde, Neil Kamman and Eric Smeltzer. March 1994.

(C) *Assessment of Sediment Phosphorus Distribution and Long-Term Recycling in St. Albans Bay, Lake Champlain.* Scott Martin, Youngstown State University. March 1994.
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10. *Population Biology and Management of Lake Champlain Walleye.* Kathleen L. Newbrough, Donna L. Parrish, and Matthew G. Mitro, Fish & Wildlife Research Unit, University of Vermont. June 1994.
11. (A) *Report on Institutional Arrangements for Watershed Management of the Lake Champlain Basin. Executive Summary.* Yellow Wood Associates, Inc. January 1995.

(B) *Report on Institutional Arrangements for Watershed Management of the Lake Champlain Basin.* Yellow Wood Associates, Inc. January 1995.

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12. (A) *Preliminary Economic Analysis of the Draft Plan for the Lake Champlain Basin Program. Executive Summary.* Holmes & Associates and Anthony Artuso. March 1995

(B) *Preliminary Economic Analysis of the Draft Plan for the Lake Champlain Basin Program.* Holmes & Associates and Anthony Artuso. March 1995
13. *Patterns of Harvest and Consumption of Lake Champlain Fish and Angler Awareness of Health Advisories.* Nancy A. Connelly and Barbara A. Knuth. September 1995.
14. (A) *Preliminary Economic Analysis of the Draft Plan for the Lake Champlain Basin Program. Executive Summary - Part 2.* Holmes & Associates and Anthony Artuso. November 1995

(B) *Preliminary Economic Analysis of the Draft Plan for the Lake Champlain Basin Program - Part 2.* Holmes & Associates and Anthony Artuso. November 1995
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16. *Background Technical Information for Opportunities for Action: An Evolving Plan for the Future of the Lake Champlain Basin.* Lake Champlain Basin Program. June 1996
17. (A) *Executive Summary. Economic Analysis of the Draft Final Plan for the Lake Champlain Management Conference.* Holmes & Associates and Anthony Artuso. July 1996

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18. *Catalog of Digital Spatial Data for the Lake Champlain Basin.* Vermont Center for Geographic Information, Inc. September 1996.
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25. *Urban Nonpoint Pollution Source Assessment of the Greater Burlington Area.* Urban Stormwater Characterization Project. James Pease, VT Dept. of Environmental Conservation. December 1997
26. *Long-Term Water Quality and Biological Monitoring project for Lake Champlain.* Cumulative Report for Project Years 1992- 1996. VT Dept of Environmental Conservation and NYS Dept of Environmental Conservation. March 1998.
27. *Cumberland Bay PCB Study.* Clifford W Callinan, NY State Dept. of Environmental Conservation; Lyn McIlroy, Ph.D., SUNY Plattsburgh; and Robert D. Fuller, PhD., SUNY Plattsburgh. October 1998.

28. *Lake Champlain Underwater Cultural Resources Survey. Volume 1: Lake Survey Background and 1996 Results.* Scott A. McLaughlin and Anne W. Lessman, under the direction of Arthur B. Cohn, Lake Champlain Maritime Museum. December 1998.
29. *Evaluation of Soil Factors Controlling Phosphorus Concentration in Runoff from Agricultural Soils in the Lake Champlain Basin.* Frederick R. Magdoff, William E. Jokela, and Robert P. Durieux, UVM Department of Plant and Soil Sciences. June 1997.
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31. *Estimation of Lake Champlain Basinwide Nonpoint Source Phosphorus Export,* William Hegman, Associates in Rural Development, Inc., Deane Wang and Catherine Borer, UVM Water Resources & Lake Study Center, September 1999.
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35. *Determination and Quantification of Factors Controlling Pollutant Delivery from Agricultural Land to Streams in the Lake Champlain Basin.* J.W. Hughes, W.E. Jokela, D. Wang, C. Borer, UVM. September 1999.

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Determination and Quantification of Factors Controlling Pollutant Delivery from Agricultural Land to Streams in the Lake Champlain Basin

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Project Personnel

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EXECUTIVE SUMMARY

This study had three distinct components. The first assessed the types of land use or "buffers" that separate agricultural fields from surface waters in the Lake Champlain Basin (LCB). The second evaluated the role of an important buffer type, grassy vegetation, in reducing phosphorus loading from agricultural fields to surface waters. This component used a field scale approach employing a variety of sites in the Lake Champlain Basin. The third component (funded separately by USDA) assessed vegetative uptake of phosphorus in riparian buffers.

The analysis of existing buffers that separate agricultural fields from surface waters was conducted for the Vermont portion of the Lake Champlain Basin using available data and maps. A systematic sampling of 5% of orthophotographs (1:5,000 scale) in this region led to the development of a classification scheme of buffer types, and to the identification of "critical" buffer areas that might significantly contribute phosphorus (P) into surface waters in the Basin.

Two thirds of the stream banks in the Lake Champlain Basin had vegetated buffers at least 10 m in width. The predominant streamside buffer was 10-15 m wide (26% of our sample), followed by buffers 20-25 m in width (23%), and 30-40 m in width (17%). The most common buffer type in the Lake Champlain Basin was a narrow buffer of grassy or herbaceous vegetation.

Three field sites with buffer areas adjacent to and downslope of cultivated cornfields were established to initiate experimental studies of these important buffer areas. The sites had predominantly grassy/herbaceous vegetation and soils with limited drainage, but sites with wide buffers were selected so that changes in water and soil chemistry across the buffer could be measured. To address buffer function, runoff samples were collected from approximately 45 runoff events using surface runoff collectors (funnel collectors). In addition, grab samples of channelized runoff were collected during 18 relatively high runoff events. The study period extended from early summer 1996 through mid-summer 1997. Water samples were analyzed for total P (TP), and selected samples were analyzed for total suspended solids (TSS), pH, soluble reactive P (SRP), and bioavailable P (BP).

Patterns of total phosphorus concentration and mass flux in runoff collected in the grass covered downslope buffers were highly variable. Some overall patterns did emerge, however. Phosphorus concentrations were almost always higher with higher intensity rainfall events. While sites tended to behave differently, there was a trend of decreasing phosphorus concentrations with distance from the edge of field. While the high variability made it difficult to identify the nature of this distance-P reduction trend, many of the results from individual rain events suggest a threshold or curvilinear relationship, especially with high intensity rain events.

High P concentrations were often reduced to half of their starting value after transit through the buffer. More moderate concentrations were also generally reduced to lower levels after passing through 10-15 m of buffer.

Sediment-bound P dominated the flux of P across the studied buffers. Our results thus suggest that the major, immediate role of buffers is to slow surface runoff to permit sedimentation of small-sized, P-rich particulates.

P storage in aboveground vegetation of buffers was only 16.9 kg ha^{-1} , but all of this P was once biologically available, and therefore likely to promote eutrophication in downslope waters. Concentration of P in different plant tissues (roots, litter, aboveground), and among

different plant species, varied little. Plant biomass in the buffer therefore had a much greater effect on P attenuation than species composition of buffer plants.

In addition to storage of P in plant tissue, vegetated buffers also reduced streamside erosion and slowed runoff from upslope fields. Flow reductions caused sediment-bound P to settle into the buffer before it reached the stream. Vegetation in buffers downslope of agricultural fields should therefore be managed to maximize surface cover and density, as well as biomass.

Based on our field studies of streamside buffers on critical sites (i.e., sites with high runoff potential), most buffers > 10 m in width significantly reduced phosphorus loading to surface waters of the Lake Champlain Basin. Our findings should not be construed to mean that buffers > 10 m in width are necessarily adequate to protect water quality in LCB. Ecologically meaningful attenuation of phosphorus in buffers is influenced by a great many factors that vary from site to site. Vegetated buffers less than 5 m in width (about 15% of the stream banks in the Champlain Basin) are probably the most critical as a rule, but upslope topography, soils, and farming practices all affect phosphorus levels entering buffers.

The variety of factors influencing buffer function appeared to be large (e.g., rain intensity, soil condition, slope, microtopographic factors, etc.). This diversity and complexity hindered development of generalizations about buffer function in a complex landscape. For example, bioturbation, especially tunneling by small mammals, was observed at one site. This activity may hinder function of grassy buffers. However, where subsurface channels were not present, grass buffers appeared to be quite effective at retaining phosphorus from upgradient fields during the growing season. This effectiveness appeared to be less consistent under conditions of snowmelt and frozen ground. Given the complex diversity of buffer types and function in the Basin, a broader sampling of buffers using a probabilistic approach may be more suitable to developing an understanding of the overall role of vegetated buffers in ameliorating phosphorus loading to Lake Champlain.

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INTRODUCTION

The movement of anthropogenic phosphorus from deposition as chemical fertilizer or manure to eventual influx into Lake Champlain is the subject of several on-going and complementary efforts in the Basin ranging from in-field nutrient management to in-stream transport and transformation (Lake Champlain Management Conference 1996). Retention of phosphorus mobilized from agricultural fields as surface runoff may be an important component of source reduction strategies (Addiscott 1997, Correll 1997).

In the Lake Champlain Basin, the buffer between managed fields and the surface water network is a complex and diverse landscape element. A wide variety of landscape types, slopes, vegetative cover, topographic positions, buffer widths, and managed conditions exist and influence the process of phosphorus retention. In order to prioritize efforts to understand and quantify the function of these buffers in the Basin, dominant and critical types need to be identified. Experimental or field research on specific buffers, particularly those downslope buffers that receive runoff funneled off of fields (flow collectors), can then be initiated in the Basin to develop a locally referenced understanding of the functioning of these systems. This research, in combination with existing empirical and modeling studies in other parts of the world (e.g., Wilson 1967, Tollner et al. 1976, 1977, Barfield et al. 1979, Schlosser and Karr 1981, Lee et al. 1989, Altier et al. 1994, Barling and Moore 1994, Uusi-Kamppa and Ylaranta 1996) can then form the basis for continuing studies necessary to understand the complex and variable process of phosphorus retention outside of agricultural source areas.

This report summarizes field and landscape-level research in the Lake Champlain Basin conducted to evaluate the potential role of buffers downslope of agricultural fields. While definitive results on such a broad question are not to be expected, initial results supplementing research in this and other areas of the country should permit an initial assessment of the ecological value of such areas and assist with setting the relative priority for management and policy initiatives.

LITERATURE REVIEW

Human pollution contributes approximately two million tons of phosphorus (P) to the ocean each year (Emsley and Hall, 1976). Much of this P originates along inland waterways at either point or non-point sources (Harper, 1992). Point sources include areas of concentrated P addition such as sewage outfall pipes, whereas non-point sources (NPS) include diffuse P additions over a large area, such as fertilizer runoff from agricultural fields.

In the last ten years, point sources of P pollution have been more easily identified and controlled. As a result, non-point sources currently contribute a greater proportion of P to surface water pollution than they did in the mid-1980's (Crowder and Young, 1988; Welsh, 1991). NPS-P pollution from agricultural land is of special concern (Lee, 1973; U.S. EPA 1995) because it is very widespread yet very difficult to control (U.S. EPA, 1990, 1995; Welsh, 1991).

Phosphorus is an essential and often limiting nutrient in freshwater ecosystems (Emsley and Hall, 1976; Harper, 1992). Large or prolonged P additions that maintain P levels of 10 $\mu\text{g/L}$ or more in surface water, however, can cause excessive plant growth (Harper, 1992; Sharpley and Smith, 1989b). This process, termed eutrophication, is characterized by algal blooms and anoxic conditions (Harper, 1992) that degrade the fishing, industrial, recreational, and aesthetic values (Dates, 1994; Harper, 1992; Welsh, 1991).

Occasional eutrophication of standing surface waters is a normal occurrence following spring and fall lake turnover and snowmelt runoff (Harper, 1992). Natural eutrophic episodes are typically of short duration, however, because the P is rapidly depleted and explosive algal growth ceases (Harper, 1992).

Surface waters from largely agricultural watersheds can be severely impacted by eutrophication (U.S. EPA 1995). For example, the nutrient status of Lake Champlain in northern Vermont is notably influenced by P additions from agricultural land in the Champlain Valley (Clausen and Meals, 1989; Meals, 1990; VT Agency. of Nat. Res., 1992). Silage cornfields are thought to be particularly important contributors to NPS P pollution because of their low vegetative cover in spring and fall, and high manure application rates (Jokela, 1991).

Phosphorus in Agricultural Soil

Phosphorus occurs in both particulate and dissolved forms in soil. Particulate-P includes phosphorus bound to inorganic and organic soil particles (Brady 1990; Pierzynski and Logan, 1993). Most dissolved-P in the soil solution occurs as one of two inorganic anionic forms, the ratio of which is dependent on pH (Brady, 1990). H_2PO_4^- is the dominant anion at pH values below 7.2 whereas the HPO_4^{2-} anion dominates at higher pH (Brady, 1990; Salisbury and Ross, 1992). These two phosphate anions are the primary components of dissolved-P and are both available for algal (and vascular plant) uptake (Sharpley et al., 1993). HPO_4^{2-} is less easily absorbed than H_2PO_4^- , however, because its -2 charge makes passage through the cell membrane more difficult (Cembella et al. 1984).

Several different chemical analyses are used to quantify presence of phosphorus in soil. Total phosphorus (TP), is the collective term for P bound to or contained in soil particles, and also P from the soil solution that became adhered to the surface of soil particles when the soil was dried. Dry soil contains from 0.02-0.50% TP (Bear, 1964).

Soil test phosphorus (STP) is an analytical attempt to correlate the regional growth response of plants to the extractable P content of soil. STP analysis methods vary between different geographic areas of the U.S., but in general consist of a weak acid extraction. As with TP measurements, STP analyses use dried soil and therefore contain both particulate P and previously dissolved P components.

Vermont soils are routinely analyzed for two types of STP, available STP (STPa) and reserve STP (STPr). Both measurements are done using the Modified Morgan extract (McIntosh, 1969), however the STPr extract also includes the addition of NH_4F to aid in the removal of aluminum bound P (Bartlett, 1982). STPa may correlate well to the amount of P that desorbs into the soil solution, or into runoff water (Sharpley et al., 1993). STPr, in contrast, estimates the amount of soil P bound in aluminum phosphates (Bartlett, 1982). Aluminum bound P is, for the most part, unavailable to plants, but can be slowly released and serve as a long term P source (Brady, 1990).

STP levels of agricultural soil are ranked high to very high for many areas of the country. In Vermont, 42% of all cornfields have STPa levels in plow layer soil that are considered high to excessive (Jokela et al., 1995), whereas 55% of all cornfields have STPr levels in plow layer soil that are high to excessive (Jokela et al., 1995).

High manure application rates over many years can cause elevated STP levels in plow-layer soil (Sharpley et al., 1993; White and Collins, 1982), one plausible explanation for the elevated STP levels of some Vermont agricultural soils. For example, farms that have a high animal density can produce more manure than is needed to fertilize fields. In such instances, manure may be over applied to fields as a waste disposal method, resulting in elevation of STP levels far above crop requirements (Sharpley et al., 1994). STP levels can also become elevated because manure application rates are often based on crop nitrogen needs (White and Collins, 1982). Cow manure has a nitrogen to phosphorus ratio of about 3:1 (mass to mass), whereas most crops require a higher ratio, about 8:1 (White and Collins, 1982). This results in an over application of manure to attain the desired nitrogen level (White and Collins, 1982).

Dissolved and particulate-P in soil are closely interconnected, with depletion of one form leading to replacement with P from other forms (Olsen and Khasawneh, 1980; Sharpley et al., 1981). For example, depletion of dissolved-P anions from the soil solution by plant uptake shifts the equilibrium between particulate and dissolved-P and instigates release of dissolved-P from particulate-P pools (Brady, 1990; Olsen and Khasawneh, 1980; Sharpley et al., 1991, 1994).

The extractable aluminum content, percent organic matter, and pH of soil can all significantly affect P availability. Areas with elevated levels of extractable aluminum can have P availability problems because the aluminum readily binds with dissolved-P that would otherwise have been available to plants (Bartlett, 1982). The detrimental effects of high aluminum levels on dissolved-P can be controlled by lime applications, because liming decreases the activity of aluminum in soil by binding aluminum ions into insoluble complexes (Bartlett, 1982).

Lime applications also increase the amount of dissolved-P in soil by increasing P mineralization rates (Trasar-Cepeda et al., 1991), and increasing soil pH (Brady, 1990; Trasar-Cepeda et al., 1991).

Dissolved-P is more available at lower pH values because, H_2PO_4^- , the more plant available phosphate anion dominates when the soil solution pH is below 7.2 (Brady, 1990).

Organic matter content in soil also influences the amount and availability of soil P. Approximately half of soil P is associated with organic matter (Bear, 1964); however, in areas like Vermont where field application of manure is widespread, this percentage may be even higher (James et al., 1996). Organic matter from manure influences the amount of plant available-P by releasing dissolved-P through mineralization (Dillaha et al., 1988), and by binding with aluminum and iron hydroxides that would otherwise bind to free P anions (Brady, 1990). Despite these ways in which manure can increase P release from buffer zones, Sharpley et al. (1991) state that particulate-P may also bind to organic matter in surface soils, possibly increasing their P retention capacity.

Phosphorus Loss From Agricultural Fields

Phosphorus is lost from agricultural fields in surface runoff and shallow groundwater flow (Peterjohn and Correll, 1984). Surface runoff carries both dissolved and particulate-P whereas groundwater carries only dissolved-P (Peterjohn and Correll, 1984). The amount of P lost from fields is not economically important to farmers (Sharpley et al., 1994), but can make significant contributions to the eutrophication potential of surface water (Truman et al., 1993).

The majority of P lost from agricultural fields is bound to soil particles that are eroded in surface runoff (Dillaha et al., 1989a; Sharpley 1985). Over three billion tons of sediment leave agricultural fields in the US every year (Truman et al., 1993), and it is not uncommon for over 70% of runoff-P from a tilled field to be particulate (Burwell et al., 1977; Sharpley et al., 1991; Sharpley et al., 1994). Particulate-P availability is highly variable (Sharpley et al. 1991), and it primarily serves as a long-term source of available-P to algae (Truman et al., 1993).

The erosive power of runoff depends largely on the type of flow moving across the field. Slope, surface roughness, and microtopography are all important in determining the rate and type of surface runoff flow (Phillips, 1989). Sheet flow is shallow (30 mm or less), uniform, slow flow that occurs on gentle, even slopes with little microtopography (Castelle et al. 1994; Dickey and Vanderholm, 1981). More extreme slopes or those with a more varied topography create areas of rapid concentrated flow known as channelized flow (Dillaha et al., 1988; Phillips 1989a). The increased speed of channelized flow allows it to carry more sediment than sheet flow (Phillips, 1989b).

Dissolved-P makes up a relatively small portion of runoff-P (5-30%), however, it increases algal growth in culture after only 2 days (Sharpley et al., 1991), and is the type of P primarily responsible for algal blooms (Sharpley et al., 1994). The amount of dissolved-P in runoff is dependent on several factors including field nutrient amendments, the season, and the amount of decaying vegetation in the buffer strip (Daniels and Gilliam, 1996; Osborne and Kovacic, 1993; Uusi-Kämpä and Yläntä 1992; Vought et al. 1994). Dissolved-P is added to surface runoff as it moves across the soil particles and decaying organic matter on the field surface (Sharpley and Smith, 1989a). These interactions typically extend only 1-2 cm into the surface soil and rarely reach deeper than 5 cm (Sharpley, 1985).

Presumably, little P is lost from agricultural fields in shallow groundwater (Jordan et al., 1993; Osborne and Kovacic, 1993; Vought et al., 1994) because dissolved-P binds rapidly to soil, and can be taken up by plants as it infiltrates (Phillips, 1989a). Soil deeper than 2-3 cm is considered an almost inexhaustible sink for dissolved-P because it contains numerous unfilled anion adsorption sites (Bear, 1964; Sharpley et al., 1993). In particular, soil with large numbers of iron and aluminum oxides (Wood, 1984), or calcium ions (James et al., 1996) are very effective at binding P into insoluble complexes. Once bound, P is considered virtually immobile in soil (Brady, 1990).

Small amounts of P leaching to subsurface flow have been reported, however (Osborne and Kovacic, 1993; Peterjohn and Correll, 1984; Vought et al., 1994). Areas with coarse soil texture or structure can have rapid infiltration and attain higher than normal groundwater P levels (Gilliam, 1994).

Particulate-P in soil is in equilibrium with dissolved-P in runoff and can contribute to runoff P in some cases (Sharpley, 1985; Sharpley et al., 1993, 1994; Sims, 1993; Stevens et al., 1993). In particular, STPa measures the potential for a given soil to enrich the P content of runoff (Sharpley et al., 1991, 1993). Eroded soil particles can also influence eutrophication by slowly releasing dissolved-P to surface water (Sims, 1993; Truman et al., 1993). Evidence supporting this was found by Sharpley et al. (1991) who reported that algal growth was highly correlated to the STP content of soil added to an assay after 15 days.

Phosphorus Retention in Buffers

The band of uncultivated land between an agricultural field and the waters edge is often termed the "riparian buffer zone" or "buffer strip". Vegetated buffer strips have been encouraged as a best management practice to help slow NPS pollution of surface water in many areas of the country (Dillaha et al., 1989b), and in Vermont, they are currently required between row crops and perennial streams (Vermont Dept. of Ag., 1995).

Buffer strips retain dissolved and particulate-P in runoff from agricultural fields (Cooper and Gilliam, 1987; Daniels and Gilliam, 1996; Lowrance et al., 1984, 1985; Peterjohn and Correll, 1984) and other sources of high nutrient runoff (Dickey and Vanderholm, 1981; Dillaha et al., 1988, 1989a; Young et al., 1990). Retention occurs through the processes of infiltration, adsorption, uptake, decay, filtration and deposition (Karr and Schlosser, 1978; Lowrance et al., 1984). Phosphorus is removed from runoff primarily through particulate-P deposition and dissolved-P binding to soil particles in the buffer (Vought et al., 1994). Thickly vegetated buffers are particularly effective at particulate-P retention because of the surface roughness created by stems that slow runoff and filter out Particulate-P (Castelle et al., 1994; Daniels and Gilliam, 1996; Gilliam, 1994; Schlosser and Karr, 1981; Vought et al., 1994). Dissolved-P retention by surface soil in buffers is not very efficient because exposed anion exchange sites are rapidly saturated (Cooper and Gilliam, 1987). Dissolved-P adsorption drops off rapidly with depth (Ahuja et al., 1981; Sharpley and Smith, 1989b) in most strips because of slow infiltration (Philips, 1989a). Soils with higher infiltration rates, however, can expose deeper soil layers and plant roots to dissolved-P for binding and uptake (Dillaha et al., 1988; Lowrance et al., 1985; Philips, 1989; Westerman et al., 1983).

Herbaceous vegetation and deciduous tree leaves do not serve as long-term P storage pools in riparian zones (Lowrance et al., 1985), but can contain a large portion of the total-P absorbed by vegetation in a season. For example, Peterjohn and Correll (1984) found that of the 9.9 kg P/ha absorbed by trees, 7.8 kg P/ha/yr. was returned to the soil as litter. Likens et al. (1977) report that forest plants take up approximately 12.5 kg P/ha/yr and return 11 kg P/ha/yr to the soil as litter. With the exception of standing stems, all P that is held in aboveground herbaceous vegetation is returned to the soil surface as litter.

Plant roots indirectly increase infiltration rate of runoff by maintaining soil structure (Castelle et al., 1994). High infiltration rates, in turn, expose plant roots to dissolved-P for absorption (Dillaha et al., 1988; Lowrance et al., 1985; Peterjohn and Correll, 1984; Westerman et al., 1983).

Increased buffer width typically corresponds to greater P storage capacity (Dillaha et al., 1988; Truman, 1993). Dillaha et al. (1989a) reported a 69% decrease in runoff TP after passage

through a 4.6 m vegetated buffer, and an 82% decrease after passage through a 9.1 m buffer. Combined data from several studies also suggest that the decrease in runoff-P with increased buffer width is exponential (Vought et al., 1994).

The first few meters of a buffer strip are the most important in nutrient retention (Daniels and Gilliam, 1996; Vought et al., 1994; Westerman et al., 1983). Daniels and Gilliam (1996) found that runoff sediment and particulate-P exhibit a particularly noticeable decrease in the first 3 m of a grassed filter strip. Vought et al. (1994), however, combined data from several studies and found that the first 5 m of buffer were most important in effecting P reductions.

Elsewhere, vegetated buffer strips at least six meters wide have retained from 60-80% of the total-P (particulate-P + dissolved-P) content of entering runoff (Daniels and Gilliam, 1996; Dillaha et al., 1988, 1989a; Lowrance, 1983; Peterjohn and Correll, 1984; Vought et al., 1994; Young et al., 1980). The level of dissolved-P retention in buffers has been more variable with reductions ranging from 20-74% after passage through buffer strips four or more meters wide (Daniels and Gilliam, 1996; Lowrance, 1984; Young et al., 1990).

Ephemeral channels through buffer strips drastically decrease the effectiveness of P-retention in buffers (Daniels and Gilliam, 1996; Dickey and Vanderholm, 1981). Dillaha et al. (1988) found that strips with concentrated flow were 61-70% less effective at total runoff-P removal than strips with sheet flow.

The dissolved and particulate-P retained in buffers is not held permanently and may still be released. For instance, when the dissolved-P binding sites in surface soil become saturated, the soil can lose P to surface water through exchange and erosion (Dillaha et al., 1989a; Sharpley, 1985; Sharpley et al., 1993, 1994). Dissolved-P in vegetation can also be released during dormancy or at senescence. The particulate-P retention capacity of buffers also may decline over time as buffers become saturated (Dillaha et al., 1988, 1989a,b; Uusi-Kämpä and Ylärinta, 1992).

Management Considerations

Buffer strip regulations have recently been established in Vermont to help reduce agricultural additions of P and other pollutants to surface water. The width requirements of the current regulations are determined by the type of runoff flow through the buffer with little consideration of other variables (Vermont Dept. of Ag., 1995). Perennial vegetation cover in buffers is required by the current Vermont regulations, but there is no recommendation on the type of vegetation (Vermont Dept. of Ag., 1995). The P-retaining efficiency of existing buffer strips could be enhanced by requiring dense vegetation to promote bank stabilization. Recommendations on the type of vegetation would also increase buffer's effectiveness as a thickly grassed strip would have a much higher stem density and particulate-P retention ability than a shrub covered bank with little undergrowth.

The ability of vegetation coverage to absorb dissolved-P and enhance the particulate-P retaining capacity of a buffer strip must be weighed against potential dissolved-P losses from vegetation. Surface applied plant litter (Sharpley and Smith, 1989) and dormant vegetation both release dissolved-P to surface water (Fisher and Likens, 1973; Osborne and Kovacic, 1993; Vought et al., 1994). Periodic harvesting of buffer vegetation has been suggested as a way to increase nutrient removal (Vought et al., 1994). Yearly harvest of above-ground biomass would increase growth rate (Lowrance et al., 1985) and reduce the potential P-release

problems from decaying vegetation (Uusi-Kämpä and Ylärinta, 1992) while maintaining roots and short stalks to minimize erosion and promote particulate-P deposition.

Other problems with buffer strip effectiveness are caused by the uneven distribution of P losses through the season. Approximately 80% of the annual P loss from an agricultural field occurs during one or two major storm events each year (Daniels and Gilliam, 1996; Schuman et al., 1973; Sharples et al., 1994; Westerman et al., 1983). The major discharge flushes associated with storms correspond to peaks in suspended solids and dissolved-P in stream water (Schlosser and Karr, 1981). Early spring is the most important time for P losses because of manure applications, young plants, bare field soil and fresh tilling (Jokela, 1991; Truman et al., 1993). Buffer vegetation cover must be maintained at this time of year if particulate-P retention in buffers is to be effective. Buffer widths may also need to be calculated to be effective during high magnitude flow events because of their central role in particulate-P retention.

It is particularly important to maintain buffer strips along small streams, because these areas represent the supply area for lakes and larger streams (Vought et al., 1994). Current regulations do not include guidelines for buffer strips between fields and intermittent drainage ditches. These areas have the potential to serve as catchments for P throughout the year with periodic flushing during high flow events in spring and fall.

PART I: Analysis of Buffer Types and Their Distribution at the Landscape Scale

MATERIALS AND METHODS

To gauge the frequency of occurrence of different buffer types in the Lake Champlain Basin (LCB), and to identify which buffers are most likely to be critical in terms of phosphorus and sediment delivery to surface waters, we systematically sampled 36 (5%) of the orthophotographs available for the Lake Champlain Basin (Fig 1). In our proposal, we said we would use a stratified random sampling design, based on a GIS inventory. As it turned out, attempts to secure a GIS inventory resulted in protracted frustration: data and assistance that were promised never materialized. Eventually we concluded that the GIS inventory would not be very useful anyway, because data resolution was inadequate for the purpose of discerning much narrower buffers. Lacking the GIS inventory, which would have permitted us to stratify the data, we then were faced with sampling the entire LC basin, only part of which (Vermont) had recent, high resolution, spatially corrected aerial photographs. We decided to use a systematic sampling design (starting with a randomly chosen starting location) rather than to create an artificial stratification. We think this was the only reasonable course of action because it was important to classify all parts of the Basin for which aerial coverage was available.

Orthophotographs covering all of Vermont, at a scale of 1:5,000 (each sheet covers a land area of 4 X 4 km), were produced from aerial photography between 1976 and 1983 by the State of Vermont. Similar spatially-corrected aerial photographs were not available for either New York or Quebec, so our remotely sensed survey was limited to Vermont. A variety of information was extracted from the buffer survey (Table 1). Streamside vegetation along each sampled watercourse was visually classified as either: forested (mostly trees), trees/shrubs, shrubs and herbs with few scattered trees, shrubs and herbs, or herbs/grass/bare soil (no woody stems). Vegetation determinations and classifications were confirmed with periodic ground verification.

Stream order (Strahler 1957) of each stream reach was determined from USGS topographic maps, and hydrologic group was based on county soil surveys (Natural Resources Conservation Service, NRCS) and the Engineering Field Manual (NRCS). The Natural Resources Conservation Service has not completed soil survey maps for six Vermont counties (Bennington, Caledonia, Orleans, Rutland, Washington, and Windsor), but some preliminary data for those counties were made available to us. We were not able to obtain detailed soils data for a total of 6 of the 36 orthophotographs that were analyzed (17 percent). Livestock population (number of animal units per town) was obtained from the VT Dairy BMP Survey (1994); animal units were subsequently divided by each town's total land area to yield animal density, expressed as animal units per hectare.

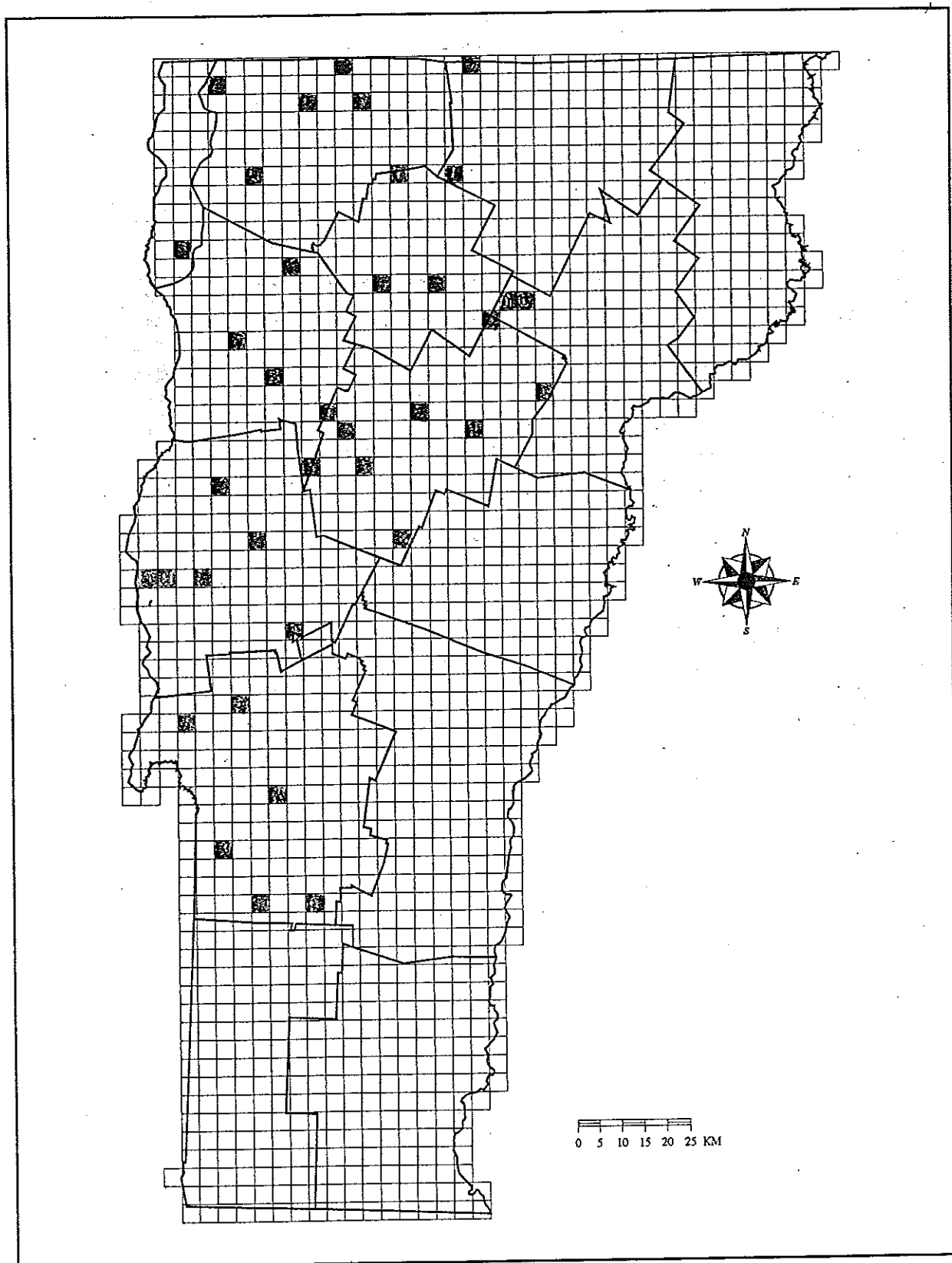


Figure 1 Map of aerial orthophotographic coverage of Vermont. Each square represents one orthophotograph (4x4km coverage; 1:5000 scale). Shaded squares were those sampled in this study.

Table 1 Data collected in survey to classify buffer types in the Lake Champlain Basin.

area	parameter	description and source
General	ortho# topographic map county agricultural intensity animal units surficial geology hydrologic group hydrologic group mean slope soils	number corresponding to northing and easting on orthophoto (state plane meters) name of USGS topographic map or maps covering orthophoto area county or counties in which the orthophoto is located county data from the 1992 Census of Agriculture animals per town from the 1994 VT Dairy BMP Survey from 1970 Surficial Geologic Map of VT, 1:250,000 USDA SCS (NRCS) Engineering Field Manual, Chapter 2: Estimating Runoff and Peak Discharges, based on soil mapping units in county soil surveys value was assigned to each letter (A=1, etc.), mean of values from stream section from county soil surveys from county soil surveys
Stream	stream section # section length (m) stream order basin # sides side length	arbitrary numbers written on the project USGS topographic maps for future reference includes only the length of stream adjacent to agricultural land. Measured from orthophoto from USGS topo maps main river into which stream drains from atlas and USGS topo sides of stream section adjacent to agricultural land (ranges from 1-2) calculated as (section length) * (#sides) = linear stream distance adjacent to agricultural land
Buffer	average width (m)	width of flow collector on each side of stream, from orthophoto; also broken into categories A ≤5 m C 20-25 m E 50-90 m B 10-15 m D 30-40 m F ≥100 m
Buffer	maximum width (m)	maximum width of flow collector on each side of stream, from orthophoto; also broken into categories A ≤15 m C 30-40 m E 100-150 m B 20-25 m D 50-80 m F ≥200 m
Buffer	minimum width (m)	minimum width of flow collector on each side of stream, from orthophoto; also broken into categories A 0 C 10-15 E ≥40 B 1-5 m D 20-30 m
Buffer	vegetation	of buffer, from orthophoto, categories: A trees only - forested (mostly trees) D shrubs/herbs B trees/shrubs E herbs/grass/bare (no trees/shrubs) C few trees (scattered) or mostly shrub/herb
Fields	field type	(of fields adjacent to flow collector), from orthophoto; categories: A plowed B not plowed C unable to tell from orthophoto

RESULTS AND DISCUSSION

A preliminary survey of buffers separating agricultural fields and surface water revealed that narrow buffers are quite common. For this reason, our approach did not include the use of existing geographic information system (GIS) data, which are only available at a coarse resolution. Using a survey of orthophotographs, we were able to better characterize the distribution of buffers in the Lake Champlain Basin.

We classified 693,700 m of linear stream from our orthophotograph survey; most of the stream length was in Addison County (27%), Washington County (17%), and Rutland County (16%). Fifty percent of the total stream length was first order streams, 18% was second order, and 16% was third order. The predominant streamside buffer was 10-15 m wide (26% of our sample), followed by buffers having widths of 20-25 m (23%), 30-40 m (17%), and < 5 m (15%). The dominant vegetation type in buffers (43%; all stream orders combined and weighted by their relative lengths) was shrub/herb with scattered trees ("woody," Table 2). Many buffers were also herb/grass/bare ground (16%) or trees and shrubs (16%). Of the hydrologic group designations that could be made with confidence, those with the highest runoff potential, C and D (2.4 - 4.4 mean scores, poorly drained), comprised 90% of the streamside surveyed. It is likely that this is a factor of being adjacent to streams, with the hydrologic conditions that occur with that association. More than 25% of all the streams surveyed for which data were located in towns characterized by high animal density (>0.15 animal units per hectare of total land area).

The dominant types of stream buffers in the Lake Champlain Basin are summarized in Table 3. Seven types accounted for 69% of the total streamside distance surveyed; the other 29 types collectively accounted for only 31% of the distance surveyed. The most problematic type of buffer in the Basin (the type that was least likely to protect surface waters from phosphorus input from upslope cornfields) was also the most common (19% of the stream length sampled). Eight percent of the surveyed stream lengths had the next most problematic situation (e.g., three of the four classified characteristics were least likely to protect surface waters; Table 2). All of the dominant types of buffers had soils with high runoff potential (C or D hydrologic group). Four of the seven dominant buffer types had low vegetative biomass (herb/grass/bare ground, shrubs/herbs, shrub/herb with scattered trees.)

Table 2 Map survey - Data summary

vegetation	width	hydrologic group	animal units	percent length	sum of % for category
woody	wide	low	low	2.9	18
woody	wide	high	low	9.8	
woody	wide	unknown	low	5.3	
woody	wide	low	high	1.1	8
woody	wide	high	high	5.9	
woody	wide	unknown	high	1.4	
woody	wide	low	unknown	0.4	5
woody	wide	high	unknown	4.6	
woody	wide	unknown	unknown	0.4	
woody	narrow	low	low	0.4	1
woody	narrow	high	low	0.7	
woody	narrow	unknown	low	0.3	
woody	narrow	low	high	0.0	0
woody	narrow	high	high	0.0	
woody	narrow	unknown	high	0.0	
woody	narrow	low	unknown	0.0	0
woody	narrow	high	unknown	0.0	
woody	narrow	unknown	unknown	0.0	
herbaceous	wide	low	low	0.7	11
herbaceous	wide	high	low	8.0	
herbaceous	wide	unknown	low	2.0	
herbaceous	wide	low	high	0.0	15
herbaceous	wide	high	high	13.6	
herbaceous	wide	unknown	high	1.6	
herbaceous	wide	low	unknown	0.3	1
herbaceous	wide	high	unknown	0.6	
herbaceous	wide	unknown	unknown	0.0	
herbaceous	narrow	low	low	2.0	14
herbaceous	narrow	high	low	8.4	
herbaceous	narrow	unknown	low	3.6	
herbaceous	narrow	low	high	0.7	23
herbaceous	narrow	high	high	18.6	
herbaceous	narrow	unknown	high	3.6	
herbaceous	narrow	low	unknown	0.0	3
herbaceous	narrow	high	unknown	2.9	
herbaceous	narrow	unknown	unknown	0.6	
				100	100

Key

vegetation: woody (trees, trees/shrubs). herbaceous (few scattered trees, shrubs/herbs, herbs/grass/bare)

average width: wide (better) 18 m; narrow (worse) < 18 m

hydrologic group: low (better) = A-B (better drained/lower runoff potential)
high (worse) = C-D (more poorly drained/higher runoff potential)

animal units per ha: low (better) = 0-0.15 (0-0.06 au/acre)
high (worse) >0.15 (>0.06 au/acre)

Table 3 Predominant buffer types in the Lake Champlain Basin

vegetation	width	hydrologic group	animal units	percent length
woody	wide	poorly drained	low	10
woody	wide	unknown	low	5
woody	wide	poorly drained	low	6
herbaceous	wide	poorly drained	low	8
herbaceous	wide	poorly drained	high	14
herbaceous	narrow	poorly drained	low	8
herbaceous	narrow	poorly drained	high	19
				Sum:70

**PART II: Patterns of Phosphorus Retention in Grass-covered Buffers
Receiving Runoff from Cornfields:
Results of Studies in the Lake Champlain Basin, VT**

MATERIALS AND METHODS

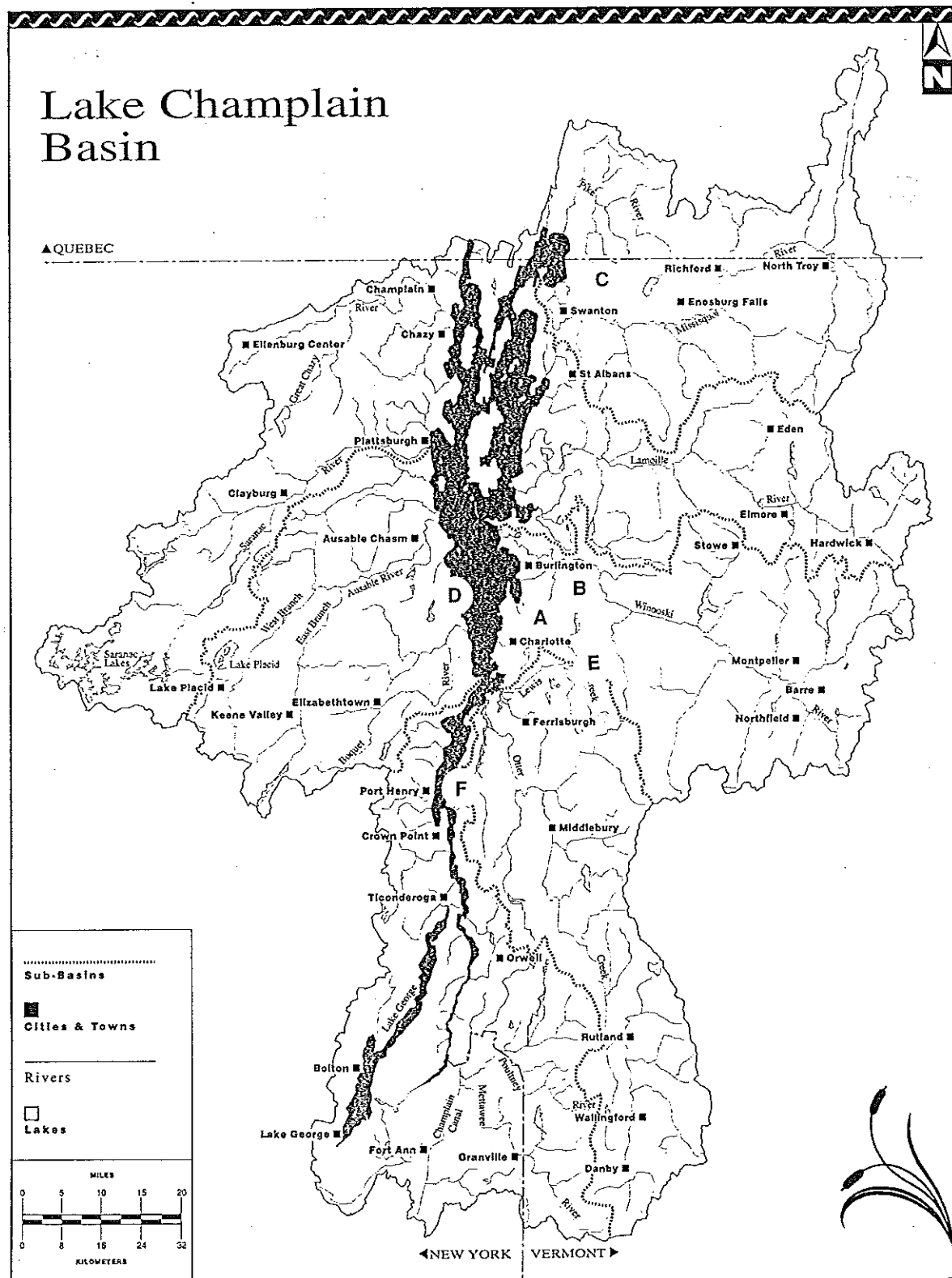
Study Sites

We used our literature review and results from Part I (the watershed survey) to guide our selection of critical downslope buffer sites (flow collectors) for field sampling. Finding study sites that met all of our criteria (and had landowner permission) proved far more difficult than we imagined. In fact we found no ideal sites for intensive sampling of critical flow collectors within 1 1/2 hour's drive of Burlington. Given time and budgetary constraints, it was not possible to sample many sites intensively, especially given our decision to sample as many runoff events as we could. Our choice then became: Would it make more sense to sample two or three different types of flow collectors, with a single replicate each (knowing that any single site we chose would have limitations), or would it be more useful to select several less-than-ideal sites of the most critical flow collector type, and intensively sample at different distances into the buffer for a large number of events. We chose this second approach by reasoning that there would be greater value in assessing variability within this critical flow collector type.

Our inventory, which was based on the orthophotograph survey (Tables 2 and 3), gave strong justification for focusing on the herbaceous/grass buffer type alone. Overall, two-thirds of all buffers were herbaceous and the remaining third were woody. But more importantly, almost all the woody buffers were wide and most were located in low animal density areas. In contrast, 60% of the herbaceous buffers were narrow and 60% were in high animal density areas, making them much more critical in terms of P loading potential.

For purposes of site selection, we defined "critical" as any buffer that had marginal characteristics vis-a-vis phosphorus retention: i.e., 1) the buffer was downslope of a cornfield where topographic features concentrated runoff off of the field, 2) the field or neighboring part of the field had a high runoff potential (hydrologic group C or D), and 3) vegetative cover in the buffer was limited to primarily herbaceous, grassy and/or shrubby vegetation. We deliberately selected sites that had wide buffers so that we could evaluate the extent to which phosphorus losses from cornfields diminished as buffer width increased. Growing corn is a more intensive use of the land than other crops with more potential for erosion and P-laden runoff. We located field sites to be representative of these features and to maximize spatial distribution within the Lake Champlain Basin. Six sites were selected (Fig. 2, Table 4), three of which (A-North, A-South, and B) were instrumented and sampled intensively as described below. Sampling at the remaining "extensive" sites (C, D, E, and F) was limited to soil analysis except for some grab sampling of runoff at site C.

At each site (intensive and extensive), we first differentiated three sampling locations having channels and three areas without obvious runoff channels. This distinction between channels and interchannel areas (ICAs) was originally intended to separate channelized vs. "sheet" flow areas, but little to no "sheet" flow was observed at any site.



Source: USGS Topographic Maps

Figure 2 Map of intensive (A, B, C) and extensive (D, E, F) field sampling sites in the Lake Champlain Basin

Table 4: Descriptions of field sites

site name/ sampling intensity	location	buffer widths	buffer vegetation	soil	description
A-north intensive	Shelburne, VT	>30 m	grassy-mowed hayfield with hedgerow	Vergennes clay	Water pools during wet conditions; runs into wetland below; then into Shelburne Pond
A-south intensive	Shelburne, VT	>30 m	grassy-mowed hayfield with hedgerow	Vergennes clay	Water pools during wet conditions; runs into wetland below; then into Shelburne Pond
B intensive	Williston, VT	5 to >30 m	meadow species and shrubs	Peru stony loam, Vergennes clay	water runs into roadside ditch; eventually into Muddy Brook
C extensive	Highgate, VT	2 to 12 m	meadow species removed by fire in early spring most years	Scantic silt loam	some tile drainage; water leaves field through narrow channels; eventually into Rock River
D extensive	Willsboro, NY	30 m	grasses; frequently mowed	Willsboro	tile drainage; no surface runoff observed; any surface water into drainage ditches; then directly into Lake Champlain
E extensive	Hinesburg, VT	1 to 4 m	grassy, herbaceous, shrubby (typical situation)	Limerick silt loam, Winooski very fine sandy loam	water leaves field through narrow channels; into drainage ditches; eventually into LaPlatte River
F extensive	Addison, VT	5 to 10 m	grasses and meadow species	Vergennes clay	water flows into seasonal stream/drainage ditch; eventually into Lake Champlain

Erosion-deposition posts.

We installed posts in all research sites to measure erosion and/or deposition (E/D posts). E/D posts consisted of a 60 cm section of fiberglass rod that was hammered into the ground to a depth of approximately 30 cm. A metal washer was placed around each post at the soil surface. Erosion was quantified as an increase in the distance from the top of the post to the top of the washer. Deposition was quantified as the material deposited on top of the washer (Jordan et al. 1993). E/D posts were installed and measured adjacent to 2 cm cores in ICAs at all sites at EOF, 2 m and 5 m, and adjacent to all surface runoff collectors.

Unfortunately, frost heaving made accurate data difficult to obtain from these devices. The Lake Champlain Basin climate, with its frequent freezes and thaws and high precipitation, was not well suited for this type of measurement. It would be necessary to hammer these posts to a much greater depth to avoid frost-heaving action during the winter. The minimal soil found deposited on top of a few washers could be of use, but there were so few of these to make any results suspect. It is likely that these are instances of microtopographic variation. Similar measurement devices were used along channels, but these were similarly unsuccessful because of frost action. Therefore, no results are reported.

Soils

Soils in each of the seven vegetated buffer sites were sampled at different depths at five different distances from the field edge. At the intensive sites (A-north, A-south, and B), soil cores (2 cm diameter) were collected within each tier of surface runoff collectors (Fig. 3; end of field [EOF], and 0m, 3m, 9m, and 21 m into the buffer). Soil cores were divided into four depth increments (0-5, 5-10, 10-20, 20-30 cm) and collected increments were pooled by depth and distance into the buffer (explained above). A total of 60 soil samples (20 from each area) were collected from the sampler areas at each site. All soil samples were oven-dried (55°C) to constant weight, weighed for bulk density, sieved (2 mm), and further composited for chemical analyses (Tables 5, 6, and 7).

The other (extensive) sampling sites (C-F) were sampled at five locations within an 8 m distance from the field edge because buffers were narrower than those at the intensive sites. Soil cores (2-cm diameter) were collected from three interchannel areas and from five (or fewer, depending on buffer width) distances across the buffer (0, 1, 2, 5, 8 m) and divided into two depths (0-10 and 10-20 cm) at sites D-F and four depths at site C (0-5, 5-10, 10-20, 20-30 cm). Samples were collected along three randomly selected transects across the buffer within each of three ICAs, and samples within each ICA at each site were pooled by distance and depth. Soil samples of channels were collected in pairs along the three channels at each site, and sample pairs were pooled by distance and depth, as for ICA samples. No channel samples were collected at site F because of extensive excavation related to another research project on the site.

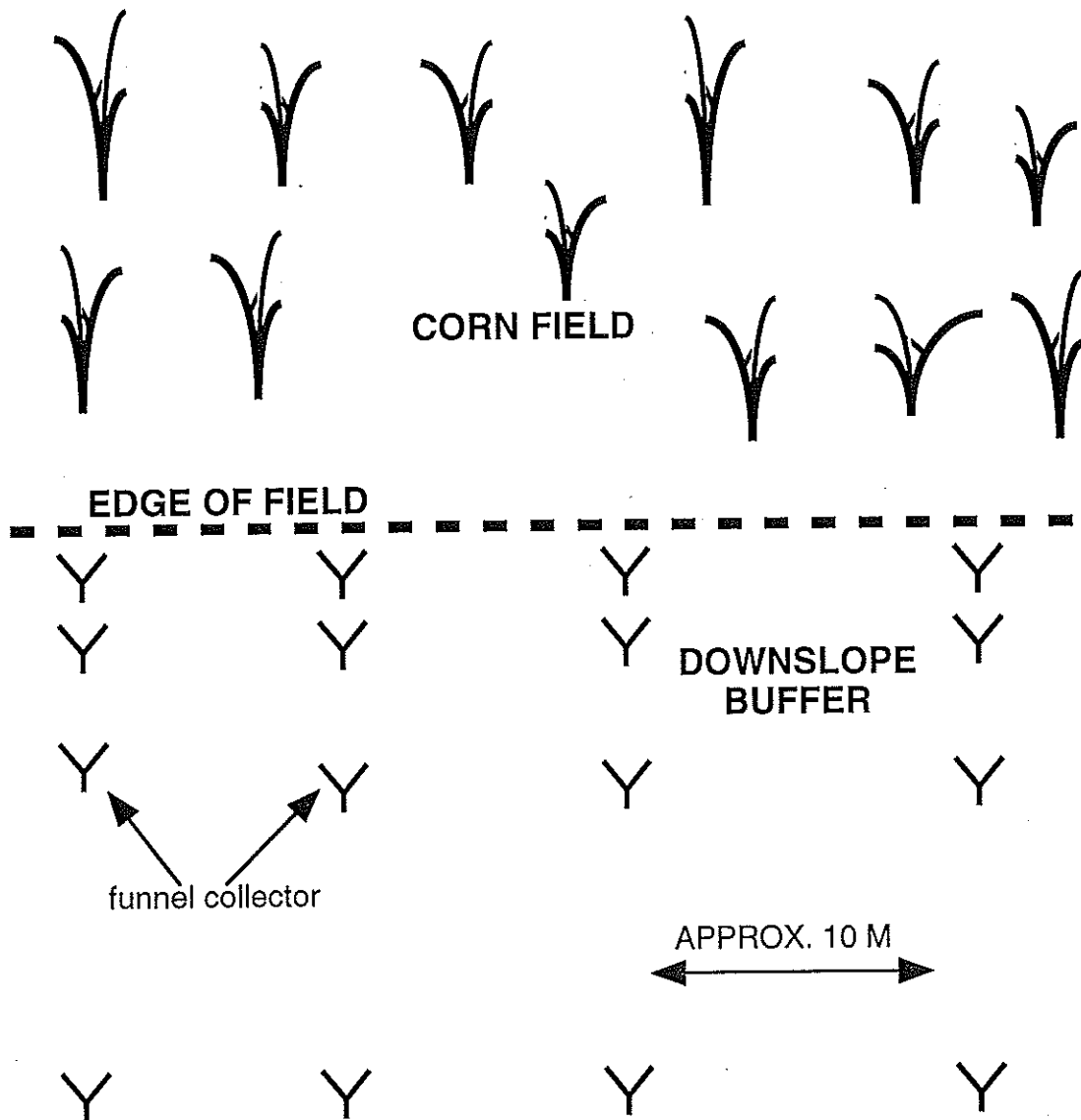


Figure 3 Schematic of the sampling design for surface runoff collections at intensively sampled sites

Table 5 Chemical analyses on samples

sample type	parameter	method	reference
Water	TP	persulfate digestion with ascorbic acid analysis	(APHA, method 4500P B5)
	SRP	filtration with ascorbic acid analysis	(APHA, method 4500P E)
	TSS	filtration and drying	(APHA, method 4500P B1)
	pH	electrometric analysis	(APHA, method 4500P B5)
	BP	iron oxide strips	(APHA, method 2540 D)
			(APHA, method 423)
Soil	pH	electrometric analysis with salt	(Robinson and Sharpley, 1994)
	organic C	loss on ignition	(NEC-67, 1995)
	BP	iron oxide strips	(NEC-67, 1995)
	available P	modified morgan extractions with ascorbic acid analysis on an automated spectrophotometer	(Robinson and Sharpley, 1994)
			(NEC-67, 1995)

Table 6 Soil sampling overview

core diam.	sampling intensity	area	areas/site	Distances (where possible)	depths	total samples
2 cm	intensive	ICA	3	EOF (10 cm), 1, 2, 5, 8 m	0-5, 5-10, 10-20, 20-30 cm	168
		Channel	3	EOF (10 cm), 1, 2, 5, 8 m	0-5, 5-10, 10-20, 20-30 cm	139
		sampler area	3 (total)	EOF, 0, 3, 9, 21 m	0-5, 5-10, 10-20, 20-30 cm	60
2 cm	extensive	ICA	3	EOF (10 cm), 1, 2, 5, 8 m	0-10, 10-20 cm	70
		channel	3	EOF (10 cm), 1, 2, 5, 8 m	0-10, 10-20 cm	48

(no channel samples at site F)

Table 7 Soil sample composites for chemical analyses

para-meter	site type	areas	distances	depths	samples /site	total samples	method
bulk density	all	all	all	all	all	all	dry wt/volume
pH	intensive	ICA	1 m, 8 m	0-5 cm, 5-10 cm	4	12	electrometric/salt
		Channel	1 m, 8 m	0-5 cm, 5-10 cm	4	12	
		sampler area	0 m, 21 m	0-5 cm, 5-10 cm	4	12	
	extensive	ICA channel	1 m, 8 m	0-10 cm	2	6	electrometric/salt
			1 m, 8 m	0-10 cm	2	4* total=46 samples	
organic C	intensive	ICA channel sampler area	1 m, 8 m	all	8	24	loss on ignition
			1 m, 8 m	all	8	24	
			0 m, 21 m	all	8	24	
	extensive	ICA channel	1 m, 8 m	both	4	12	loss on ignition
			1 m, 8 m	both	4	8* total=92 samples	
crop available P	intensive	ICA channel sampler area	1 m, 8 m	all	8	24	Modified morgan extractions; ascorbic acid analysis
			1 m, 8 m	all	8	24	
			0 m, 21 m	all	8	24	
	extensive	ICA channel	1 m, 8 m	both	4	12	same as above
			1 m, 8 m	both	4	8* total=92 samples	
Bioavail-able P	intensive	sampler area	all	0-5 cm	5	15	Fe oxide strips; ascorbic acid analysis

*No channel samples were collected at site F because of extensive excavation for another project at this site.
[total P - combined as for organic C, total = 92 samples]

Surface runoff

Runoff samples from intensive sites were collected using two different methods: grab samples, and composite samples collected via surface runoff samplers (funnel collectors). Runoff samplers were installed at all three intensive sites to enable us to collect samples over the course of each runoff event (Fig. 3). Samplers consisted of half of a plastic funnel (approximately 20 cm in diameter) with a 15 cm length of PVC tubing attached to the bottom. Samplers were pressed into the ground to collect surface runoff as well as subsurface flow within roughly the top five cm of soil. We painted any exposed surface adjacent to the samplers with a fiberglass paint to stabilize the soil surface and to minimize erosion that might

occur as a result of samplers. Water samples were collected into clean plastic bags attached to the PVC tube via a rubber band.

Sets of samplers were positioned at the field edge and in the grassed area below, centered below channels of concentrated runoff from the corn field. Groups of four samplers were installed at each of four distances across the grass buffer: 0 m, 3 m, 9 m, and 21 m. Sites differed somewhat in location of the lowermost edge of the plowed field and the corresponding top of the vegetated buffer area, so we also sampled at the bottom edge of the planted field (EOF).

The spring of 1996 was quite wet, preventing farmers from planting in some low areas in their fields. When samplers were installed, it was assumed that the edge of the corn was the true edge of the field, but because of continued herbicide treatments, the edge of the bare soil was actually lower in some cases. Distances in graphs and analyses have been corrected so that in all cases "0 m" represents the lower edge of the bare soil; EOF collectors have been assigned negative distances.

After each runoff event, sample collection bags were collected and new bags were installed. Sample bags were collected but not replaced when the collector/area was covered with standing water or ice. Volumes for each collector sample were measured separately, and then water samples were pooled from the four (or available) collectors at each distance within each sampler area. Worms, slugs, spiders, frogs, large insects, etc. in the water samples were noted and removed at this point.

Surface runoff collected with funnel collectors was obtained from a total of 47 events, for a total of 496 composite samples, and 1297 individual collector volumes. Samples were collected and processed from all three sites for most events from late summer, 1996 through mid-summer, 1997. Collected samples were analyzed for TP, most were analyzed for TSS, and a few were analyzed for SRP and/or bioavailable P (BP) (Table 7). After the decision was made to analyze funnel collector samples for SRP and BP as well, sample volume was often a limiting factor. For samples where volume was inadequate, analyses were prioritized in the order: TP, TSS, SRP, and BP.

Grab samples were collected at four sites (A-North, A-South, B, and C) in narrow, highly channelized areas where depth was adequate for sampling. The spatial location of sample channels was mapped, measured, and remeasured from permanently marked points to assess the extent to which channels migrated laterally.

Grab samples were collected during 19 rain events from early summer 1996 through mid-summer 1997, for a total of 223 grab samples. Samples were collected in three channels at each site, at the edge of the field (EOF) and, when possible, at two other distances across the buffer.

Surface water was often present at EOF, but it infiltrated into the soil before reaching far into the buffer. To the extent possible, grab samples of runoff were collected at all four sites, but during a number of events, it was not possible to sample from all sites because of storm timing or inadequate surface water. All grab samples were analyzed for total phosphorus (TP), many samples were analyzed for total suspended solids (TSS), and a limited number of samples were analyzed for bioavailable phosphorus (BP), soluble reactive phosphorus (SRP), and/or pH (Table 7).

Analysis

For analysis of runoff P data, we divided events into categories based on the maximum intensity (cm per hour) or total amount (cm) of precipitation that fell during each event (Table 8). Most events fell into the same category on the basis of both event amount and intensity. Runoff events in the late December to mid-April period resulted primarily from snow melt and were placed in a separate category.

RESULTS AND DISCUSSION

Soil Phosphorus

Crop-available P, or soil test P (modified Morgan's P extractant), from soil samples taken in the immediate vicinity of each runoff collector gives an indication of historical P loading at different distances into the grass buffer area. It is a more appropriate measure than total P because it is the P fraction that is more reactive or available to plants. Because the grass buffers at the A sites are also managed hay fields, soil test P also reflects P additions in the form of fertilizer and manure, and removals in harvested crops. The P status of the soil in the buffer, while affected by P entering from an upgradient field, can, in turn, affect the P concentration of soluble P in runoff passing over it (Sharpley, 1995).

The two intensively sampled sites showed the same general pattern of extractable P with depth – highest in the surface 5-cm and decreasing with depth (Figs. 4, 5). Missing subsurface samples at site B prevent a definitive interpretation, but the data collected are consistent with this pattern of P decline with depth. Surface layers of untilled soils typically have higher concentrations of extractable P in surface layers from surface-applied fertilizer and manure, in combination with fallen or unharvested plant material.

Table 8 Classification of rainfall events for purpose of analysis of P in runoff

Category	Amount/Quantity	Intensity*
	cm/event	cm/hr
Low	0-0.5	0-0.25
Medium	0.51-2.0	0.251-0.65
High	>2	>0.65

* Note: intensity is measured for a one hour period during sampling, not averaged for the entire event.

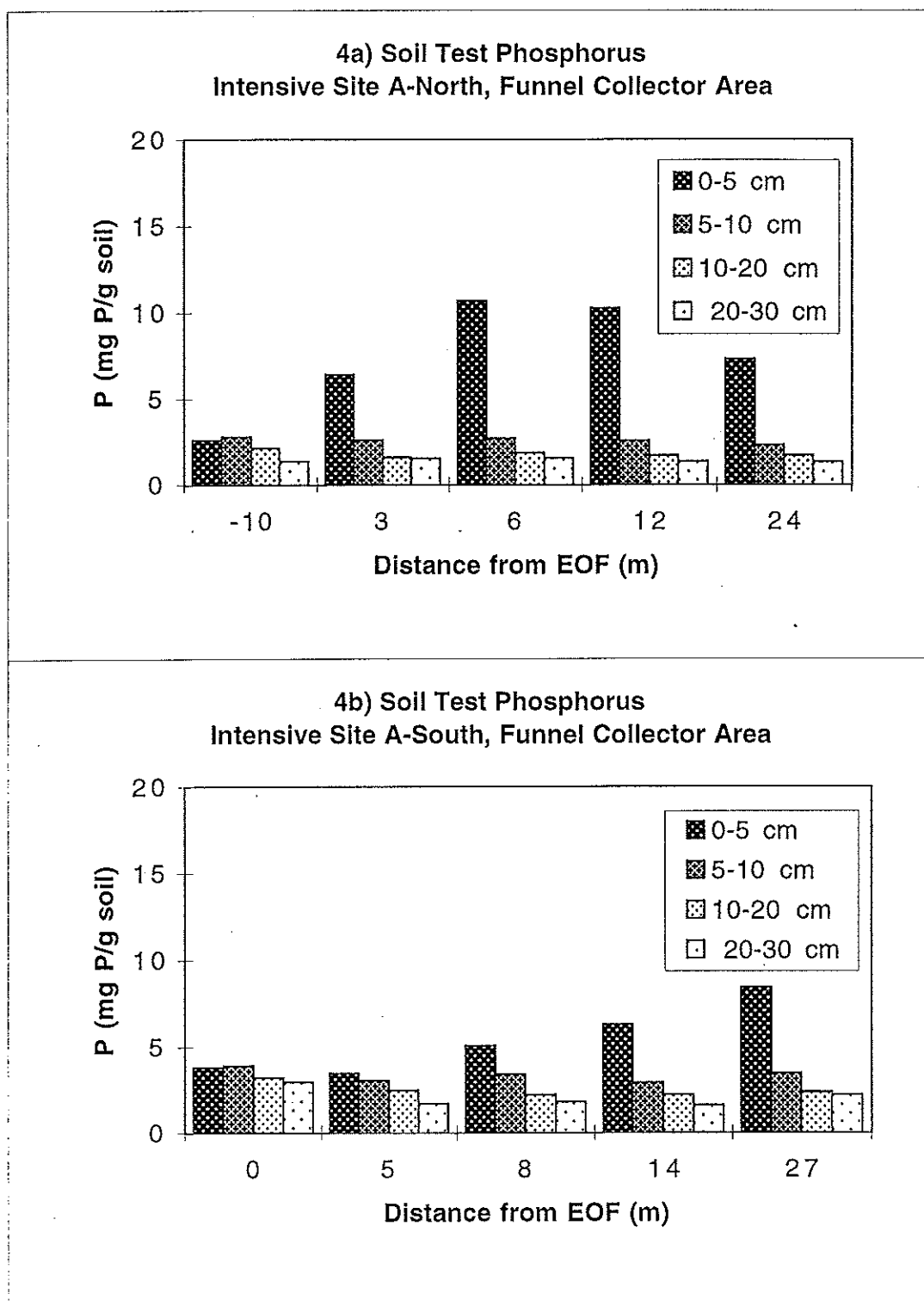


Figure 4 Concentrations of soil test phosphorus in funnel collector areas at different depths and at different distances from the end of the upslope cornfield (EOF): a) intensive site A-North, b) intensive site A-South, c) intensive site B

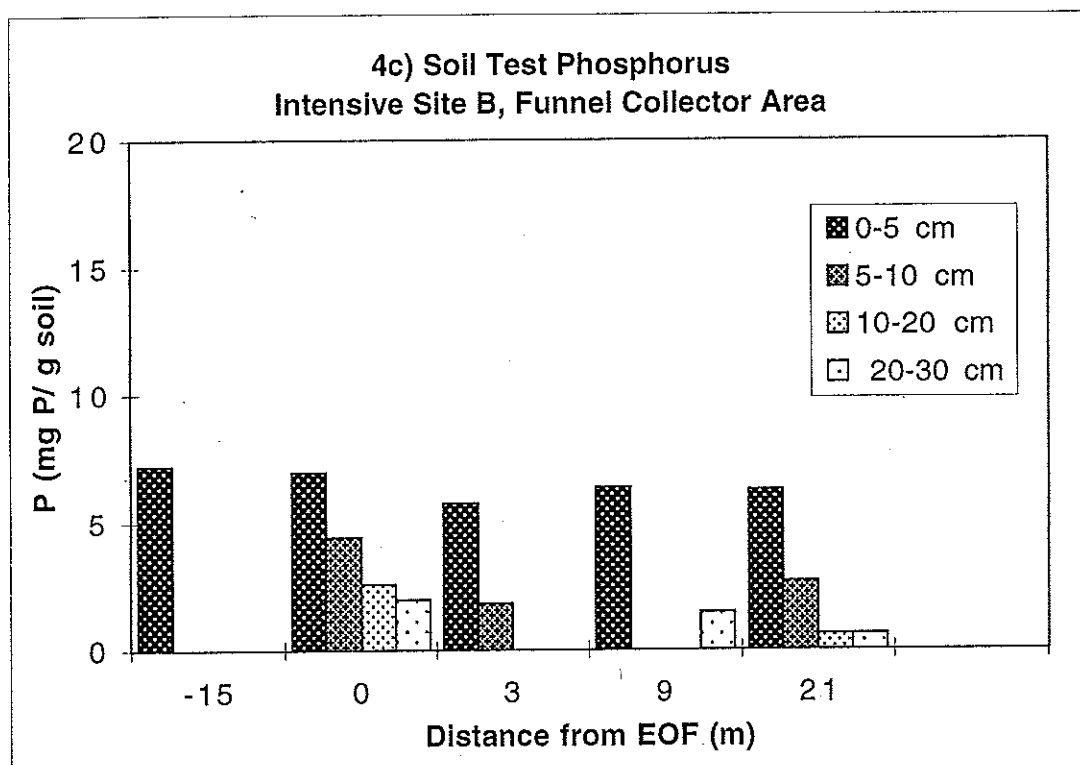


Figure 4 (cont'd).

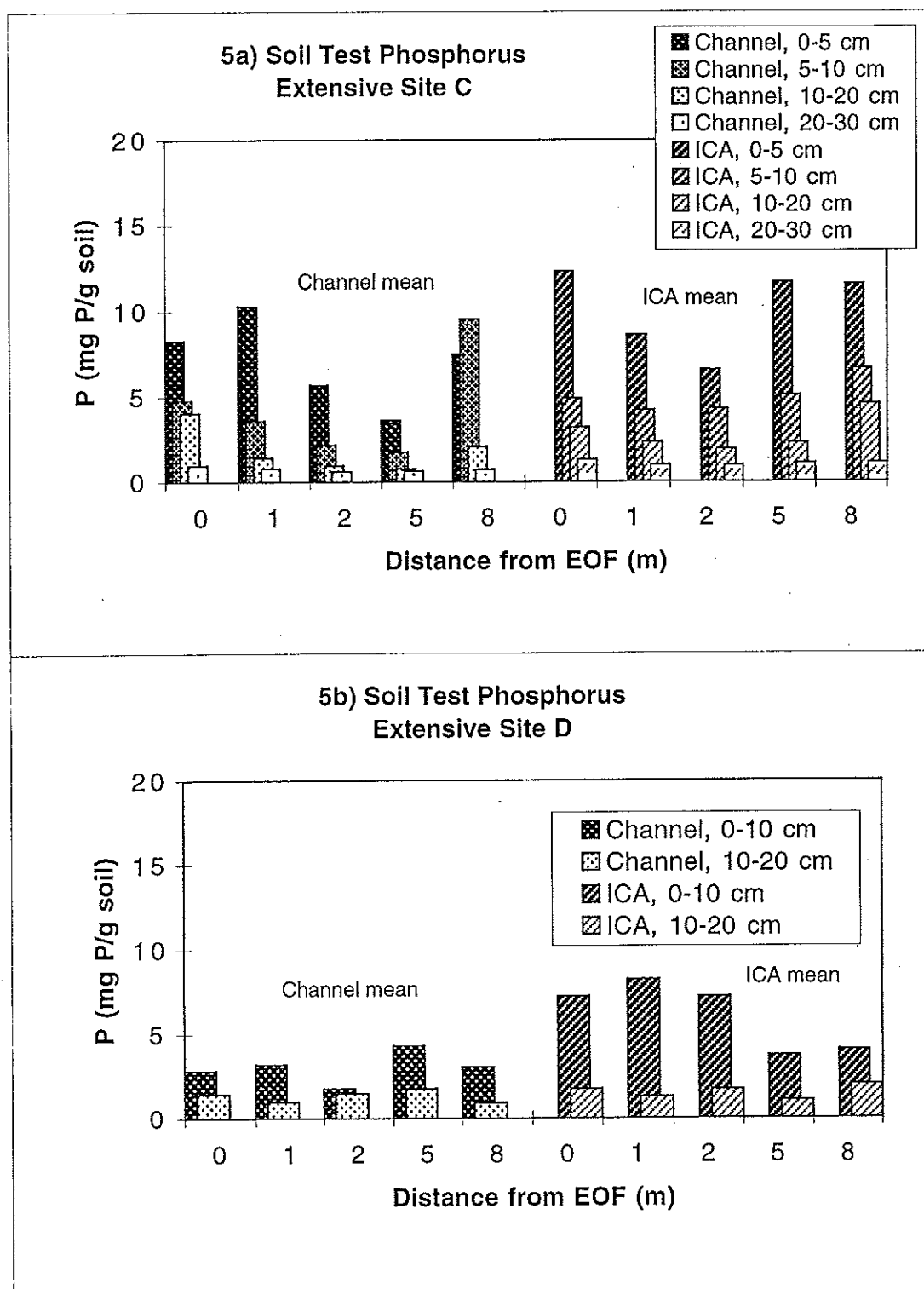


Figure 5 Concentrations of soil test phosphorus in runoff channel and interchannel areas (ICA) at different depths and different distances from the end of the upslope cornfield (EOF): a) extensive site C, b) extensive site D, c) extensive site E, d) extensive site F

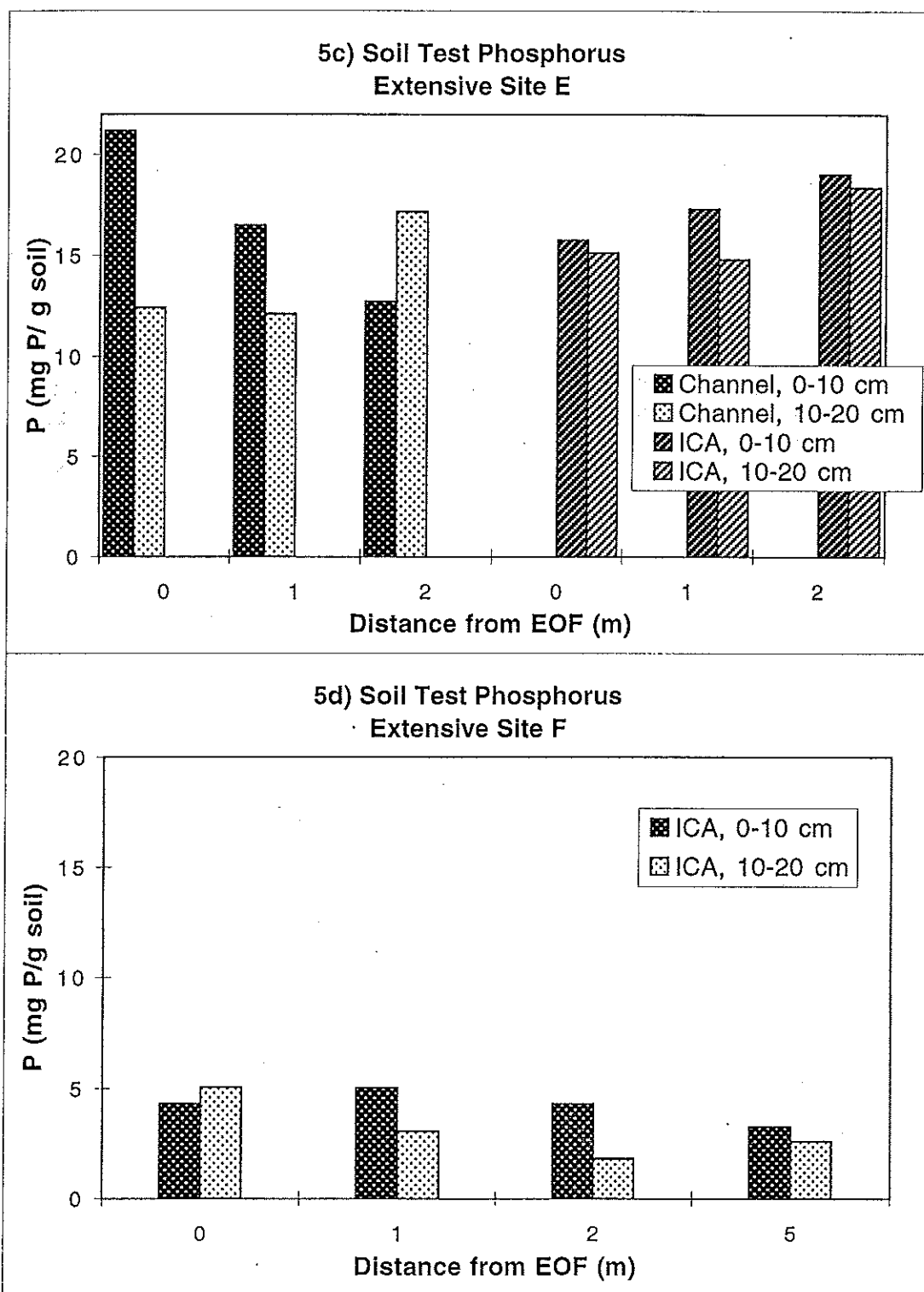


Figure 5 (cont'd).

The only exceptions to this trend in our study were the most upgradient samples (those at the field edge) at the A-North, A-South, E, and F sites, where the two upper layers were essentially the same. This was a result of tillage in the field, which mixed the upper 15 to 20 cm of soil annually. At site A-North, the upgradient sample (-10 m) was actually located 10 m into the field as it had been farmed most years, although in the project year it was at the edge of the corn-planted area because of spring wetness in the lower part of the field. This field position may explain the relatively low available P level in that sample, a result of erosion from a field planted to silage corn.

The depth profile of available soil P below 5 cm was very similar at all distances into the grass buffer at both A sites. The surface increment, however, increased with distance into the buffer area (away from the corn field). This would suggest increasing deposition of sediment-bound P with increasing distance from the corn field. At site A-North, the maximum soil P levels at the 6 and 12 m distance probably were related to pooling of runoff in depressions at those locations. The lower soil P level at 24 m may indicate that suspended/soluble P in runoff was not being removed as effectively at this point, resulting in less accumulation in the soil.

At the A-South site, extractable P increased with distance into the buffer to the farthest sampling location (27 m into the buffer). This can be explained by a slightly different topography at the South location, flattening out in the vicinity of the 27 m sampling area. The surface layer of the soil at the B site showed essentially no change with distance into the buffer (Fig. 4c), indicating there was no gradient in P accumulation across the buffer area. Soil test P in the surface layer of the other sites, C-F (Figs. 5a-5d) was variable with distance and showed no consistent trends.

Runoff Characteristics

There was a strong relationship ($R^2 = 0.88$) between TP and TSS in both types of runoff collections (funnel and grab samples; Fig. 6). The strength of the TP:TSS relationship varied from site to site, however. When data were analyzed on a site-specific basis, resulting R^2 values were 0.79, 0.91, 0.83, and 0.40. Clearly, a major source of TP loss from many sites was TP adsorbed to soil particles.

Grab samples consistently had much lower TSS than funnel collector samples. TSS ranged from <100 mg/l for grab samples to 3800 mg/l for funnel collectors. TP showed similar extremes in concentration.

There was no detectable lateral migration or expansion of channels from November 1996 through June 1997. This suggests that channelized flow in buffers has little physical contact with buffer soils and therefore little effect on phosphorus reduction.

There was a trend toward low P concentrations in larger runoff volumes and higher concentrations in lower runoff volumes (Fig. 7). Presumably, this was a result of dilution of P during higher volume events.

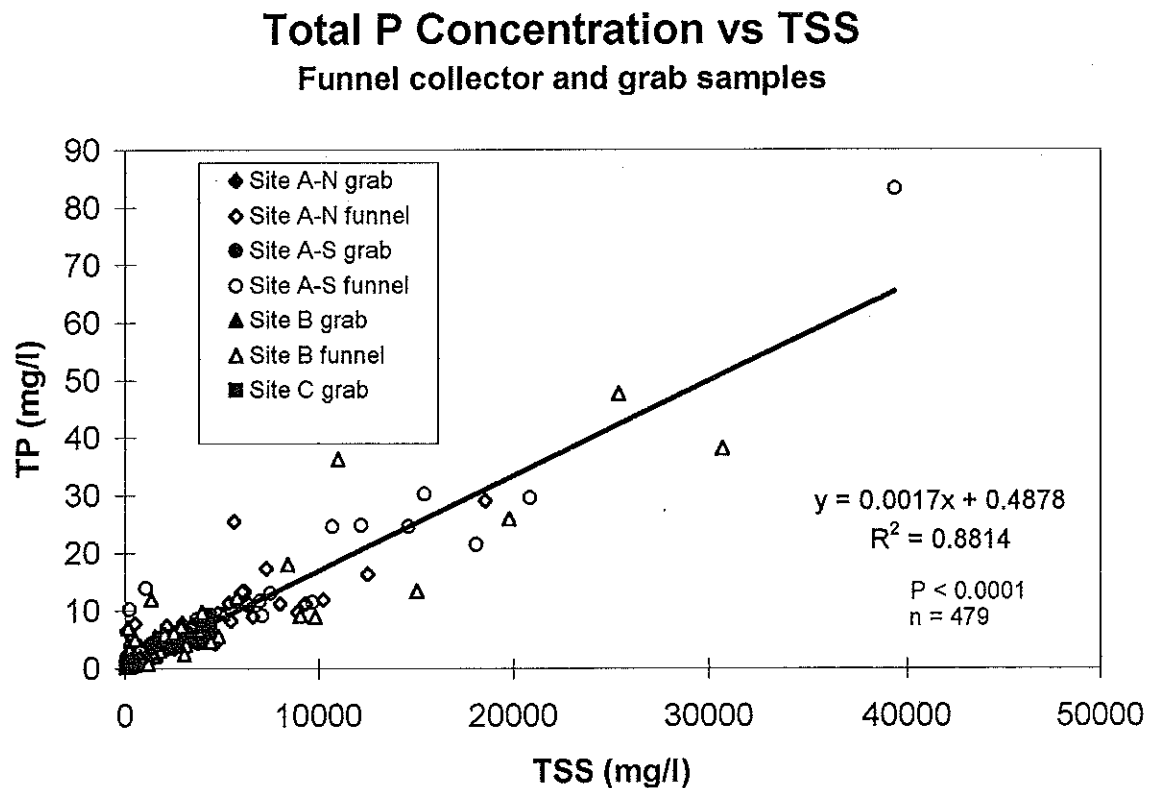


Figure 6 Relationship between total phosphorus (TP) and total suspended solids (TSS) in runoff collections from channel and interchannel areas at the three intensively sampled field sites

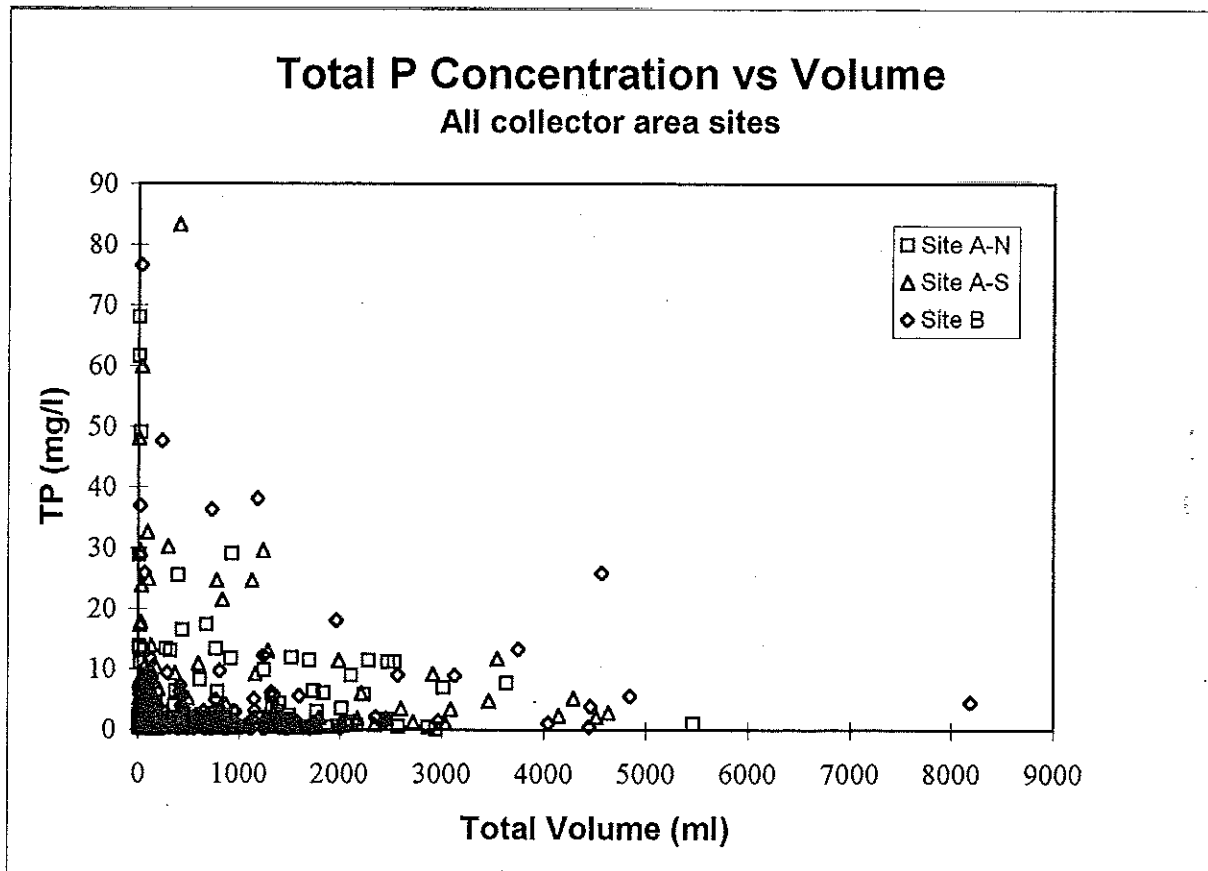


Figure 7 Relationship between total phosphorus (TP) concentrations and volume of runoff

Runoff P in funnel collectors

An effective riparian buffer should reduce the concentration and/or mass of P in runoff as it passes through the buffer. We evaluated this by plotting total P concentration vs. distance from the cornfield edge for all events at each intensive site (Figs. 8-10). Based on best-fit regression through the data points, there was a trend toward decreasing P concentration with distance for moderate and high rain intensity events at the A-north (Figs. 8b, 8c) and A-south (Fig. 9b, 9c) locations. However, there was a great deal of scatter in the data and low R-square values (with $P = 0.25-0.5$ in most cases, but < 0.10 in some), indicating a very weak relationship at best. Log transformation improved the relationship slightly in some cases but worsened it in others, so only the untransformed data are shown. Site B (Fig. 10b) showed a similarly weak relationship at moderate rain intensity, but with an increase in concentration with distance. There was no trend at high rain intensity. Distance into the buffer had no effect on phosphorus concentrations in snow-melt and thaw events during winter and early spring when the ground was frozen or covered with snow (Figs. 8d, 9d, 10d).

P concentrations in runoff from low rain intensity events were in the same range as, or in some cases higher than, concentrations in moderate and high rain events. Runoff volumes were lower, however, as were the P loads passing through buffers during low rainfall events. Moreover, concentration of P in runoff from low intensity rains did not appear to change as it passed through riparian buffers. We therefore focused our attention on runoff from moderate and high rain intensity events.

The data discussed above showed high variability because runoff events varied greatly in P concentrations and in change with distance. We therefore also explored how P mass changes as it passed through buffers for some rainfall events. Regression line fit for individual events was fairly good, with most R^2 values at 0.9 or higher. In most cases the best fit regression was a quadratic, but if a linear regression fit almost as well, as determined by visual inspection and R^2 values, then a linear regression was used. This approach revealed a consistent decrease in P with increasing distance from the edge of field for almost all events with moderate or high rain intensity at the A-North and A-South sites (Figs. 11, 12). [Note that there are two graphs for each set of data; the second graph in each pair includes only events with lower values. An expanded scale is used to show more detail].

A trend of P decline in runoff as distance into the buffer increased was also observed for most snow-melt events, but this trend was less consistent than for moderate and high rainfall events. This decreasing trend with distance was not evident at site B (Figs. 10, 13, discussed further below).

In general, regression lines for runoff events with higher P concentrations or mass had steeper slopes. This suggests that vegetative buffers were more effective at removing P when runoff had larger quantities of P (more sediment vs. soluble P). Based on the regression curve and examination of individual data points, the P concentrations/mass for most events reached a minimum, or close to it, before the farthest collector in the buffer, typically at 12 to 14 m from the upslope cornfield. This suggests that 12 to 14 m wide vegetative buffers (of the type we studied) would substantially reduce the P load leaving corn fields.

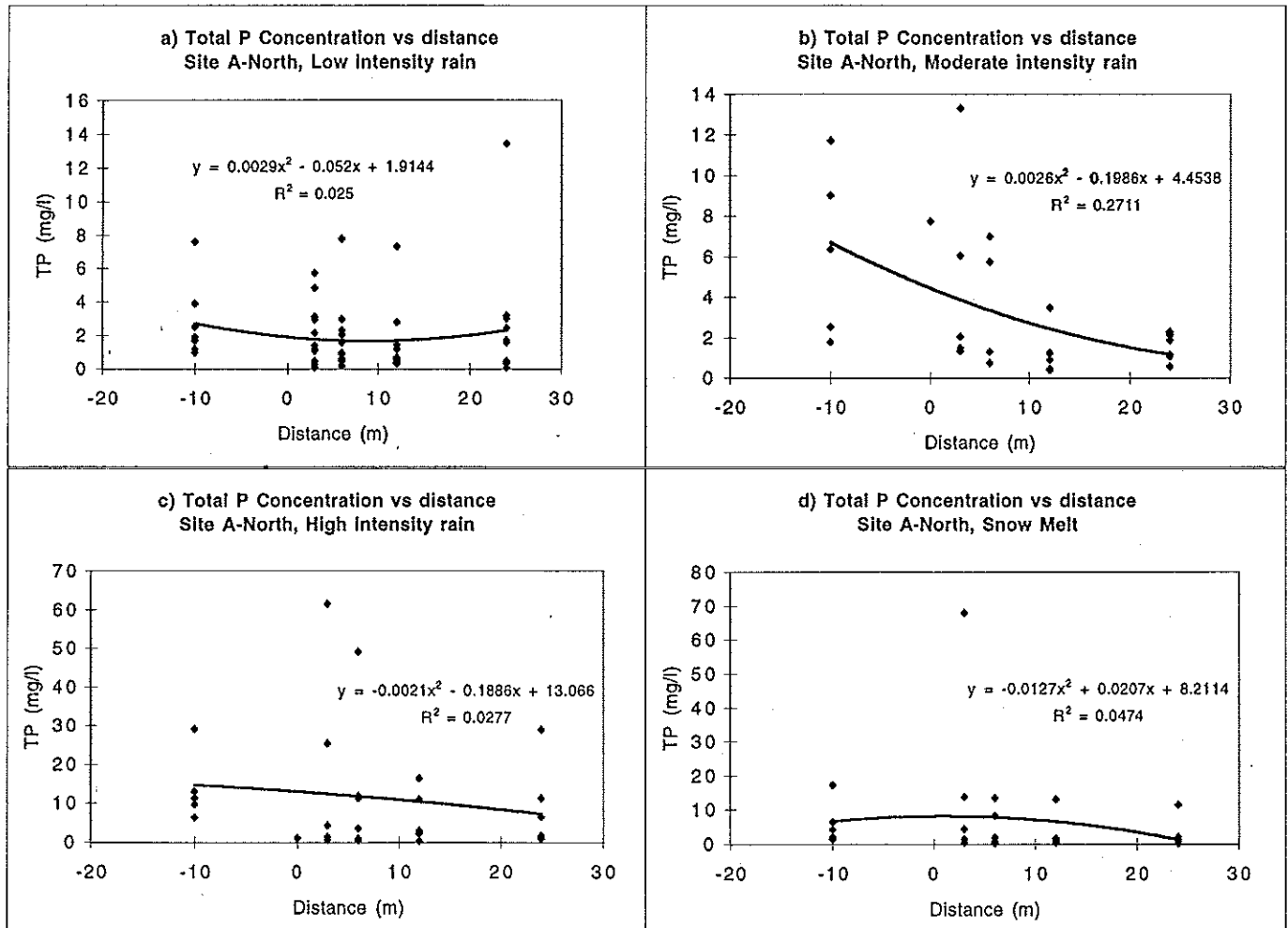


Figure 8 Change in concentration of total phosphorus (TP) in runoff collected in the riparian zone site of site A-north at different distances from the upslope cornfield during a) low intensity rain, b) moderate intensity rain, c) high intensity rain, and d) snow melt

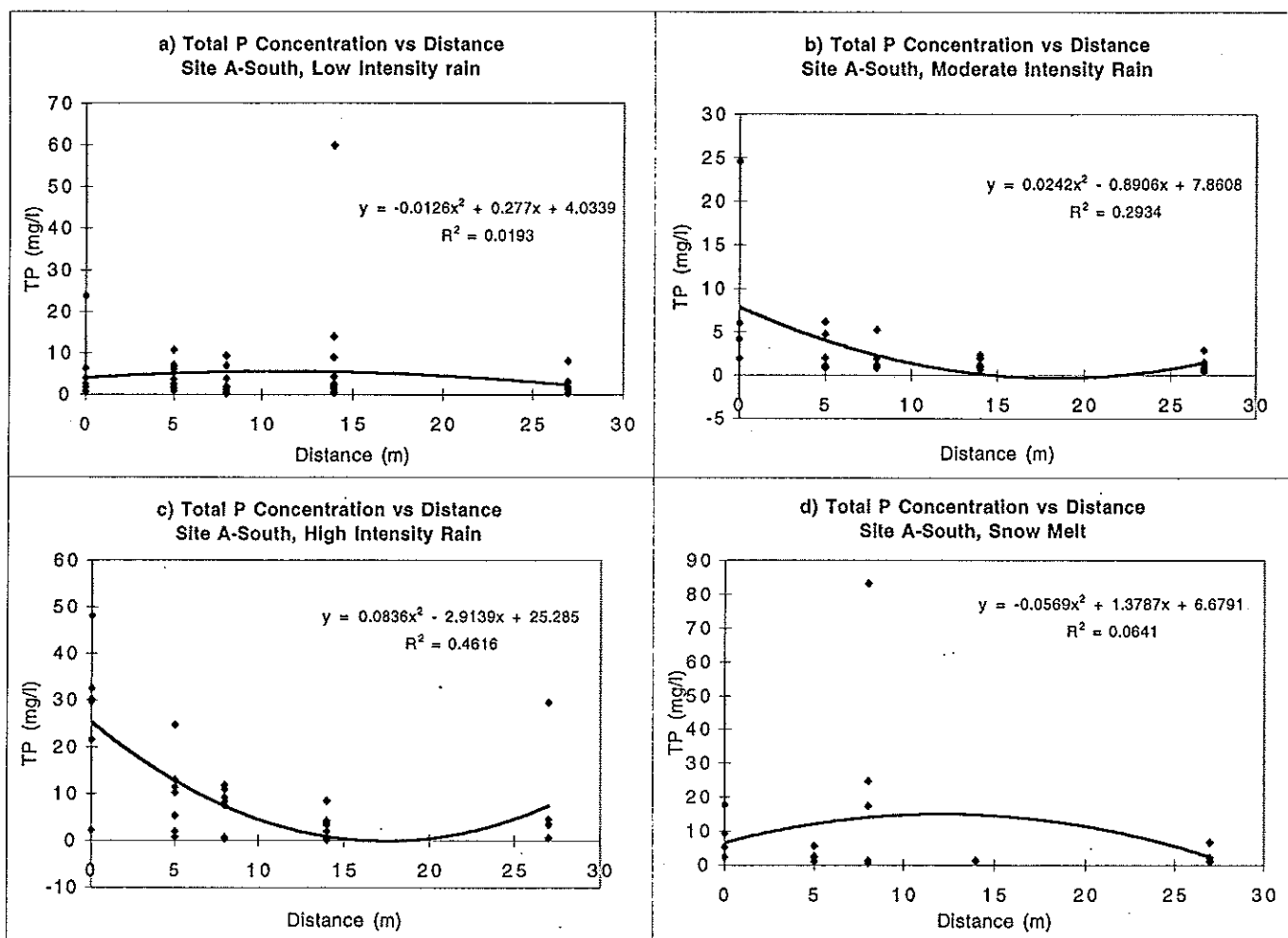


Figure 9 Change in concentration of total phosphorus (TP) in runoff collected in the riparian zone site of site A-south at different distances from the upslope cornfield during a) low intensity rain, b) moderate intensity rain, c) high intensity rain, and d) snow melt.

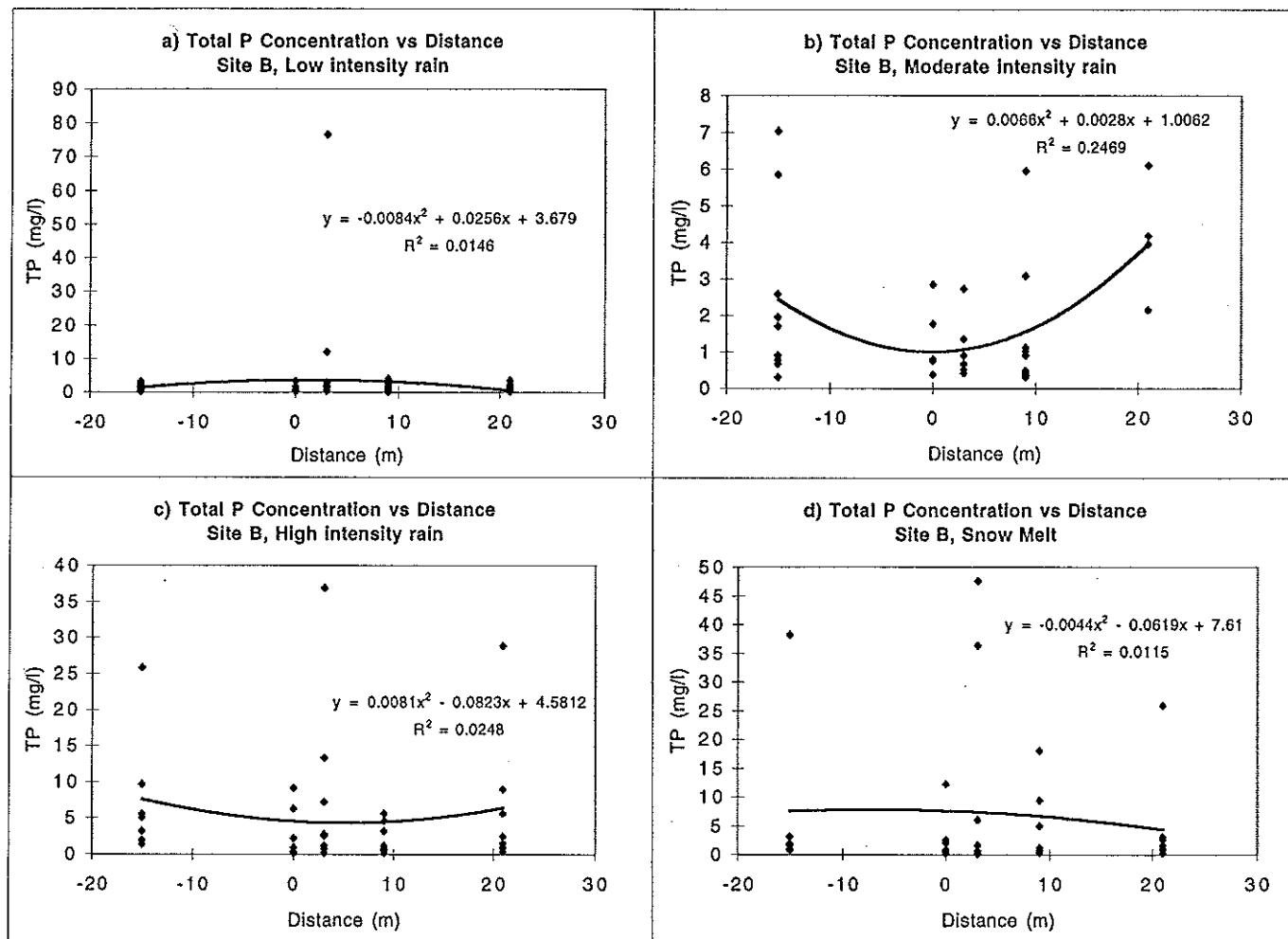


Figure 10 Change in concentration of total phosphorus (TP) in runoff collected in the riparian zone site of site B at different distances from the upslope cornfield during a) low intensity rain, b) moderate intensity rain, c) high intensity rain, and d) snow melt.

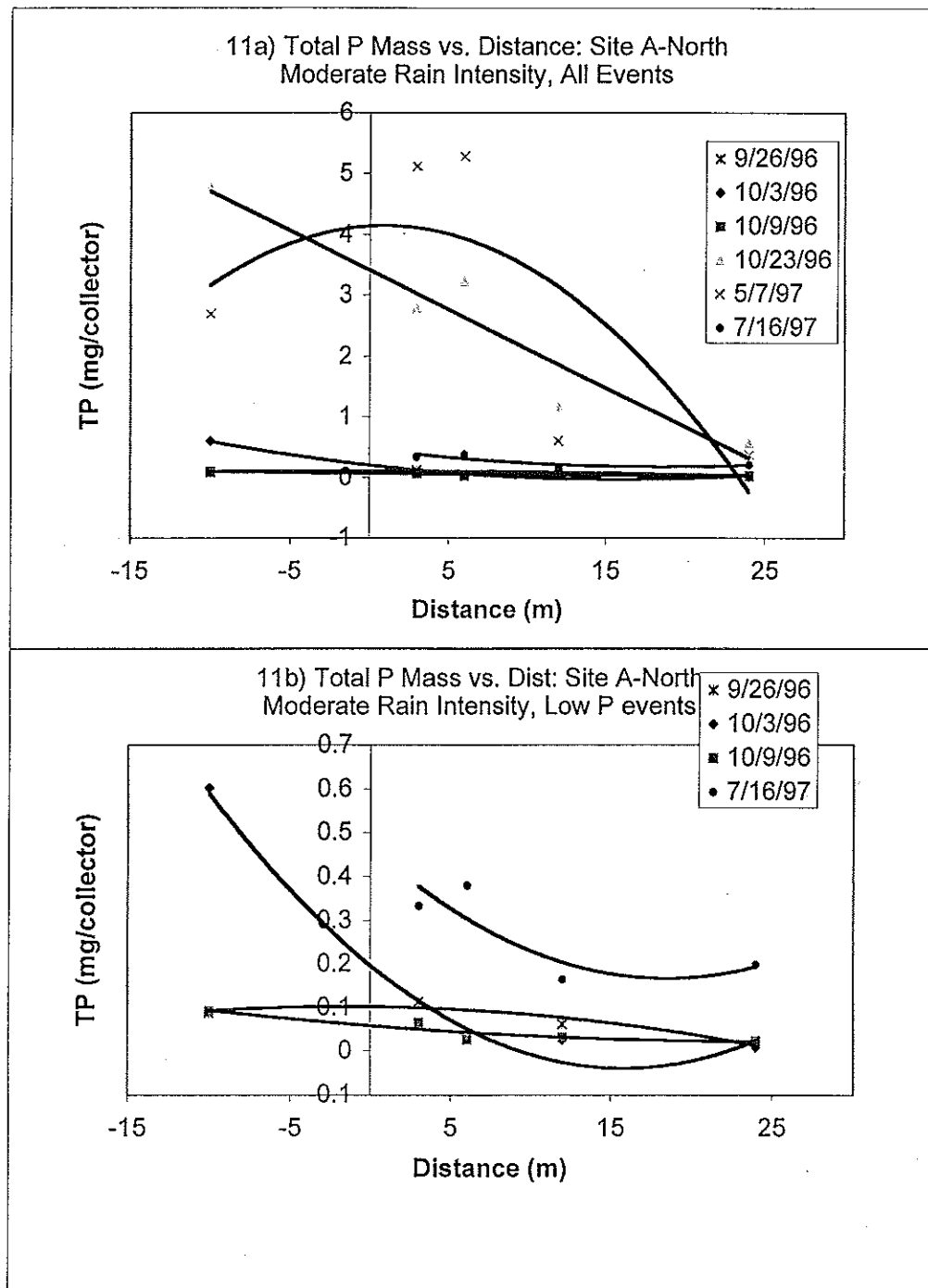


Figure 11 Change in TP flux (mass) in runoff collected in the buffer zone of site A-north at different distances from the upslope cornfield on selected sampling dates: a) moderate rain intensities, all events shown, b) moderate rain intensities, only low P events shown, c) high rain intensities, all events shown, and d) high rain intensities, only low P events shown.

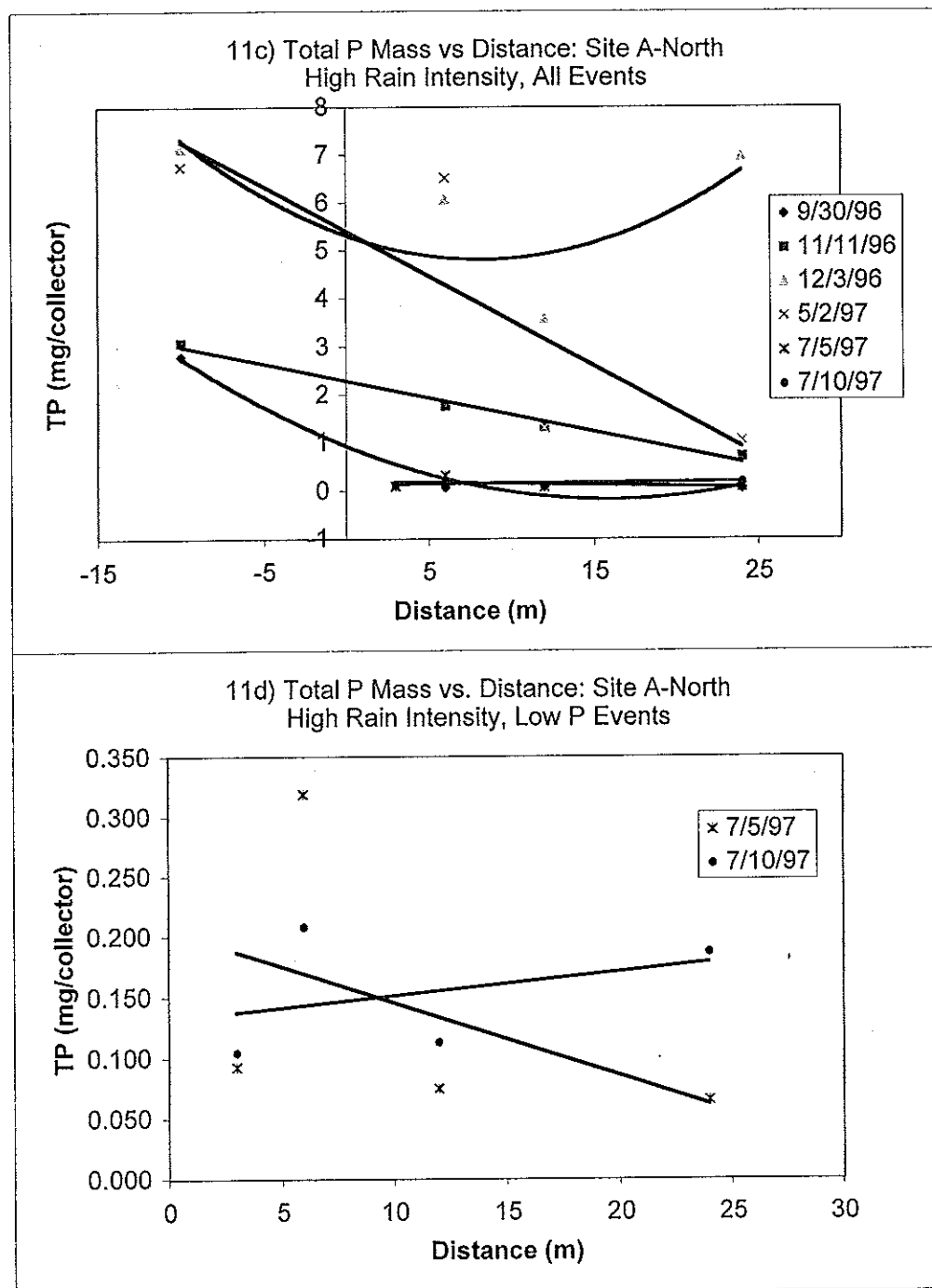


Figure 11 (cont'd).

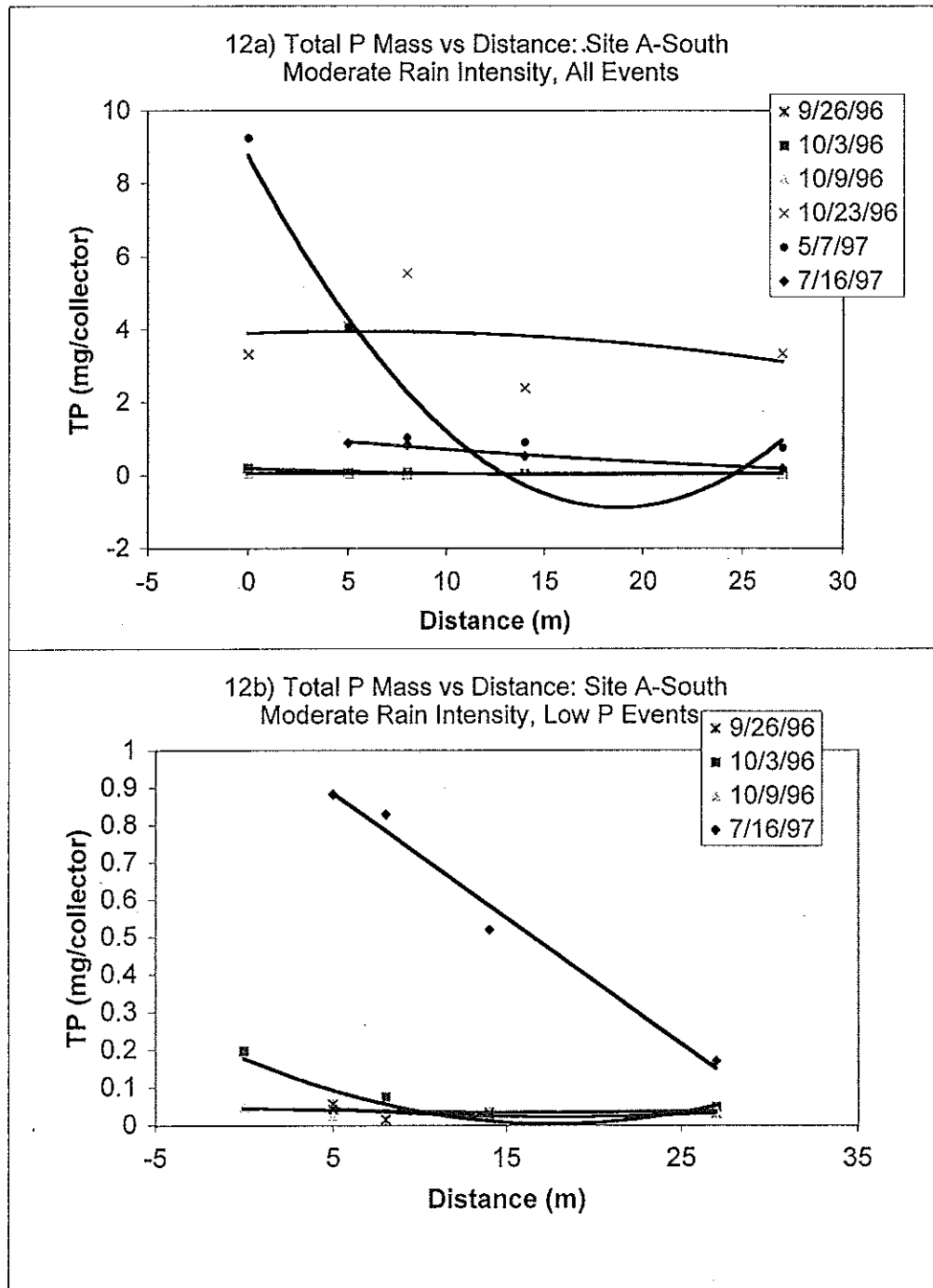


Figure 12 Change in TP flux (mass) in runoff collected in the buffer zone of site A-south at different distances from the upslope cornfield on selected sampling dates: a) moderate rain intensities, all events shown, b) moderate rain intensities, only low P events shown, c) high rain intensities, all events shown, and d) high rain intensities, only low P events shown

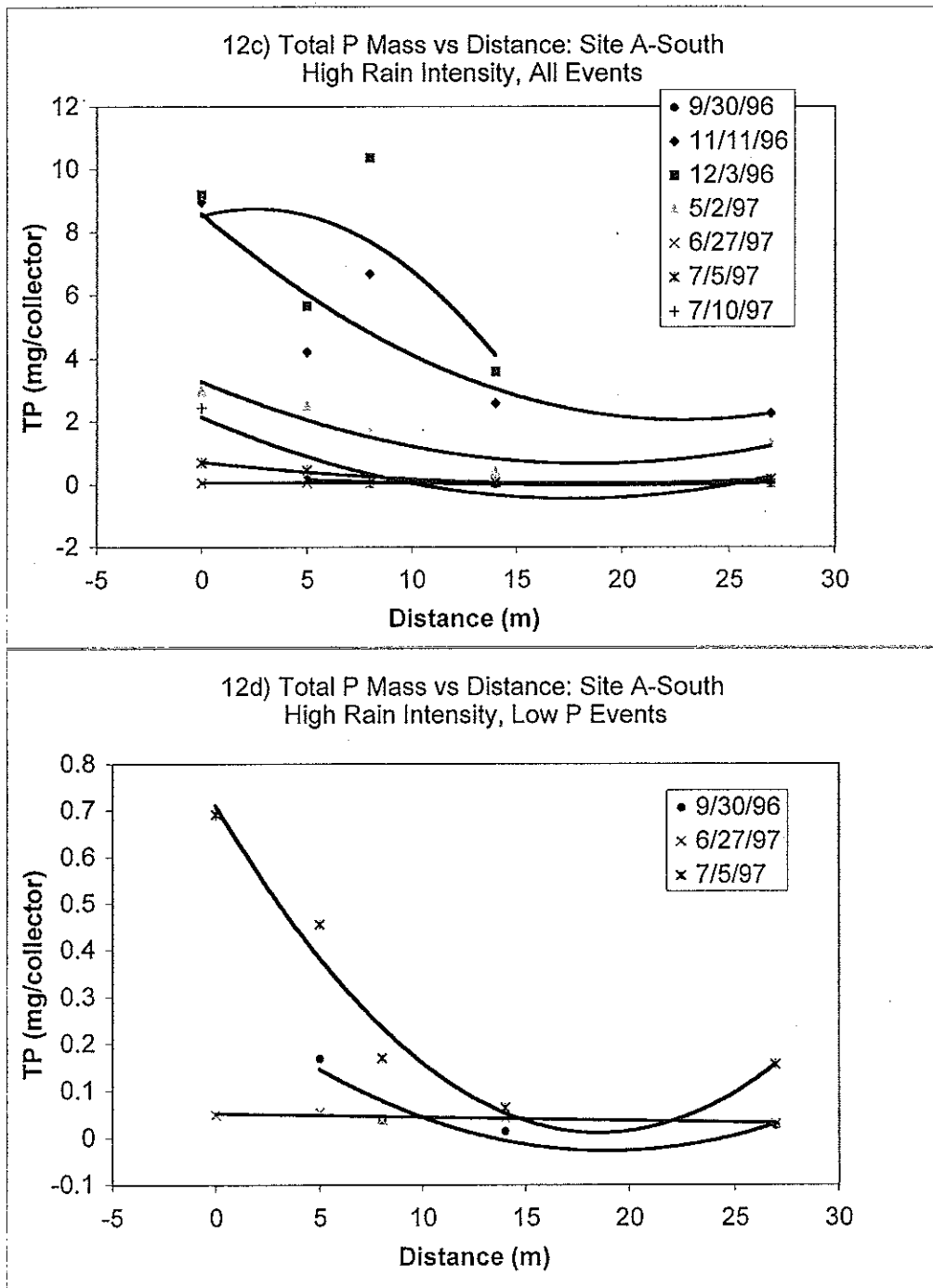


Figure 12 (cont'd).

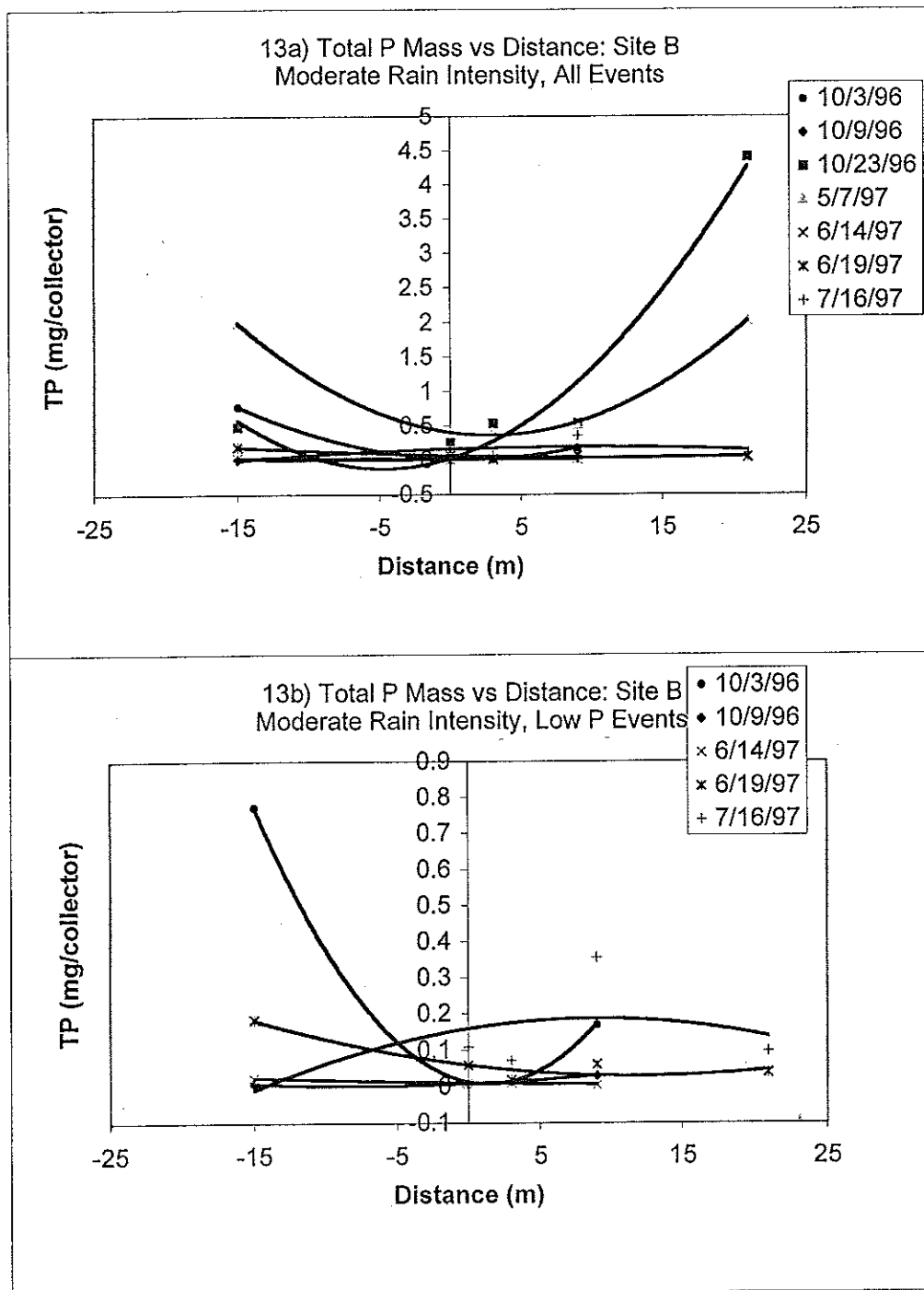


Figure 13 Change in TP flux (mass) in runoff collected in the buffer zone of site B at different distances from the upslope cornfield on selected sampling dates: a) moderate rain intensities, all events shown, b) moderate rain intensities, only low P events shown, c) high rain intensities, all events shown, and d) high rain intensities, only low P events shown.

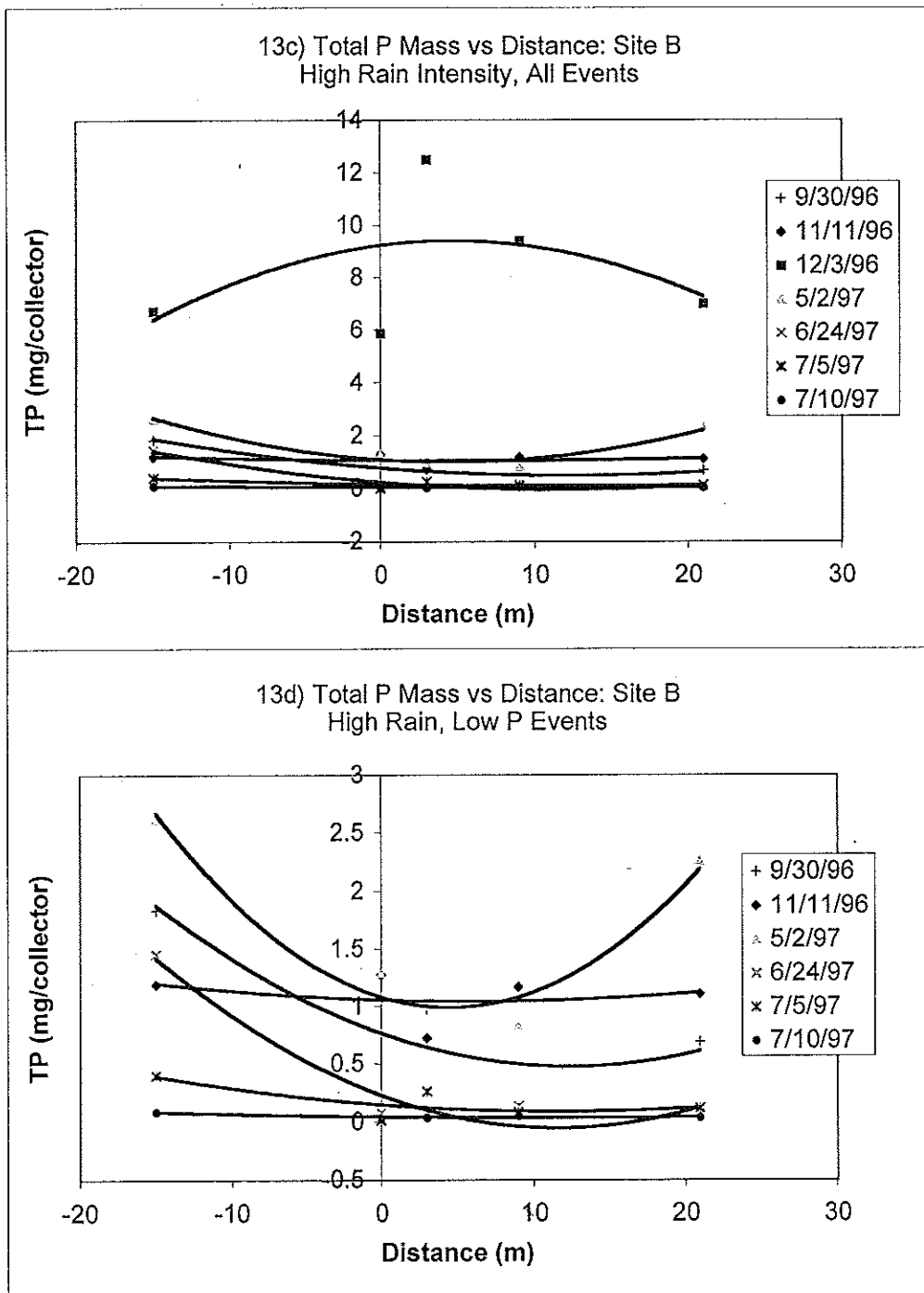


Figure 13 (cont'd).

Runoff P concentrations for most of the events were reduced to levels of 2 to 3 mg/L or less. Notable exceptions were three events at site A-North and one at A-South, which entered the downslope buffer zones at concentrations of 20 to 60 mg/L. An apparent anomaly occurred in a few runoff events, primarily at the A-North site – an increase in P concentration in the last collector (24 m). We have no explanation for these unexpected results.

Phosphorus in runoff from site B did not decline noticeably as it passed through the buffer. In fact, for several events, there was an increase in P concentration (Fig. 10 a-d) or mass flux (Fig. 13 a-d) from the edge of the field through the buffer. The ineffectiveness of this buffer at removing P was apparently related to channelized flow created by small mammals. During rain events, as we searched for locations to collect grab samples, it was rare to find any running water on the surface in certain areas, but the sound of running water could still be heard. Further investigation revealed small (roughly 3 cm diameter) tunnels just below the ground surface through which large volumes of water were running. During other site visits, it was noted that there was a large rodent population in the same area. It is likely, therefore, that the presence of rodent burrows in the soil had a significant impact on buffer efficacy by providing a bypass route for runoff that otherwise would have flowed through the vegetative buffer. Under these conditions, buffer width probably has little effect on the extent to which phosphorus is attenuated as it passes through buffers. Further studies to determine the prevalence and effect of this condition are needed.

Bioavailable phosphorus (BP) in runoff varied by site and distance into the buffer, but there tended to be a slight decline in BP concentrations at all three sites as distance into the buffer increased, especially after 15 to 20 meters of travel (Fig. 14). The BP/TP ratio (i.e., the percentage of TP that was biologically available) did not appear to change as distance into the buffer increased, however (Fig. 15). Soluble reactive P (SRP) in runoff also changed little as it passed through the three site buffers, and there was no consistent pattern in the SRP/TP ratio as distance into the buffer increased.

Runoff P in channelized flow

There was a slight decline in the concentration of total phosphorus (TP) in our grab samples of channelized flow as distance from the cornfield increased, but TP concentrations in grab samples were low at all distances (<10 mg/l for all collections, and <0.5 mg/l for more than half of the collections) (Figure 16). Grab samples of channelized flow had much lower TP concentrations than in corresponding funnel samples, where concentrations ranged as high as 82 mg/l (Fig. 17).

It is likely that this difference between sample types corresponds to differences in sampling technique rather than to differences in the runoff. In general, channelized flow was through small rivulets which were difficult to sample. Because of this, many of the grab samples were collected in spots with water that was deep enough to sample without unduly disturbing the water. Running into pooled areas reduced the velocity and energy of the water flow, and enabled solids, and thus P, to settle out, resulting in lower concentrations in the grab samples.

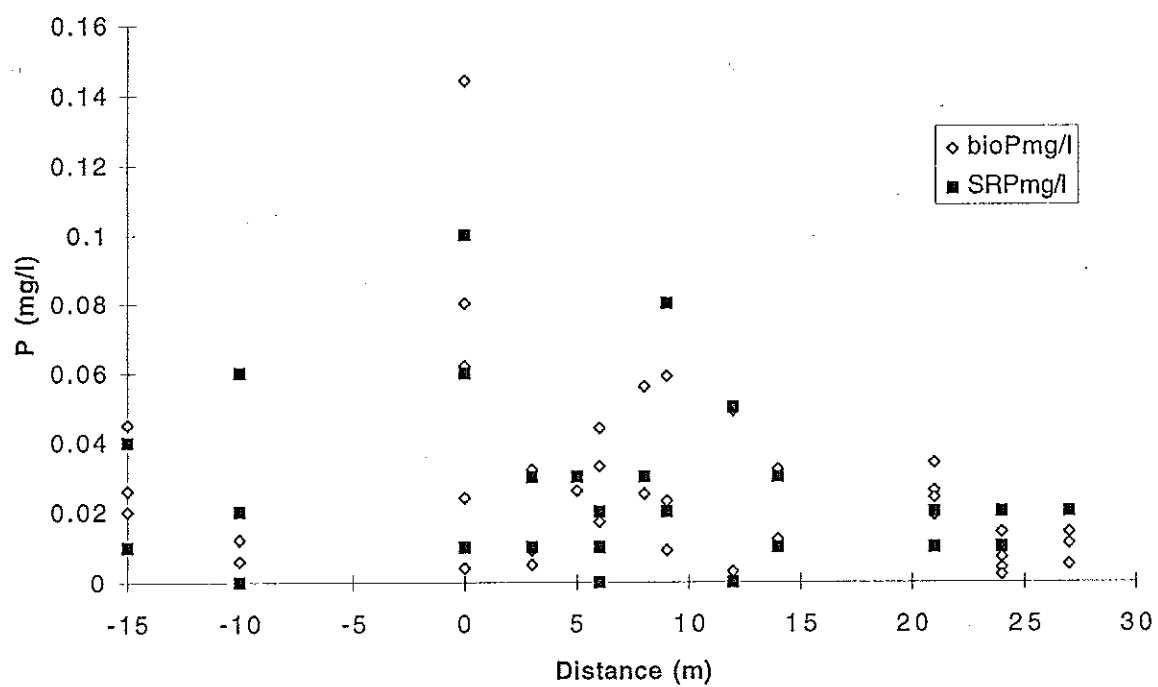


Figure 14 Concentrations of bioavailable P (bio P) and soluble reactive P (SRP) in runoff passing through different buffer widths downslope of cornfields

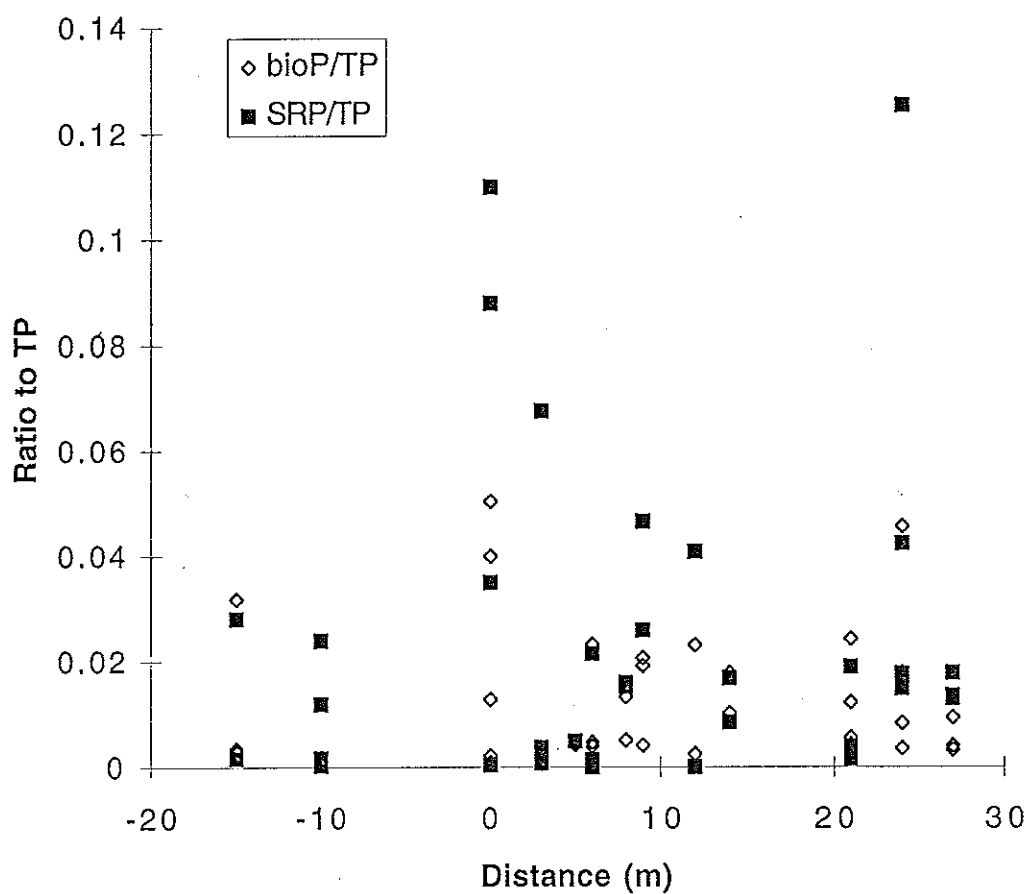


Figure 15 Change in ratios of bioP/TP and SRP/TP in runoff passing through different buffer widths downslope of cornfields

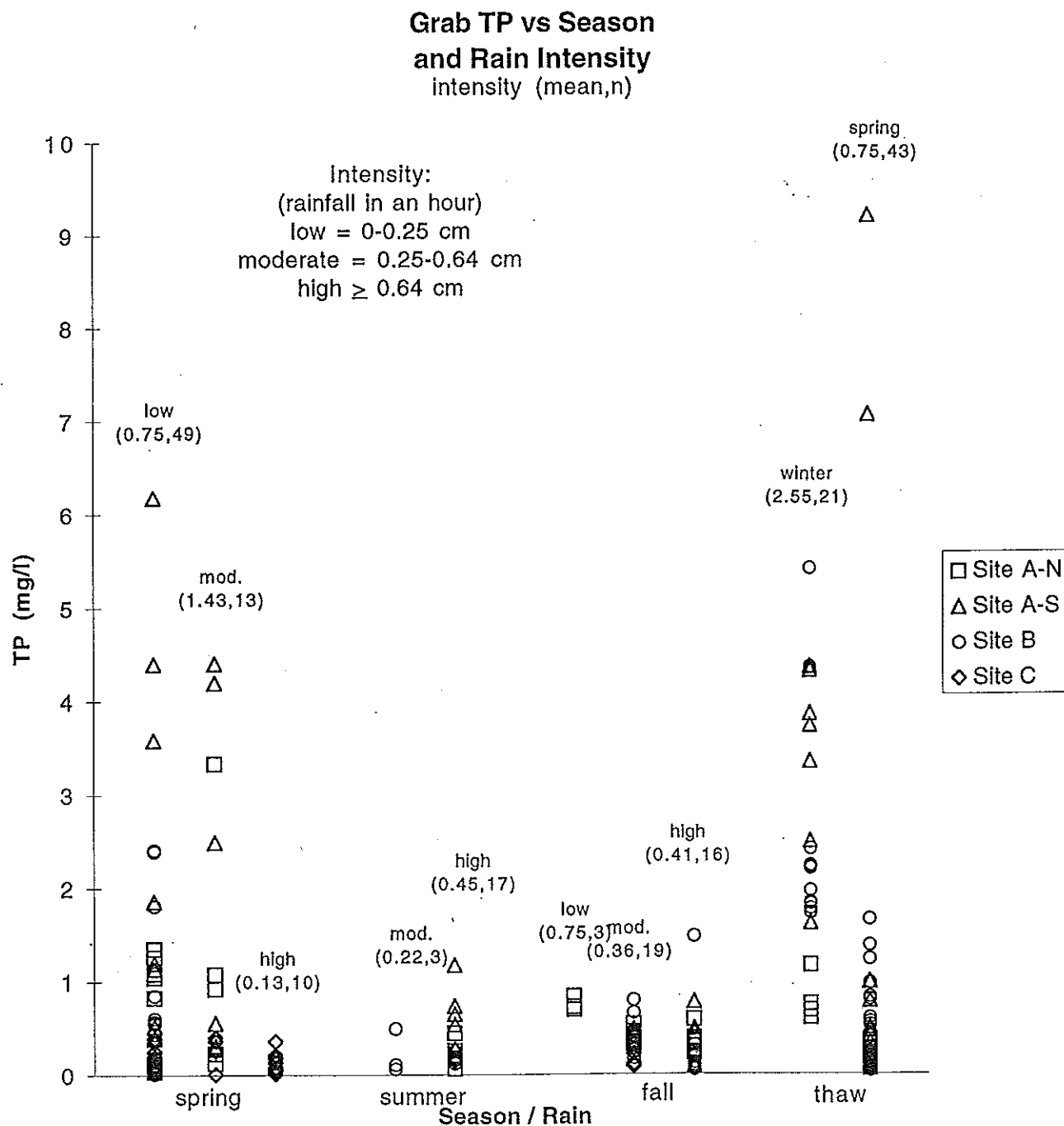


Figure 16 Comparison of TP concentrations in channelized runoff (grab samples) collected during different seasons and different rain intensity events

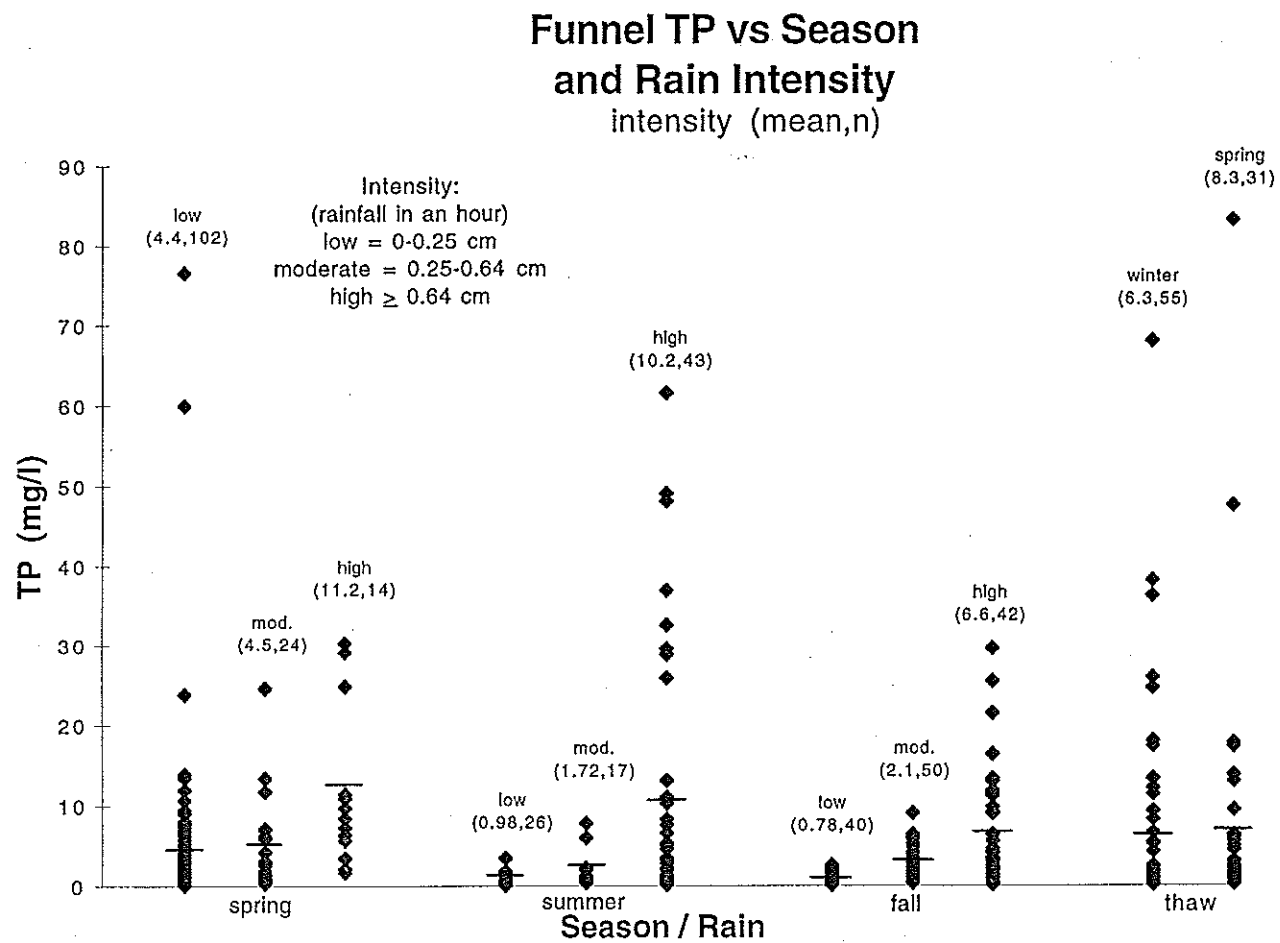


Figure 17 Comparison of TP concentrations in runoff collected by funnel collectors during different seasons and different rain intensity events

High and Low Runoff Events

The highest overall concentrations of TP passing through buffers both in grab and composite samples occurred in spring, particularly during thaws or low rainfall events (Figs. 16, 17). The highest overall concentrations of TP collected by funnel samplers (82 mg/l) occurred during a spring thaw, and during a low rainfall spring storm (78 mg/l). On average, however, the highest TP concentrations (Fig. 17) occurred during both winter and spring thaws (6.3 mg/l and 8.3 mg/l, respectively), as well as during high intensity storms during all seasons (11.2 mg/l, spring; 10.2 mg/l, summer, and 6.6 mg/l, fall). Low intensity rainfall events did not produce important TP fluxes as measured by the samplers, except in the spring (mean = 4.4 mg/l, high = 78 mg/l). The higher values during this period may correspond to saturated or partially frozen ground, and may have little relevance to the storm intensity. Some funnel collectors failed to collect samples during rainfall events. Micro-topographic variation within the flow collectors appeared responsible for much of this.

Grab samples from channelized flow (Fig. 16) showed a similar pattern, with some high values during spring thaw events as well as low intensity storms during the spring. In addition, spring events of moderate intensity produced some high concentration values, as well as a relatively high mean value (1.43 mg/l). The highest mean concentration in channelized flow samples (2.55 mg/l) was seen during winter thaw events.

Critical Runoff Events

Storms producing high TP runoff concentrations are critical events for P migration through buffers into surface waters. Whereas all event types, particularly at sites A-north and A-south, showed reduced P concentrations with distance away from the cornfield, the events producing high TP concentrations showed clearer trends towards TP removal within the buffer during unfrozen periods. Moreover, many of the peak values were only seen in the first 10 or so meters of buffer length, indicating that the highest P concentrations were reduced within this buffer distance.

In terms of total movement of P via surface runoff through the buffers, measures of P concentration alone were not as revealing as measures of P mass. High rainfall events produced higher flux of P mass through all three intensively sampled sites (A-north, A-south, B). There was considerable site-to-site variability, but less TP was found in collections made at the field/flow collector interface than in the upslope cornfield. In general, the lowest masses of TP in collectors tended to occur furthest from the field edge, with the greatest effect in the first 10 to 15 meters. Thus, these particular buffer-cornfield associations appear to provide an important ecological function during times of high P mobilization from agricultural fields.

Both runoff sample types indicate that thaw events, and corresponding situations of saturated or partially frozen soil, constitute the most sensitive and important period for P migration from cornfields. This period should be the focus of regulatory work and preventative measures.

PART III: PHOSPHORUS STORAGE IN BUFFER VEGETATION

MATERIALS AND METHODS

Study sites

We studied vegetative uptake of phosphorus in six riparian buffer strips located downslope of silage cornfields in the Champlain Valley of Vermont, USA (Table 1; Fig. 1). All buffer strip soils were Inceptisols (predominantly Fluventic Haplaquepts and Fluventic Dystrochrepts) with a silt-loam texture and a slope less than 4% (Griggs, 1971; Flynn and Joslin, 1979; Allen, 1989). Half (three) of the buffer strip study sites were adjacent to intermittent waters; the other three were along perennial streams.

Each buffer strip study site consisted of a strip at least 50 m long dominated by herbaceous meadow vegetation (predominantly graminoids, goldenrods (*Solidago* spp.), and milkweeds (*Asclepias* spp.) and free of obvious human disturbances such as recent mowing or plowing. Buffer widths ranged from 2-15 m, with boundaries defined as the edge of the current year's plow furrow edge to the top of the steeply sloping ditch or stream bank. All cornfields adjacent to study sites were in second or third-year silage corn and under alfalfa-corn rotations for at least 10 years. The primary outside addition of P to the cornfields was manure from dairy cows, with fields receiving spring and fall manure applications totaling 45-90 Mg ha⁻¹-yr (Table 1). No chemical P fertilizer was applied to the study cornfields, except as starter fertilizer during planting (about 0.03 Mg ha⁻¹-yr).

Within each site, three (four at one site) randomly located transects were placed perpendicular to the cornfield edge. Transects were repositioned if they were (a) within 5 m of another transect, (b) on an altered drainage channel, or had (c) woody vegetation along the transect taller than 2 m, or with a diameter greater than 1 cm at breast height (1.46 m). One plot (0.5 x 2.0 m), with its long axis parallel to the field edge, was placed along each transect at three standard distances from the field edge (0-0.5 m, 2.0-2.5 m, and 4.5-5.0 m). The total number of plots sampled at the farthest distance from the field edge (10 plots) was less than at 2.5 m from the field edge (15 plots) or at 0.5 m (17 plots) due to variation in width of existing buffers at the different sites (Table 1).

Field Methods

Sites were sampled from 1 July - 15 August 1994 for P storage in litter, above-ground vegetation, and roots (0-20 cm and 20-40 cm depths). Above-ground vegetation in each plot was clipped at ground level and sorted by species. Species that were difficult to sort (graminoids and bindweeds) were grouped without further sorting. Species with fewer than five stems in a plot were sorted by stem type (herbaceous or woody). Litter, defined as fallen leaves, detached, exposed roots, and partially decayed plant parts, was collected in a 0.5 x 0.5 m subplot placed in the center of each vegetation plot (Fig. 2). Litter was collected by gently scraping the ground to remove all identifiable plant residues. Roots were separated from soil by passing excavated soil from each depth interval through a hardware cloth screen (1 cm² mesh). To prevent phosphorus contamination during handling, all sampling was done with gloved hands. All samples were stored in plastic bags in the shade until the end of the day when they were returned to the lab and transferred to paper bags.

All samples except roots were immediately placed in a drying room at 80°C, dried to constant weight, and weighed. Roots were air dried for 24 hours, then were carefully cleaned with a stiff plastic brush to remove soil (Fahey et al., 1988). Following soil removal, roots also were dried to constant weight at 80°C and weighed.

Sample Preparation

Individual samples of above-ground vegetation were ground to pass a 20 mesh screen in a cyclone mill. Samples from each plot were then recombined in proportion to their respective contributions to total plot biomass (Mou et al., 1993). Fine root and litter samples were coarsely clipped with scissors, then ground to dust in a cyclone mill; coarser samples were reduced to segments with a chisel, passed through a #3 Wiley Mill (20 mesh; 0.85 mm diameter), then ground to dust in a cyclone mill as above.

Chemical Analyses

Litter and plant tissues were digested in a Kjeldahl block digester with NBS reference material, using the lithium sulfate digest method of Parkinson and Allen (1975). The TP content of digests was then determined colorimetrically using the ascorbic acid method (Clesceri et al. 1989), adapted for use on a Technicon Autoanalyzer II.

Statistical Analyses

Data were analyzed using JMP, Version 1.2 (SAS Institute 1994), with a significance level of 0.05. Prior to analysis, plot values were averaged for each variable for each distance within each site. This yielded a total of 15 averaged values (six for 0.5 m from the cornfield edge, five values for 2.5 m, and four values for 5.0 m). Analysis of Covariance was used to examine storage trends related to distance and depth (for roots), with site entered as a random error term. One-way Analysis of Variance was used for comparisons related to distance from cornfield.

RESULTS AND DISCUSSION

All six buffer strips were immediately downslope of cornfields that received dairy manure applications estimated by the farmers at 45-90 Mg ha⁻¹/year. These inputs, spread on unvegetated cornfields in fall and spring, added about 4700 kg P ha⁻¹ (unpublished data, Univ. VT Agricultural and Environmental Testing Lab) to surface soils. Manure application was thus the main source of P enrichment of surface cornfield soil, and erosional losses and surface runoff undoubtedly transported much of the P in manure to surface soils in buffers. Some direct loading of P to buffers may also have occurred if manure was inadvertently spread across field boundaries. Year-to-year shifts in location of field edges also may have contributed to higher phosphorus in surface soils, but dense root mats at the field edge suggest that field edges have moved very little from one year to the next.

The amount of phosphorus stored in buffer vegetation and litter was more a function of mass of the storage component than of P concentration in the storage component (Fig. 18). The biomass of above-ground vegetation therefore appears to be tightly linked to its effectiveness at retaining phosphorus released from upslope cornfields. Christine and Moorby (1975) also found that total TP storage (in grasses) was more tightly linked to plant biomass than to tissue concentration. Results from Fail et al. (1986) were more equivocal, however, as both biomass and tissue concentrations in downslope buffers were highest near the source of runoff.

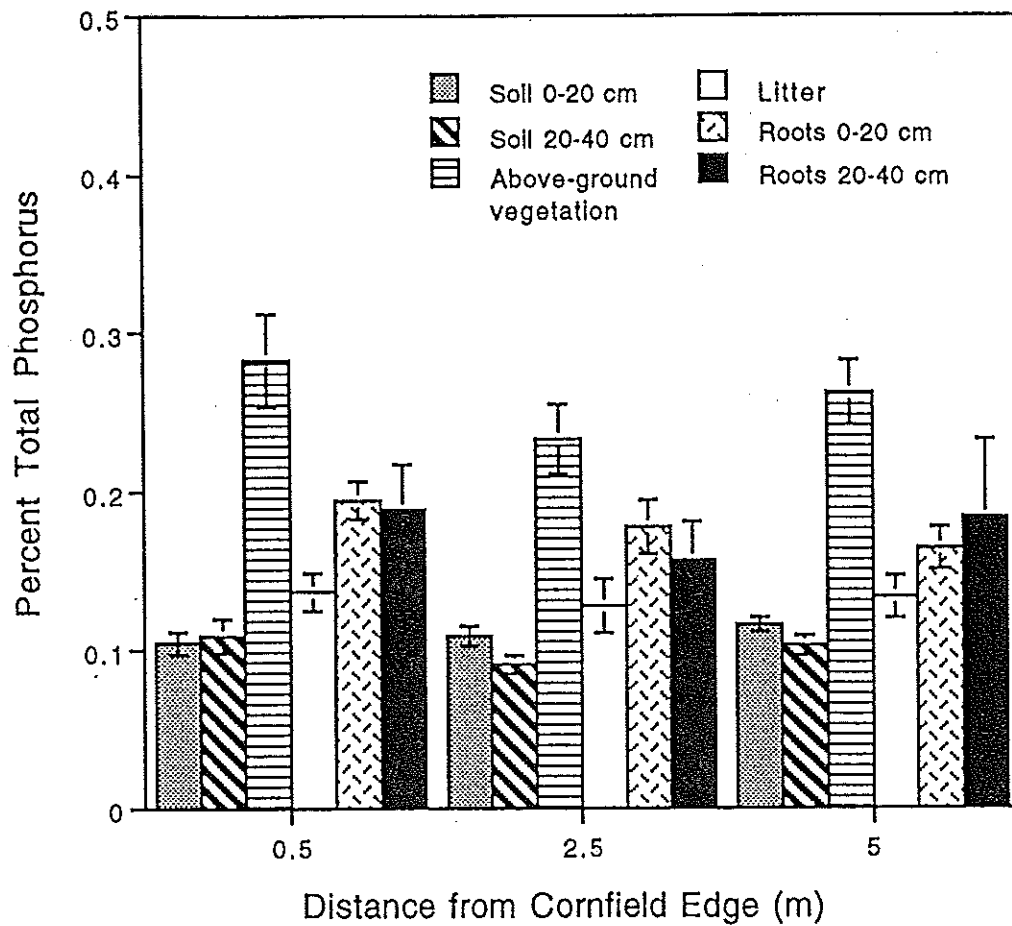


Figure 18 Percent P on a dry weight basis for soil and plant tissue in buffers at different distances from the field edge

TP stored in above-ground vegetation declined as distance from cornfield edges increased. This trend was the result of greater biomass in plots closer to cornfield edges rather than higher phosphorus concentrations in the plant tissue (Fig. 18). Concentrations in vegetation nearest the field edge (0.28%) and farthest from the field edge (0.26%) were similar, whereas plant biomass at the field edge (7255 kg ha^{-1}) was 1.2 times higher than biomass at 5.0 m from the edge. We suspect that high biomass at the field edge resulted from nitrogen fertilization via runoff; this fertilization effect probably declined as distance from the field edge increased (Peterjohn and Correll, 1984).

MANAGEMENT RECOMMENDATIONS

Management of agricultural fields upslope of waterways probably represents the most promising opportunity to reduce non-point source phosphorus pollution in Champlain Valley surface waters. Appropriate management strategies include a variety of soil and water conservation practices:

- maintain a residue cover on fields during periods of high runoff (fall and spring melt). This could be achieved by interseeding fall or spring cover crops,
- reduce fall tillage to maintain residue cover and reduce erosion
- disperse channelized runoff in the upslope field before it enters a buffer
- in larger fields having long, erosive slopes, establish field strips/contour strips of close-seeded legume-grass forages to break the downslope flow. Contour strips could be harvested three times annually for an economic return to the farmer.

With respect to management of the buffer itself, storage of TP in buffer vegetation and litter might appear inconsequential, especially when compared to storage of phosphorus in soil. When evaluated in terms of mass of phosphorus stored, however, both litter ($10.7 \text{ kg P ha}^{-1}$) and live vegetation ($12.3 \text{ kg P ha}^{-1}$) were important at retaining phosphorus that otherwise would have entered surface waters. The biologically active form of phosphorus that was taken up by the vegetation also represented the form of P that most compromises water quality (Sharpley et al., 1993). As buffer vegetation dies, however, much of the stored phosphorus is released, some as dissolved-P (Fisher and Likens, 1973; Osborne and Kovacic, 1993; Vought et al., 1994). Removal of standing vegetation and litter in buffers is therefore probably needed to protect against re-release of stored P. Above-ground stubble after harvest also probably slows runoff and promote deposition of particulate-P (Pearce et al., 1997).

Regular harvest of above-ground biomass (three times/year) would eliminate much of the potential P-release problem while leaving roots intact to minimize soil erosion. The harvests would also provide economic return to the farmer for land that is removed from corn production.

Best Management Practices (BMPs) and state regulations rarely specify what types of vegetation should be maintained or managed in buffer strips to protect water quality. Thickly grassed strips with a high stem density and thick groundcover probably have the highest particulate-P retaining capacity. Strips with high plant biomass store the most phosphorus in plant tissue, but this biomass-bound phosphorus is ultimately re-released to the system through litterfall and leaching. Periodic harvesting and removal of buffer vegetation is therefore warranted.

BMPs and regulations also commonly fail to address management of intermittent waterways and adjacent vegetation. Intermittent waterways such as drainage ditches, which are common in the Champlain Valley, probably receive particulate and dissolved-P from runoff events throughout the year. Storage of phosphorus in these ditches is only temporary, however, for high flow events periodically flush deposited sediment into permanent receiving waters. For example, after a heavy autumn rainfall, previously dry or stagnant drainage ditches on our sites had flows exceeding 40 cm in depth. Maintenance of buffers along these intermittent waterways would reduce loading of P during such high flow events.

Results from our study indicate that high plant biomass in buffers should be promoted, and that periodic harvests may be desirable to protect against re-release of stored P. In addition to serving as a storage pool (15-20 kg ha⁻¹ in our study) for the forms of phosphorus that exert the most immediate impact on water quality, high biomass in buffers is likely to promote retention of particulate-P (Dillaha et al., 1988; Vought et al., 1994; Daniels and Gilliam, 1996), stabilize stream banks (Karr and Schlosser, 1978), and reduce erosion within the buffer (Robinson et al., 1996). But the potential for narrow strips of buffer vegetation to retain agriculturally-released phosphorus is limited. A much greater potential rests in management of upslope cornfields to reduce loss of P-laden sediment from the fields. Farm management practices that minimize soil disturbance (such as minimum tillage (Miranowski et al., 1982), and maximize vegetative cover (such as cover cropping), probably hold the greatest promise for reducing phosphorus pollution of surface waters.

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