ABSTRACT

BOND, CHRISTOPHER RYAN. Phosphorus Characteristics of North Carolina Soils and Riparian Buffers. (Under the direction of John L. Havlin and Rory O. Maguire)

Non-point phosphorus (P) losses from agricultural fields have the potential to accelerate eutrophication of North Carolina surface waters. In 1998, the US Environmental Protection Agency reported as much as 60% of the US fresh waters were impaired by non-point source nutrient pollution stemming primarily from agricultural contributions. Phosphorus has been marked as the most limiting nutrient in fresh waters. Yet in NC, historically excessive applications of P in the form of fertilizer, e.g. tobacco fields, and manures has resulted in elevated soil P concentrations well above levels required to optimize crop performance and yield. In agricultural fields with elevated soil P concentrations, the risk of P loss to surface waters is also elevated.

Soil testing, i.e. Mehlich-3, has been identified as an important factor in determining P losses from soils. However, there in a lack of information on how fertilization and initial Mehlich-3 P (M3P) interact to affect water soluble P (WSP) in soils. Such soil dependent relationships may assist in ranking agricultural fields from low to high on their potential to lose P in the soluble form. Overall, our objectives were to validate the use of the Mehlich-3 soil test as a useful indicator of P loss risks from fields receiving animal wastes. In doing so, soil or soil group dependent critical M3P and/or M3P-saturation ratio thresholds (or change points) may be identified.

In an incubation study (Chapter 2), our objectives were to (1) quantify the relationship between WSP and M3P for four texturally diverse benchmark soils of North

Carolina (NC), and (2) quantify the change in WSP concentrations following P additions to soils over a wide range of initial M3P. One hundred and seven samples known to represent a wide range in M3P were collected from an Autryville loamy sand, Wasda muck, Georgeville silt loam, and Pacolet sandy clay loam and analyzed for M3P, Fe and Al and WSP. An incubation study was also conducted where four samples representing a range in M3P from each series were fertilized at rates of 150 and 300 kg P ha^{-1}, and WSP was measured at 1, 7 and 21 d after fertilization. The Wasda muck exhibited a change point at 115 mg P kg^{-1} across a broad range of M3P concentrations (60-238 mg kg^{-1}) while Autryville, Georgeville, and Pacolet series (with ranges in M3P of 32-328, 119-524, 0-1034 mg P kg^{-1}, respectively) maintained linear relationships between WSP and M3P. For the fertilized soils, significant increases in WSP occurred regardless of P rate. However, greater increases in WSP were observed following P application to soils of relatively greater initial M3P. As WSP is linked to soluble P losses in runoff, these data suggest that shifting animal waste applications to fields of relatively lower M3P concentrations would have an immediate impact on reducing risk for P losses, if all other factors are equal.

In a P leaching study (Chapter 3), our objectives were to i) determine the extent of P leaching in Piedmont and Mountain soils amended with animal wastes, (ii) assess the validity of grouping soils into soil management groups to more accurately predict P leaching, and (iii) evaluate soil factors affecting the relationship between Mehlich-3 P (M3P) and soluble ($CaCl_2$-extractable) P. Twenty-seven soils from 7 Piedmont and Mountain counties were collected to a maximum depth of 91 cm. All soils were analyzed for M3P, Fe, Al, and $CaCl_2$-P. Despite the historically excessive applications of P in the

form of animal wastes to NC Piedmont and Mountain soils, the net accumulation of P did not excessively (M3P>53 mg kg^{-1}) accumulate to depths below the plow-layer (upper 30 cm of soil profile) of most soils studied. The finer textured, Fe-oxide dominated soils of these physiographic regions of the state represent the importance of these soils properties in fixing P and inhibiting P leaching. In comparison, a coarser textured floodplain soil exhibited lower P sorption capacities and illustrated a greater P leaching potential. Soil management groups currently employed by the PLAT appear to be justified for use in predicting soil P leaching potentials. From the relationship between the M3PSR and $CaCl_2$-P, we identified mineral-dependent critical environmental M3PSR thresholds for these soils at 0.06(M3PSR) and 0.15(M3PSR), above which potentially greater risks of soluble P losses via surface or subsurface pathways may prevail.

In the middle Coastal Plain of NC, soil dependent P leaching potentials were also evaluated as well as the associated risk of P loss to nearby surface waters via subsurface lateral transport (Chapter 4). Leaching of M3P in NC coastal plain soils to depths exposed to the water table (often <1 m from the soil surface) may increase the risk of soluble P loss to surface waters, but may be mitigated by riparian buffers (RBs). Our objectives were to evaluate NC Coastal Plain soils to (i) validate the use of M3P to predict P leaching in these soils, and (ii) evaluate the effects of RBs for attenuating potential subsurface P losses from high P fields. Eleven soil series were sampled to a maximum depth of 165 cm along transects oriented in the direction of groundwater flow leading from the field into bordering riparian buffers. Soil drainage classification appeared to influence the pathway(s) by which P losses to neighboring RBs occurred from fields. “Drier” soils had greater potentials for surface P loss than “wetter” soils. In general, the “drier” soils exhibited greater P sorption capacities than “wetter” soils as exhibited by their respective M3PSR change point values. The accumulation of humic matter (HM) content in “wetter” soils resulted in lower P sorption capacities and greater potential for P leaching and subsurface lateral P losses. Overall, excessive applications of swine waste resulted in M3P leaching in all NC Coastal Plain mineral soils. In well-drained soils, P loss appeared to have occurred as a surface phenomenon as opposed to subsurface despite excessive P leaching losses in the field. Yet, greater surface (~75 cm) HM content resulted in less P sorption capacity (M3PSR) and greater M3P leaching than all other soil series. In reference to the Pantego loam M3P interpolation, the data suggests a real potential for lateral (from the field) subsurface (>120 cm) M3P accumulation in the RB. Due to limited data, no apparent trends in groundwater soluble P were evident. Therefore, further research and emphasis should be placed particularly on soils with relatively greater organic matter to better understand the potential risk for P losses to nearby surface waters so that a more sustainable approach to P management may be developed and implemented.

PHOSPHORUS CHARACTERISTICS OF NORTH CAROLINA SOILS AND RIPARIAN BUFFERS

by

CHRISTOPHER RYAN BOND

A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

SOIL SCIENCE

Raleigh

2006

APPROVED BY:

John L. Havlin (Soil Science) Co-Chair of Advisory Committee	Rory O. Maguire (Soil Science) Co-Chair of Advisory Committee
David A. Crouse (Soil Science) Committee Member	Robert O. Evans (Biological and Agricultural Engineering) Committee Member

BIOGRAPHY

C. Ryan Bond was born in Roanoke, VA on April 1, 1974, yet raised in Winnsboro, SC. Upon graduation from Richard Winn Academy, he attended the University of South Carolina and later completed his Bachelors of Science in Agronomy (emphasis in soils) in 1996 at Clemson University. In 1999, he earned a Masters of Science in Crop and Soil Environmental Science with a minor in Plant Pathology from Clemson University. His MS research investigated the effects of the Columbia lance nematode on cotton growth, maturity, and yield. Following graduation from Clemson, he worked as a turf and ornamental sales representative in NC, SC, and GA, and later moved to New Orleans, LA to work a LA, MS, AL, and FL territory in the same capacity. Ryan and his wife Kay currently live in Raleigh, NC.

ACKNOWLEDGEMENTS

I would like to thank Drs. John Havlin and Rory Maguire for affording me the opportunity to study the discipline of soil science at NC State University. I learned a great deal from these two within and beyond soils. Also, I thank Dr. David Crouse for his openness and willingness to listen and actively participate in my research. Dr. Robert Evans also provided me with sound guidance, and I thank him. I am particularly grateful for the never-tiring interest and instruction that Drs. Eugene Kamprath and Dean Hesterberg gave me. Without these folks, I surely would have struggled to finish this degree…especially on time! So thanks!

I am also very appreciative for the hard work put forth by two true friends, Mr. Charles Karpa and Mr. Todd Carpenter, which ranged from helping design experiments to collecting samples (lots of samples!!). I also thank the undergraduate student lab assistants, Mr. James Lamberth, Mr. Colt Gatlin, and Miss Jennifer Amick, for their dedication not only to getting the samples organized and processed, but getting them done correctly and efficiently.

And without a doubt, I am thankful for the undying support received from my wife, Kay!!

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

CHAPTER 2

CHAPTER 3

CHAPTER 4

LIST OF FIGURES

Page

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 1

General Literature Review - Phosphorus

Phosphorus and the Environment

Phosphorus (P) is one of life's essential elements for successful crop and animal production. In general, the concentration of total P in temperate soils ranges from 200 to 5,000 mg kg^{-1} and averages 600 mg P kg^{-1} soil (Lindsay, 1979; Leinweber et al., 2002). In most plants, P concentration in their tissues averages 2000 mg P kg^{-1} indicating that most soils utilized for crop production are P deficient (Salisbury and Ross, 1992). Phosphorus availability is generally low in highly weathered temperate soils and tropical soils with no history of P applications (Koopmans, 2004). Soil P concentration varies with soil parent material, texture, and management factors such as rate of P and cultivation practices (Maguire et al., 2004). A crop has the capacity to absorb P from the soil solution of low P concentration (0.2-0.3 mg P L^{-1}). However, below a soil test P (STP) critical level, conversion of unavailable P does occur, albeit at a rate too slow to satisfy crop P requirements for optimal growth and productivity (Sharpley, 1996).

Crop specific P requirements for optimal growth and yield are estimated via an agronomic P-index system. Agronomic P-indices utilizing soil extraction methods, e.g., Mehlich-3 and Olsen, have assisted in calibrating P application rates to suit crop P requirements during a growing season to optimize yield. Agronomic P-index critical levels predict fertilizer P inputs required to replace STP (an approximate measure of plant available P) removed by the crop and to estimate additional P needed to maximize crop growth and yield during one growing season. Any additional P applied that would result in a STP over the critical STP level is not expected to increase crop performance or yield

(Havlin et al., 1999). On the other hand, excessive P applications may result in high STP levels leading to soil P loss to surface and ground waters (Maguire et al., 2004).

Phosphorus is an essential crop nutrient and a primary water contaminant. Anthropogenic activities within and outside the scope of agriculture have raised concerns about P use and its impact on water quality (USEPA, 1996) and have created the need for P loss assessment strategies and for the development of P loss assessment tools (Sharpley et al., 2003). Development of environmental and adaptation of agronomic P-index systems have assisted in estimating soil P loss to surrounding water bodies. The amount of STP or plant available P is representative of the P that may be lost from the soil to the surrounding environment. Soil test P concentrations are measures of not only plant available P but also indicators of P loss via hydrologic pathways, e.g., leaching via matrix flow or accelerated flow from artificial drainage, erosion, and surface runoff (Koopmans, 2004). High STP values increase the risk of P loss to ground and surface waters. Soil specific critical STP levels serve as indicators or threshold points at which undesirable P loss to surrounding water bodies is expected. Such critical environmental STP or threshold levels are never distinct values and may vary based on soil management strategies (Maguire et al., 2004). Phosphorus concentrations of 0.02 to 0.03 mg L^{-1} mark the minimum P required for increased biological activity of surface waters causing eutrophication (Sharpley, 1996), which has increased over the last several decades (Johnston et al., 1997).

Eutrophication

Second to nitrogen, P is the most limiting element for increased biological activity leading to eutrophication in surface waters (Leinweber et al., 2002). The effects of eutrophication can lead to decreased water quality that has negative economic impacts. Eutrophication may be described by its four eutrophic stages, oligotrophic, mesatrophic, eutrophic, and hypereutrophic. Beyond the third stage, the degrading effects of eutrophication are marked by a decrease in water usage for fishing, industry, recreation, and drinking. Marked by an increase in biological activity, nutrient loading is responsible for the accelerated growth of aquatic plants and algae and the accumulation of organic matter. Organic matter degradation consumes dissolved oxygen in the water leading to decreases in the growth and diversity of aquatic species and under extreme conditions, fish kills (Pierzynski et al., 2000). As early as the late 1950's, nutrient loading was suggested to contribute towards eutrophication. By the 1970's, the importance of N and P towards eutrophication was acknowledged by state and federal governments. By the late 1990s, USEPA developed an initiative to reduce both N and P by 40%.

Phosphorus and Animal Agriculture

In recent decades, traditional animal agriculture has shifted towards confined animal feeding operations (CAFO) marking the effects of social, political, and economic pressures towards increased specialization. Production improvements and economic benefits have encouraged the concentration of animal production, more so than traditional farms of the past. Economic restrictions linked to production and transportation costs have regionalized CAFO locations in the US and NC near processing and shipping facilities. Unfortunately, USA CAFO regions, such as located in NC, have located themselves in areas insufficient in grain production used for animal feed. High-valued nutrient-rich supplemental feed is often imported from mid-western USA states in greater quantities than the low-value nutrient-rich animal excrement exported from CAFO regions, i.e., Delaware Peninsula, NC Coastal Plain. These circumstances have developed nutrient imbalances resulting in more P imported than exported and have created the need for more innovative nutrient management programs to protect water quality. An estimated 83% of the feed nutrients are imported to CAFO areas while only 30% of the nutrients needed to meet corn grain requirements are reallocated to corn (or grain) producing lands (cited from Tarkalson, 2001 citing Sharpley and Tunney, 2000). The challenge to producers and researchers is to develop nutrient management plans that efficiently utilize all sources of nutrients and at the same time maintain or increase agricultural profitability and environmental quality. The goal of the animal producer is to operate in a sustainable manner (Tarkalson, 2001). Nutrient management programs should not strive for an excessive nutrient buildup of P. Although P is a finite resource, it appears that grower mentality considers manure P as a disposable resource. While crop P requirements are typically much lower than their nitrogen requirements, manure is often applied at N-based rates. Nitrogen-based manure rates may result in P rates two to three times the crop P requirement. Compared to commercially available fertilizers, manure is significantly lower in elemental N, P, and K concentrations with the exception of some micronutrients, i.e., Cu. Therefore, transportation costs per kilogram of nutrient hauled inhibit growers from exporting low-P (nutrient) manure offsite. Furthermore, economic considerations restrict manure applications to fields located in close proximity to the animal production facilities, manure lagoons, or composting sites. As research suggests, the accumulation of P in these soils may increase the threat of soil P loss to nearby surface and ground waters.

A rapid proliferation of CAFO in the US and especially in eastern NC has raised concerns of possible nutrient loading impacts on water quality. North Carolina remains the country's largest producer of meat products ranking as one of the top producing states of swine (9.7 million head in 2002) and poultry. Since 1961, demand of meat products has increased the number of swine, chickens, and turkeys produced in the US. From 1985 to 1995 in NC, swine, turkey, and broiler chickens increased in inventory by 5.4 million, 30 million, and 22.4 million, respectively, reflecting a 248, 92, and 50 percent increase, respectively (Cahoon et al., 1999). Yet since 1961, the number of animal farms in the US has decreased as a result of the CAFO movement. Overall, the US has seen a decrease in the number of hog operations (of all sizes) of 49% (from 113,590 to 76,250) (USDA NASS, 2004). As of 1999, North Carolina hog producers represent 4.5% (3000) of the total US operations (67,770) (Cahoon et al., 1999).

Phosphorus Management and Losses

An increase in point and non-point source inputs of N and P into the nation's fresh waters have been marked by an increase in surface water eutrophication (USEPA, 1996). The potential for increased P delivery to fresh waters rises with elevated STP levels. Soil P loss is influenced by various factors such as hydrology and soil type of various physical, chemical, and biological properties (Havlin, 2002). Soil test P concentrations are measures of not only plant available P but also indicators of P loss via spatially and temporally diverse hydrological pathways, e.g., soil erosion, surface runoff, and leaching via preferential flow, matrix flow, or accelerated flow from artificial drainage, and the proximity of a site to a water body (Koopmans, 2004; Sharpley and Tunney, 2000; Havlin et al., 2002). Since soils are not infinite sinks for P, agronomic management plans encourage the use of methods to minimize P losses. Best management practices (BMP) are planned accordingly to mediate predicted soil P losses stemming from numerous interactions of factors (listed above) with additional factors such as P source, rate, and timing of application. Such BMP strategies sometimes utilize present or newly constructed vegetated buffer zones designed to decrease the loss of sediment-bound and dissolved forms of P from the field.

Phosphorus Leaching

Numerous researchers have evaluated the potential for soils to leach P (Ham, 1999; Maguire and Sims, 2002; Nelson, 2004). Maguire and Sims (2002) illustrated a rapid increase in leachate P from light textured Delaware topsoils that had exceeded a threshold of 181 mg P kg^{-1}. Similarly, broad levels of Mehlich-3 P (1 mg kg^{-1} to 1197 mg kg^{-1}; standard deviation of 140 mg kg^{-1}) have been reported for NC topsoils however no threshold levels were reported. Leaching of soil P to depths of 70 cm indicated by moderate to high-P Mehlich-3 levels in these soils indicates the effect for heavy manure P applications (Ham, 1999). When P leaches below the root zone, intensive subsurface drainage will increase potential for subsurface transport. Subsurface drainage also decreases surface runoff that reduces potential runoff P loss (Skaggs et al., 1982; Gilliam and Skaggs, 1986; Evans et al., 1995; Gilliam et al., 1999). North Carolina coastal plain sandy soils subject to a seasonally high water table presents substantial risk to P contamination of ground and surface waters as found in Florida spodosols (Villapando and Graetz, 2001).

Riparian Buffers and Nutrient Loss Mitigation

Riparian buffers essentially act to physically restrict sediment-bound and actively assimilate dissolved forms of P upon exiting an agricultural field. Riparian buffers have been noted for their efficiency in improving water quality of neighboring surface waters via the removal of NO_3-N in the groundwater (Lowrance et al., 1984; Peterjohn and Correll, 1984; Haycock and Pinay, 1993; and Smith, 2005; and King, 2005). Numerous researchers have also noted the RB efficacy of mitigating surface P losses from agricultural fields (Dillaha et al., 1989; Parsons et al., 1991; Abu-Zreig et al., 1999; Abu-Zreig, 2001). More recently, due to the historically excessive applications of animal wastes, P leaching has been identified as a potential water quality problem in the Coastal Plain, yet little is known about the potential for riparian buffers to mitigate P losses through subsurface pathways. A recent study by Novak et al. (2002) suggested buffers could mitigate subsurface losses in the Coastal Plain to some extent, but little is known about factors that determine the effectiveness of buffers for subsurface pathways, or how this could be quantitatively incorporated into PLAT.

References

Abu-Zreig, M.,. 2001. Factors affecting sediment trapping in vegetated filter strips: simulation study using VFSMOD. Hydrologic Proc. 15:1477-1488.

Abu-Zreig, M. R.P. Rudra, and H. Whitley. 1999. Sediment trapping in vegetated filter strips. 1999 ASAE/CSAE. #99-2078. ASAE, St. Joseph, MI.

Albrecht, Wm.A. 1958. Soil fertility and animal health. Fred Hayne Printing Company. Webster City, Iowa. p. 232.

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. Trans. of ASAE. 32:491-496.

Ham, R.J. 1999. Phosphorus movement in poultry, swine, and tobacco farm soil in the North Carolina Coastal Plain. M.S. Thesis. N.C. State Univ.

Havlin, J., S. Hodges, D. Osmond, A. Johnson, D. Crouse, W. Skaggs, R. Evans, J. Parsons, P. Westerman, L. Price, and R. Reich. 2002. Assessing the risk of phosphorus delivery to North Carolina waters. 2002 ASAE Annual International Meeting/CIGR XVth World Congress. Chicago, IL.

Haycock, N.E., and G. Pinay. 1993. Groundwater nitrate dynamics in grass and poplar vegetated riparian buffer strips during the winter. J. Environ. Qual. 22:273-278.

Johnston, A.E., H. Tunney, and R.H. Foy. 1997. Phosphorus loss from agriculture to water: Synthesis and summary. *In* Phosphorus Loss from Soil to Water. Ed. H. Tunney and O.T. Carton. CAB International. New York, NY. p. 455-461.

King, S.E. 2005. Riparian buffer effectiveness in removing groundwater nitrate as influenced by vegetative type. M.S. Thesis. NC State Univ. Raleigh, NC.

Koopmans, G., 2004. Characterization, desorption, and mining of phosphorus in noncalcareous sandy soils. Doctoral thesis, Wageningen University, Wageningen, the Netherlands. p.168.

Lindsay, W.L. 1979. Chemical Equilbria in Soils. John Wiley & Sons. New York, New York.

Leinweber, P., B.L.Turner, and R. Meissner. 2002. Phosphorus. *In* P.M. Haygrath and S.C. Jarvis (eds.) Agriculture, Hydrology and Water Quality. CABI Publishing. New York, NY.

Lowrance, R.R., Todd, J. Fail., Jr. O. Hendrickson, Jr., R. Leonard, and L. Asmussen. 1984. Riparian forests as nutrient filters in agricultural watersheds. BioScience 34:374-377.

Maguire, R.O., W.J. Chardon, and R.R. Simare. 2004. Assessing potential environmental impacts of soil phosphorus by soil testing. *In* J.T. Sims and A.N. Sharpley (eds.) Phosphorus: Agriculture and the Environment. ASA-CSSA-SSSA Monograph, Madison, WI.

Maguire, R.O., and J.T. Sims. 2002. Soil testing to predict phosphorus leaching. J. Environ. Qual. 31:1601-1609.

Miner, J.R., F.J. Humenik, and M.R. Overcash. 2000. Managing Livestock Wastes to Preserve Environmental Quality. Iowa State Press. Ames, IA.

Nelson, N. 2004. Soil and waste management effects on phosphorus leaching in acid sandy soils of the North Carolina coastal plain. Ph.D. Dissertation. N.C. State Univ. 156 pp.

Parsons, J.E., R.B. Daniels, J.W. Gilliam, and T.A. Dillaha. 1991. The effect of vegetation filter strips on sediment and nutrient removal from agricultural runoff. In Proc. of the Environmentally Sound Agricultural Conf., ed. A.B. Bottcher, K.L. Campbell, and W.D. Graham. 324-332. Orlando, FL. Apr. 16-8, 1991.

Peterjohn, W.T., and D.L. Correll. 1984. Nutrient dynamics in an agricultural watershed: Observations on the role of a riparian forest. Ecology. 65:1466-1475.

Pierynski, G.M., J.T. Sims, and G.F. Vance. 2000. Soils and environmental quality. CRC Press. Boca Raton, FL. p. 459.

Salisbury, F.B., and C.W. Ross. 1992. Plant Physiology. 4th ed. Wadsworth Publishing Company. Belmont, CA p. 682.

Sharpley, A. 1996. Myths about phosphorus. *In* Animal Agriculture and the Environment: Nutrients, Pathogens, and Community Relations. Proceedings from the Animal Agriculture and the Environment North America Conference. Northeast Regional Agricultural Engineering Service. Rochester, NY. p. 60-75.

Sharpley, A., and H. Tunney. 2000. Phosphorus research strategies to meet agricultural and environmental challenges of the 21st century. J. Environ. Qual. 29:176-181.

Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A. Moore, and G. Mullins. 2003. Development of phosphorus indices for nutrient management planning strategies in the United States. J. Soil. Wat. Conserv. 58:137-152.

Smith, T.A. 2005. Shallow groundwater nitrate and breeding bird habitat in a riparian buffer restored by volunteer vegetation. M.S. Thesis. NC State Univ. Raleigh, NC.

USDA-NASS. 2004. www.nass.usda.gov/index.asp

USEPA. 1996. Environmental indicators of water quality in the United States. EPA-841-R-96-002. US EPA, Office of Water (4503F), U.S. Government Printing Office, Washington, DC.

CHAPTER 2

Change in Soluble Phosphorus in Soils Following Fertilization is Dependent on Initial Mehlich-3 Phosphorus

Introduction

Surface water quality can be threatened by elevated P concentrations in runoff from agricultural fields receiving animal wastes (USEPA, 1996; Tarkalson and Mikkelsen, 2004). Continued over-application of fertilizer and animal waste P relative to crop uptake has resulted, in some cases, in M3P concentrations greater than agronomic values identified for optimal crop yield (Sims et al., 2002; Johnson et al., 2005). In response to concerns over P losses from agricultural lands, most states have developed P indices that assess the risk for P loss from a field (Sharpley et al., 2003). These indices use P source and transport factors to identify critical source areas for P loss, and one of the criteria used to identify P sources is soil test P. If a high risk of P loss is identified, then improved P management is required on that field.

The NC P index is called the Phosphorus Loss Assessment Tool (PLAT). As in most P indices, PLAT assesses potential P loss from agricultural fields by various P loss pathways including sediment- and particulate-bound P, source (fertilizer and manure) P, and soluble P (NC PLAT Committee, 2005). Numerous researchers have shown that elevated risk of soluble P loss in runoff may be associated with increases in M3P concentrations (Pote et al., 1996; Eghball and Gilley, 1999). The PLAT utilizes the M3P soil test as an indicator for soluble P losses and soil dependent environmental M3P thresholds have been established above which soluble P concentrations increase rapidly and thereby increase the potential risk of P loss via runoff. This is based on the concept that soils have a finite capacity to adsorb P and as they become saturated, soluble P rises quickly with increasing soil P (Fox and Kamprath, 1970; McDowell et al., 2001; Maguire and Sims, 2002b). Variations in soil texture and Fe- and Al-oxide concentrations affect the relationship between M3P and WSP (Shelton and Coleman, 1968; Fox and Kamprath, 1970; Novais and Kamprath, 1978; Doberman et al., 2002; Maguire and Sims, 2002a). Therefore, suggested soil P threshold concentrations are assumed to vary among soils (Cox and Hendricks, 2000; Maguire and Sims, 2002a). Such thresholds have been established for all NC soils organized into 27 soil management groups (SMGs) according to their respective particle size classes (50, 100, 200, and 500 mg P kg^{-1} for organic, sandy, loamy, and clayey SMGs, respectively). The M3P threshold concentrations in PLAT indicate potential soluble P levels in runoff equivalent to 1 mg P L^{-1} (NC PLAT Committee, 2005). These thresholds identify soils of concern, but PLAT uses a linear increase of soluble P in runoff per unit increase in soil M3P concentration for each soil due to lack of information for high M3P soils (NC PLAT Committee, 2005).

Our first objective was to quantify the relationship between WSP and M3P for four benchmark soils of NC over a wide range of M3P. This will help identify if linear or change point relationships are more appropriate for these soils. Where P indices rank fields high for P loss on animal farms, one option to reduce risk is to move manure P applications away from these higher ranked fields to lower ranked ones (Sharpley et al., 1996; Tarkalson, 2001). As these fields will probably have different M3P levels, it is therefore important to understand how P applications to soils varying in initial M3P affect WSP and risk for P losses. Therefore, our second objective was to quantify the change in WSP concentrations affected by P additions to soils with a broad range of initial M3P. This will assist in assessing the potential risk of soluble P loss from agricultural fields to surface waters following fertilizer P and animal waste applications.

Materials and Methods

Soil Selection and Sample Collection

From three physiographic regions (Piedmont, Upper Coastal Plain and Lower Coastal Plain) of NC, four benchmark soil series ranging in physical and chemical properties were selected for this study. These soil series are representative of the majority of prime farm land within each region. Soil test data provided by the NC Department of Agriculture and Consumer Services were used to select soils from agricultural fields that ranged in M3P from “low” to “very high” in reference to current environmental M3P threshold levels in PLAT. Bulk surface soil samples were collected (0-10 cm depth) and composited from agricultural fields utilized for corn (*Zea mays*), wheat (*Triticum spp.*), soybeans (*Glycine max*), or hay, i.e. common bermudagrass (*Cynodon dactylon*) or tall fescue (*Festuca spp.*), production. The native soil data set for this study consisted of 107 topsoils [17 Autryville loamy sand (loamy, siliceous, subactive, thermic Arenic Paleudults), 25 Wasda muck (fine-loamy, mixed, semiactive, acid, thermic Histic Humaquepts), 22 Georgeville silt loam (fine, kaolinitic, thermic Typic Kanhapludults), and 43 Pacolet sandy clay loam (fine, kaolinitic, thermic Typic Kanhapludults) soils] obtained from pasture or crop land used to produce a variety of row crops managed under no-till.

Soil Analysis

All field soil samples collected were dried at 65˚C for 24 hours and ground to pass a 2-mm sieve. Soil pH (1:1 soil:deionized water) and humic matter (HM) content were measured by standard methods of the NCDA (Mehlich, 1984b). Soils were analyzed for (i) WSP (1:10 soil to deionized water, 1-h reaction time, filtration through Whatman #2 filter paper); (ii) M3P (1:10 soil to 0.2 *M* CH_3COOH + 0.25 *M* NH_4NO_3 + 0.015 *M* NH_4F + 0.13 *M* HNO_3 + 0.001 *M* EDTA, 5-min reaction time, filtration through Whatman #2 [Maidstone, UK] filter paper) (Mehlich, 1984a). The Mehlich-3 extract was analyzed for P (M3P), Al (M3Al), and Fe (M3Fe) by inductively coupled plasma atomic emission spectroscopy (ICP-AES). The Mehlich 3 P saturation ratio (M3PSR) was calculated (mmol kg^{-1}) by:

$$\text{M3PSR} = \text{M3P} / (\text{M3Al} + \text{M3Fe}) \qquad [1]$$

(Sims et al., 2002). Water soluble P extracts were analyzed colormetrically by the molybdate blue method of Murphy and Riley (1962).

Incubation study

Soil container capacity (CC), which is an approximate measurement of field capacity, was determined for each soil series by saturating a 50 g air-dried soil sample with deionized water, freely draining it for 48 hours, and reweighing it to determine water content. CC was calculated by:

$$\text{CC} = M_w / M_s \qquad [2]$$

where CC (kg water/kg soil) represents the ratio of deionized water (M_w) held by a mass of soil (M_s) in the container draining under an atmospheric pressure gradient at room temperature (22˚C) (Cassel and Nielsen, 1986).

Four soil samples per soil series were selected to represent a broad range of M3P levels and fertilized at rates equivalent to 0, 150, or 300 kg P ha^{-1} (assuming 2242 Mg soil ha^{-1}), maintained at 70% CC and incubated in a dark cupboard at room temperature for 3 weeks. At 1, 7 and 21 d after fertilizer additions, 2 g for WSP analysis and 2.5 cm^3 for Mehlich-3 analysis sub-samples were collected from each soil, dried at 35˚C for 24 hours, and ground to pass a 2-mm sieve. These samples were analyzed for WSP and M3P as described above.

Statistical Analysis

All correlation and regression analyses were conducted by standard procedures of SAS Version 9.1 (SAS Institute, 2002). The split-line linear regression (NLIN) procedure within SAS 9.1 was used to determine change points, as described by McDowell and Sharpley (2001) and Sims et al. (2002).

Results and Discussion

Soil Characteristics

All soils were moderately acidic and exhibited agronomic P values suitable for optimal crop performance and yield (Table 1) (Crozier et al., 2004; Fox and Kamprath, 1970). The pH of the Wasda muck (5.2) was the lowest of the four soils that ranged from 5.2 to 6.3 and can be explained by its relatively high HM content. Although not a direct measure of organic matter (OM) content, HM is well correlated with soil OM, and as a result these soils have a lower recommended soil pH for agronomic production due to less concern over Al toxicity since Al is complexed by OM (Pierzynski et al., 2000; Evans and Kamprath, 1970). The mean HM content of the Wasda muck (9.38 g 100 cm^{-3}) was greater than the other three soils that ranged from 0.47 to 0.91 g 100 cm^{-3}. In NC, soils are classified for agronomic nutrient and pesticide management purposes by their HM content and identified as mineral (HM < 5.5 g 100 cm^{-3}), mineral-organic (5.5 > HM < 10 g 100 cm^{-3}), or organic soils (HM > 10 g 100 cm^{-3}) (Hardy et al., 2003).

For crop production in NC, critical agronomic soil M3P levels have been characterized for numerous crops and vary widely depending on crop and soil type and their management (Crozier et al., 2004). In NC, researchers recognize a critical agronomic M3P level of 53 mg kg^{-1} (Johnson et al., 2005). In some cases, geographically associated soil series with similar inherent HM contents may exhibit greater agronomic critical M3P levels, e.g. Portsmouth fine sandy loam and Wasda muck (40 mg kg^{-1}) than neighboring relatively low HM soil series, e.g., Goldsboro fine loamy sand and Autryville loamy sand (21 mg kg^{-1}) (Crozier et al., 2004). This phenomenon was explained by Fox and Kamprath (1970) who illustrated that mucks of the NC Coastal Plain without appreciable clay contents exhibited no capacity to absorb P relative to NC agricultural mineral soils. Yet, the mean M3P (mg kg^{-1}) levels for the Autryville loamy sand (132), Wasda muck (134), Georgeville silt loam (291), and Pacolet sandy clay loam (394) were greater than the NC recognized critical agronomic M3P threshold. This indicates historically excessive P applications as a sole source of P to these soils contributed to the observed accumulation of M3P (Table 1).

The mean M3Al was greatest in the Wasda muck (1705 mg kg^{-1}) and smallest in the Autryville loamy sand (531 mg kg^{-1}) (Table 1). The significantly ($P< 0.05$) greater M3Al in the Wasda muck may be due to its significantly ($P< 0.05$) greater HM content. Organic soils in NC with appreciable mineral matter have large amounts of Al held by organic matter (Mengel and Kamprath, 1978). Maguire and Sims (2002b) reported that organic matter can increase the amorphous nature and hence extractability of Al. Mean M3Al values (mg kg^{-1}) for both the Georgeville silt loam (799) and Pacolet sandy clay loam (869) were not significantly ($P < 0.05$) different from one another yet were approximately half that of the Wasda muck. The mean M3Fe content of the Autryville (136 mg kg^{-1}) soil was significantly ($P < 0.05$) less than the Wasda muck (Table 1). The mean M3Fe (mg kg^{-1}) was greatest in the Wasda muck (197), however it was not significantly ($P < 0.05$) greater than the Georgeville silt loam (179) or Pacolet sandy clay loam (162). Relatively greater amounts of M3Fe extracted from the Wasda muck may be due to its significantly ($P < 0.05$) greater HM content leading to greater extractability of M3Fe as discussed above for M3Al, or due to reducing conditions that sometimes occur in these soils due to a high water table.

The M3PSR represents the ratio of labile P to the P sorption capacity of a soil, wherein numerous researchers have indicated its usefulness in serving as a potential indicator of P loss from agricultural fields (Maguire and Sims, 2002b; Nair et al., 2004). Maguire and Sims (2002b) reported a M3PSR value of 0.52 to be correlated to a DPS_{ox} of 100% marking the P saturation capacity of soils based on assumed equivalent sorption capacities of Al and Fe-oxides; where degree of P saturation [$DPS_{ox} = 0.5(Al+Fe)$] on a molar-basis was determined by a oxalate-P, Al, and Fe extraction procedure. Among all four soils of this study, the mean M3PSR values ranged from 0.07 to 0.36, wherein the Wasda muck exhibited the lowest degree of P saturation (0.07) due to its greater M3Al concentrations (1705 mg kg^{-1}) than the other three soils (Table 1). In Delaware, the Pocomoke fine loamy sand with a high OM content (>60 g kg^{-1}) also exhibited a lower mean M3PSR (0.12) due to a greater mean M3Al (1718 mg kg^{-1}) concentration (Maguire and Sims, 2002b). The mean M3PSR for all other Coastal Plain Delaware soils included in their study ranged from 0.08 to 0.24. The mean M3PSRs for the Autryville loamy sand (0.20), Georgeville silt loam (0.29), and Pacolet sandy clay loam (0.36) in this study were not significantly ($P < 0.05$) different from one another.

Relationship between Mehlich-3 Phosphorus and Water Soluble Phosphorus

Across the broad range of M3P concentrations, significant ($P<0.001$) positive linear relationships were observed between M3P and WSP concentrations for each soil series (Fig. 1). However, the mean rate of increase in WSP per unit of M3P varied by soil series and decreased in the following order for the single slope relationships (mg WSP kg^{-1}/ mg M3P kg^{-1}): Autryville loamy sand (0.14) > Georgeville silt loam (0.09) > Pacolet sandy clay loam (0.04) (Fig. 1). Although these three soil series exhibited linear relationships across a broad range of M3P levels, nonlinear soluble P (0.01 M $CaCl_2$ extractable) and M3P (estimated from Mehlich-1 P data) relationships for geographically associated soils with narrower M3P levels have been reported, i.e. Cecil sandy clay loam (~55-155 mg kg^{-1}) and Norfolk loamy sand (~60-245 mg kg^{-1}) (Reddy et al., 1980).

A change point was determined for the Wasda muck (115 mg kg^{-1}) relationship between WSP and M3P, where the split-line linear model (NLIN) explained 90% of the overall variance and provided an accurate estimation of the change point. The change point is an estimate of the M3P concentration at which a significant change in the rate at which WSP concentrations increase with each unit increase in M3P (Kleinman et al., 2000; McDowell et al., 2001). The change point for the Wasda muck was well above an agronomic optimum M3P value (~40 mg kg^{-1}) for a variety of row crops grown in this soil,(McCollum, 1991; Cox, 1992; Crozier et al., 2004; NC PLAT Committee, 2005). A ten-fold increase in the rate of increase in WSP per unit increase in M3P below [WSP = 0.02(M3P)] versus above [WSP = 0.20(M3P)] the estimated change point was observed. Therefore, the risk in soluble P loss from the Wasda soil with M3P concentrations above 115 mg kg^{-1} is greatly elevated because P adsorption sites are saturated.

Sharpley et al. (1996) reported the regionalization of confined animal operations in many areas has resulted in elevated soil P concentrations above agronomic critical levels for optimal crop yield. In NC, researchers have reported 78% of the state's agricultural land surveyed by county has been fertilized with P to meet or exceed agronomic critical M3P levels (Johnson et al., 2005). Nearly all soils collected for this study were greater than optimal agronomic P thresholds for adequate crop yield (McCollum, 1991; Johnson et al., 2005).

<u>Relationship between Mehlich-3 Phosphorus Saturation Ratio and Water Soluble Phosphorus</u>

Researchers have measured M3PSR values up to approximately 0.60 and suggested them as useful indicators in accessing the variable risk of soluble P loss (Sims et al., 2002; Maguire and Sims, 2002b). In this study, positive linear relationships of

WSP as a function of M3PSR reflected corresponding increases in WSP as M3PSR increased and the soils became more P saturated (Fig. 2). Sims et al. (2002) reported change points for leaching and runoff at M3PSR values of 0.20 and 0.14, respectively. The Autryville loamy sand, Georgeville silt loam and Pacolet sandy clay loam had M3PSR values that ranged well above and below their reported change points, but no change point was observed for these soils. The reason why no change points could be observed across such a wide range of M3PSR, when other researchers have reported them, is unclear. However, the variability of M3Al may be part of the explanation. For example, the Pacolet sandy clay loam had a mean M3Al concentration of 869 mg kg^{-1}, with a standard deviation of 348 mg kg^{-1}. Sims et al. (2002) reported regression coefficients of 0.73 and 0.87 for their change point relationships between runoff or leachate and M3PSR, but our regression coefficients were only 0.60 to 0.67 for the three linear relationships (Fig. 2). The Wasda muck had no M3PSR values above 0.2, but the relationship between WSP and M3PSR was best explained by an exponential regression. This indicates greater increases in WSP per unit increase in M3PSR at higher M3PSR values, however the NLIN split line model did not identify or converge on a change point.

Influence of Time on Water Soluble Phosphorus following Fertilization

Similar WSP trends following fertilization were exhibited for all soils, with WSP decreasing over time (Fig. 3). Between fertilization of the soils and 21 d, our data show that a majority (~67%) of the initial WSP at 1 d for both fertilizer P rates (150 or 300 kg ha^{-1}) was sorbed by the second sampling event at d 7 (Fig. 3). By 21 d the regression lines were flattening out, indicating that there was little more P sorption occurring. Researchers have illustrated soils vary in their P sorption capacities as well as their P sorption rates (Fox and Kamprath, 1970; Maguire et al., 2001a). Fertilizer P is rapidly sorbed by Al and Fe oxides (Dobermann et al. 2002; Laboski and Lamb, 2003). In an incubation study of acid soils of Ireland, 55% of soluble P was sorbed by soils within 15 d (Maguire et al. 2001a). Fox and Kamprath (1970) reported that approximately 67% of soluble P applied at 500 mg P kg^{-1} soil was sorbed within 8 d following application.

Water Soluble Phosphorus Following Fertilization of Soils with a Wide Range of Initial Mehlich-3 Phosphorus

To isolate the effect of fertilization on WSP from the initial WSP concentration present in the soils, WSP of the unfertilized soil was subtracted from WSP of the fertilized soil to show the change that occurred. Following fertilization, WSP increased in all soils irrespective of fertilization rate or soil type (Fig. 4). As would be expected, WSP increased more in the soils fertilized with 300 kg P ha^{-1} than in equivalent soils fertilized with 150 kg P ha^{-1}. After 1 d, there was a clear trend for WSP to increase more in soils that had greater initial M3P. For example, when two Wasda muck soil samples were fertilized with 150 kg P ha^{-1}, the WSP increased by 3 mg kg^{-1} in the soil with initial M3P of 62 mg kg^{-1}, while WSP increased by 16 mg kg^{-1} in the soil with initial M3P of 238 mg kg^{-1} (Fig. 4). These results agree with the concept of a change point, where soluble P increases more rapidly as soils become more saturated with P, even though no change points were seen in Figs. 1 and 2 for three of the soil series. Again, change points in Figs. 1 and 2 may have been obscured by scatter in the data. This agrees with Pote et al. (2003)

who found that increases in soil WSP following fertilization with poultry litter or inorganic P were significantly correlated to initial soil WSP, with higher initial WSP leading to greater increases in WSP following fertilization. Fox and Kamprath (1970) also reported that increases in soluble P were directly related to initial soil test P, with greater increases in soluble P where initial soil test P was higher. Fertilizer additions also increased M3P in these soils (data not shown), but there was too much variability in the data resulting in inconsistent trends relating to the effects of fertilizer rate or initial M3P on M3P.

Although the trends in changes in WSP were the same for all soils, the scale of the changes was soil dependent. For example, following fertilization with 300 kg P ha^{-1}, WSP increased on average by 20, 27, 31 and 46 mg kg^{-1} for the Wasda muck, Pacolet sandy clay loam, Georgeville silt loam, and Autryville loamy sand respectively. The M3Fe was generally similar among these soils, but the M3Al in these soils followed the same order as these increases in WSP, being 1705, 869, 799, and 531 mg kg^{-1} for the Wasda muck, Pacolet sandy clay loam, Georgeville silt loam, and Autryville loamy sand respectively (Table 1). Previous research has shown the links between soil Al and P sorption (Sims et al., 2002). No link between change in WSP and M3Fe could be seen, probably as Mehlich-3 is a poor extractant for reactive Fe (Novais and Kamprath, 1978; Maguire and Sims, 2002b). The increases in WSP following fertilization decreased with time from 1 d to 21 d (Fig. 3, 4, and 5). For example, for the Pacolet sandy clay loam, the increase in WSP following fertilization decreased from 27 to 15 mg kg^{-1} on average. Similar decreases with time have been observed over 51 d, with most of the decrease occurring in the first week (Maguire et al., 2001b). Gaston et al. (2003) also reported mean temporal (year by year) reductions in WSP levels ranging from 8 to 70% for Coastal Plain Louisiana soils amended with poultry litter dependent upon their application history (1 to 20 years).

Comparing the 150 and 300 kg P ha^{-1} applications, the 300 kg P ha^{-1} rate led to more than twice the increase in WSP as the 150 kg P ha^{-1} rate throughout the 21 d of the incubation (Fig. 6). The slope of the regression line between change in WSP following fertilization with 300 kg P ha^{-1} and 150 kg P ha^{-1} was 2.49 after 1 d, decreased to 2.27 after 7 d and remained relatively constant to 21 d (2.26). Adding twice as much P more than doubles the increase in WSP and illustrates an increased risk in potential soluble P loss from soils receiving excessive rates of fertilizer P.

Conclusions

The buildup of P in soils in areas of intensive animal production has received considerable attention due to concerns over P losses to surface waters. Despite an agronomic optimum M3P of approximately 50 mg P kg (depending on the soil and crop), we measured M3P values of up to 961 mg kg^{-1}. Obviously, historically excessive applications of fertilizer and manure P have resulted in elevated M3P concentrations above critical agronomic P limits for optimum crop yield in many NC agricultural soils. In NC, PLAT was developed to assess risk of P loss from agricultural fields and improve P management where losses were of concern. However, PLAT does not recognize a change point in the relationship between soluble P in runoff and M3P and this relationship is based on linear extrapolations of datasets that were missing high M3P values. Our data supports the use of these linear extrapolations, as a change point was only found for one out of four soil series. Despite the lack of change points, when these soils were fertilized the WSP increased to a greater extent in soils with a higher M3P. Previous research has shown that runoff P losses are closely correlated to WSP. Therefore, these results show the importance of avoiding P applications to soils that already have elevated M3P, as this will raise the risk of P loss to a greater extent than applying P to a soil with lower M3P.

References

Cassel, D.K, and D.R. Nielsen. 1986. Field capacity and available water capacity. *In* A. Klute (ed.) 1986. Methods of Soils Analysis. Pt 1. Physical and mineralogical methods, 2nd Ed.. Madison, Wisconsin, Soil Sci. Soc. Am.

Cox, F.R. 1992. Range in soil phosphorus critical levels with time. Soil Sci. Soc. Am. J. 56:1504-1509.

Cox, F.R., and S.E. Hendricks. 2000. Soil test phosphorus and clay content effects on runoff water quality. J. Environ. Qual. 29:1582-1586.

Crozier, C.R., B. Walls, D.H. Hardy, and J.S. Barnes. 2004. Response to cotton to P and K soil fertility gradients in North Carolina. J. Cotton Sci. 8:130-141.

Dobermann, A., T. George, and N. Thevs. 2002. Phosphorus fertilizer effects on soil phosphorus pools in acid upland soils. Soil Sci. Soc. Am. J. 66:652-660.

Eghball, B. and J.E. Gilley. 1999. Phosphorus and nitrogen in runoff following beef cattle manure or compost application. J. Environ. Qual. 28:1201-1210.

Evans, C.E., and E.J. Kamprath. 1970. Lime response as related to percent Al saturation, solution Al, and organic matter content. Soil Sci. Soc. Am. Proc. 34:893-896.

Fox, R.L., and E.J. Kamprath. 1970. Phosphorus sorption isotherms for evaluating the phosphate requirement of soils. Soil Sci. Soc. Am. Proc. 34:902-907.

Gaston, L.A., C.M. Drapcho, S. Tapadar, and J.L. Kovar. 2003. Phosphorus runoff relationships for Louisiana Coastal Plain soils amended with poultry litter. J. Environ. Qual. 32:1422-1429.

Hardy, D.H., M.R. Tucker, and C.E. Stokes. 2003. Crop fertilization based on North Carolina soil tests. http://www.ncagr.com/agronomi/obook.htm.

Johnson, A.M., D.L. Osmond, and S.C. Hodges. 2005. Predicted impact and evaluation of North Carolina's phosphorus indexing tool. J. Environ. Qual. (in press).

Kleinman, P.J.A., R.B. Bryant, W.S. Reid, A.N. Sharpley, and D. Pimentel. 2000. Using soil phosphorus behavior to identify environmental thresholds. Soil Sci. 165:943-950.

Laboski, C.A.M., and J.A. Lamb. 2003. Changes in soil test phosphorus concentration after application of manure or fertilizer. Soil Sci. Soc. Am. J. 67:544-554.

Maguire, R.O., and J.T. Sims. 2002a. Soil testing to predict phosphorus leaching. J. Environ. Qual. 31:1601-1609.

Maguire, R.O., and J.T. Sims. 2002b. Measuring agronomic and environmental soil phosphorus saturation and predicting phosphorus leaching with Mehlich 3. Soil Sci. Soc. Am. J. 66:2033-2039.

Maguire, R.O., R.H. Foy, J.S. Bailey, and J.T. Sims. 2001a. Estimation of the phosphorus sorption capacity of acidic soils in Ireland. Eur. J. Soil Sci. 52:479-487.

Maguire, R.O., J.T. Sims, S.K. Dentel, F.J. Coale, and J.T. Mah. 2001b. Relationships between biosolids treatment process and soil phosphorus availability. J. Environ. Qual. 30:1023-1033.

McCollum, R.E. 1991. Buildup and decline in soil phosphorus: 30-year trends on a Typic Umbraquults. Agron. J. 83:77-85.

McDowell, R.W. and A.N. Sharpley. 2001. Approximating phosphorus release from soils to surface runoff and subsurface drainage. J. Environ. Qual. 30:508-520.

McDowell, R., A. Sharpley, P. Brookes, and P. Poulton. 2001. Relationship between soil test phosphorus and phosphorus release to solution. Soil Sci. 166:137-149.

Mehlich, A. 1984a. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409-1416.

Mehlich A. 1984b. Photometric determination of humic matter in soils, a proposed method. Commun Soil Sci Plant Anal 15:1417–22.

Mengel, D.B., and E.J. Kamprath. 1978. Effect of soil pH and liming on growth and nodulation of soybeans in histosols. Agron. J. 70:959-963.

Murphy, L., and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chem. Acta. 27:31-36.

Nair, V.D., K.M. Portier, D.A. Graetz, and M.L. Walker. 2004. An environmental threshold for degree of phosphorus saturation in sandy soils. J. Environ. Qual. 33:107-113.

Novais, R., and E.J. Kamprath. 1978. Phosphorus supplying capacities of previously heavily fertilized soils. Soil Sci. Soc. Am. J. 42:931-935.

N.C. PLAT Committee. 2005. North Carolina Phosphorus Loss Assessment: I. Model Description and II. Scientific Basis and Supporting Literature, North Carolina Agricultural Research Service Technical Bulletin 323, North Carolina State University, Raleigh, NC.

Pierzynski, G.M., J.T. Sims, and G.F. Vance. 2000. Soils and environmental quality. 2nd ed. CRC Press, Boca Raton, FL.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, D.R. Edwards, and D.J. Nichols. 1996. Relating extractable soil phosphorus to phosphorus losses in runoff. Soil Sci. Soc. Am. J. 60:855-859.

Pote, D.H., J.A. Lory, and H. Zhang. 2003. Does initial soil P level affect water-extractable soil P response to applied P? Adv. Environ. Res. 7:503-509.

Reddy, K.R., M.R. Overcash, R. Khaleel, and P.W. Westerman. 1980. Phosphorus and adsorption-desorption characteristics of two soils utilized for disposal of animal wastes. J. Environ. Qual. 9:86-92.

SAS Institute. 2002. SAS user's guide: Statistics. Version 9.1 ed. SAS Inst., Cary, NC.

Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A. Moore, and G. Mullins. 2003. Development of phosphorus indices for nutrient management planning strategies in the United States. J. Soil Wat. Conserv. 58:137-152.

Sharpley, A.N., T.C. Daniel, J.T. Sims, and D.H. Pote. 1996. Determining environmentally sound soil phosphorus levels. J. Soil and Water Cons. 51:160-166.

Shelton, J.E., and N.T. Coleman. 1968. Inorganic phosphorus fractions and their relationship to residual value of large applications of phosphorus on high phosphorus fixing soils. Soil Sci. Soc. Am. Proc. 32:91-94.

Sims, J.T., R.O. Maguire, A.B. Leytem, K.L. Gartley, and M.C. Pautler. 2002. Evaluation of Mehlich-3 as an agri-environmental soil phosphorus test for the mid-Atlantic United States of America. Soil Sci. Soc. Am. J. 66:2016-2032.

Tarkalson, D.D. 2001. Phosphorus loss in surface runoff from piedmont soils receiving animal manure and fertilizer additions. Ph.D. Dissertation. North Carolina State University. 218 pp.

Tarkalson, D.D., and R.L. Mikkelsen. 2004. Runoff phosphorus losses as related to phosphorus source, application method, and application rate on a Piedmont soil. J. Environ. Qual. 33:1424-1430.

USEPA. 1996. Environmental indicators of water quality in the United States. EPA-841-R-96-002. US EPA, Office of Water (4503F), U.S. Government Printing Office, Washington, DC.

Table 1. Native soil characteristics for Autryville loamy sand, Wasda muck, Georgeville silt loam, and Pacolet sandy clay loam soil series.

Texture	**pH**	**Humic matter**	**WSP**	**Mehlich-3**			**M3PSR**
				P	**Al**	**Fe**	
		g 100 cm^{-3}	——	**mg kg^{-1}**	——		
Loamy sand	5.5 ± 0.5 c[†]	0.91 ± 0.34 b	17.4 ± 11.1 b	132 ± 63 b	531 ± 63 c	136 ± 28 c	0.20 ± 0.07 b
Muck	5.2 ± 0.4 c	9.38 ± 1.44 a	8.7 ± 9.7 c	134 ± 55 b	1705 ± 232 a	197 ± 33 a	0.07 ± 0.03 c
Silt loam	6.3 ± 0.3 a	0.47 ± 0.13 c	26.3 ± 12.0 a	291 ± 112 c	799 ± 95 b	179 ± 38 ba	0.29 ± 0.12 ba
Sandy clay loam	5.8 ± 0.7 b	0.70 ± 0.25 bc	18.2 ± 13.4 b	394 ± 320 c	869 ± 348 b	162 ± 63 bc	0.36 ± 0.27 a

[†] Means followed by different letters are significantly different at $P = 0.05$.

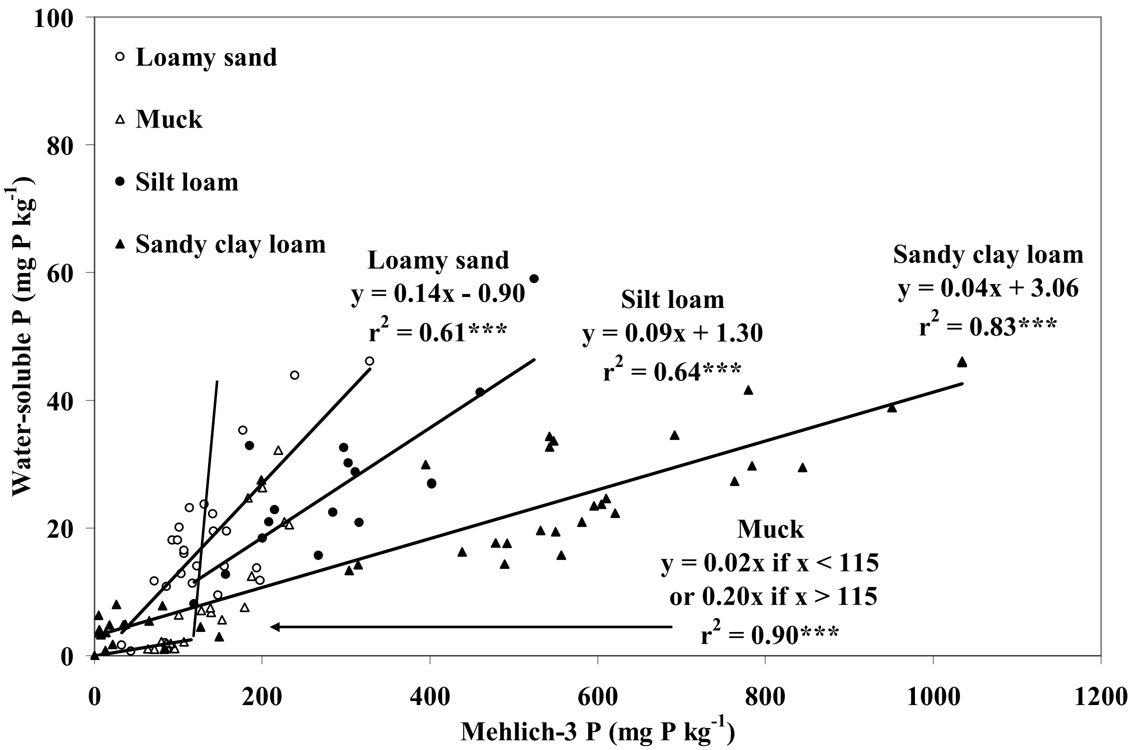

Figure 1. Water soluble P as a function of Mehlich-3 P for native Autryville loamy sand, Wasda muck, Georgeville silt loam, and Pacolet sandy clay loam.

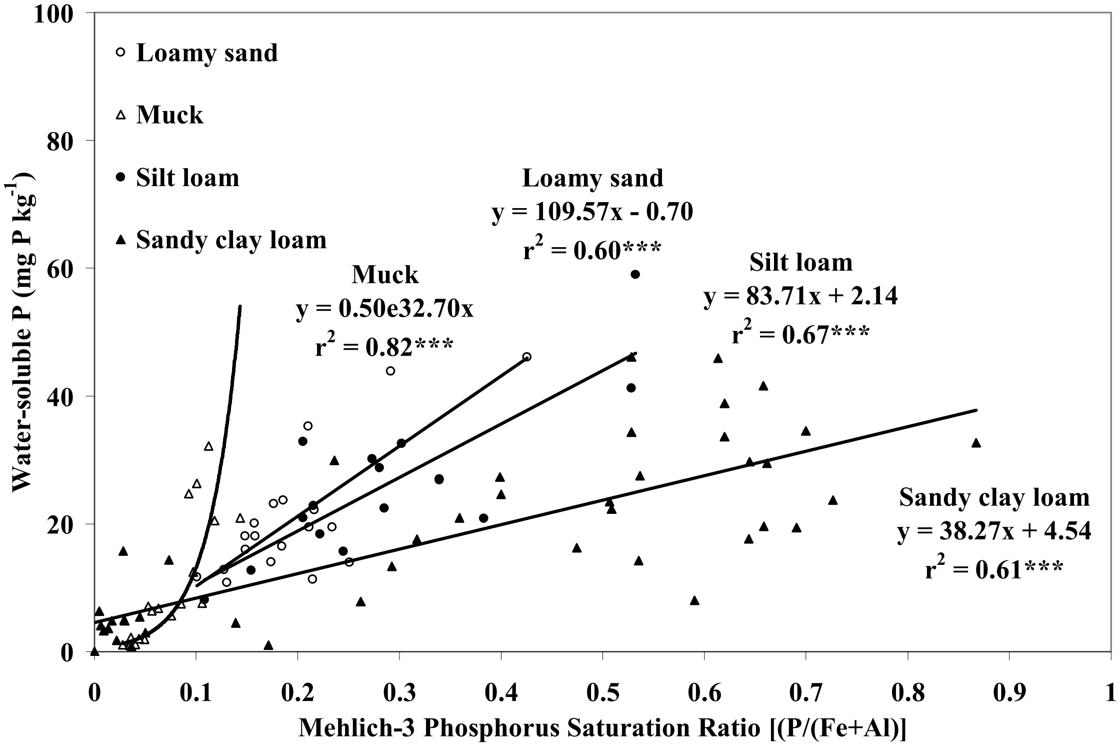

Figure 2. Water soluble P as a function of Mehlich-3 P sorption ratio for native Autryville loamy sand, Wasda muck, Georgeville silt loam, and Pacolet sandy clay loam.

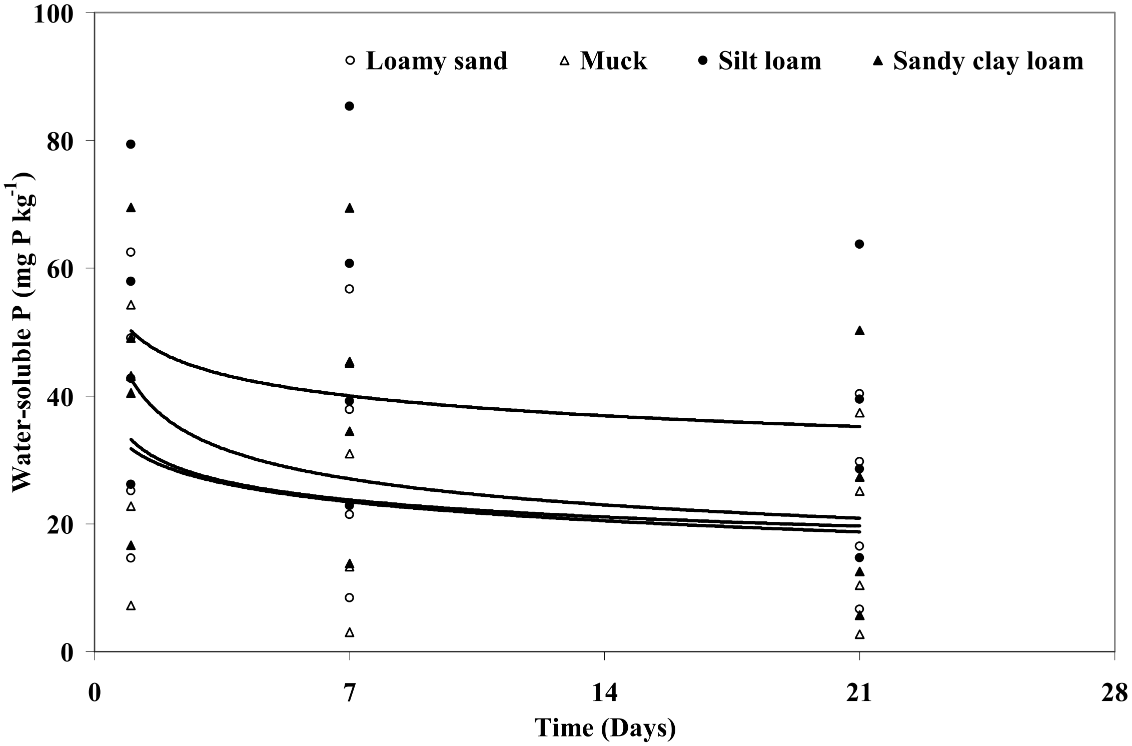

Figure 3. Water soluble P concentrations of all soils incubated during the 21 day incubation study.

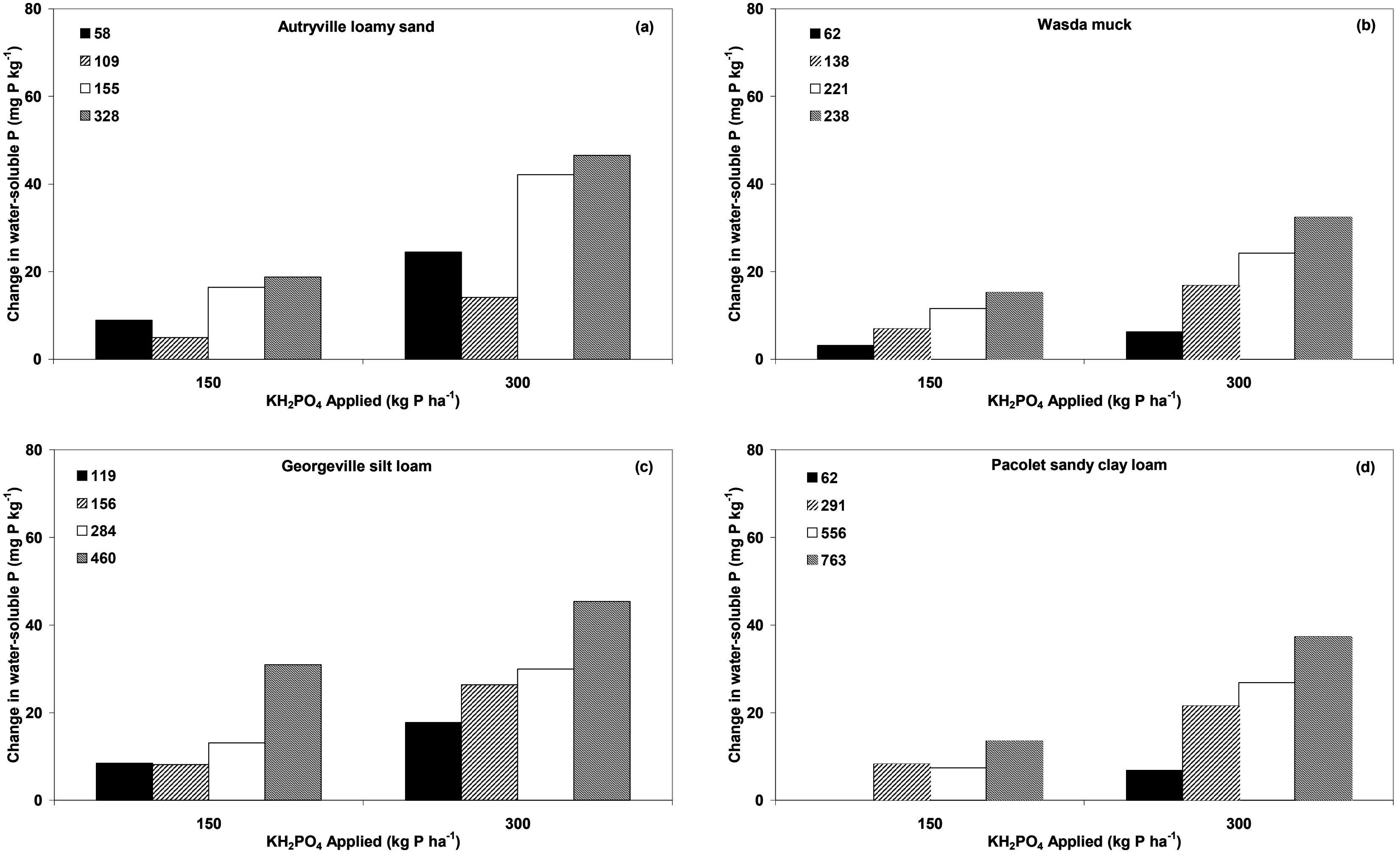

Figure 4. Change in WSP as a function of initial soil M3P (relative to an unfertilized sample), 1 day after fertilization with 150 or 300 kg P ha^{-1} for the (a) Autryville loamy sand, (b) Wasda muck, (c) Georgeville silt loam, and (d) Pacolet sandy clay loam.

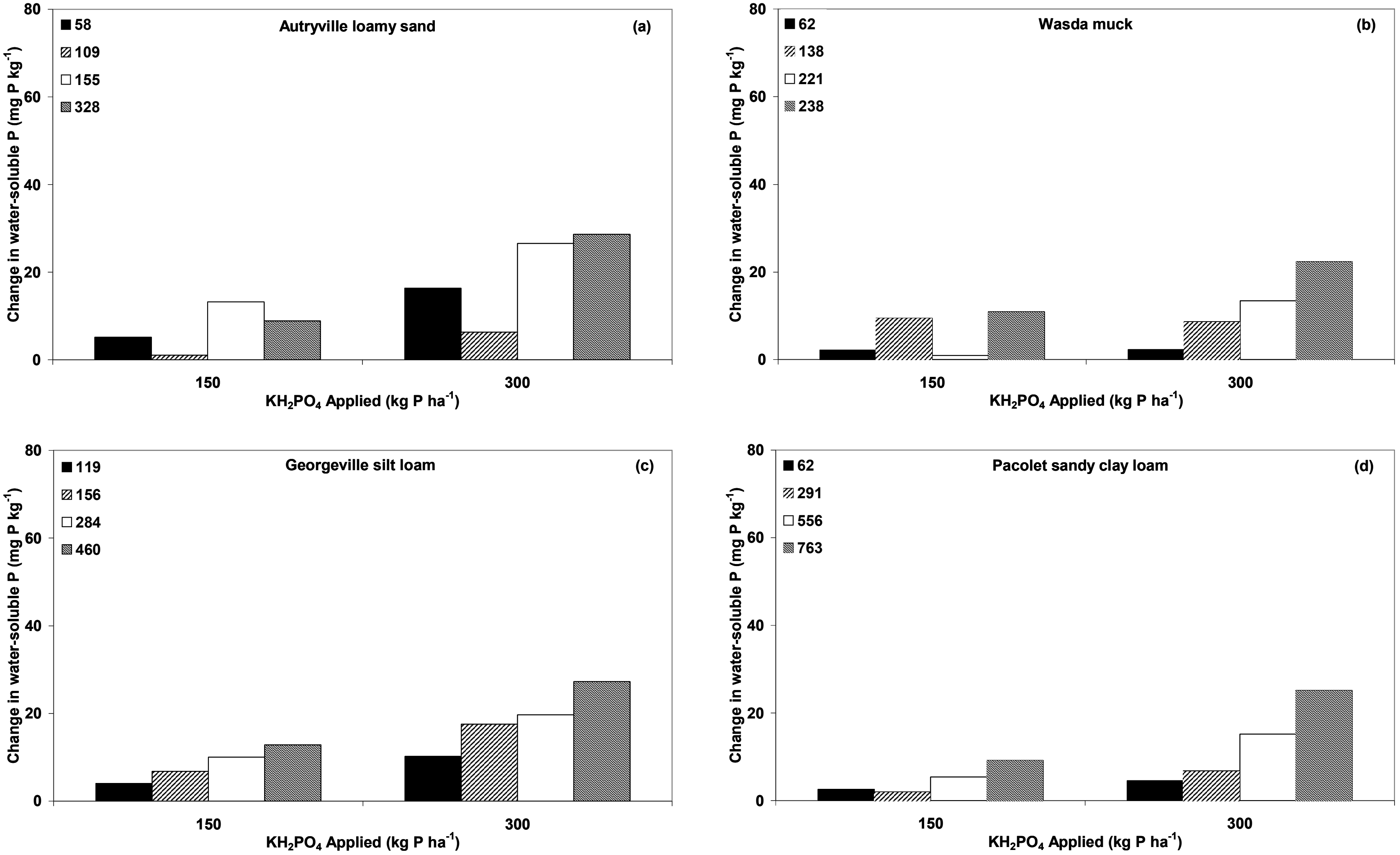

Figure 5. Change in WSP as a function of initial soil M3P (relative to an unfertilized sample), 21 days after fertilization with 150 or 300 kg P ha^{-1} for the (a) Autryville loamy sand, (b) Wasda muck, (c) Georgeville silt loam, and (d) Pacolet sandy clay loam.

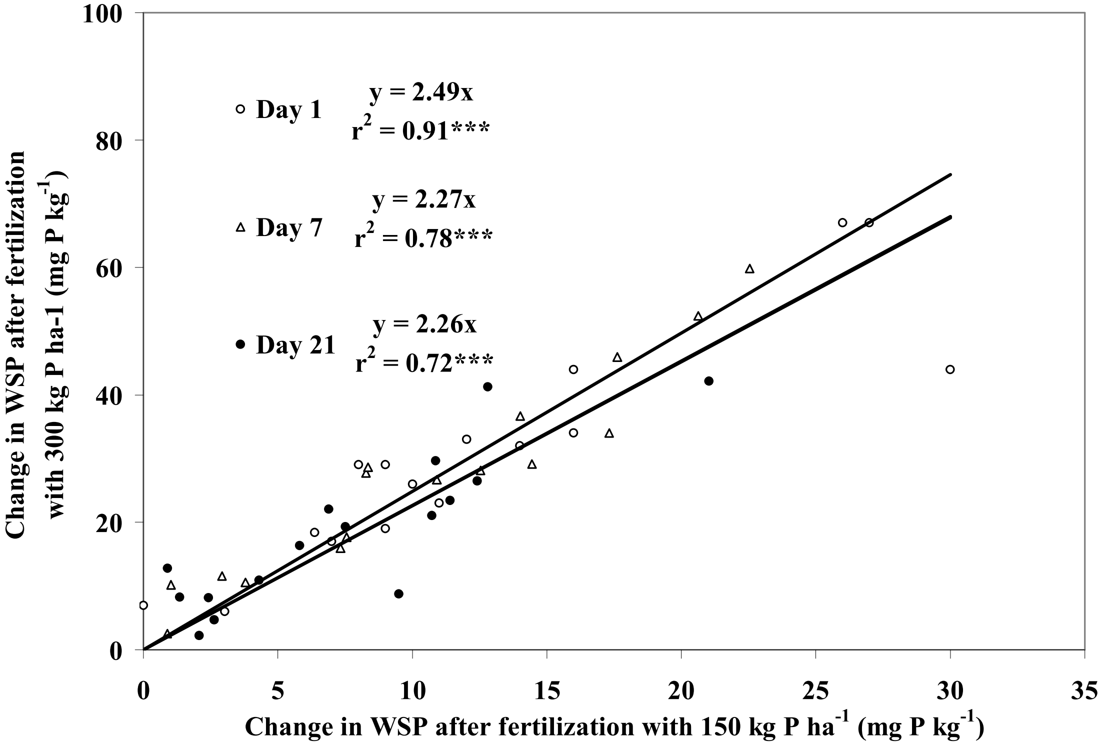

Figure 6. Relationship between the change in water soluble P following fertilization with 300 kg P ha^{-1} and 150 kg P ha^{-1}.

CHAPTER 3

Phosphorus Accumulation in North Carolina Piedmont Soils Receiving Animal Wastes

Introduction

Agricultural losses of nutrients, including phosphorus (P), from agricultural fields enhance the development of eutrophic conditions threatening surface water quality. Regardless of soil type, its inherent characteristics and management, soil P loss can be attributed to sediment-bound P, soluble P, or particulate P in surface runoff or to soluble P leached below the root zone. Concerns over such losses have resulted in the development of the North Carolina (NC) Phosphorus Loss Assessment Tool (PLAT), an environmental P-index, developed to improve the management of P in NC's agricultural fields. As in most P-indices, a field is ranked by its potential to lose P, wherein a P loss estimate is correlated to a field's soil test P concentration and dominant factors affecting P transport. In general, an elevated risk of soluble P loss from a field is assumed to increase with increases in soil test P concentrations; especially when soil test P values are above the agronomically optimum range (Pote et al., 1996; Eghball and Gilley, 1999; Pautler and Sims, 2000; PLAT Committee, 2005; Bond et al. 2006). Yet, recent studies suggest that the degree of P saturation, as estimated by the Mehlich-3 P saturation ratio (M3PSR) which relates Mehlich-3 P (M3P) to the sum of Mehlich-3-extractable Fe and Al, is a good indicator of a soil's potential to release P; better than M3P concentration alone (Sims et al., 2002; Kleinman and Sharpley, 2002; Maguire and Sims, 2002; Bond et al., 2006). While current P management relies heavily on soil test P concentrations, improved P loss risk assessment of NC fields requires evaluation of soil P concentrations relative its level of P saturation or M3PSR (Nair et al., 2004).

Numerous researchers have shown soils vary in their P sorption capacities as well as their P sorption rates (Fox and Kamprath, 1970; Maguire et al., 2001; Bond et al., 2006). Currently, the PLAT estimates P losses based on soil M3P concentrations and does not account for a soil's saturation level as can be estimated by its M3PSR [(P/(Fe+Al)] (PLAT Committee, 2005). In most acidic soils, P sorption predominately occurs on Fe- and Al-hydroxide coatings on mineral particle surfaces; wherein Fe:Al (by oxalate extraction) ratios range from 0.23 (organic) to 0.84 (clays) (Fox and Kamprath, 1970; Kleinman and Sharpley, 2002; Johnson, 2004). Factors such as soil mineralogy, texture, and drainage class also influence P sorption and desorption processes in soils (Kleinman et al., 2000). For example, anaerobic conditions may lead to the dissolution of Fe-bound P as Fe(III) is reduced to Fe(II), thereby increasing the risk of releasing elevated concentrations of soluble P to surface or ground waters (Hutchison and Hesterberg, 2004; Murray, 2004; Nair et al., 2004). In NC, historically excessive applications of animal wastes have led to the net accumulation of P in both surface (<25 cm) and subsurface (>25 cm) soils (Ham, 1999; Tarkalson, 2001; Johnson, 2004). Johnson (2004) illustrated the importance of P loading in soils, both surface and subsurface, wherein application of forms of animal wastes more concentrated in P, i.e. poultry litter versus swine effluent, resulted in deepening zone of P saturation for a range of NC soil profiles studied.

In the Piedmont and Mountains physiographic regions of NC, the soils are diverse; representing four major soil systems distinguished by the major forms of parent materials (Daniels et al., 1999). The majority of the poultry and dairy confined animal feeding operations in NC are centralized in two of these soil systems, the felsic and Carolina Slatebelt terrains. The risk of P loss from soils in these regions has been traditionally associated with surface transport pathways. Yet, the effects of historically excessive applications of P applied to crops at nitrogen-based rates warrants investigation into the effects of P source and loading rates on the potential for these soils to leach P.

Our research objectives were to (i) determine the extent of P leaching in Piedmont and Mountain soils amended with animal wastes, (ii) assess the validity of grouping soils into soil management groups to more accurately predict P leaching, and (iii) evaluate soil factors affecting the relationship between Mehlich-3 P (M3P) and soluble ($CaCl_2$-extractable) P.

Material and Methods

Site and Soil Selection

Sites were selected based on physiographic region (Piedmont or Mountains), farm type (dairy, poultry, or swine), age of farm (and thus assumed age of P application), and landscape position (floodplain, stream terrace, or upland). Forty-two sites were selected for study with soils exceeding M3P concentrations in the surface (0-20 cm) of 100 mg kg^{-1}; above the maximum agronomic threshold (M3P>53 mg kg^{-1}) for an expected crop response to P additions. All sites selected had not received animal waste within four months of soil sampling. From the 42 sites, 75 fields and 27 soil series were sampled using a truck-mounted 5-cm diameter probe to a maximum depth of 91 cm (Table 1). Across each field, three intact soil cores were collected and dissected into 10-cm incrementally depths and composited by depth. Soils were further grouped into predetermined soil management groups (Hodges, 2000).

Soil Analysis

All field soil samples collected were dried at 65˚C for 24 hours and ground to pass a 2-mm sieve. Soil pH (1:1 soil:deionized water) and humic matter (HM) content were measured by standard methods of the NCDA (Mehlich, 1984b). Soils were analyzed for (i) $CaCl_2$-P (1:10 soil to 0.01 M $CaCl_2$-P, 1-h reaction time, filtration through Whatman #42 filter paper); (ii) M3P (1:10 soil to 0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.13 M HNO_3 + 0.001 M EDTA, 5-min reaction time, filtration through Whatman #2 [Maidstone, UK] filter paper) (Mehlich, 1984a). The Mehlich-3 extract was analyzed for P (M3P), Al (M3Al), and Fe (M3Fe) by inductively coupled plasma atomic emission spectroscopy (ICP-AES). The Mehlich 3 P saturation ratio (M3PSR) was calculated (where P, Al, and Fe were in units of mmol kg^{-1}) by:

$$\text{M3PSR} = \text{M3P} / (\text{M3Al} + \text{M3Fe}) \qquad [1]$$

(Sims et al., 2002). Water soluble P extracts were analyzed colormetrically by the molybdate blue method of Murphy and Riley (1962). Particle size distribution was determined by the hydrometric method (Day, 1965).

Statistical Analysis

All correlation and regression analyses were conducted by standard procedures of SAS Version 9.1 (SAS Institute, 2002). The split-line linear regression (NLIN) procedure within SAS 9.1 was used to determine M3PSR environmental thresholds (also referred to as change points), as described by McDowell and Sharpley (2001) and Sims et al. (2002).

Results and Discussion

Soil Characteristics

Across all soils, pH varied broadly from 4 to 9 within the surface (0-10 cm) layer while subsurface soils were slightly more acidic and ranged from 4.9 to 7.5. Greater surface pH values are assumed to reflect the effects of limestone additions traditionally made by growers to manage soil acidity. In all soils, HM content was lower than 3.2 g 100 g^{-1} soil indicating all soils were mineral in nature (Hardy et al., 2003). Dependent upon soil type and landscape position, soils varied greatly in their textures with coarser textured soils found more in floodplains with finer texture soils located along the upland landscape positions.

The soils exhibited a broad range in M3P concentrations (0-1221 mg kg^{-1}), wherein average M3P concentrations of 161 mg kg^{-1} were found within the upper 30 cm of the profile (Table 2). Below the 30 cm depth, mean M3P concentrations were 42 mg kg^{-1} when averaged across all soils studied. In general, the rooting depth for most agronomic crops is assumed to be within the upper 30 cm of the soil profile. Therefore, growers often till their soils to this depth, thereby incorporating any surface applied materials. So, these data indicate both the effects of tillage as well as exhibit the limited mobility of P below the rooting zone. In contrast, several researchers reported extensive P leaching in NC coastal plain soils that had received animal waste over decades of time. The extensive P leaching was attributed to the relatively lower P sorption capacities of these soils compared to those of the Piedmont (Ham, 1999; Johnson, 2004). Once the P sorption capacity of the surface soil was met, any additional P was assumed by the authors to remain soluble and leached down the profile resulting in the net accumulation of M3P in the subsoil.

Effects of Phosphorus Loading on Soil Profile Mehlich-3 Phosphorus Distribution

It was not possible to determine the actual P rates and amounts of P applied to these soils. Therefore, we employed farm age (± 20 years) as the distinguishing factor for the effects of long-term P applications on M3P distribution in the profile. Within the plow layer (0-30 cm), the importance of a 20-year history of excessive P additions was apparent (Figure 2). At 30 cm, M3P was approximately 50 mg kg^{-1}; an adequate M3P concentration for optimal growth and yield of most agronomic crops (Hardy et al., 2003). At the 20-cm depth, soils with 20+ years of animal waste applied had a ~30% greater ($P \leq 0.05$) M3P concentration than soils that had received animal waste for less than 20 years. Within the top 10 cm of the soil profile, the difference (125 mg kg^{-1}; $P \leq 0.05$) was more pronounced.

The effects of manure source on M3P concentrations among soils were significantly ($P \leq 0.05$) greater (33 mg kg^{-1}) for those soils having received dairy slurry as opposed to poultry litter. The differences (mg kg^{-1}) in M3P between dairy slurry and poultry litter (46) and diary slurry and swine effluent (13) were not significant. In addition, there was a SMG by source interaction for SMGs 111 and 113, wherein M3P concentrations (mg kg^{-1}) were significantly ($P \leq 0.10$) greater (20) in SMG 111 soils that had received poultry litter rather than dairy slurry. In contrast, M3P concentrations (mg kg^{-1}) for SMG soils that received poultry litter was significantly ($P \leq 0.05$) less (52) than those that received dairy slurry. No SMG 111 soils received swine effluent in this study; therefore no comparisons were made among the three animal waste sources within SMG 111.

Overall, the source of P did not significantly influence the degree of P leaching in these soils. However, Johnson (2004) reported the importance of P source by measuring the degree of P leaching in a range of NC soils (ex. Piedmont versus Coastal Plain) studied, wherein various sources of animal wastes were applied. For example in the Johnson (2004) study, all soils amended with excessive amounts of manure P resulted in P leaching, yet the soils that had received the more concentrated form of animal waste, i.e. dry poultry litter, had greater M3P concentrations with depth than similar soils that received the more dilute forms of animal waste, i.e. liquid swine effluent. In our Piedmont and Mountain soils, vertical P movement in the soil profile was restricted to the plow layer with exception of the Rosman-Reddies complex representing SMG 207.

Distribution of Mehlich-3 Phosphorus in Soils Grouped by Soil Management Group

In an attempt to more accurately predict P leaching from soils receiving animal wastes, the PLAT adopted and implemented the use of soil management groups. Factors such as soil mineralogy, texture, and drainage class were taken into consideration to establish SMGs, yet limited field data existed at the time to attest for the validity of SMGs to accurately predict P leaching. Noticeable differences in the distribution of M3P with depth were exhibited among the soils in SMGs 105, 109, 110, 111, 113, 115, and 207. The SMG 207 displayed the greatest leaching potential among the SMGs and consisted solely of the Rosman-Reddies complex, a coarse-textured floodplain system with an umbric epipedon that had received 38 years of poultry litter (Fig. 3). At a 60-cm depth, the SMG 207 M3P concentration was ~100 mg kg^{-1}, considerably greater than the minimum optimal agronomic M3P concentration of 53 mg kg^{-1} (for most crops) and up to 100 times greater than other SMGs studied in the of Piedmont and Mountain regions. The SMG 105 also displayed a greater P leaching potential than the remaining SMG studied. Although SMG 105 surface (0-10 cm) M3P concentration was considerably lower than other SMG, its subsurface (>10 cm) M3P concentrations were significantly greater (up to 3 times). By the 60-cm depth, the SMG 105 M3P concentration had decreased to less than the agronomic optimum concentration of 53 mg kg^{-1}, similar to all other SMG except SMG 207. The SMG 105 soils received 18 less years of animal waste than that of SMG 205, possibly accounting for the difference in M3P concentrations at depth between the two SMG, yet its coarse texture and presumably lower P sorption capacity permitted substantial P leaching (Fig. 3). SMGs 207 and 105 had the lowest clay concentration (Fig. 4). The Buncombe and Toccoa series represented the two of the eight soils that make up the SMG 105 that was located along floodplains of the Piedmont and Mountain regions, as was the Rosman-Reddies complex representing SMG 205. In comparison, the upland series that made up SMG 111 (Appling, Cecil, Clifford, Fairview, Madison, Pacolet, and Vance) consisted of finer textured soils with presumably greater P sorption capacities (Figure 3). The distribution of M3P with depth for SMG 111 represented the general trend among all other upland soils [SMG 109 (Hiwassee and Lloyd), 110 (Mecklenburg), 113 (Georgeville, Nanford, and Tatum), and 115 (Masada)] studied and separated into various SMG based primarily on drainage class and mineralogy. Thus, the predictability of Piedmont and Mountain soils to leach P does not appear to be lessened by grouping soils as they are currently grouped.

Soil Factors Affecting Mehlich-3 Phosphorus Leaching in Piedmont and Mountain Soils

The vertical distribution of M3P concentration in the Piedmont and Mountain soils was significantly ($P \leq 0.0001$) correlated to soil clay content and M3Fe concentration, wherein less leaching was observed in finer (more clay) textured soils or SMGs with greater M3Fe concentrations (Fig. 4). A greater proportion of Fe-oxides to Al-oxides have been reported in NC Piedmont soils as opposed to NC Coastal Plain soils due to in part to the greater clay contents and better drainage of Piedmont soils (Fox and Kamprath, 1970; Novais and Kamprath, 1978; Cox, 1994; Cox and Hendrix, 2000). Mehlich-3 Al was not significantly correlated to M3P concentrations exhibited by these soils. These data suggest that Fe-oxides were the main soil reaction component for P in the Piedmont and Mountain soils. Thus as the sorption sites on the Fe-oxides become P saturated, the risk of P leaching may be enhanced.

Relationship Between Mehlich-3 Phosphorus Saturation Ratio and Calcium Chloride Extractable Phosphorus

For soils with kaolinitic (>50% kaolinite and <10% 2:1 layer minerals) mineralogy, mean M3PSR values were strongly correlated ($r^2 = 0.88$) with $CaCl_2$-P concentrations when averaged across soil series, waste source, and P loading (or years of P application) rate (Fig. 5). The $CaCl_2$-P concentrations increased linearly at a 13x (x = M3PSR) rate until soils reached a M3P saturation threshold or change point at a M3PSR value of 0.15, above which the rate of $CaCl_2$-P increased to 57x for each unit increase in M3PSR (Fig. 4). Soils with mixed mineralogy exhibited a M3PSR change point at 0.06, wherein the rate of change in $CaCl_2$-P was 3.2x and 39x below and above the change point, respectively. The variability in the $CaCl_2$-P data for soils of mixed mineralogy especially at greater (>40 mg kg^{-1}) concentrations may have influenced the shift of the change point of 0.15(M3PSR) to 0.06(M3PSR) (Fig. 5).

The type of animal waste applied to these soils did not significantly affect their $CaCl_2$-P concentrations, implying no $CaCl_2$-P stemmed directly from the animal waste applied at least four months prior to soil sampling. Mehlich-3 P, M3Fe, clay content, and P loading (or years of application) were all factors that affected measured $CaCl_2$-P concentrations of these soils, as observed in the M3P data.

Conclusions

Despite the historically excessive applications of P in the form of animal wastes to NC Piedmont and Mountain soils, the net accumulation of P did not excessively (M3P>53 mg kg^{-1}) accumulate to depths below the plow-layer (upper 30 cm of soil profile) of most soils studied. The finer textured, Fe-oxide dominated soils of these Mountain and Piedmont regions of the state represent the importance of these soils properties in fixing P and inhibiting P leaching. In comparison, a coarser textured floodplain soil exhibited lower P sorption capacities and illustrated a greater P leaching potential. From the relationship between M3PSR and $CaCl_2$-P, we identified mineral-dependent critical environmental M3PSR thresholds for these soils at 0.06(M3PSR) and 0.15(M3PSR), above which potentially greater risks of soluble P losses via surface or subsurface pathways may prevail. Soil management groups in Mountain and Piedmont regions currently employed by the PLAT appear to be justified for use in predicting soil P leaching potentials.

References

Bond, C.R., R.O. Maguire, and J.L. Havlin. 2006. Change in soluble phosphorus in soils following fertilization is dependent on initial Mehlich-3 phosphorus. J. Environ. Qual. *In press.*

Cox, F.R. 1994. Predicting increases in extractable phosphorus from fertilizing soils of varying clay content. Soil Sci. Soc. Am. J. 58:1249-1253.

Cox, F.R., and S.E. Hendricks. 2000. Soil test phosphorus and clay content effects on runoff water quality. J. Environ. Qual. 29:1582-1586.

Daniels, R.B., S.W. Buol, H.J. Kleiss, and C.A. Ditzler. 1999. Soil Systems in North Carolina. N.C. State Coop. Ext. Tech. Bull. 314. N.C. State Univ.

Day, P. R. 1965. Particle fractionation and particle size analysis, p. 545–567. *In* C. A. Black (ed.), Methods of soil analysis, vol. 1. Am. Soc. Agron. Madison, Wis.

Eghball, B. and J.E. Gilley. 1999. Phosphorus and nitrogen in runoff following beef cattle manure or compost application. J. Environ. Qual. 28:1201-1210.

Fox, R.L., and E.J. Kamprath. 1970. Phosphorus sorption isotherms for evaluating the phosphate requirement of soils. Soil Sci. Soc. Am. Proc. 34:902-907.

Ham, R.J. 1999. Phosphorus movement in poultry, swine, and tobacco farm soil in the North Carolina Coastal Plain. M.S. Thesis. N.C. State Univ.

Hardy, D.H., M.R. Tucker, and C.E. Stokes. 2003. Crop fertilization based on North Carolina soil tests. http://www.ncagr.com/agronomi/obook.htm.

Hodges, S.C. 2000. Soil management groups for North Carolina. N.C. State Univ. Ext. Bull.

Hutchison, K.J., and D. Hesterberg. 2004. Dissolution of phosphate in a phosphorus-enriched Ultisol as affected by microbial reduction. 33:1793-1802.

Johnson, A.M. 2004. Phosphorus loss assessment in North Carolina. Ph.D. Dissertation. N.C. State Univ. 150 pp.

Kleinman, P.J.A., R.B. Bryant, W.S. Reid, A.N. Sharpley, and D. Pimentel. 2000. Using soil phosphorus behavior to identify environmental thresholds. Soil Sci. 165:943-950.

Maguire, R.O., and J.T. Sims. 2002. Measuring agronomic and environmental soil phosphorus saturation and predicting phosphorus leaching with Mehlich 3. Soil Sci. Soc. Am. J. 66:2033-2039.

Maguire, R.O., R.H. Foy, J.S. Bailey, and J.T. Sims. 2001. Estimation of the phosphorus sorption capacity of acidic soils in Ireland. Eur. J. Soil Sci. 52:479-487.

McDowell, R.W. and A.N. Sharpley. 2001. Approximating phosphorus release from soils to surface runoff and subsurface drainage. J. Environ. Qual. 30:508-520.

Mehlich, A. 1984a. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409-1416.

Mehlich, A. 1984b. Photometric determination of humic matter in soils, a proposed method. Commun Soil Sci Plant Anal 15:1417–22.

Murphy, L., and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chem. Acta. 27:31-36.

Murray, G.C. 2004. Dissolution of phosphate in mixed Fe- and Al-oxide mineral suspensions as influenced by reducing conditions. M.S. Thesis. N.C. State Univ. 99 pp.

Nair, V.D., K.M. Portier, D.A. Graetz, and M.L. Walker. 2004. An environmental threshold for degree of phosphorus saturation in sandy soils. J. Environ. Qual. 33:107-113.

Novais, R., and E.J. Kamprath. 1978. Phosphorus supplying capacities of previously heavily fertilized soils. Soil Sci. Soc. Am. J. 42:931-935

N.C. PLAT Committee. 2005. North Carolina Phosphorus Loss Assessment: I. Model Description and II. Scientific Basis and Supporting Literature, North Carolina Agricultural Research Service Technical Bulletin 323, North Carolina State University, Raleigh, NC.

Pautler, M.C. and J.T. Sims. 2000. Relationships between soil test phosphorus, soluble phosphorus, and phosphorus saturation in Delaware soils. Soil Sci. Soc. Am. J. 64.765-773.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, D.R. Edwards, and D.J. Nichols. 1996. Relating extractable soil phosphorus to phosphorus losses in runoff. Soil Sci. Soc. Am. J. 60:855-859.

SAS Institute. 2002. SAS user’s guide: Statistics. Version 9.1 ed. SAS Inst., Cary, NC.

Sims, J.T., R.O. Maguire, A.B. Leytem, K.L. Gartley, and M.C. Pautler. 2002. Evaluation of Mehlich-3 as an agri-environmental soil phosphorus test for the mid-Atlantic United States of America. Soil Sci. Soc. Am. J. 66:2016-2032.

Tarkalson, D.D. 2001. Phosphorus loss in surface runoff from piedmont soils receiving animal manure and fertilizer additions. Ph.D. Dissertation. N.C. State Univ. 218 pp.

Table 1. List of Piedmont and Mountain soil series sampled for P leaching study.

Series	Taxonomic Name	Soil Management Group[a]	Drainage Class
Appling	Fine, kaolinitic, thermic Typic Kanhapludults	111	Well
Badin	Fine, mixed, semiactive, thermic Typic Hapludults	113	Well
Buncombe	Mixed, thermic Typic Udipsamments	105	Moderately Well
Callison	Fine-silty, siliceous, semiactive, thermic Aquic Hapludults	106	Moderately Well
Cecil	Fine, kaolinitic, thermic Typic Kanhapludults	111	Well
Chewacla	Fine-loamy, mixed, active, thermic Fluvaquentic Dystrudepts	102	Somewhat Poorly
Clifford	Fine, kaolinitic, mesic Typic Kanhapludults	111	Well
Colvard	Coarse-loamy, mixed, active, nonacid, mesic Typic Udifluvents	205	Somewhat Poorly
Fairview	Fine, kaolinitic, mesic Typic Kanhapludults	111	Well
Fannin	Fine-loamy, paramicaceous, mesic Typic Hapludults	214	Well
Georgeville	Fine, kaolinitic, thermic Typic Kanhapludults	113	Well
Goldston	Loamy-skeletal, siliceous, semiactive, thermic, shallow Typic Dystrudepts	117	Well
Hayesville	Fine, kaolinitic, mesic Typic Kanhapludults	210	Well
Hiwassee	Very-fine, kaolinitic, thermic Rhodic Kanhapludults	109	Well
Lloyd	Fine, kaolinitic, thermic Rhodic Kanhapludults	109	Well
Madison	Fine, kaolinitic, thermic Typic Kanhapludults	111	Well
Masada	Fine, mixed, semiactive, thermic Typic Hapludults	115	Well
Mecklenburg	Fine, mixed, active, thermic Ultic Hapludalfs	110	Well
Misenheimer	Loamy, siliceous, semiactive, thermic, shallow Aquic Dystrudepts	104	Moderately Well
Nanford	Fine, kaolinitic, thermic Typic Kanhapludults	113	Well
Pacolet	Fine, kaolinitic, thermic Typic Kanhapludults	111	Well
Rosman	Coarse-loamy, mixed, superactive, mesic Fluventic Humic Dystrudepts	207	Moderately Well
Tatum	Fine, mixed, semiactive, thermic Typic Hapludults	113	Well
Toccoa	Coarse-loamy, mixed, active, nonacid, thermic Typic Udifluvents	105	Moderately Well
Vance	Fine, mixed, semiactive, thermic Typic Hapludults	111	Well
Warne	Fine, mixed, semiactive, thermic Aeric Endoaquults	11	Poorly
Whitestore	Fine, mixed, active, thermic Oxyaquic Vertic Hapludalfs	107	Moderately Well

[a] Soil management groups in the 100s and 200s are located in the Piedmont and Mountain regions, respectively.

Table 2. Soil characteristics averaged across all soils and by select soil management groups.

	pH	HM	Clay	Mehlich-3			CaCl$_2$-P
				P	Fe	Al	
		%		mg kg^{-1}			
Mean (Std)	5.8 (0.9)	0.20 (0.28)	32 (16)	68 (152)	82 (81)	946 (218)	2.3 (7.1)
Range	4.0 - 9.0	0.0 - 1.9	2 - 74	0 - 1221	16 - 505	267 - 1535	0 - 60

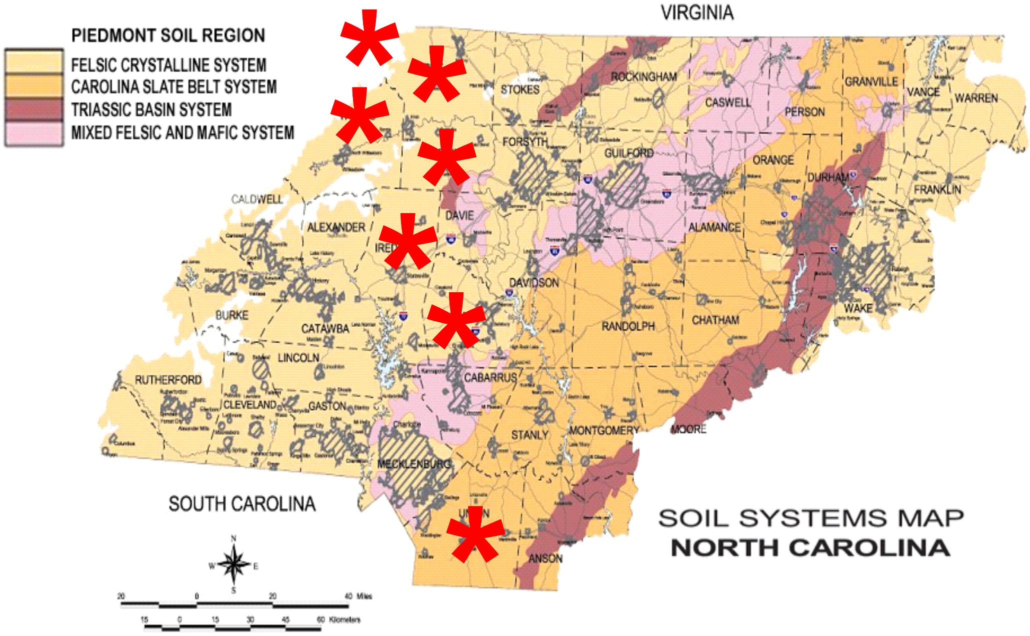

Figure 1. The soil systems of the North Carolina Piedmont physiographic region. The asterisks indicate counties in which soil sample were collected for study. Adopted from Daniels et al., 1999.

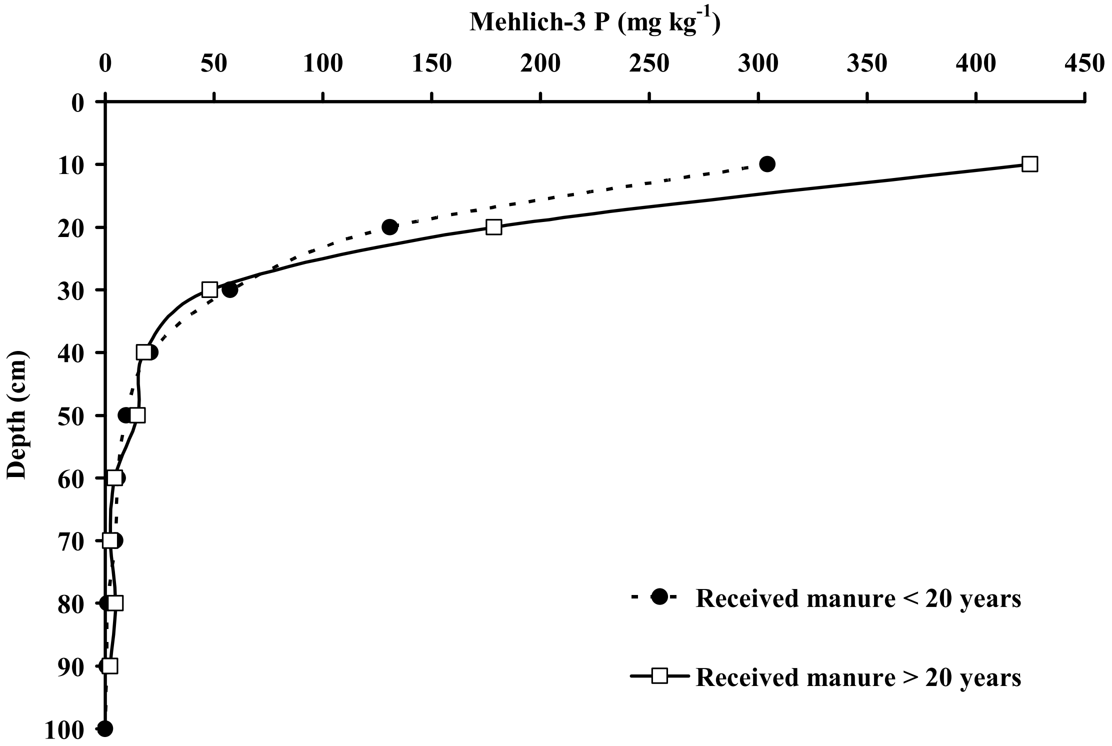

Figure 2. Mehlich-3 phosphorus (mg kg^{-1}) distribution by depth (cm) in soils having received either less than or more than 20 years of surface applied animal wastes.

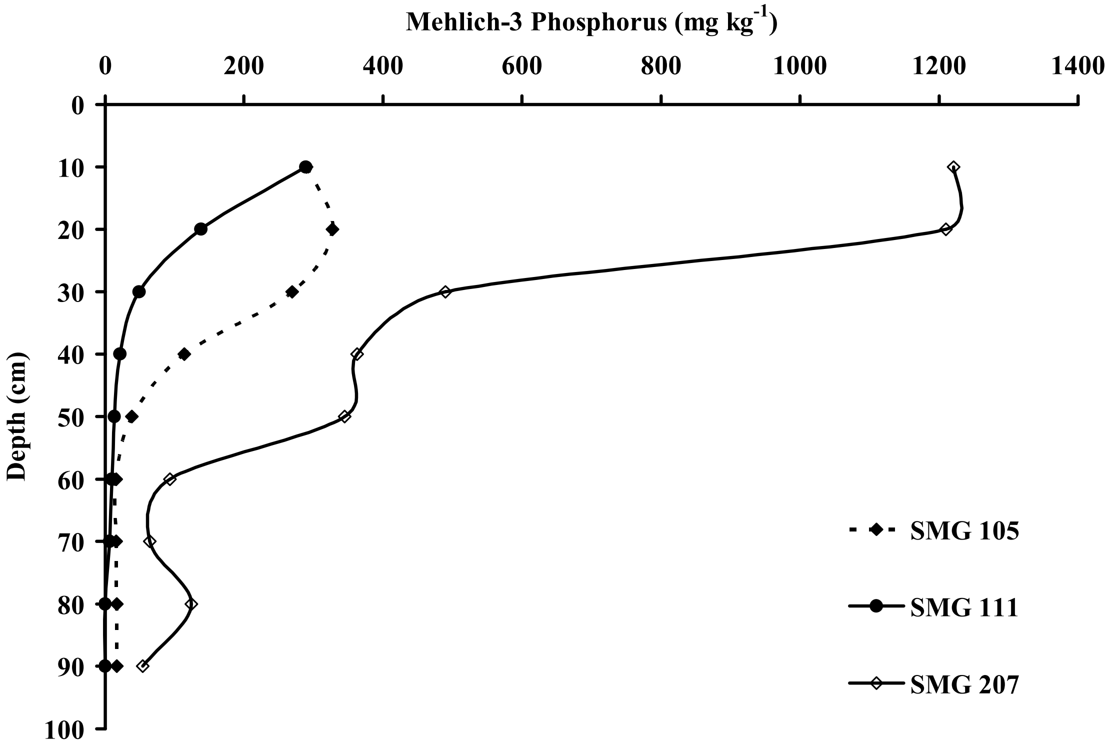

Figure 3. Mehlich-3 phosphorus distribution by depth for soil management groups 105, 111, and 205. Data not shown for SMGs 109, 110, 113, and 115 due to similarities with SMGs105, 111, and 207.

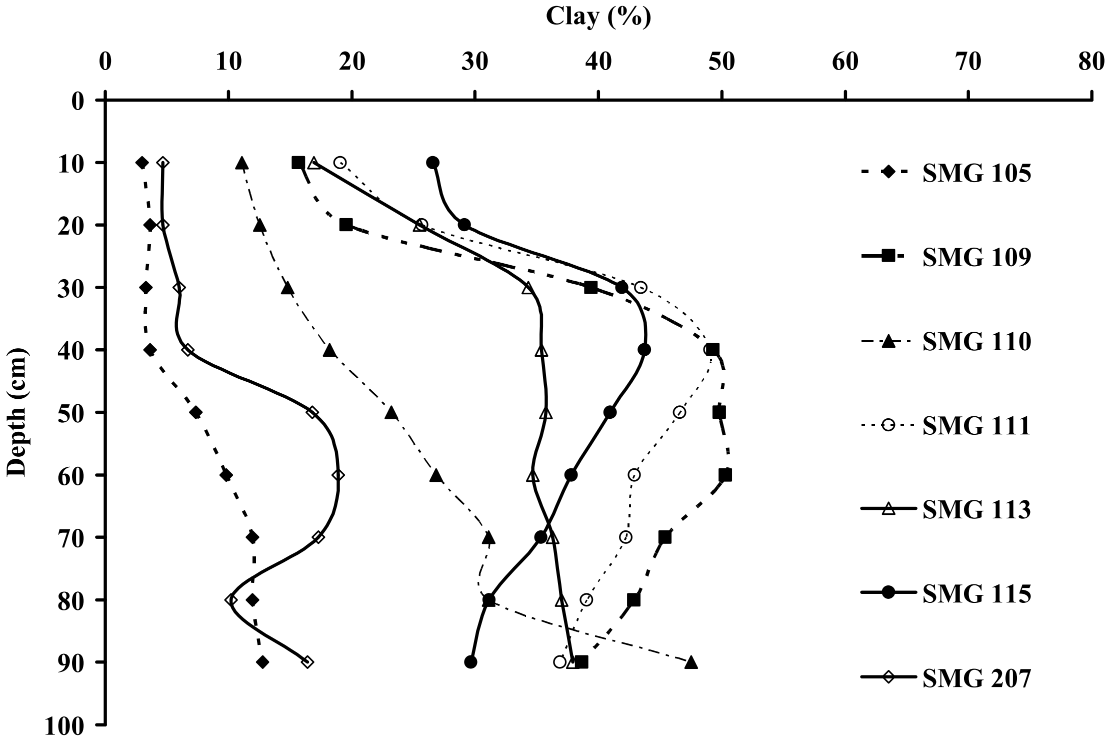

Figure 4. The distribution of clay (%) with depth (cm) for soils grouped into soil management groups.

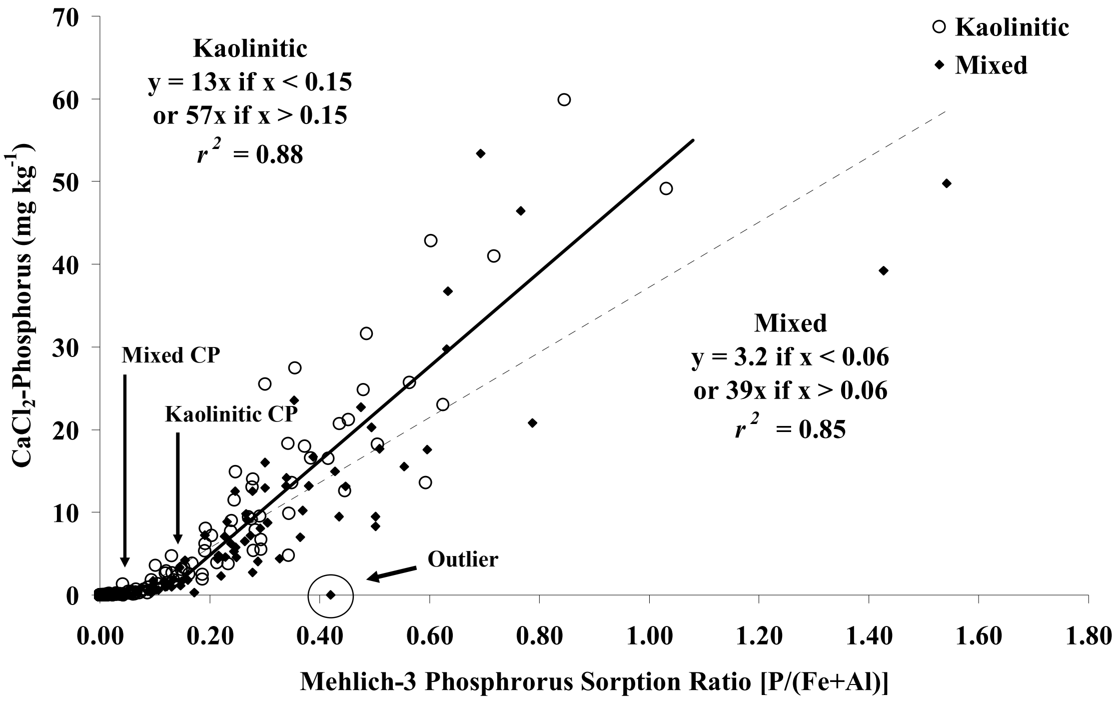

Figure 5. Calcium chloride extractable phosphorus concentration (mg kg^{-1}) as a function of Mehlich-3 phosphorus (mg kg^{-1}) concentration for soils grouped by mineralogy (kaolinitic or mixed). A change point (CP) was identified for each relationship for each mineralogy group.

CHAPTER 4

Multi-Field Assessment of Riparian Buffer Effectiveness in Mitigating Soil Phosphorus Losses

Introduction

Riparian buffers (RBs) have been identified as an effective best management practice (BMP) to attenuate nutrient losses, i.e. nitrogen (N) and phosphorus (P), from agricultural fields receiving animal wastes to protect surface water quality (Lowrance, 1997; Synder et al., 1995; Jordon et al., 1993; Peterjohn and Correll, 1984). The North Carolina (NC) Phosphorus Loss Assessment Tool (PLAT) also recognizes the effects of RBs on attenuating sediment-bound P loss but not for other P loss pathways as follows: (i) leached P, (ii) soluble P, and (iii) source P (N.C. PLAT Committee, 2005). Within the PLAT, one of the main variables determining P delivery to surface waters via these four P loss pathways is soil Mehlich-3 P (M3P) concentrations. Soil M3P concentration has been shown to serve as an estimate of the risk of P loss to surface waters (Bond et al., 2006). However, other site factors such as soil P sorption capacity, best management practices (BMPs), and field hydrology also influence the transport pathway of soil P released to surface waters. For example in PLAT, soil P loss to surface water via leaching is considered a function of its M3P concentration, leaching potential, and P sorption capacity (NC PLAT Committee, 2005).

Installation of RBs is promoted by state and federal government agencies based on their proven ability to reduce sediment and nutrient loads into surface waters (Daniels and Gilliam, 1996; NC PLAT Committee, 2005). However, riparian zones utilized as sediment and filters for P loss prevention have been reported to be less effective than similar systems utilized to mitigate N losses (Cooper and Gilliam, 1987). Yet, researchers have reported that 50-94% of sediment-bound P lost from NC Coastal Plain agricultural fields may be retained within the first 100 m of a wooded RB beginning at the field edge (Daniels and Gilliam, 1996; Cooper et al., 1987; Peterjohn and Correll, 1984). Elevated soil M3P concentrations beyond those required for agronomically optimal yields may contribute to greater potential soluble P exiting the field, and therefore are at a greater risk of P loss to surface waters (Bond et al., 2006). Soil P accumulation and movement to groundwater from excessive P loads applied as swine waste to NC coastal plain soils were shown to increase shallow (approximately 100 cm below soil surface) groundwater soluble P concentrations by 1,100% (from 40 to 480 mg L^{-1}) over a 10 y period (Novak et al., 2000). Studies indicate RBs are poor filters of soluble P in surface runoff while documentation of RB effectiveness to attenuate potential subsurface soluble P losses are limited (Nash and Murdoch, 2000; Peterjohn and Correll, 1984). Yet, Novak et al. (2002) suggested limited movement of P-enriched groundwater below and from manure application fields to nearby surface waters due to the attenuation of soluble P by neighboring RBs.

In some cases, NC Coastal Plain soils have been subjected to historically excessive applications of P from fertilizer, e.g. tobacco fields, and from animal wastes generated from confined animal feeding operations, resulting in the net accumulation of M3P (>53 mg kg^{-1}) with depth (>75 cm) (Ham, 1999). The PLAT assesses soil P leaching potentials by combining M3P and surface soil texture. If M3P exceeds the critical level for a particular texture, then M3P is measured at a depth of 76.2 cm. If M3P at this depth exceeds 50 mg kg^{-1}, then no further P applications are permitted (NC PLAT Committee, 2005).

Leaching of M3P in NC coastal plain soils to depths exposed to the water table (often <1 m from the soil surface) may increase the risk of soluble P loss to surface waters, but may be mitigated by RBs. Our objectives were to evaluate NC Coastal Plain soils to (i) validate the use of M3P to predict P leaching in these soils, and (ii) evaluate the effects of RBs for attenuating potential subsurface P losses from high P fields.

Materials and Methods

Soil Selection and Sample Collection

From the middle Coastal Plain region of NC, Lakeland sand (Thermic, coated Typic Quartzipsamments), Autryville loamy sand (Loamy, siliceous, subactive, thermic Arenic Paleudults), Marvyn loamy sand (Fine-loamy, kaolinitic, thermic Typic Kanhapludults), Norfolk loamy sand (Fine-loamy, kaolinitic, thermic Typic Kandiudults), Varina sandy loam (Fine, kaolinitic, thermic Plinthic Paleudults), Wagram loamy sand (Loamy, kaolinitic, thermic Arenic Kandiudults), Goldsboro loamy sand (Fine-loamy, siliceous, subactive, thermic Aquic Paleudults), Lynchburg loamy fine sand (Fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults), Ocilla loamy sand (Loamy, siliceous, semiactive, thermic Aquic Arenic Paleudults), Lynn Haven fine sand (Sandy, siliceous, thermic Typic Alaquods), and Pantego loam (Fine-loamy, siliceous, semiactive, thermic Umbric Paleaquults) soils that received swine waste and represented various PLAT soil management groups and leaching potentials were selected for study (Table 1). Site selection was limited to “high” P (>81 mg M3P kg^{-1}) and naturally-drained agricultural fields with shallow (within ~1 m annually) water tables boarded by an at-least 18.2-m mixed-wooded (*Liquidambar styraciflua L.*, *Quercus alba*, and *Pinaceae spp.*) riparian buffer from the field edge to the neighboring stream edge. Felds were cropped with either a rotation of corn (*Zea mays*), wheat (*Triticum spp.*), and soybean (*Glycine max*) under conventional tillage with a 30-cm plow depth or cropped to pasture forages, that is, common bermudagrass (*Cynadon dactylon*) over-seeded with winter rye (*Lolium spp.*) for beef cattle (*Bos spp.*) grazed year-round. The soils were collected with a 7.6-cm diameter Giddings (Windsor, CO) hydraulic probe at 15-cm increments to a maximum depth of 168 cm along the 36.6-m by 73.2-m sampling grid. At the time of sampling, three soil cores (~3 m apart) were collected wherein soils at each incremental depth were composited.

Soil Analysis

All soil samples collected were dried at 65˚C for 24 hours and ground to pass a 2-mm sieve. Soil pH (1:1 soil:deionized water) and humic matter (HM) content were measured by standard methods of the NCDA (Mehlich, 1984b). Soils were analyzed for (i) $CaCl_2$-P (1:10 soil to deionized water, 1-h reaction time, filtration through Whatman #2 filter paper); (ii) M3P (1:10 soil to 0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.13 M HNO_3 + 0.001 M EDTA, 5-min reaction time, filtration through Whatman #2 [Maidstone, UK] filter paper) (Mehlich, 1984a). The Mehlich-3 extract was analyzed for P (M3P), Al (M3Al), and Fe (M3Fe) by inductively coupled plasma atomic emission spectroscopy (ICP-AES). The M3P saturation ratio (M3PSR) was calculated by (on a mmol kg^{-1} basis):

$$M3PSR = M3P / (M3Al + M3Fe) \qquad [1]$$

(Maguire et al., 2002). Water soluble P extracts were analyzed colormetrically by the molybdate blue method of Murphy and Riley (1962). We chose to utilize ICP-AES and colorimetric methods for analyzing soluble P because earlier research reported a strong correlation ($r^2 = 0.98$) between ICP-AES and colorimetric soil P concentrations (Sikora et al., 2004).

Predicted $CaCl_2$-P concentrations were calculated for each soil by multiplying the drainage class critical M3PSR threshold value (independent variable) by the slope of the line either below or above the M3PSR change point. Comparisons were made among extracted and estimated $CaCl_2$-P concentrations for each soil and drainage classification group, respectively, to assess the accuracy of grouping soils by drainage class.

Particle size analysis was determined on a subset of fields (Farms A2, G2, F1, and C2) and soils as described by Kettler et al. (2001).

Groundwater Collection and Analysis

Groundwater samples were collected monthly from piezometers located in fields labeled A2 and G2 using a peristaltic pump collecting water into a 125-ml acid-washed plastic bottle. All samples were filtered with Whatman membranes with 0.45-µm openings prior to colormetric analysis on the Lachat auto-analyzer via the Murphy-Riley molybdate blue method (Murphy and Riley, 1962).

Experimental Design

Field sampling grids consisted of three 73.2-m transects (18.3 m apart) with five cores per transect. Soil cores were collected in the field (3), at the field edge (1), and 18.3 m into the buffer (1) nearing the stream. Groundwater samples were collected at the field edge and 18.3 m into the buffer in fields A2 and G2 from nested twin-set piezometers (30.5-cm screen with 110 nm openings) placed at two screen depths, one above and one below the seasonally high water table with each field as determined by the presence of soil redoximorphic features (chroma ≤ 2), per nest at 61.0-91.4 cm and 152.4-182.9 cm and 61.0-91.4 cm and 91.4-121.9 cm, respectively. Parallel transect orientations within a field were arranged in the direction of winter seasonal (for this study) groundwater flow as approximated by the Heath (1980) method also known as the "three-point well" method. The soil samples were analyzed for WSP and M3P and soluble P as described above.

Statistical Analysis

All correlation and regression analyses were conducted by standard procedures of SAS Version 9.1 (SAS Institute, 2002). Analysis of variance was conducted on all data using PROC MIXED within SAS 9.1 to model data with non-constant variances across groups, i.e. drainage class or soil management groups, as well as to account for random missing data values, i.e. soil or groundwater samples not collected due to excessive wetness or lack thereof, respectively, whereas PROC GLM would have eliminated such data points. The split-line linear regression (PROC NLIN) procedure within SAS 9.1 was used to determine environmental M3P and M3PSR thresholds or change points, as described by McDowell and Sharpley (2001) and Sims et al. (2002). Data interpolations by location for various soil test parameters were conducted within ArcMap (9.1) of ArcGIS (9) using the spline interpolation procedure (Frankie, 1982). The spline interpolation method was chosen to provide a visual representation of the soil test parameter's approximate distribution within the soil profile across the sampling zone at each site. Via the spline method, cell values were estimated using a mathematical function designed to minimize surface curvature, resulting in a smooth surface that passes exactly through each data point for the particular soil parameter mapped.

Results and Discussion

Soil Characteristics

For soils grouped into drainage classes, mean soil pH averaged across all depths ranged from 5.4 to 5.7 (Table 2). Humic matter content was greatest ($P \leq 0.10$) in Poorly (1.82) drained soils versus "drier" (HM<0.62) soils, illustrating the influence of increased wetness on soil organic matter accumulation. Both M3Fe and M3Al concentrations among soil drainage classes were similar to previously reported values from soils of the NC and Mid-Atlantic Coastal Plain physiographic regions (Maguire and Sims, 2002; Bond et al., 2006). Poorly drained soils also exhibited the greatest M3Al content (944 mg kg^{-1}). Mean M3P concentrations among soil drainage class groups across all depths were moderate to high (>50 mg kg^{-1}) due to the effects of prolonged swine effluent application over numerous years (10-40). Mean M3P concentrations averaged across depths ranged from 36 mg kg^{-1} (Excessively Well) to 92 mg kg^{-1} (Somewhat Poorly).

Effects of Soil Drainage and Mineralogy on the Mehlich-3 Phosphorus Saturation Ratio and Calcium Chloride Extractable Phosphorus Relationship

Among soil drainage groups, mean M3PSR environmental thresholds (aka "change points") ranged from 0.05 to 0.17 (Table 2; Figure 1). These critical M3PSR threshold ratios (on a mmol kg^{-1} basis) represent the drainage class-specific M3PSR value beyond which a significant (*P≤0.10*) increase in $CaCl_2$-P occurred per unit increase in M3PSR. Comparison of these critical M3PSR among soils or drainage classes allowed for assessment of the relative risk of potential soluble P losses via runoff or leaching. Thus the lower the M3PSR change point, the greater is the potential risk of elevated $CaCl_2$-P concentrations in the runoff or leachate at relatively lower P saturation ratios.

Inherent soil properties such as mineralogy obviously may affect the P sorption capacity of these soils, and thereby may affect the soil- or soil drainage class-specific critical environmental M3PSR threshold(s). For example, kaolinitic soils exhibited a critical mean M3PSR threshold of 0.19 compared to that of siliceous soils (0.09) (Table 2). Therefore, finer-textured or clayey soils exhibited a greater (*P≤0.10*) P sorption capacity than coarser textured, siliceous soils. All of the kaolinite-dominated soils were classified as well-drained, while well-drained soils included only one siliceous series, the Autryville loamy sand (Tables 2 and 3). By including the Autryville loamy sand in the "Well" drainage class, the mean M3PSR for the drainage group lessened by 0.02 from 0.19 to 0.17, thereby illustrating the effects of mineralogy on soil P sorption capacity and critical M3PSR values. Among siliceous soils, the mean critical M3PSR threshold ranged from 0.05 to 0.06 (Somewhat Poorly to Excessively Well, respectively; not significantly different) to 0.12 to 0.13 (Poorly to Moderately Well, respectively; not significantly different) (Table 2). Although inherently siliceous, the Goldsboro loamy sand series exhibited a subsurface accumulation of clay (Bt horizon) that may explain the relatively greater M3PSR change point of the siliceous soils studied. The relatively greater HM content of the Poorly drained soils was obviously a result of prolonged soil wetness. The Poorly drained soils exhibited a 6-fold increase in HM content averaged across all depths compared to all other soils. More specifically, mean HM content averaged across all depths of the Pantego loam (2.3 g 100 g^{-1}) was 3.5-fold greater ($P \leq 0.05$) than that of the Lynn Haven fine sand (0.67 g 100 g^{-1}). Mean HM content (4.3 g 100 g^{-1}) of the overlying surface (0-76 cm) soil was also significantly ($P \leq 0.05$) greater than the subsurface (>76 cm) soil. The HM accumulation due to wetness in the surface horizons resulted in a lower critical M3PSR value (~0.05) than the subsurface critical M3PSR threshold (>0.05) (Fig. 2). The lack of an identifiable change point of the subsurface soils of the Pantego was unclear, yet soils with broader M3PSR values have been reported to maintain linear relationships between $CaCl_2$-P and M3PSR (Bond et al., 2006).

Correlations among soils of the Mid-Atlantic Coastal Plain between leachate dissolved reactive P (DRP) and M3PSR values were also reported collectively to exhibit a M3PSR change point of 0.23, above which the concentration of DRP increased at significantly ($P \leq 0.0001$) greater rate (~3,000-fold) than below (Maguire and Sims, 2002). Using this relationship, the PLAT M3PSR change point was estimated at 0.21 when a leachate DRP concentration equivalent to that of adopted runoff threshold of 1 mg L^{-1} was used (PLAT Committee, 2005) (Fig. 3). Maguire and Sims (2002) reported that in all soils studied the agronomic optimum M3PSR of 0.23 (assuming M3P = 50 mg kg^{-1} as optimum) was below the soils' agronomic optimums. Similarly, they would be below that of the estimated PLAT M3PSR change point of 0.23. In our study, the majority of soil and drainage class critical M3PSR values were well below the estimated PLAT change point of 0.21. Only the Varina sandy loam exhibited a M3PSR change point equivalent to the estimated PLAT change point of 0.21 (Table 3).

Phosphorus Leaching Potential Among Soils Grouped by Drainage Classes

The net subsurface accumulation of M3P below the rhizosphere (0-30 cm) at concentrations greater than the agronomic minimum (53 mg kg^{-1}) marked the affect of excessive P applied as swine effluent (Figs. 4 through 41). Similar results would have been expected if excessive amounts of P were applied from another manure source. Numerous researchers have established reliability in the use of the M3P soil test for P loss risk assessment from agricultural fields (Sims et al., 1998; Maguire and Sims, 2002). Yet, substantially less research has been conducted on leaching and drainage of P through soil because of its relative immobility. Soil factors, i.e. texture and percent organic matter, affecting P mobility have been well established (Fox and Kamprath, 1970; Novais and Kamprath, 1978; Maguire and Sims, 2002). In general, greater M3P concentrations increase the potential for P leaching (Sim et al., 1998; Nelson, 2004). In addition, soils reaching critical P sorption concentrations, as estimated by M3PSR or similarly by the degree of P saturation by oxalate extraction, also tend to increase the potential for subsurface P loss. In some cases, 25% oxalate extractable soil P in relation to the sum of soil Fe and Al has been well correlated with significantly elevated subsurface drainage P concentrations, i.e. approaching 1 mg L^{-1}, wherein soluble P appeared to escalate above this suggested degree of P saturation threshold (Hesketh and Brookes, 2000). Yet, M3PSR values (equivalent to DPS_{ox} of 25%) from Mid-Atlantic coastal plain soils studied in a soil column experiment exhibited critical change points that corresponded to leachate concentrations as low as 0.063 mg L^{-1} (Maguire and Sims, 2002). In other studies, agricultural drainage waters have contained dissolved P concentrations ranging from 0.02 to 1.8 mg L^{-1} (Sims et al., 1998). In the NC Coastal Plain, Novak et al. (2002) measured mean groundwater P concentrations ~0.04 mg L^{-1} in soils that had received swine waste for ~10 years in which M3P concentrations well exceeded agronomic optimum concentrations of 50 mg kg^{-1}.

Spline interpolations of soil test parameters illustrated the distribution of M3P and $CaCl_2$-P concentrations and M3PSR values, wherein the potential to lose P (M3P > 53 mg kg^{-1} below a 76-cm depth) due to leaching was evident (Figs. 4 through 22). In some fields, the non-uniformity of swine effluent applications was also evident (assuming all other factors equal). For example, at Farm G1 lateral mean M3P concentrations referenced at each depth significantly ($P \leq 0.05$) decreased from the center-most sampling point of the field (54.8 m) to the field/buffer edge (Fig. 16; Table A-26). The influence of elevated HM contents due to soil wetness was illustrated by spline interpolations of the Pantego loam (Farm D1) soil M3P, $CaCl_2$-P, and M3PSR values, wherein the critical M3PSR (0.03) of the surface (0-76 cm) soils was exceeded resulting in the net subsurface (>76 cm) accumulation of M3P and subsequently elevated subsurface $CaCl_2$-P and M3PSR values (Fig. 14). In this poorly drained soil, the drainage class critical M3PSR threshold (0.12) was exceeded at depths exposed to the water table. Therefore, the risk of subsurface lateral P loss was assumed to be greatest in the Pantego loam (Farm D1) due to prolonged exposure to laterally flowing shallow groundwater exiting the field.

Soluble Phosphorus in Shallow Groundwater

The mean groundwater soluble P concentrations collected at the field/buffer edge and 18.3 m into the RB at Farms A2 and G2 ranged from 0 to 0.89 mg L^{-1} (Tables 4 and 5). No apparent seasonal trend was apparent in these data. At Farm A2, field/buffer edge shallow (30 to 61 cm) soluble P concentrations along transect 1 (data not shown) were relatively greater on average compared to transects 2 and 3. Transect 1 was oriented along the middle of a natural drainage way in the field, and runoff was likely channeled through it. To date, researchers have established the concept of concentrated flow of nutrients through RB, yet primarily the studies have monitored more mobile nutrients (i.e. N), rather than P (Cooper and Gilliam, 1987; Novak et al., 2002).

Conclusions

Soil drainage classification appeared to influence the pathway(s) by which P losses to neighboring RBs occurred from fields. “Drier” soils, i.e. Norfolk loamy sand, had greater potentials for surface P loss than “wetter” soils, i.e. Pantego loam (Fig. 20 and14, respectively). In general, the “drier” soils exhibited greater P sorption capacities than “wetter” soils as exhibited by their respective M3PSR change points values (Table 2; Fig. 1). The accumulation of humic matter (HM) content in “wetter” soils, i.e. Poorly drained Pantego loam of Farm D1, resulted in lower P sorption capacities and greater potential for P leaching and subsurface lateral P losses (Table 1; Fig. 1 and 2). Overall, excessive applications of swine waste resulted in M3P leaching in all NC Coastal Plain mineral soils, wherein the mean M3PSR change point was greater for Kaolinitic (0.19) than Siliceous (0.09) soils. In addition, siliceous, low HM (<0.62 g 100 g-1) soils resulted in the lowest M3PSR change points among soils due to their inherently low P sorption capacities. In well-drained soils, i.e. Norfolk loamy sand of Farm H1, P loss occurred as a surface phenomenon as opposed to subsurface despite excessive P leaching losses in the field. Yet, greater Pantego loam surface (~75 cm) HM content resulted in less P sorption capacity (M3PSR) and greater M3P leaching than all other, i.e. Norfolk, soil series. In reference to the Pantego loam M3P interpolation, the data suggests a real potential for lateral (from the field) subsurface (>120 cm) M3P accumulation in the RB. Due to limited data, no apparent trends in groundwater soluble P were evident. Therefore, further research and emphasis should be placed particularly on soils with relatively greater organic matter to better understand the potential risk for P losses to nearby surface waters so that a more sustainable approach to P management may be developed and implemented.

References

Cooper, J.R. and J.W. Gilliam. 1987. Phosphorus redistribution from cultivated fields into riparian areas. Soil Sci. Soc. Am. J. 51:1600-1604.

Cooper, J.R., J.W. Gilliam, R.B. Daniels, W.P. Robarge. 1987. Riparian areas as filters for agricultural sediment. Soil Sci. Soc. Am. J. 51:416-420.

Daniels, R.B. and J.W. Gilliam. 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Sci. Soc. Am. J. 60:246-251.

Frankie, R. 1982. Smooth interpolation of scattered data by local thin plate splines. Comp. and Math. Appls. 8(4):237-281.

Fox, R.L., and E.J. Kamprath. 1970. Phosphorus sorption isotherms for evaluating the phosphate requirement of soils. Soil Sci. Soc. Am. Proc. 34:902-907.

Ham, R.J. 1999. Phosphorus movement in poultry, swine, and tobacco farm soil in the North Carolina Coastal Plain. M.S. Thesis. North Carolina State University. Raleigh, NC.

Heath, R.C. 1980. Basic elements of ground-water hydrology with reference to conditions in North Carolina. USGS. Water-Resources Investigations Open-File Report 80-44. Raleigh, NC.

Hesketh, N., and P.C. Brookes. 2000. Development of an indicator for risk of phosphorus leaching. J. Environ. Qual. 29:105-110.

Johnson, A.M., D.L. Osmond, and S.C. Hodges. 2005. Predicted impact and evaluation of North Carolina’s phosphorus indexing tool. J. Environ. Qual.

Jordan, T.E., D.L. Correll, and D.E. Weller. 1993. Nutrient interception by a riparian forest receiving inputs from adjacent croplands. J. Environ. Qual. 22:467-473.

Kettler, T.A., J.W. Doran, T.L. Gilbert. 2001. Simplified method for soil particle-size determination to accompany soil-quality analyses. Soil Sci. Soc. Am. J. 65:849-852.

Lowrance, R. 1997. The potential role of riparian forests as buffer zones. *In* N.E. Haycock et al. (ed.) Buffer Zones: Their Processes and Potential Water Protection. Quest Environ.

Maguire, R.O., and J.T. Sims. 2002. Measuring agronomic and environmental soil phosphorus saturation and predicting phosphorus leaching with Mehlich 3. Soil Sci. Soc. Am. J. 66:2033-2039.

McDowell, R.W. and A.N. Sharpley. 2001. Approximating phosphorus release from soils to surface runoff and subsurface drainage. J. Environ. Qual. 30:508-520.

Murphy, L., and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chem. Acta. 27:31-36.

Nash, D., and C. Murdoch. 2000. Phosphorus in runoff from a fertile dairy pasture. *In* First National Soil Phosphate Conference 35(2):419-429.

Nelson, N. 2004. Soil and waste management effects on phosphorus leaching in acid sandy soils of the North Carolina coastal plain. Ph.D. Dissertation. N.C. State Univ. 156 pp.

Novais, R., and E.J. Kamprath. 1978. Phosphorus supplying capacities of previously heavily fertilized soils. Soil Sci. Soc. Am. J. 42:931-935.

Novak, J.M., D.W. Watts, P.G. Hunt, and K.C. Stone. 2000. Phosphorus movement through a coastal plain soil after a decade of intensive swine manure application. J. Environ. Qual. 29:1310-1315.

Novak, J.M., P.G. Hunt, K.C. Stone, D.W. Watts, M.H. Johnson. 2002. Riparian zone impact on phosphorus movement to a coastal plain black water stream. J. Soil and Water Conserv. 57:127-133.

Peterjohn, W.T. and D.L. Correll. 1984. Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology 65:1466-1475.

Sikora, F.J., P.S. Howe, L.E. Hill, D.C. Reid, and D.E. Harover. 2004. Comparison of colorimetric and ICP determination of phosphorus in Mehlich-3 soil extracts. Commun. Soil. Sci. Plant Anal. 36:875-887.

Sims, J.T., R.R. Simard, and B.C. Joern. 1998. Phosphorus loss in agricultural drainage: historic perspective and current research. J. Environ. Qual. 27:277-293.

Sims, J.T., R.O. Maguire, A.B. Leytem, K.L. Gartley, and M.C. Pautler. 2002. Evaluation of Mehlich-3 as an agri-environmental soil phosphorus test for the mid-Atlantic United States of America. Soil Sci. Soc. Am. J. 66:2016-2032.

Snyder, N.J., S. Mostaghimi, D.F. Berry, R.B. Reneau, E.P. Smith. 1995. Evaluation of a riparian wetland as a naturally occurring decontamination zone. *In* Clean Water, Clean Environment - 21st Century. Vol. 3: Practices, Systems, and Adoption. American Society of Agricultural Engineers. Mar. 5-8, 1995. Kansas City, Mo., St. Joseph, Mich. p. 259-262.

Table 1. List of Coastal Plain soil series sampled.

Series	Taxonomic Name	Drainage Class
Lakeland sand	Thermic, coated Typic Quartzipsamments	Excessively Well
Autryville loamy sand	Loamy, siliceous, subactive, thermic Arenic Paleudults	Well
Marvyn loamy sand	Fine-loamy, kaolinitic, thermic Typic Kanhapludults	Well
Norfolk loamy sand	Fine-loamy, kaolinitic, thermic Typic Kandiudults	Well
Varina sandy loam	Fine, kaolinitic, thermic Plinthic Paleudults	Well
Wagram loamy sand	Loamy, kaolinitic, thermic Arenic Kandiudults	Well
Goldsboro loamy sand	Fine-loamy, siliceous, subactive, thermic Aquic Paleudults	Well
Lynchburg loamy fine sand	Fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults	Somewhat Poorly
Ocilla loamy sand	Loamy, siliceous, semiactive, thermic Aquic Arenic Paleudults	Somewhat Poorly
Lynn Haven fine sand	Sandy, siliceous, thermic Typic Alaquods	Poorly
Pantego loam	Fine-loamy, siliceous, semiactive, thermic Umbric Paleaquults	Poorly

Table 2. The critical Mehlich-3 phosphorus saturation ratio and soil characteristics for North Carolina Coastal Plain soils grouped by drainage class.

Drainage Class	Particle Size	Mineralogy	M3PSR	HM	pH	M3P	M3Fe	M3Al
Series	Class		Change Point	g 100 g^{-1}		——	mg kg^{-1}	——
Excessively Well			0.06 c	0.42 c	5.4 b	36 d	61 d	604 d
Lakeland	Sandy	Siliceous						
Well			0.17 a	0.31 c	5.4 b	54 cb	72 bc	865 b
Autryville	Loamy	Siliceous						
Marvyn	Fine-loamy	Kaolinitic						
Norfolk	Fine-loamy	Kaolinitic						
Varina	Fine	Kaolinitic						
Wagram	Loamy	Kaolinitic						
Moderately Well			0.13 b	0.34 c	5.7 a	55 b	64 dc	765 c
Goldsboro	Fine-loamy	Siliceous						
Somewhat Poorly			0.05 c	0.62 b	5.6 a	92 a	82 a	852 b
Lynchburg	Fine-loamy	Siliceous						
Ocilla	Loamy	Siliceous						
Very Poorly			0.12 b	1.82 a	5.4 b	42 cd	73 ba	944 a
Lynn Haven	Sandy	Siliceous						
Pantego	Fine-loamy	Siliceous						

alpha = 0.05

LSD_{XB} = 0.03

Table 3. Environmental thresholds (change points) for the relationship between calcium chloride extractable phosphorus and Mehlich-3 phosphorus saturation ratio (M3PSR) for each soil series sorted by mineralogy.

								M3PSR			
Farm	**Field**	**Series**	**Drainage Class**	**PSC**	**Mineralogy**	**Intercept**	**B**[a]	**XB**	**D**	**r**^{2***}	**Notes**
GG	1	Lakeland	Excessive	Sandy	Siliceous	0	2.9	0.06	8.66	0.90	
A	1	Goldsboro	Moderately Well	Fine-loamy	Siliceous	0.00	5.3	0.13	26.8	0.91	
A	2	Lynchburg	Somewhat Poorly	Fine-loamy	Siliceous	0.00	2.2	0.06	16.0	0.87	
F	1	Ocilla	Somewhat Poorly	Loamy	Siliceous	0	3.2	0.05	16.69	0.94	
G	2	Lynn Haven	Very Poorly	Sandy	Siliceous	0	0.9	0.13	19.40	0.80	
D	1a	Pantego	Very Poorly	Fine-loamy	Siliceous	0.00	1.3	0.10	14.91	0.64	surface (0-76 cm) - Mucky
D	1b	Pantego	Very Poorly	Fine-loamy	Siliceous	0.02	0.9	-	-	0.93	subsurface (77-168) linear
B	1	Autryville	Well	Loamy	Siliceous	0.00	7.5	0.08	18.4	0.84	
C	1	Autryville	Well	Loamy	Siliceous	0.00	1.9	0.10	19.4	-	failed to converge therefore estimated
B	2	Autryville	Well	Loamy	Siliceous	-0.04	14.5	-	-	0.78	linear
H	1	Autryville	Well	Loamy	Siliceous						sigmoidal
C	4	Marvyn	Well	Fine-loamy	Kaolinitic	0.00	3.3	0.23	12.9	0.57	
I	2	Marvyn	Well	Fine-loamy	Kaolinitic	0.02	5.4	-	-	0.87	linear
I	1	Norfolk	Well	Fine-loamy	Kaolinitic	0.00	4.59	0.14	23.82	0.85	
A	3	Norfolk	Well	Fine-loamy	Kaolinitic	0.00	4.2	0.15	40.1	0.89	
C	3	Norfolk	Well	Fine-loamy	Kaolinitic	0.01	5.2	0.16	40.7	0.91	
H	2	Norfolk	Well	Fine-loamy	Kaolinitic	0.03	8.0	-	-	0.77	linear
C	2	Varina	Well	Fine	Kaolinitic	-0.04	2.5	0.21	41.1	0.95	
G	1	Wagram	Well	Loamy	Kaolinitic	0	5.8	0.20	38.02	0.59	
B	3	Wagram	Well	Loamy	Kaolinitic	0.00	14.9	0.22	59.7	0.97	

***Significant at 0.0001

[a] B = slope below XB; XB = change point; D = slope above XB

Table 4. Farm A2 (Lynchburg loamy sand) groundwater soluble P (mg L^{-1}) collected from piezometers located along field transects 1, 2, and 3 set at shallow (61 to 91 cm) and deep (122 to 152 cm) depths.

	At field/buffer edge						18.3 m into RB					
	Transect						Transect					
	1	2	3	1	2	3	1	2	3	1	2	3
	shallow (61 to 91 cm)			Deep (122 to 152 cm)			shallow (61 to 91 cm)			Deep (122 to 152 cm)		
Month	Soluble P (mg L^{-1})						Soluble P (mg L^{-1})					
July 2005				0.01	0.02	0.00				0.02	0.00	0.00
Sept 2005				0.04	0.02	0.03			0.00	0.05	0.00	0.00
Dec 2005	0.17	0.01	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.16	0.00	0.35
Jan 2006	0.34	0.02	0.01	0.00	0.01	0.01	0.07	0.00	0.00	0.01	0.28	0.00
Feb 2006	0.58	0.01	0.03	0.01	0.02	0.00	0.16	0.01	0.00	0.01	0.01	0.00
Mar 2006	0.16	0.04	0.03	0.03	0.03	0.03	0.11	0.03	0.03	0.03	0.02	0.03
Apr 2006	0.04		0.01	0.02	0.01	0.01	0.07	0.02		0.00	0.00	
May 2006	0.13	0.02	0.01	0.01	0.01	0.01	0.89	0.14	0.01	0.26	0.00	0.01
June 2006	0.75	0.14	0.04	0.03	0.04	0.04	0.20	0.03	0.03	0.00	0.03	0.03

Table 5. Farm G2 (Lynn Haven fine sand) groundwater soluble P (mg L^{-1}) collected from piezometers located along field transects 1, 2, and 3 set at shallow (31 to 61 cm) and deep (91 to 121 cm) depths.

	At field/buffer edge						18.3 m into RB					
	Transect						Transect					
	1	2	3	1	2	3	1	2	3	1	2	3
	shallow (31 to 61 cm)			Deep (91 to 121 cm)			shallow (31 to 61 cm)			Deep (91 to 121 cm)		
Month	Soluble P (mg L^{-1})						Soluble P (mg L^{-1})					
Mar 2006	0.03	0.03	0.01	0.04	0.03	0.01	0.82	0.01	0.01	0.01	0.00	0.00
Apr 2006	0.04	0.02	0.02	0.03	0.02	0.01	0.07	0.00	0.00	0.29	0.00	0.01
May 2006	0.03	0.02	0.01	0.03	0.01	0.01	0.05	0.14	0.01	0.26	0.00	0.01
June 2006	0.04	0.04	0.03	0.04	0.06	0.03	0.57	0.09	0.03	0.03	0.03	0.03

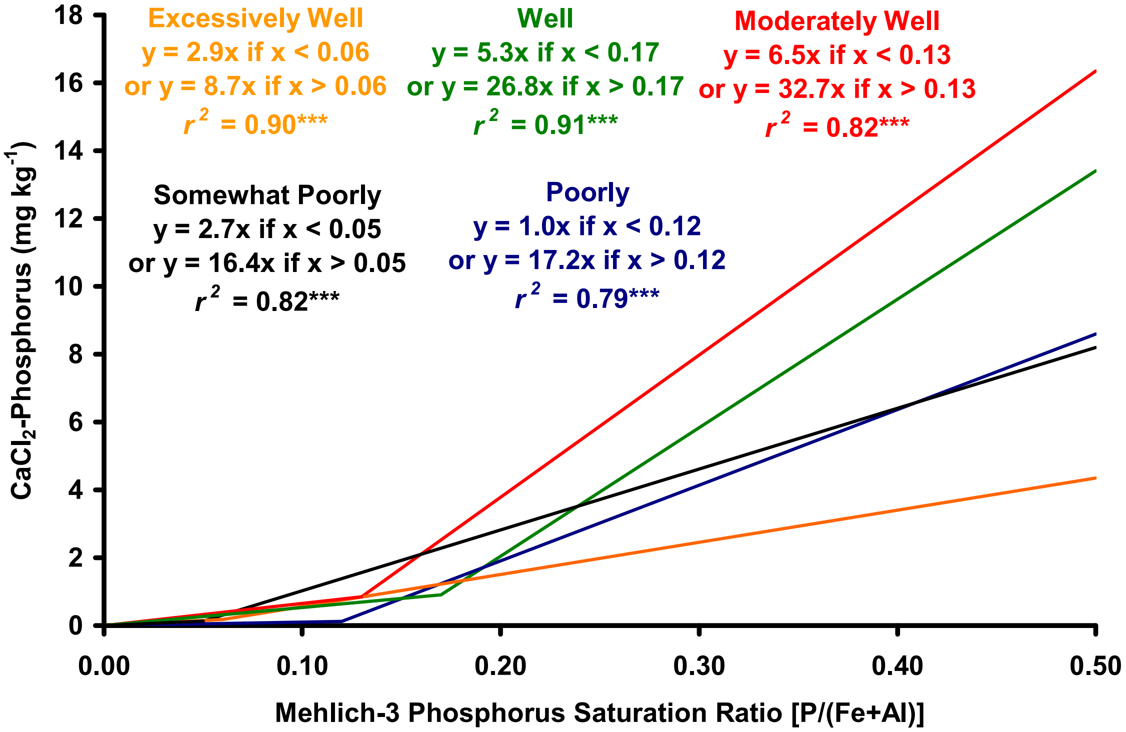

Figure 1. Calcium chloride phosphorus versus Mehlich-3 phosphorus saturation ratio relationships and change points for soils grouped by drainage class.

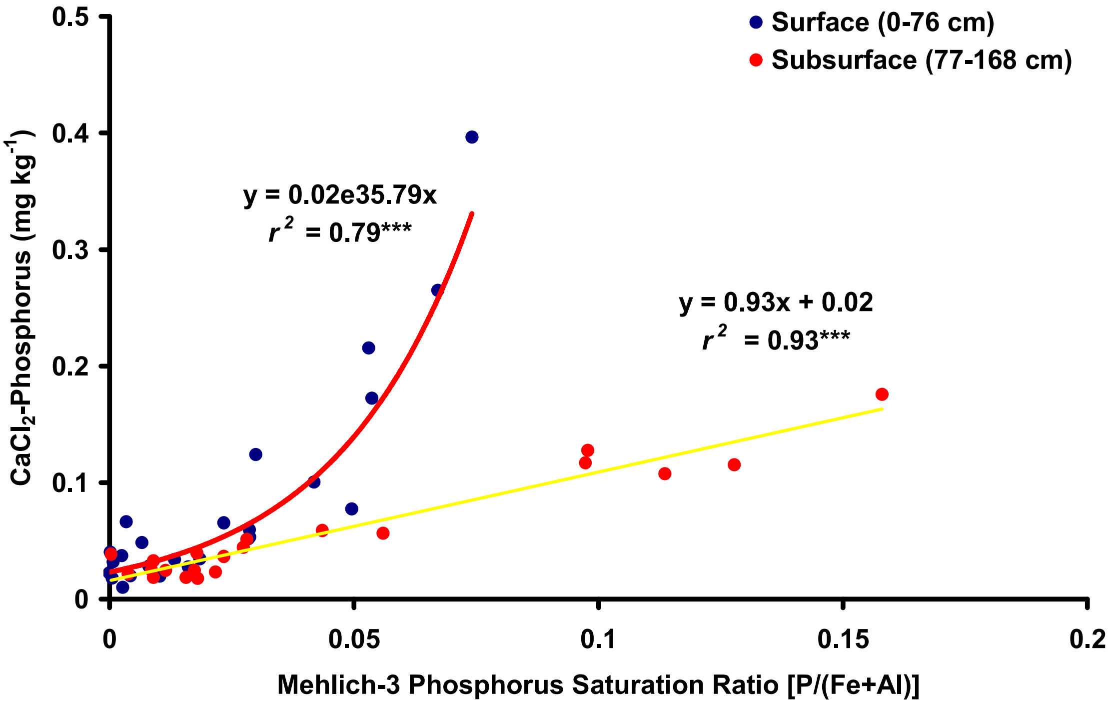

Figure 2. Effects of elevated humic matter (HM) content on the relationship between and water soluble phosphorus Mehlich-3 phosphorus saturation ratio for the Pantego loam [surface 76 cm (●) and subsurface (●) samples] of the "Poorly" drainage class.

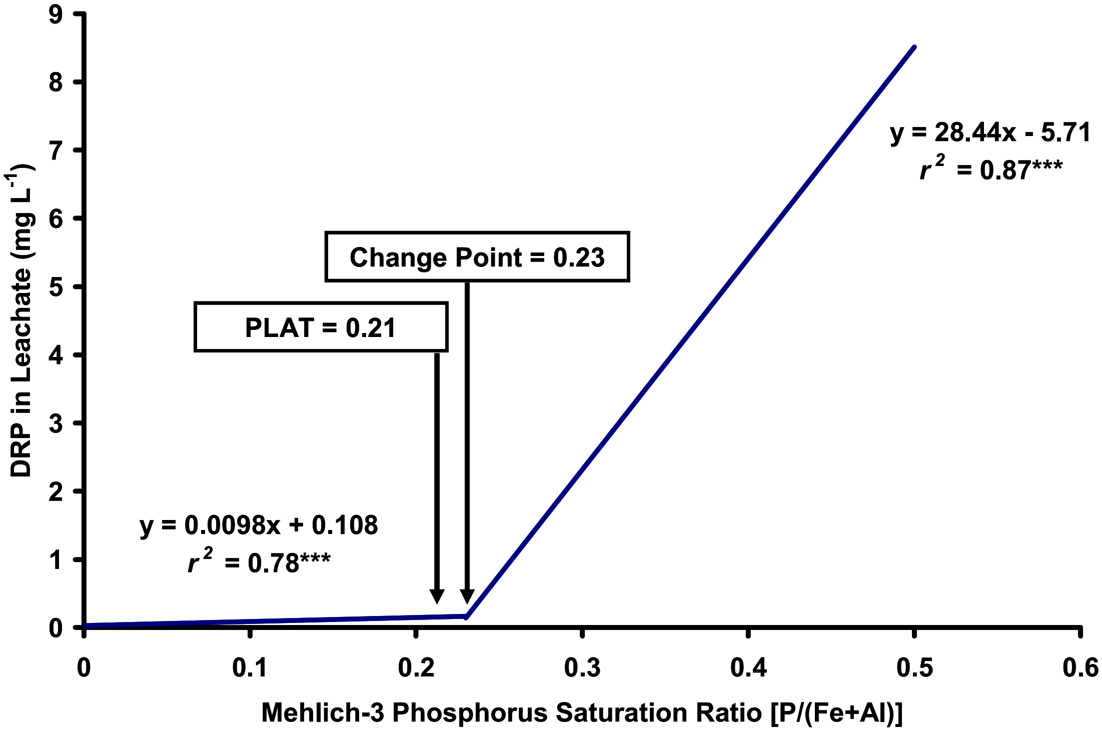

Figure 3. The comparison of dissolved reactive phosphorus (DRP) to the Mehlich saturation ratio for Mid-Atlantic Coastal Plain soils of the Mid-Atlantic region (adapted from Maguire and Sims, 2002). The PLAT estimated change point was based on a 1 mg L^{-1} environmental threshold (PLAT Committee, 2005).

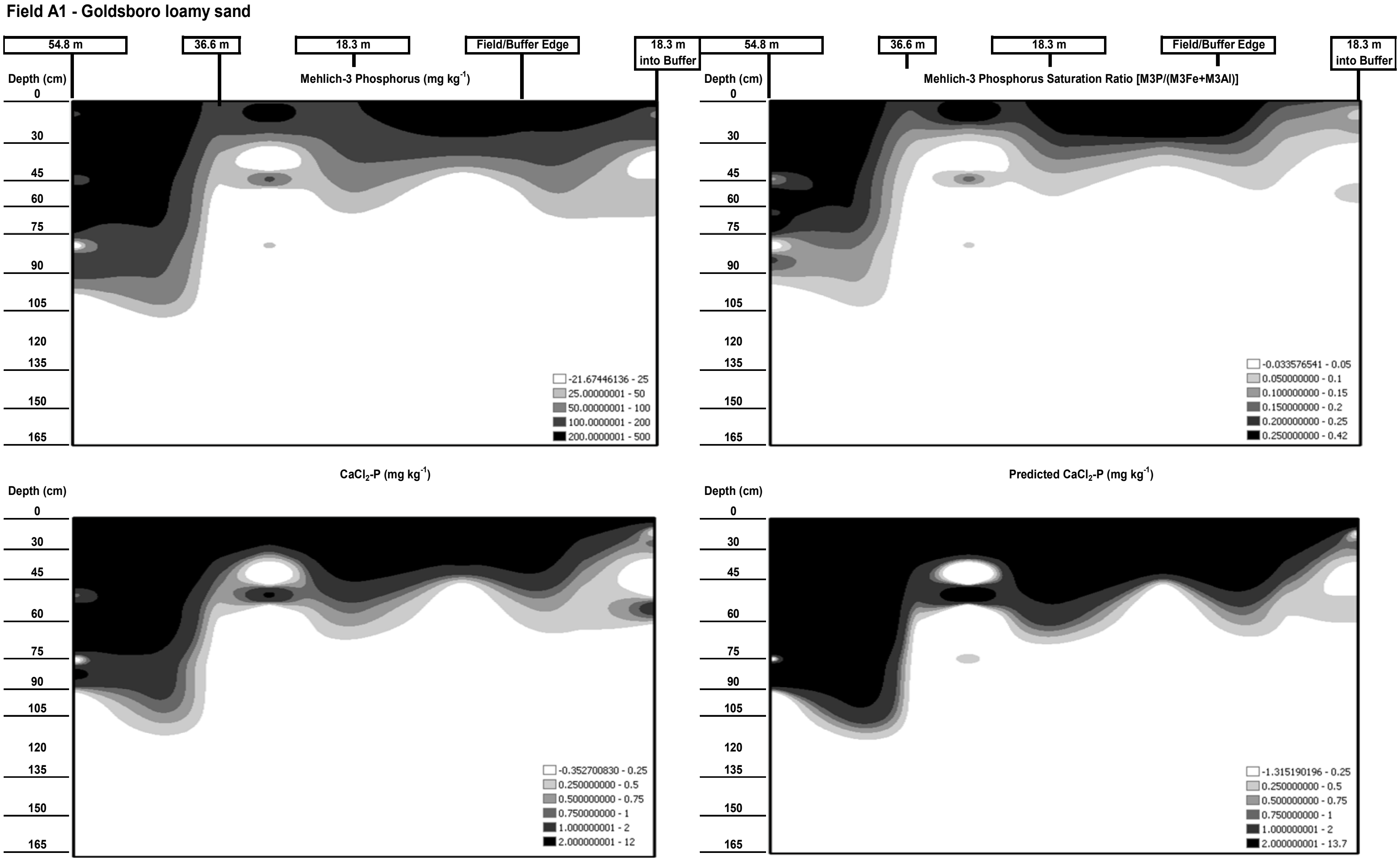

Figure 4. Spline interpolations for Mehlich-3 phosphorus and $CaCl_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted $CaCl_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Moderately Well drained Goldsboro loamy sand located on Farm A1.

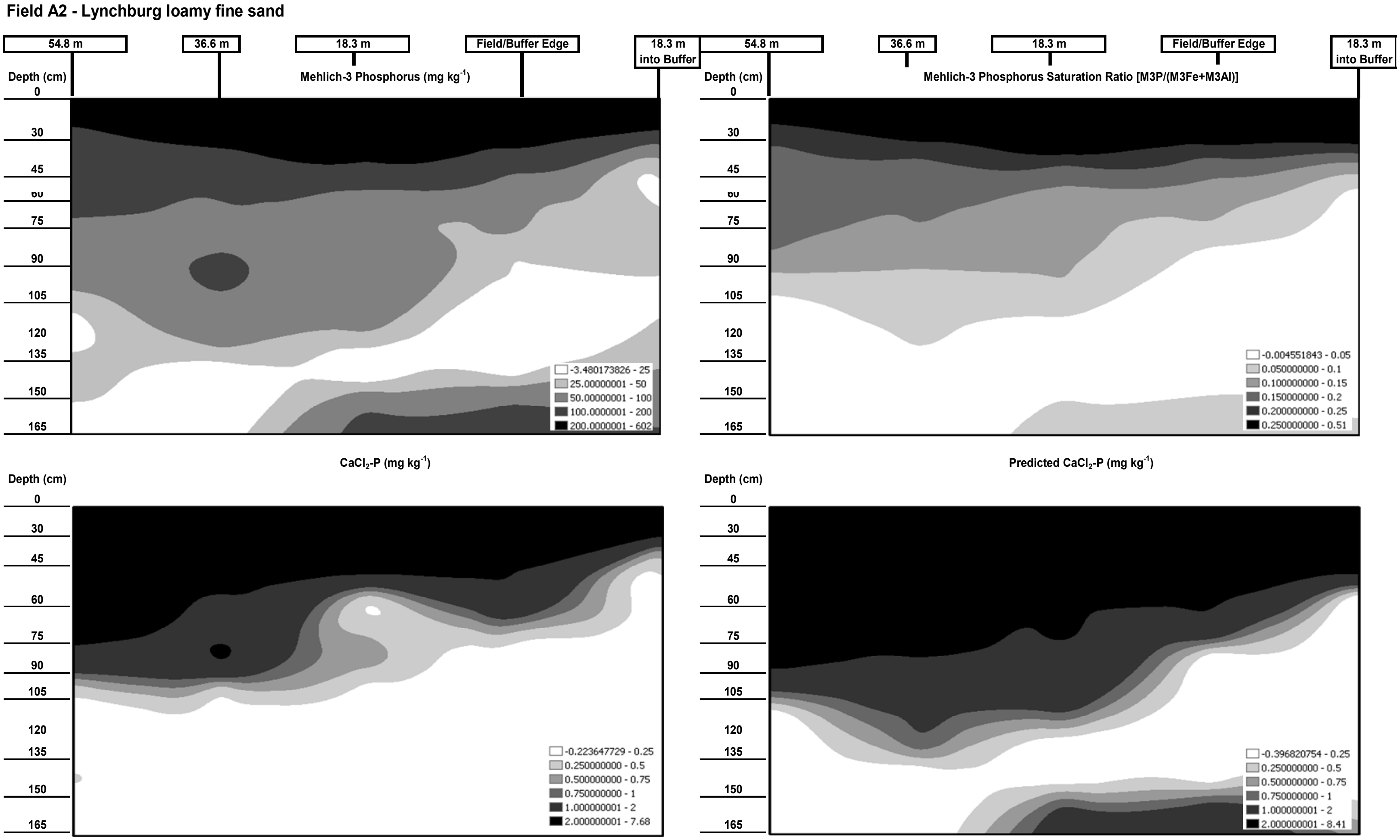

Figure 5. Spline interpolations for Mehlich-3 phosphorus and CaCl$_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted CaCl$_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Somewhat Poorly drained Lynchburg loamy fine sand located on Farm A2.

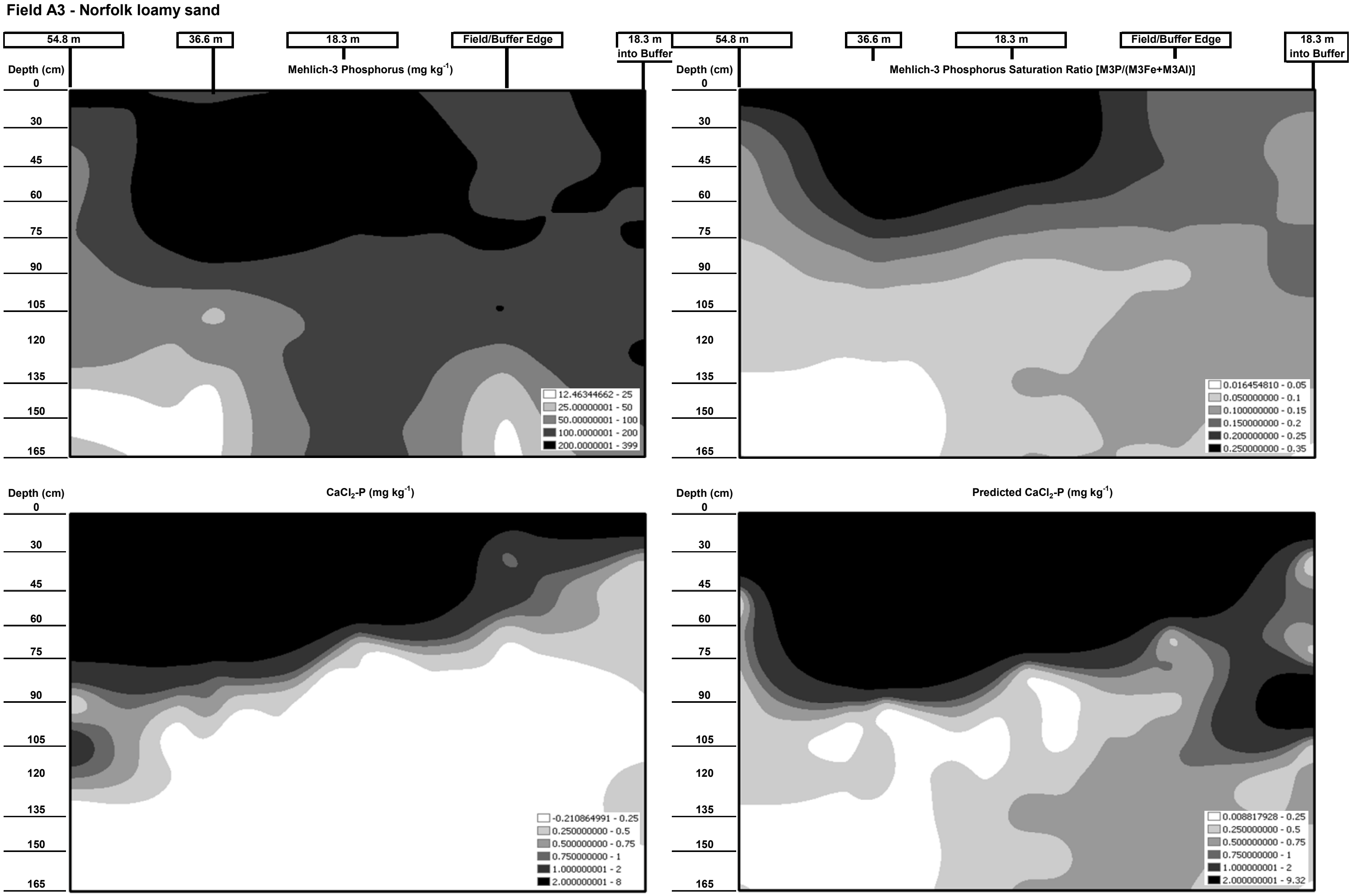

Figure 6. Spline interpolations for Mehlich-3 phosphorus and $CaCl_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted $CaCl_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Well drained Norfolk loamy sand located on Farm A3.

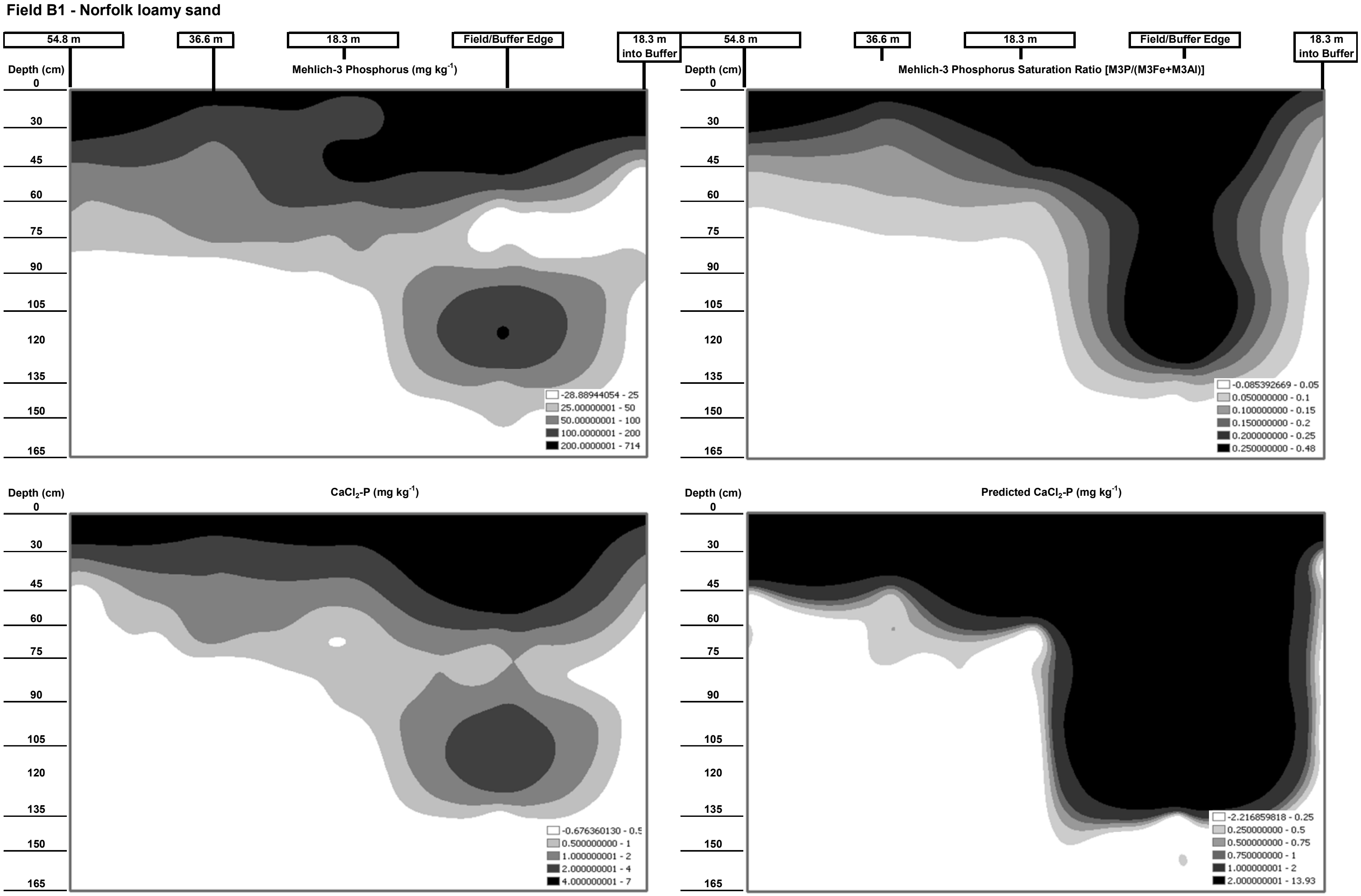

Figure 7. Spline interpolations for Mehlich-3 phosphorus and CaCl$_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted CaCl$_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Well drained Norfolk loamy sand located on Farm B1.

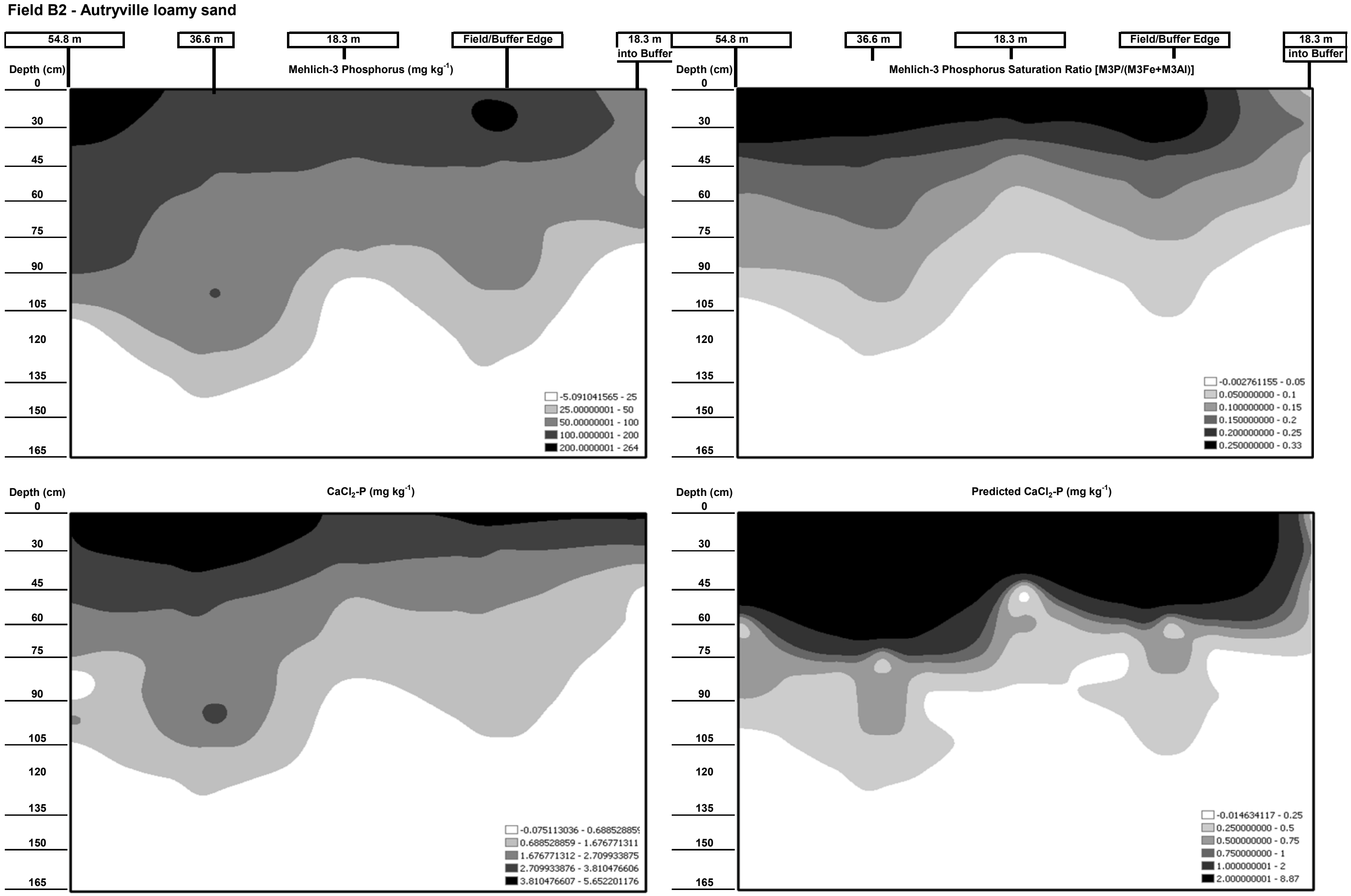

Figure 8. Spline interpolations for Mehlich-3 phosphorus and CaCl$_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted CaCl$_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Well drained Autryville loamy sand located on Farm B2.

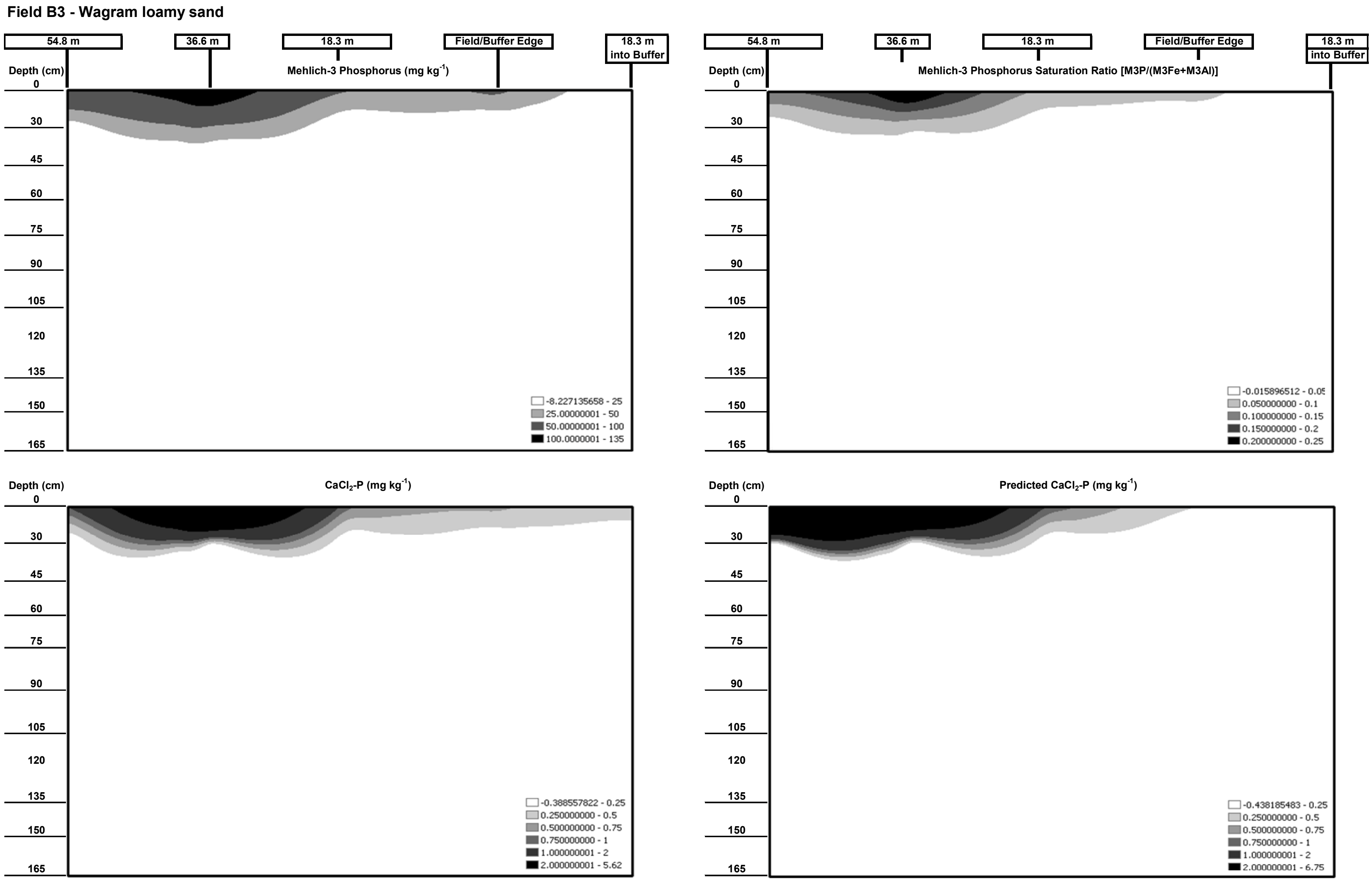

Figure 9. Spline interpolations for Mehlich-3 phosphorus and $CaCl_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted $CaCl_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Well drained Wagram loamy sand located on Farm B3.

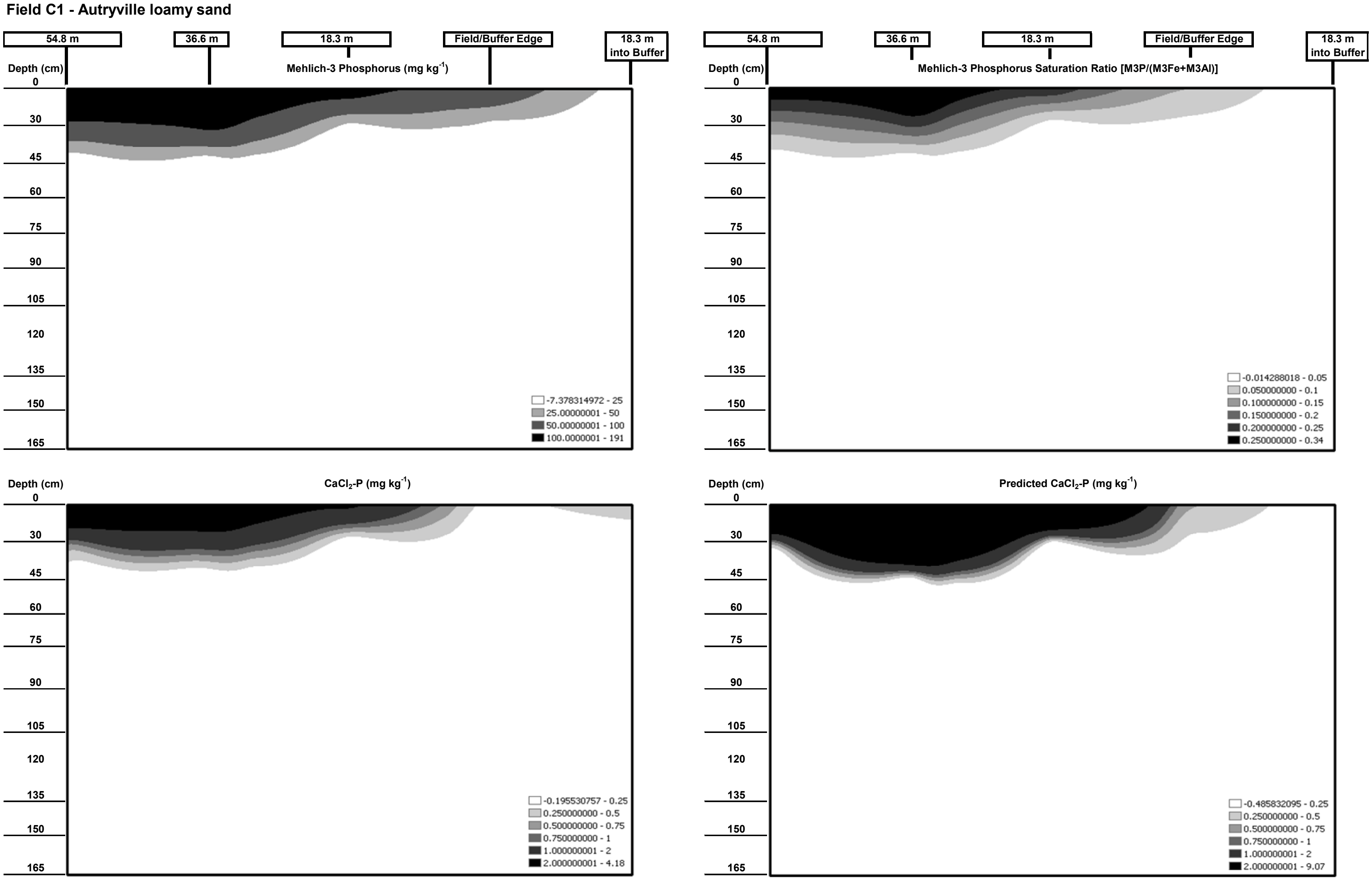

Figure 10. Spline interpolations for Mehlich-3 phosphorus and $CaCl_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted $CaCl_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Well drained Autryville loamy sand located on Farm C1.

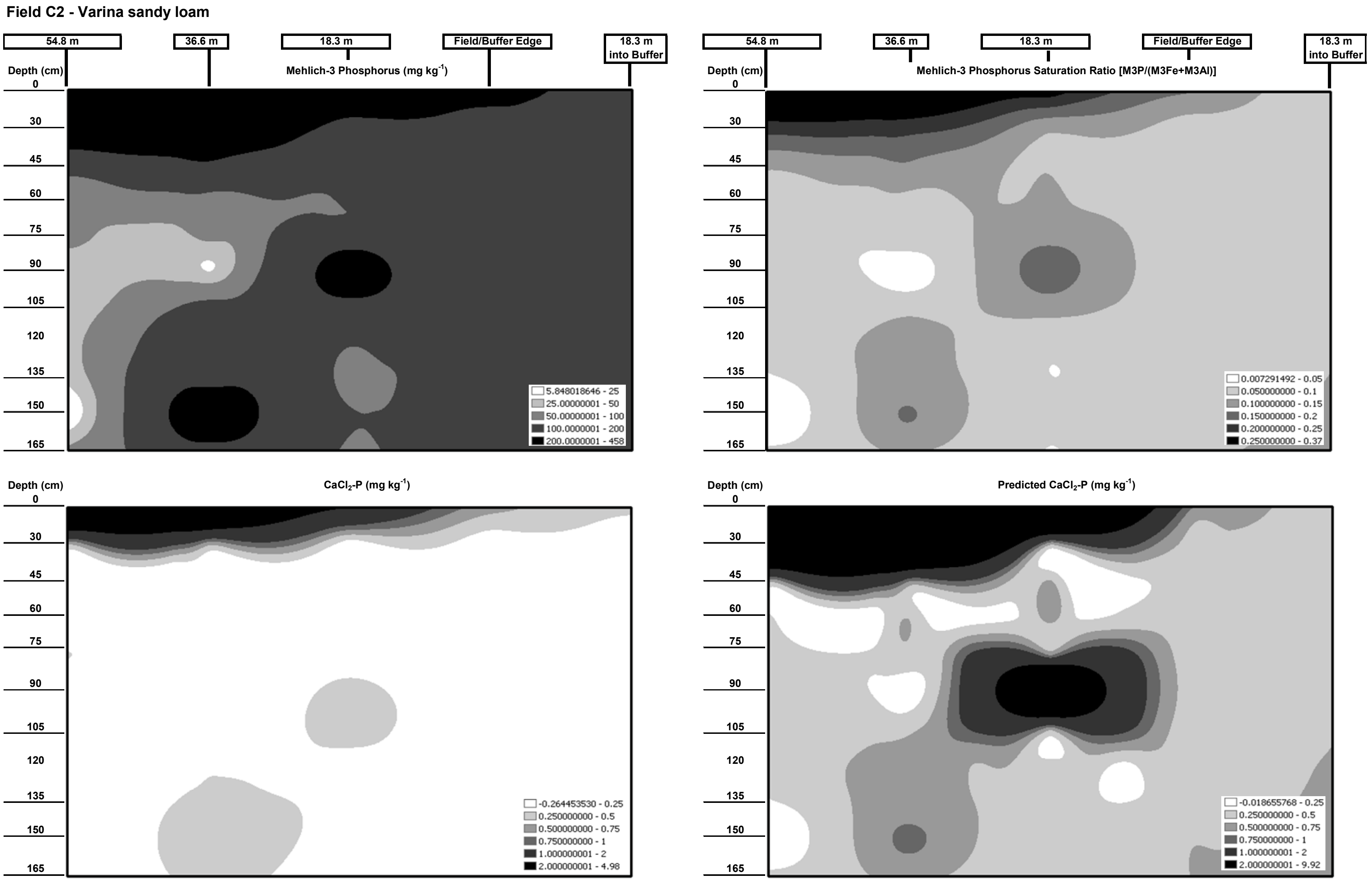

Figure 11. Spline interpolations for Mehlich-3 phosphorus and $CaCl_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted $CaCl_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Well drained Varina sandy loam located on Farm C2.

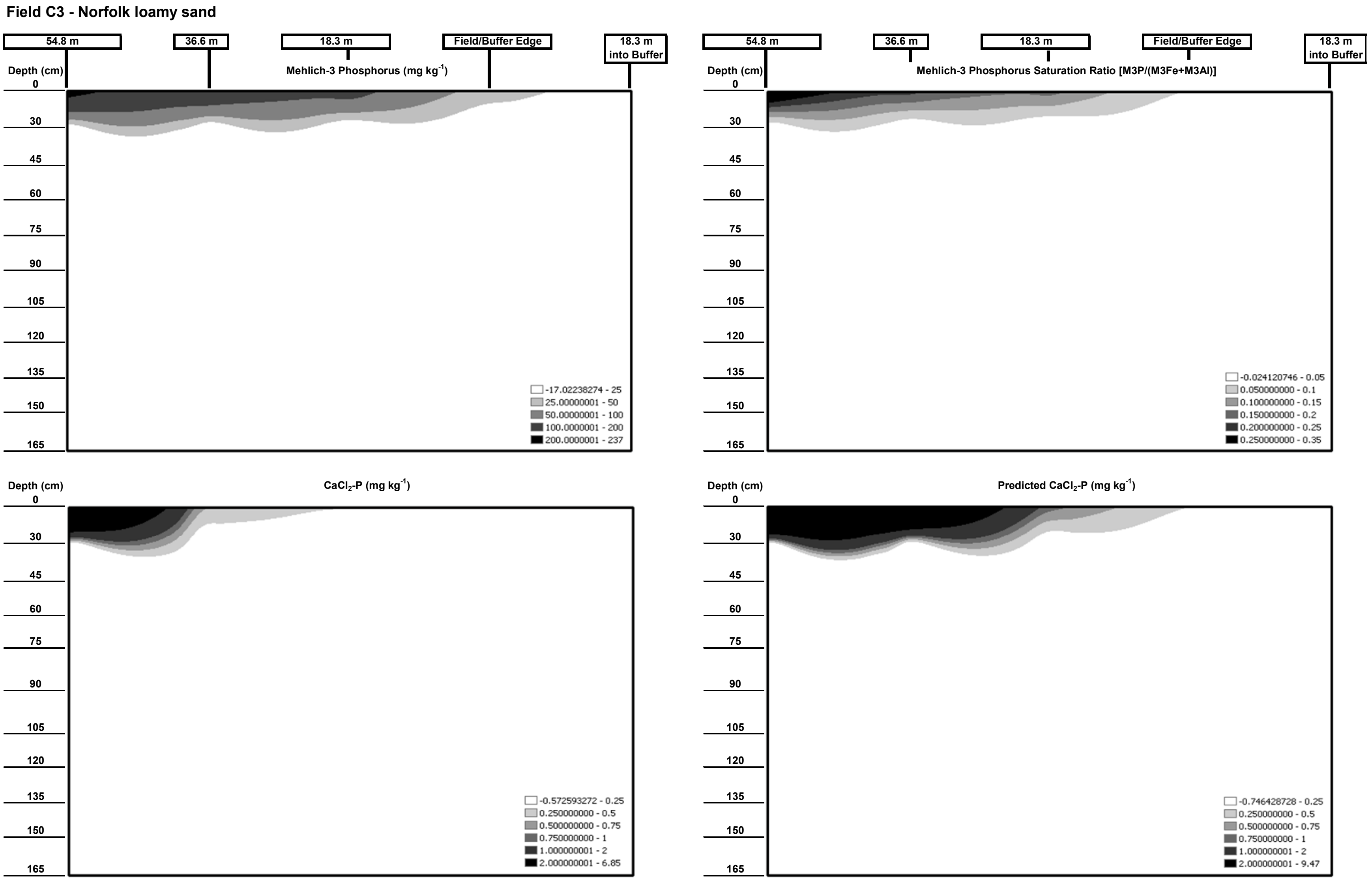

Figure 12. Spline interpolations for Mehlich-3 phosphorus and CaCl$_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted CaCl$_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Well drained Norfolk sandy loam located on Farm C3.

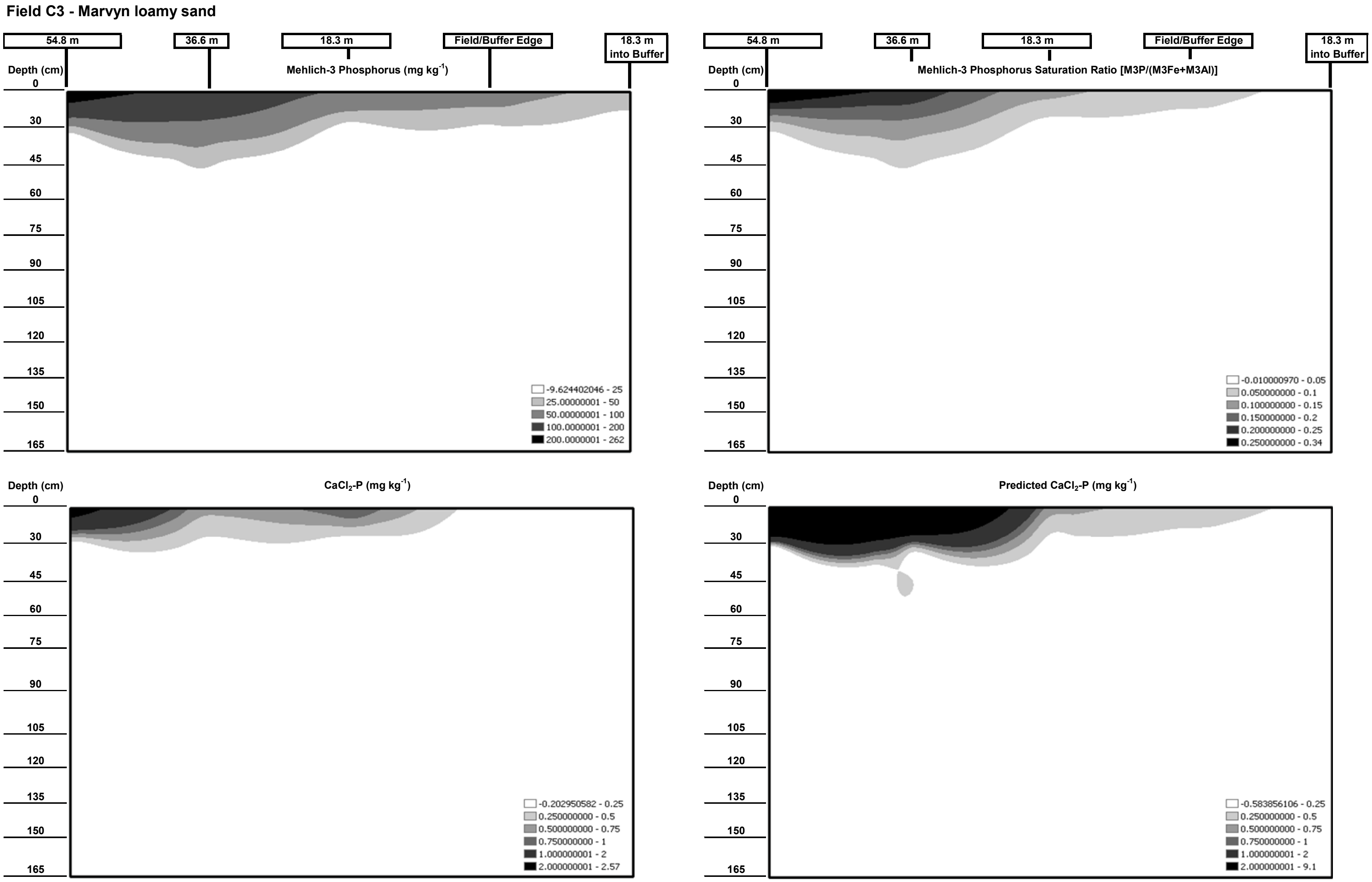

Figure 13. Spline interpolations for Mehlich-3 phosphorus and $CaCl_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted $CaCl_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Well drained Wagram loamy sand located on Farm C4.

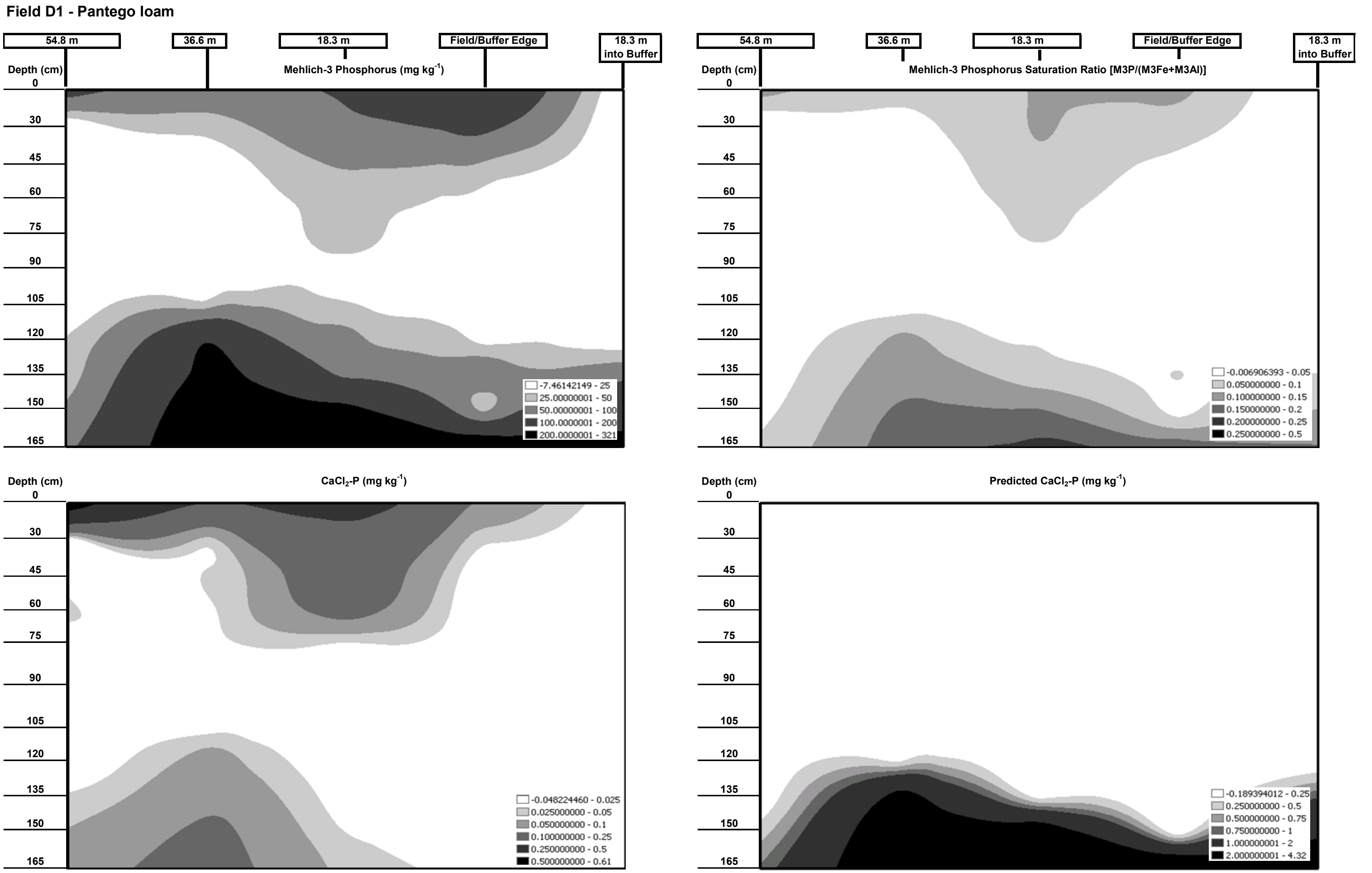

Figure 14. Spline interpolations for Mehlich-3 phosphorus and CaCl$_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted CaCl$_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Poorly drained Pantego loam located on Farm D1.

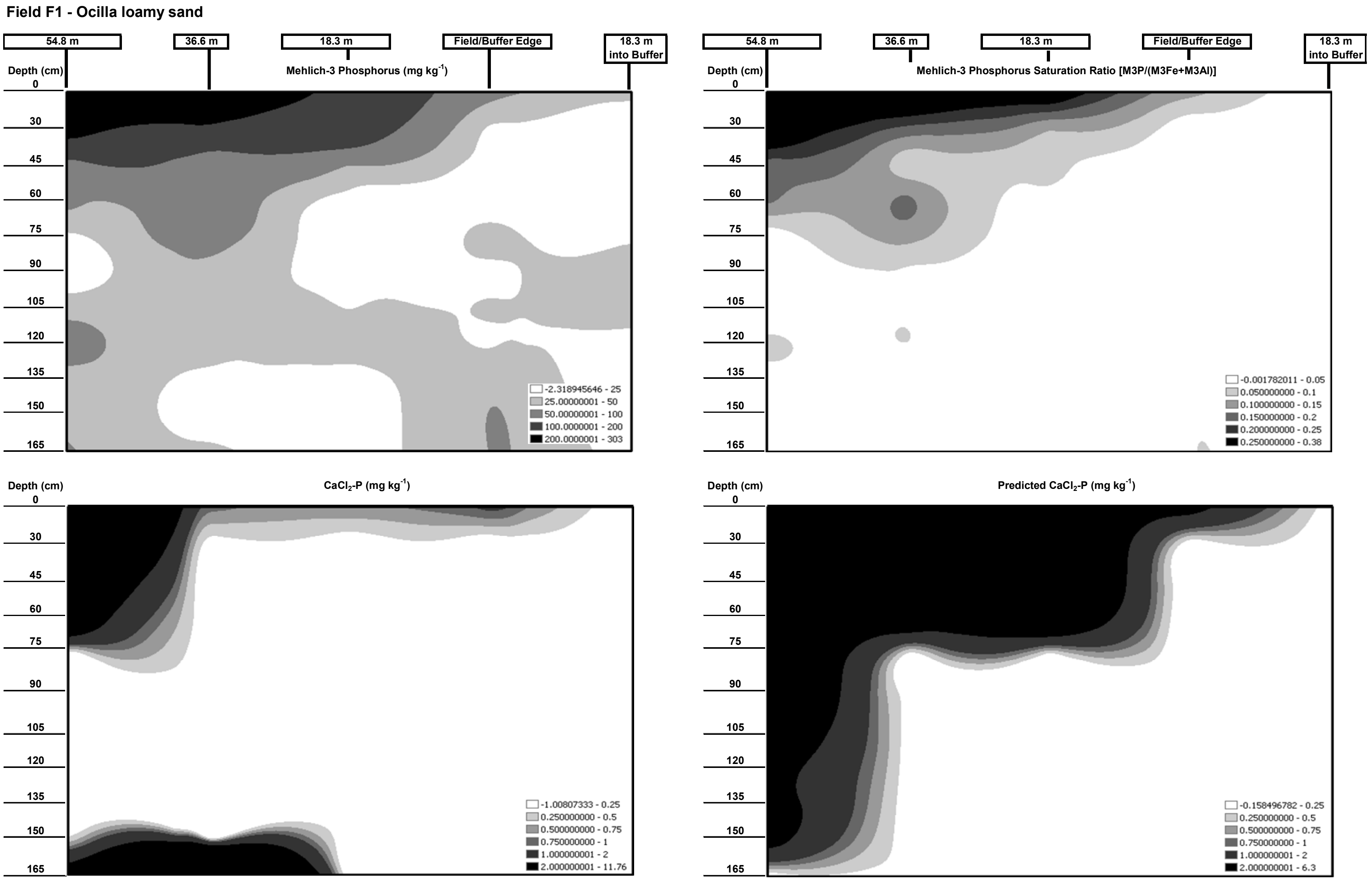

Figure 15. Spline interpolations for Mehlich-3 phosphorus and $CaCl_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted $CaCl_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Somewhat Poorly drained Ocilla loamy sand located on Farm F1.

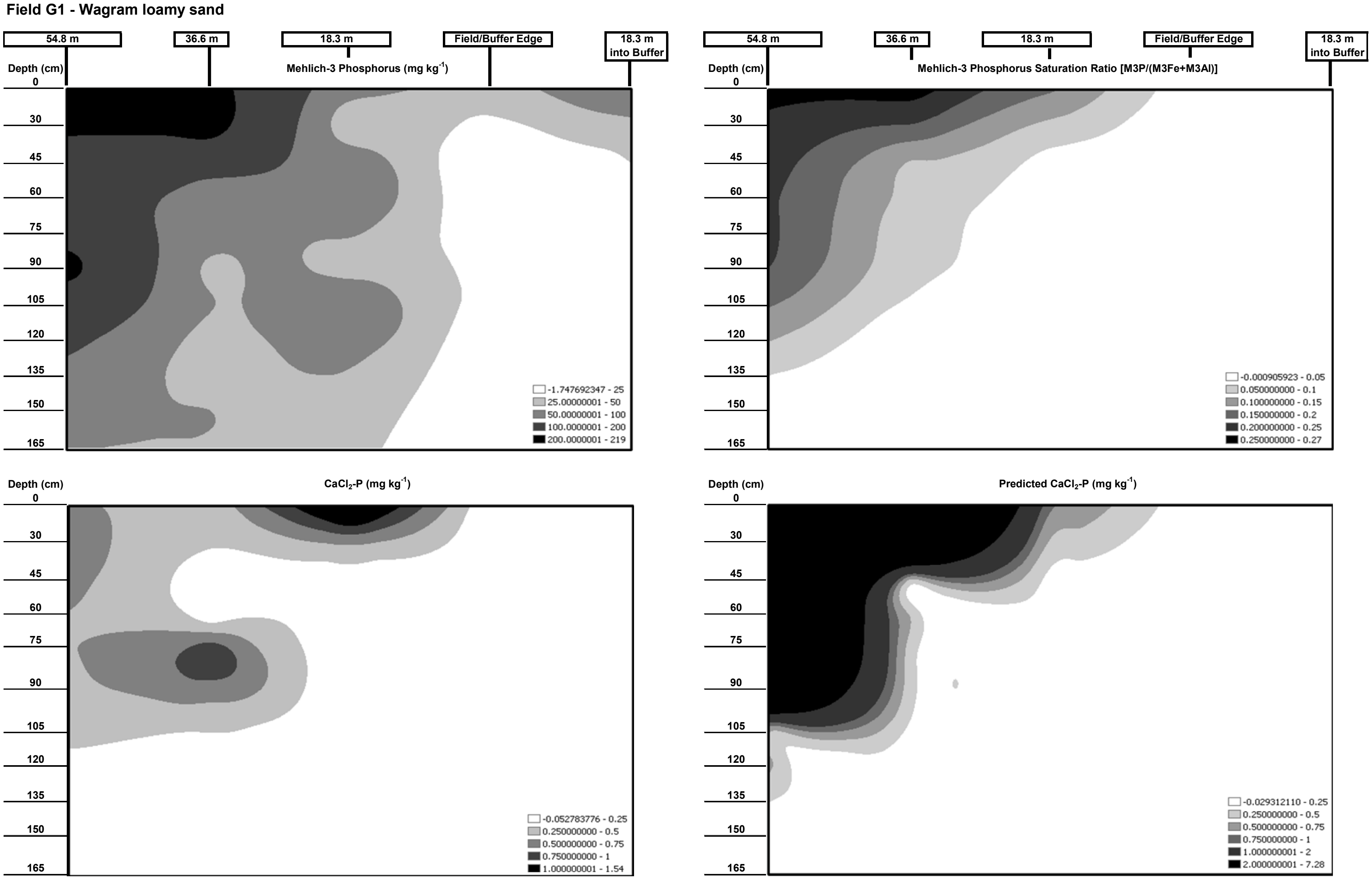

Figure 16. Spline interpolations for Mehlich-3 phosphorus and $CaCl_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted $CaCl_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Well drained Wagram loamy sand located on Farm G1.

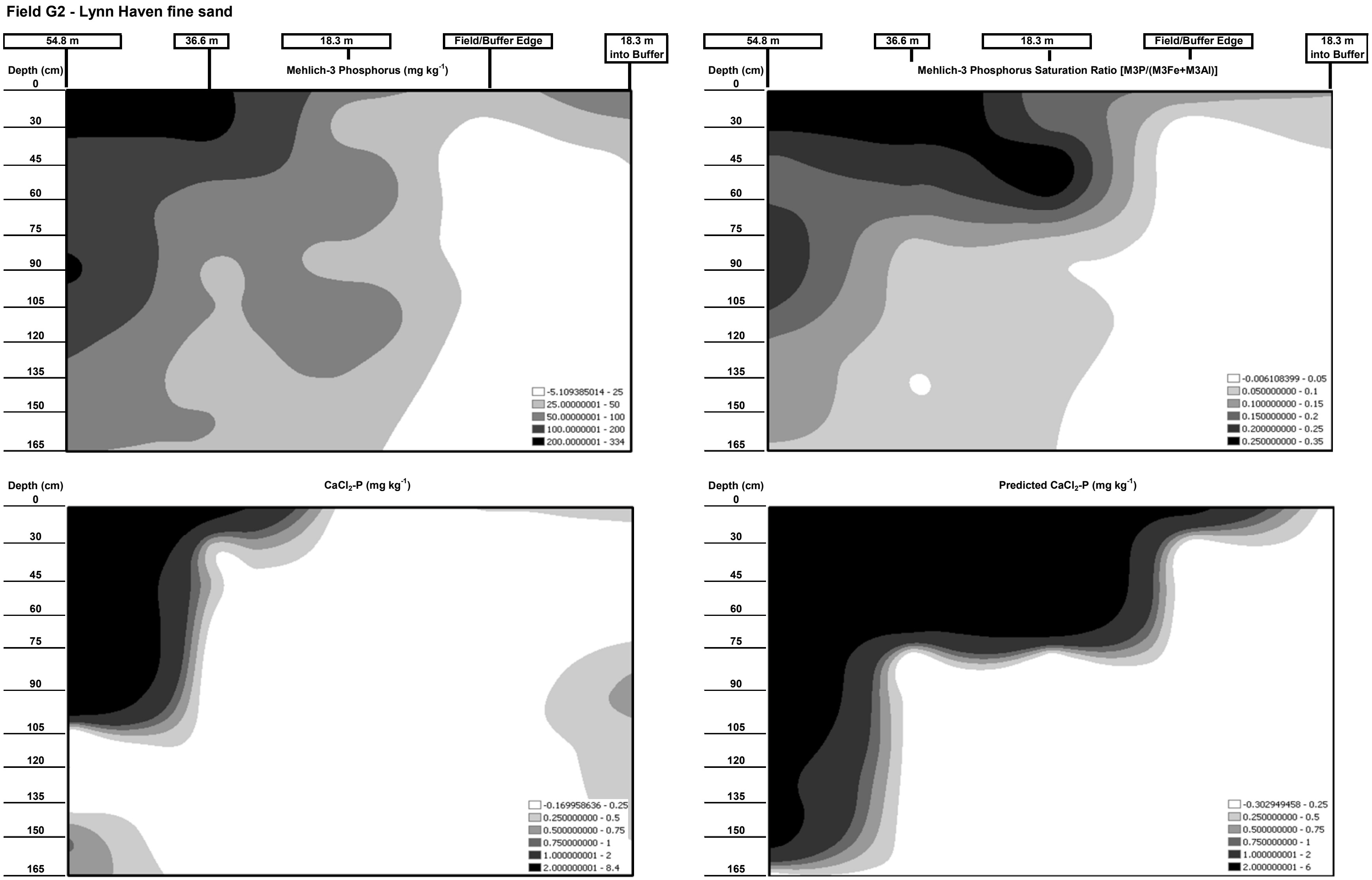

Figure 17. Spline interpolations for Mehlich-3 phosphorus and $CaCl_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted $CaCl_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Poorly drained Lynn Haven fine sand located on Farm G2.

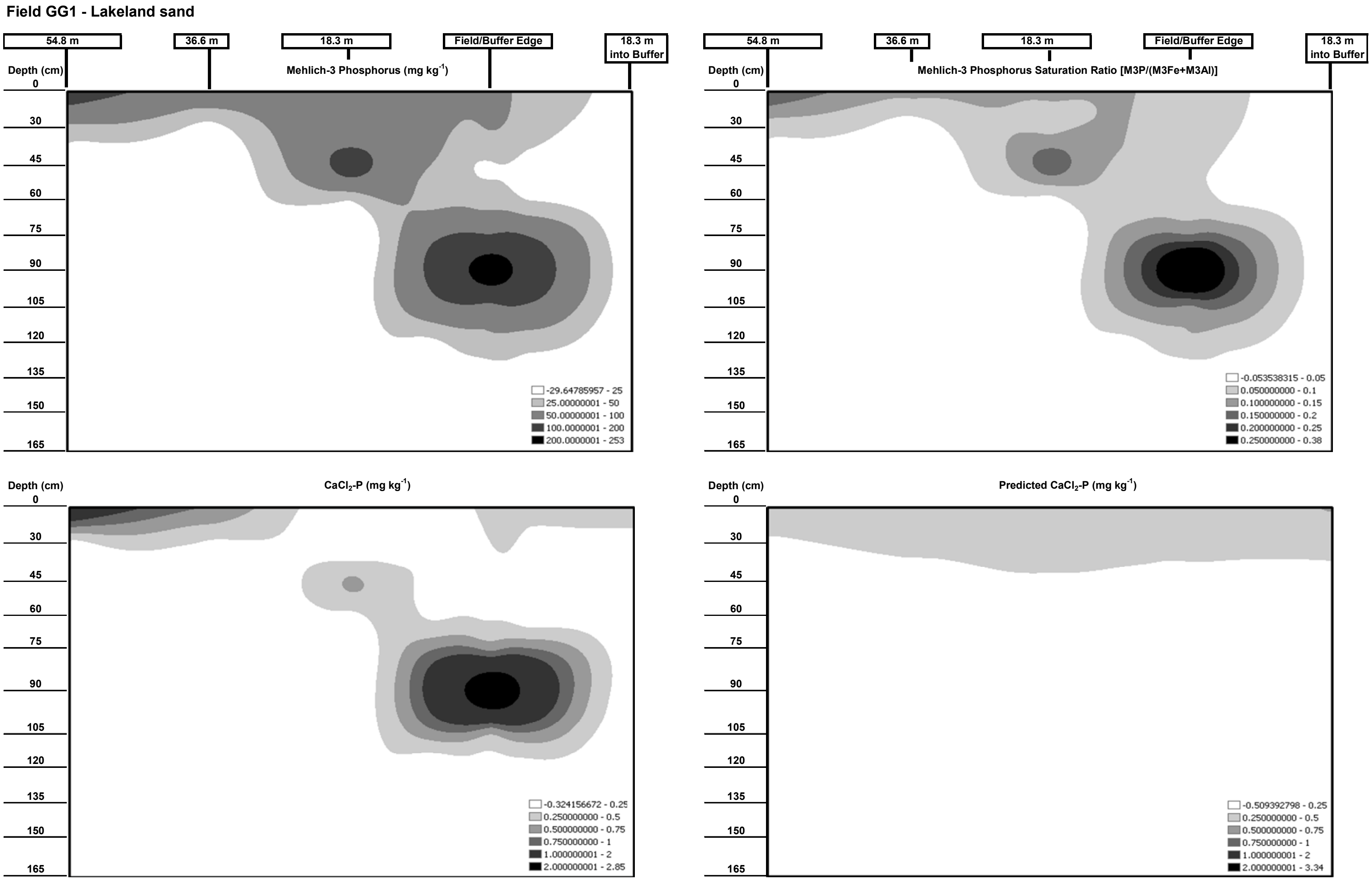

Figure 18. Spline interpolations for Mehlich-3 phosphorus and $CaCl_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted $CaCl_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Excessively Well drained Lakeland sand located on Farm GG1.

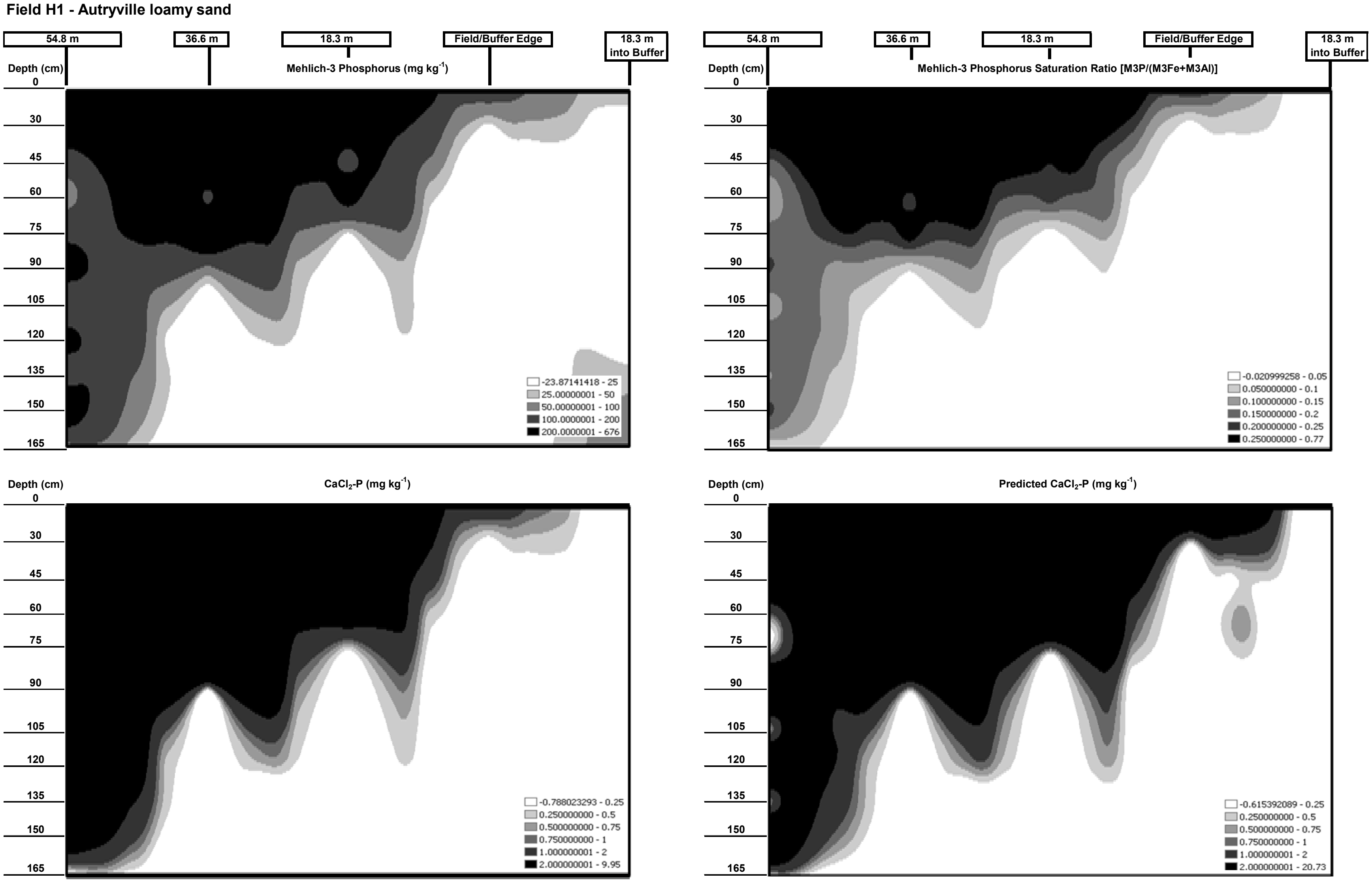

Figure 19. Spline interpolations for Mehlich-3 phosphorus and $CaCl_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted $CaCl_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Well drained Autryville loamy sand located on Farm H1.

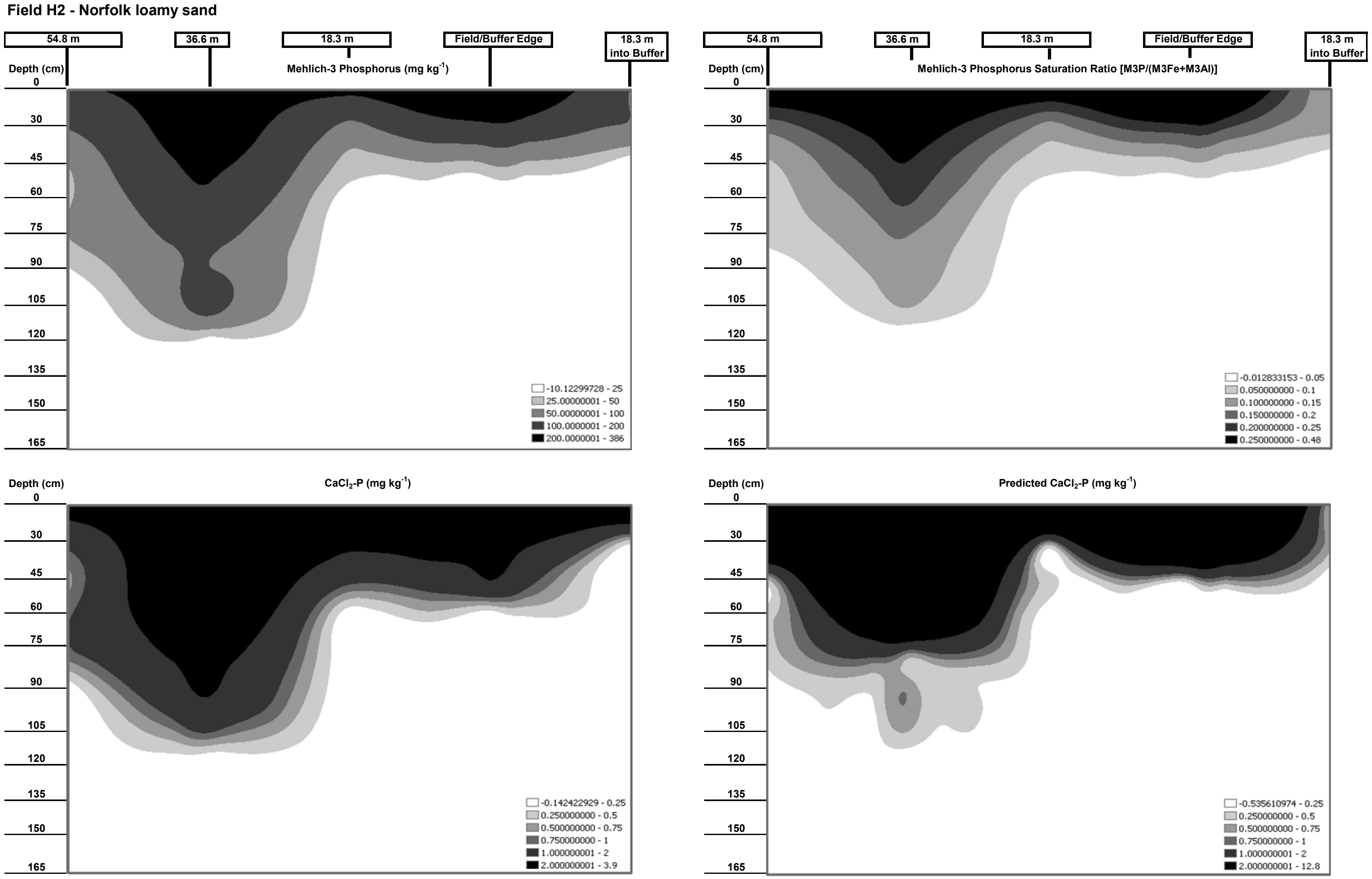

Figure 20. Spline interpolations for Mehlich-3 phosphorus and $CaCl_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted $CaCl_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Well drained Norfolk loamy sand located on Farm H2.

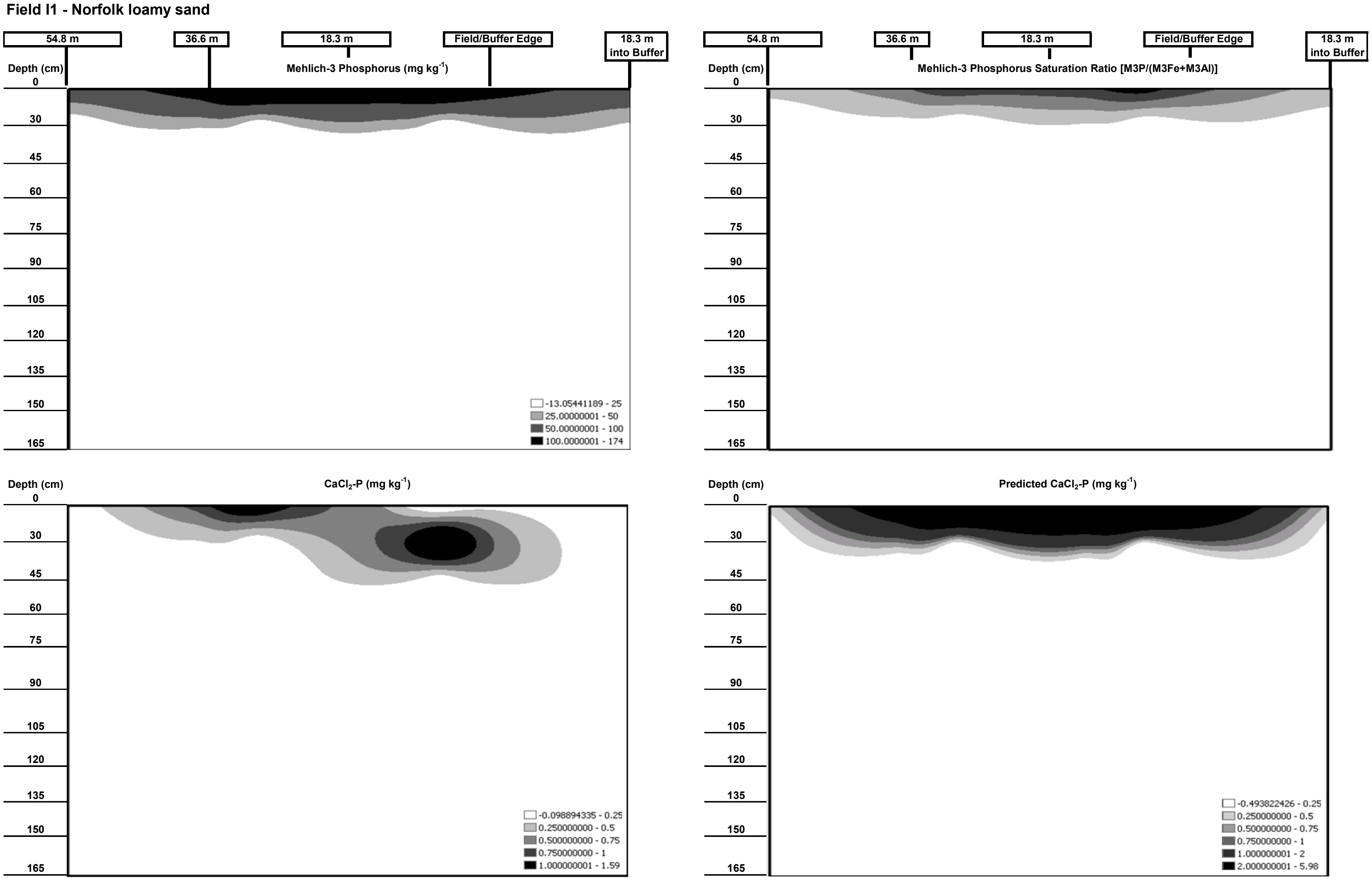

Figure 21. Spline interpolations for Mehlich-3 phosphorus and CaCl$_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted CaCl$_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Well drained Norfolk loamy sand located on Farm I1.

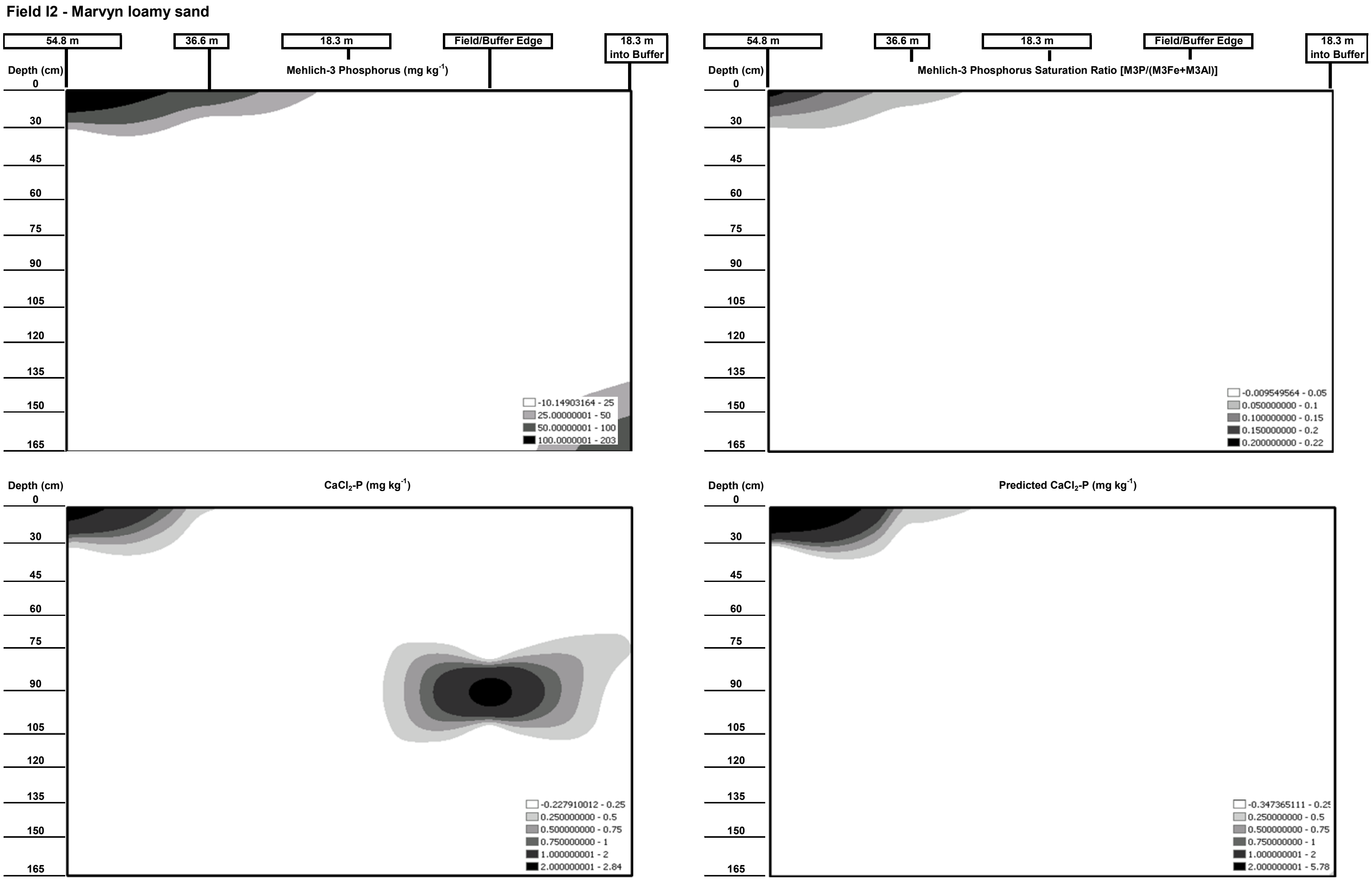

Figure 22. Spline interpolations for Mehlich-3 phosphorus and CaCl$_2$-P concentrations, Mehlich-3 phosphorus saturation ratios, and predicted CaCl$_2$-P concentrations distributions within the sampling grid by depth (0-168 cm) of the Well drained Marvyn loamy sand located on Farm I2.

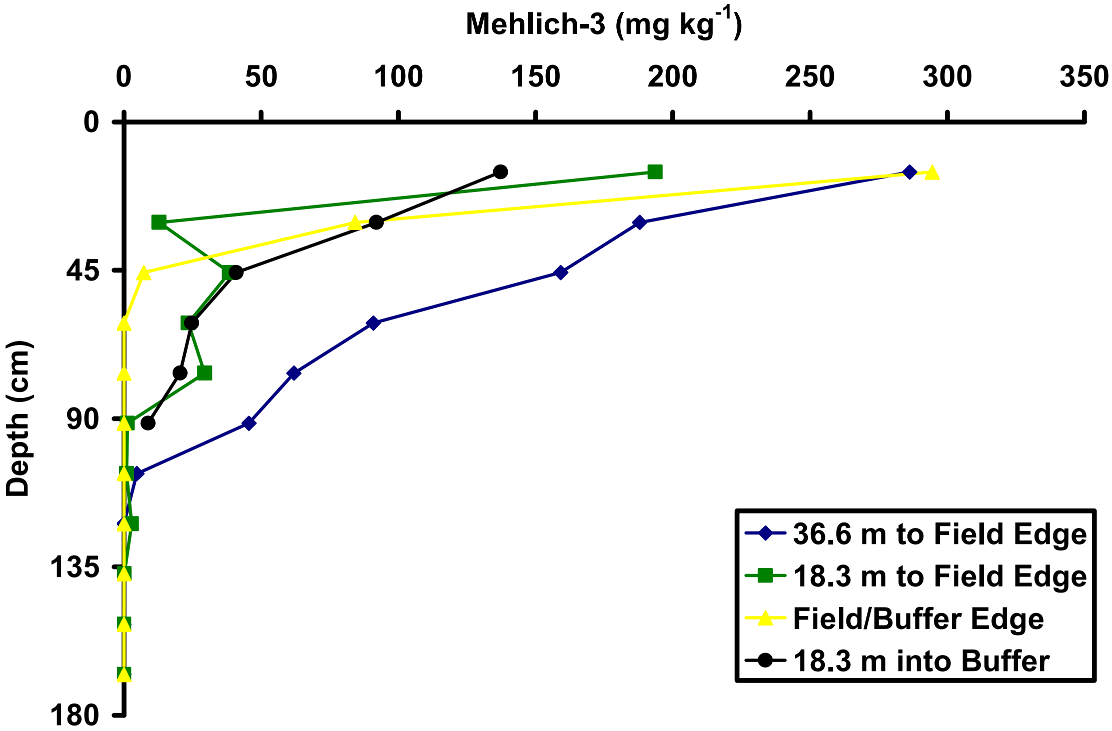

Figure 23. Site A1 Goldsboro series Mehlich-3 phosphorus distribution by depth for soil cores collected at 36.6 m and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

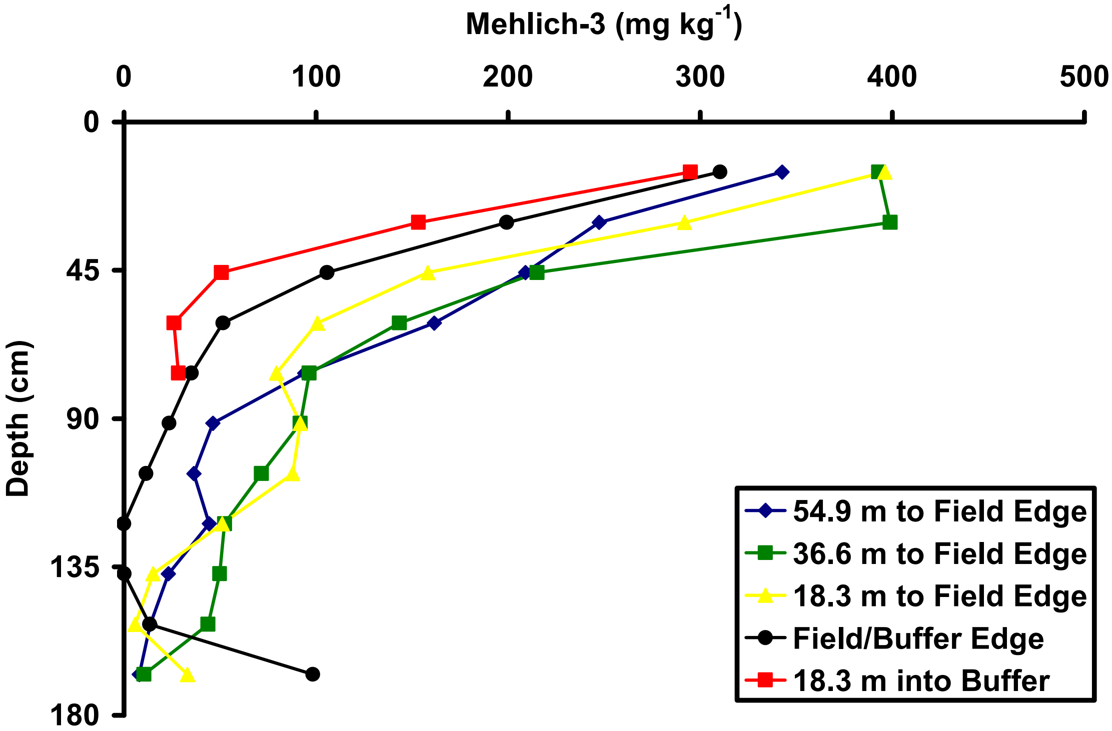

Figure 24. Site A2 Lynchburg series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

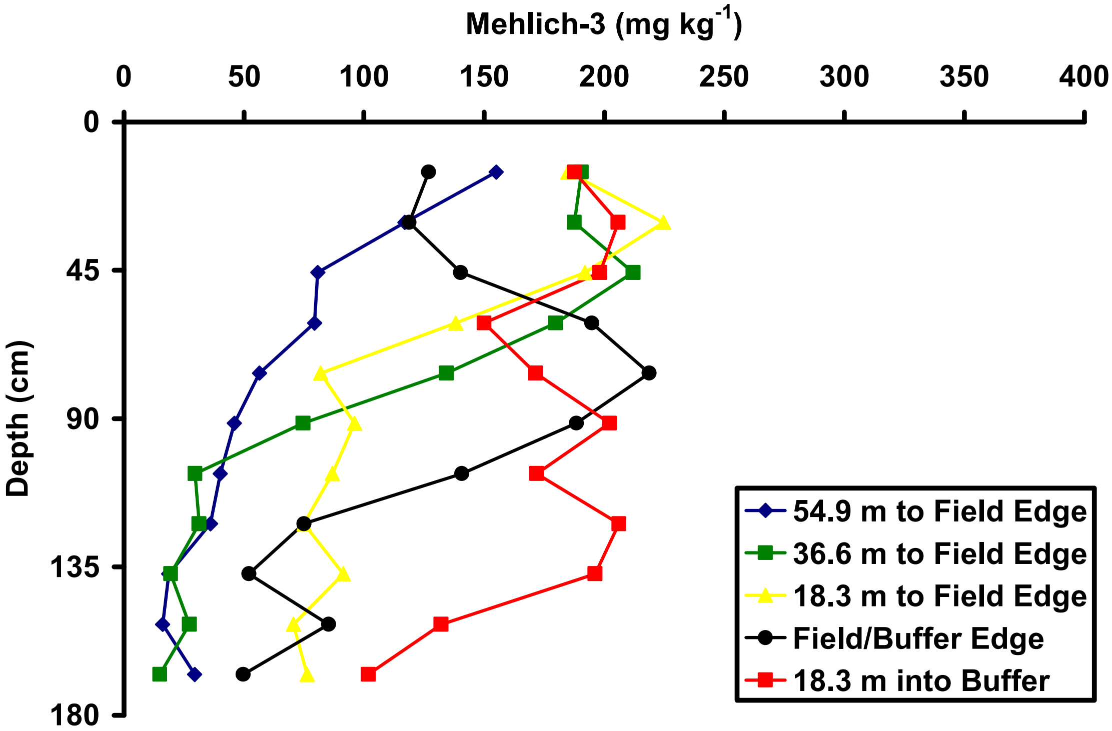

Figure 25. Site A3 Norfolk series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

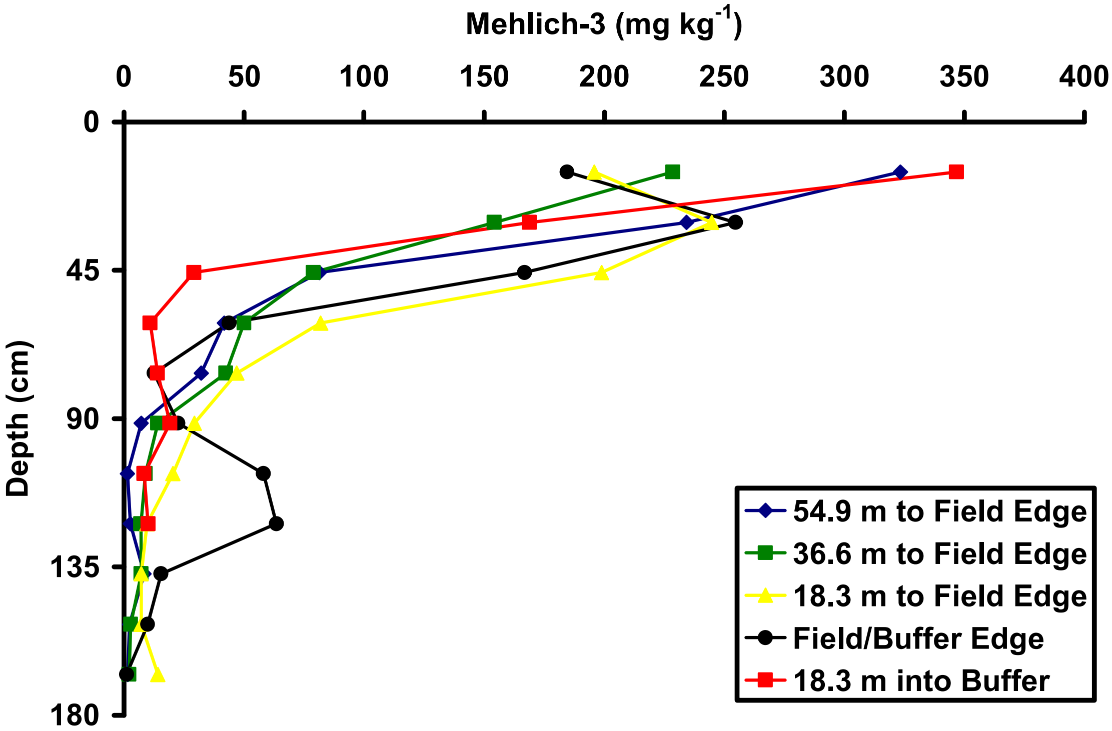

Figure 26. Site B1 Autryville series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

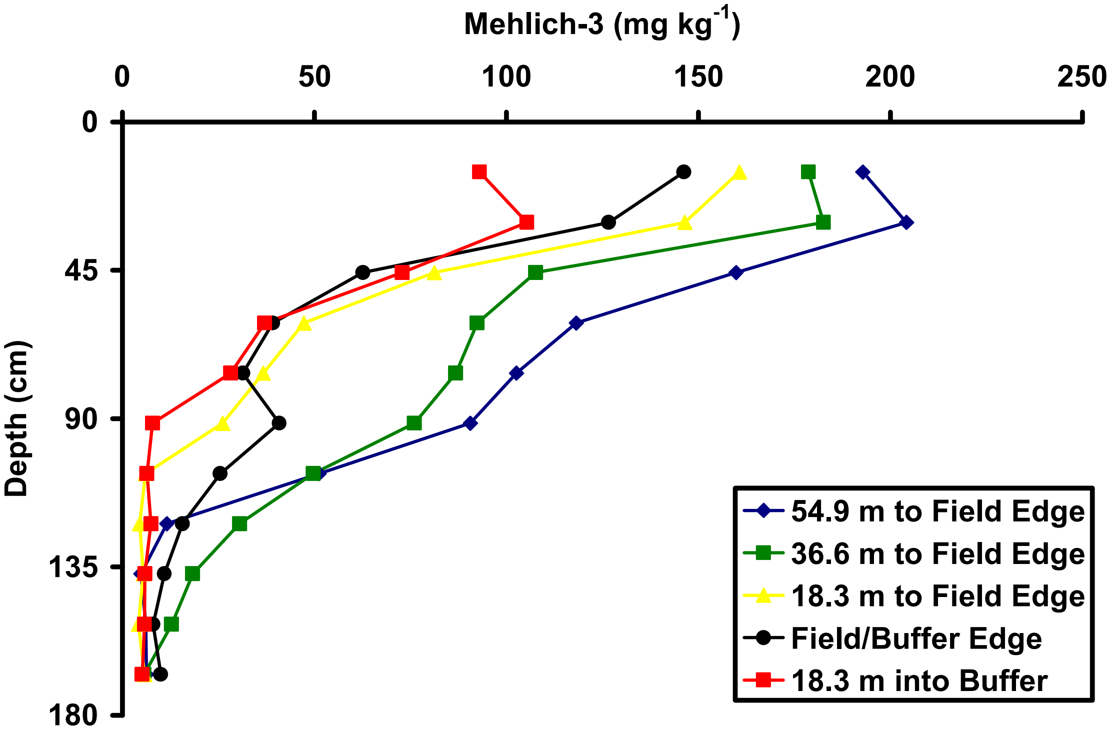

Figure 27. Site B2 Autryville series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

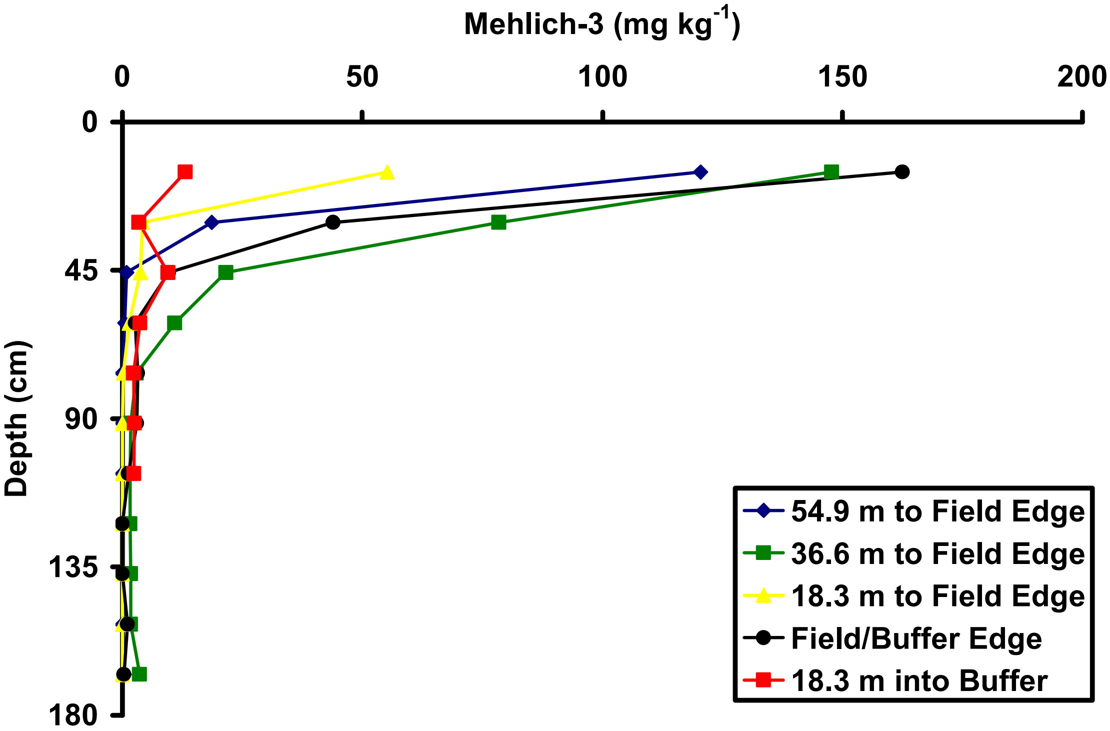

Figure 28. Site B3 Wagram series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

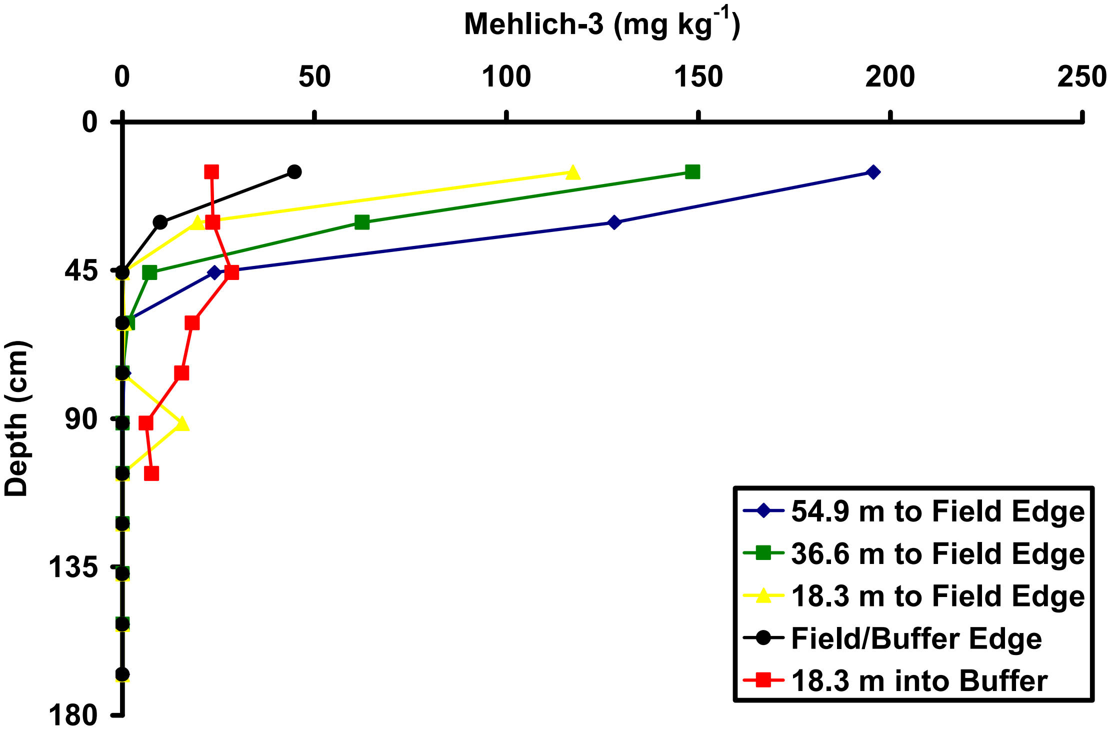

Figure 29. Site C1 Autryville series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

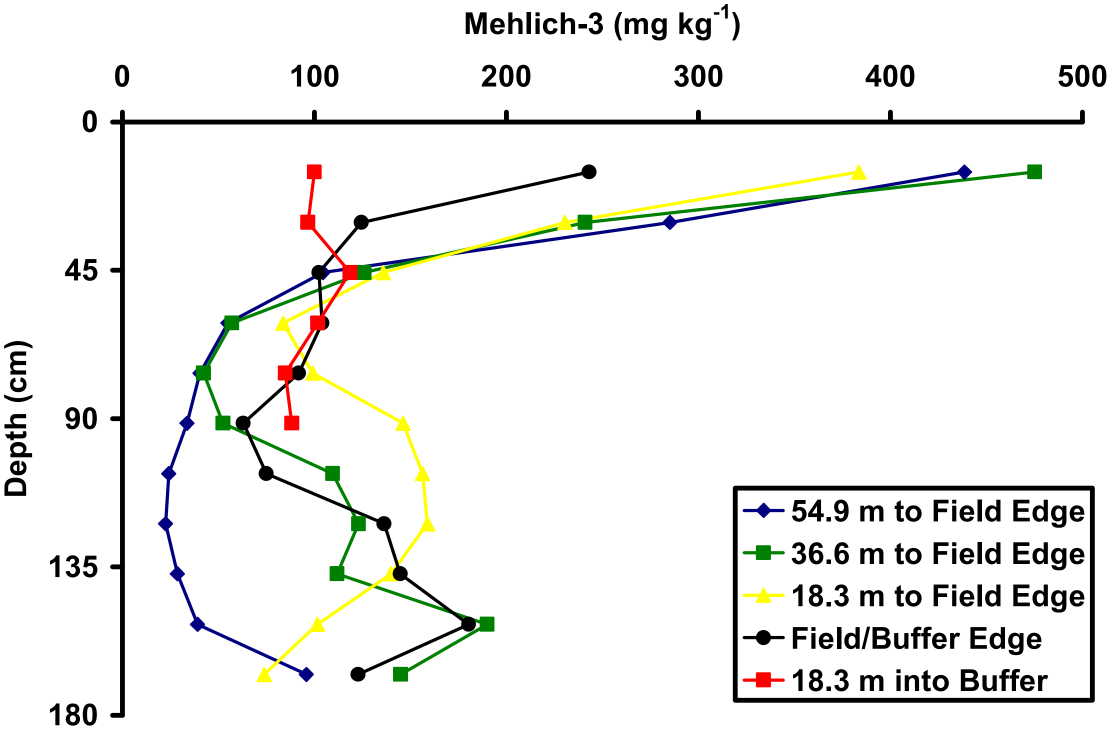

Figure 30. Site C2 Varina series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

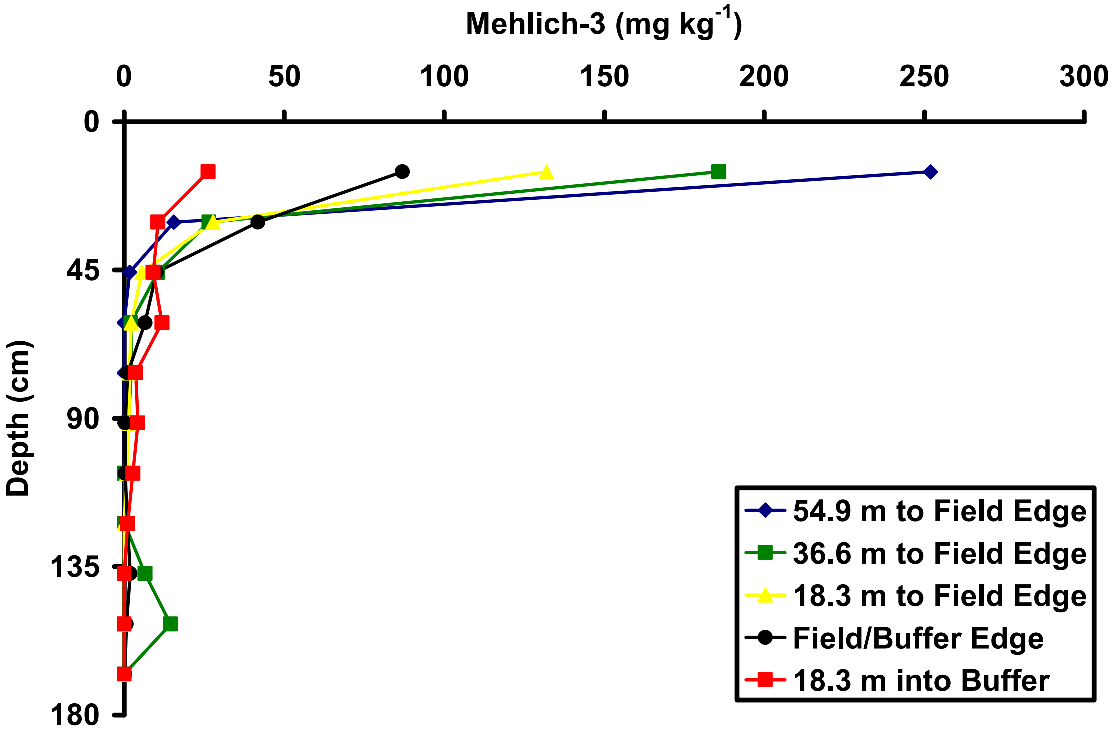

Figure 31. Site C3 Norfolk series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

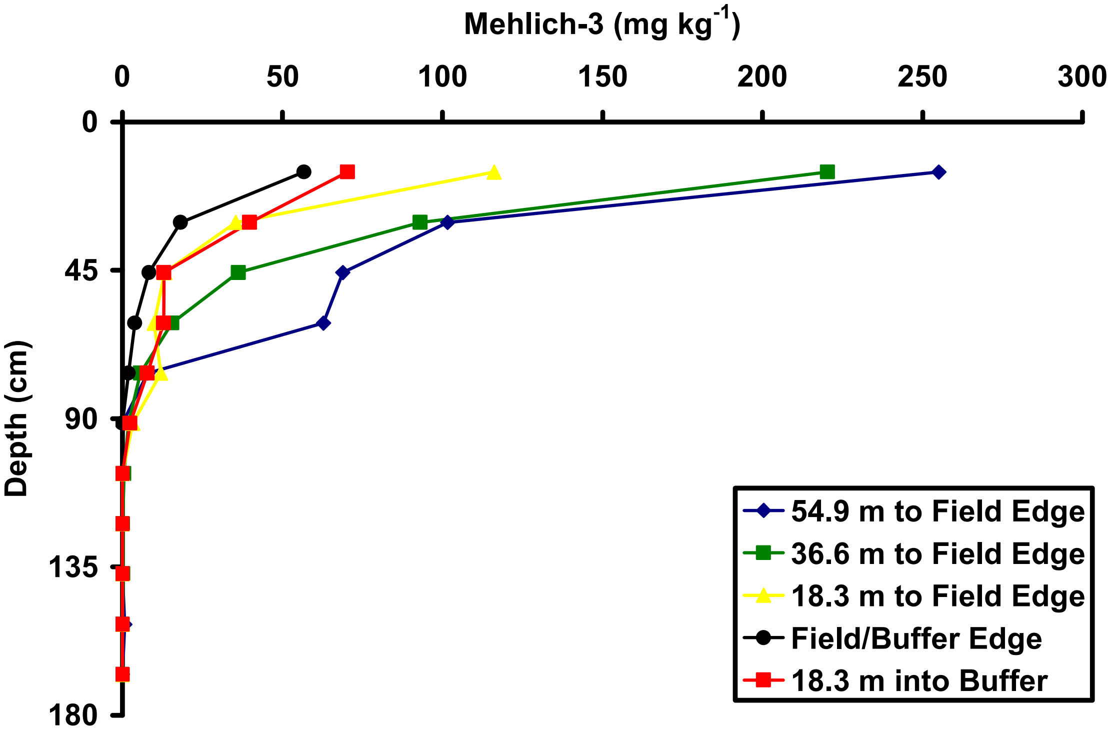

Figure 32. Site C4 Marvyn series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

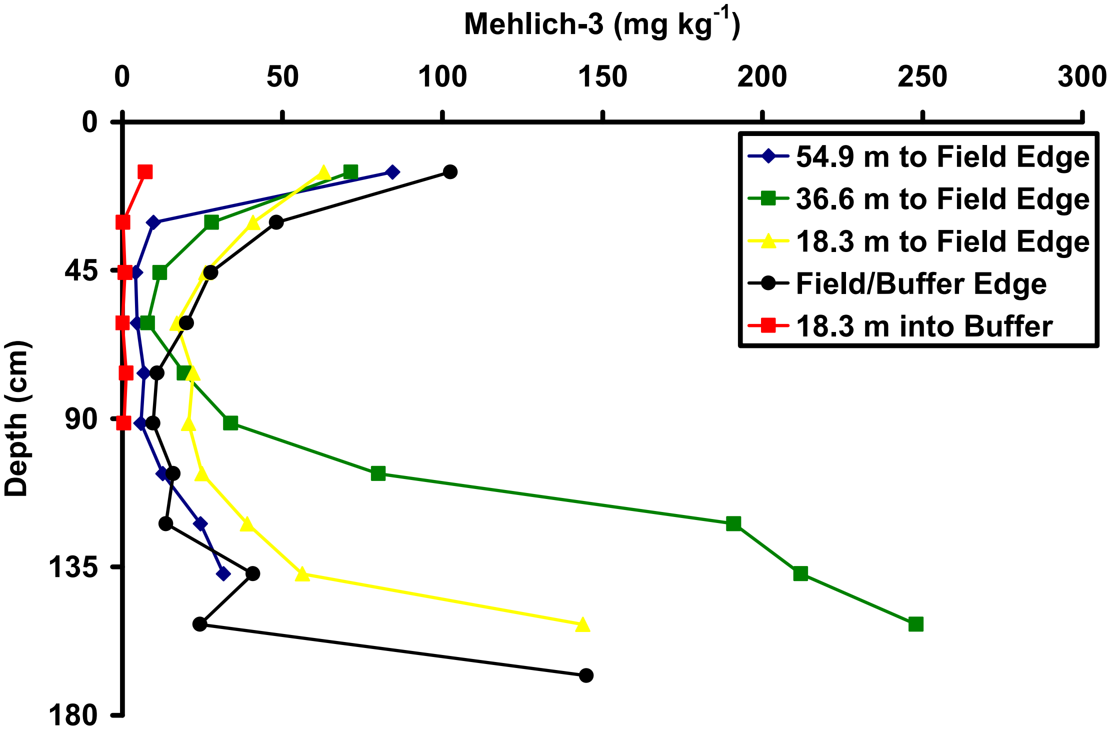

Figure 33. Site D1 Pantego series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

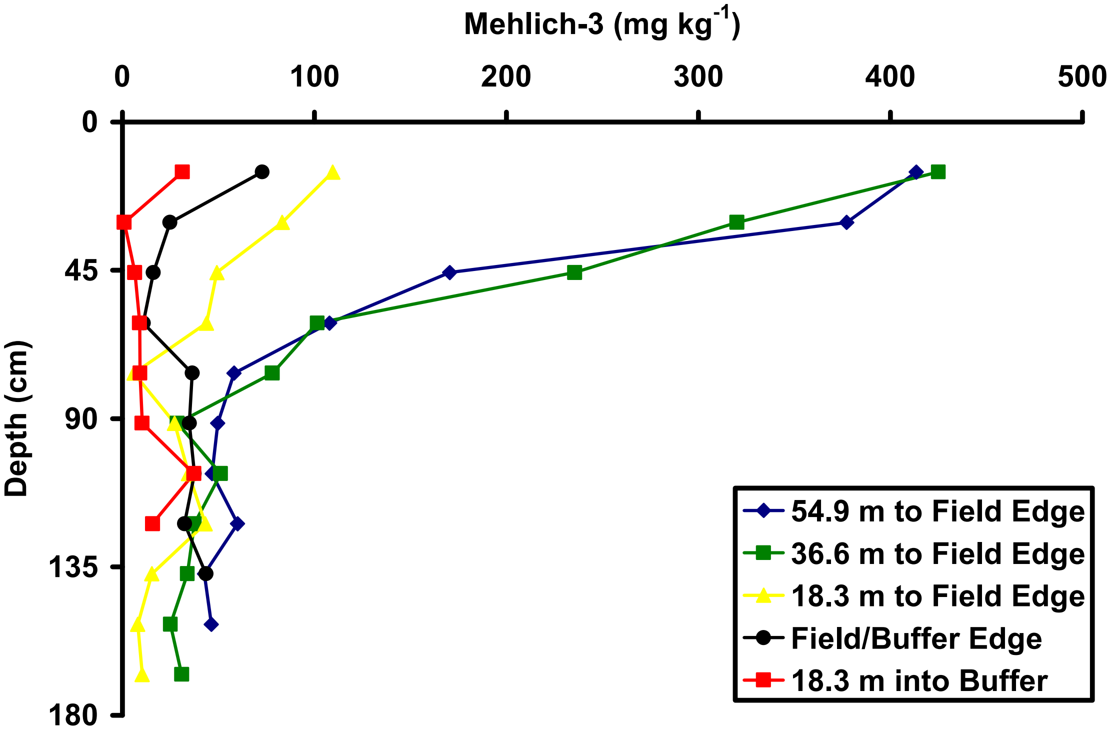

Figure 34. Site F1 Ocilla series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

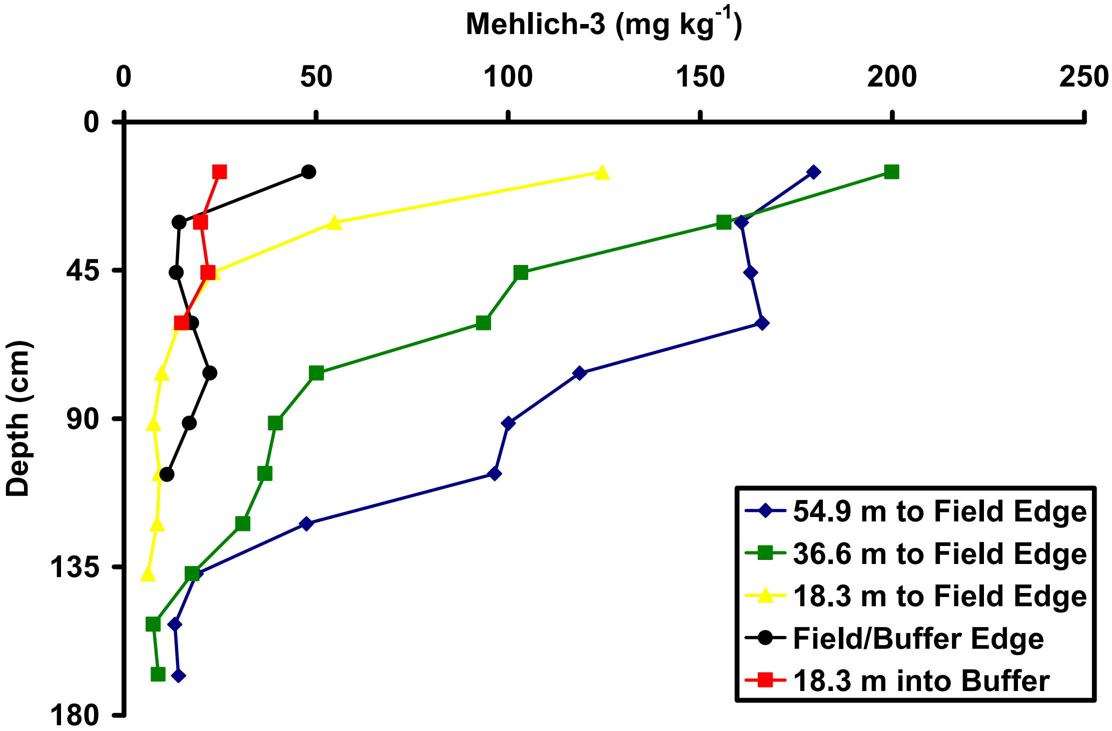

Figure 35. Site G1 Wagram series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

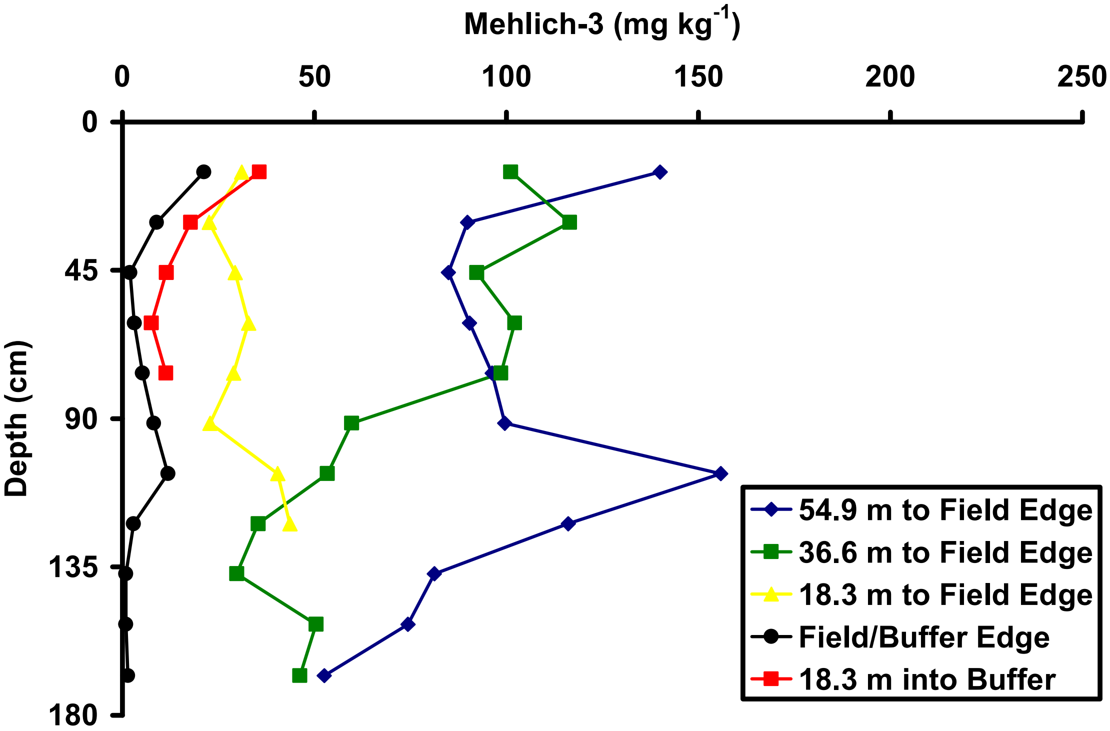

Figure 36. Site G2 Lynn Haven series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

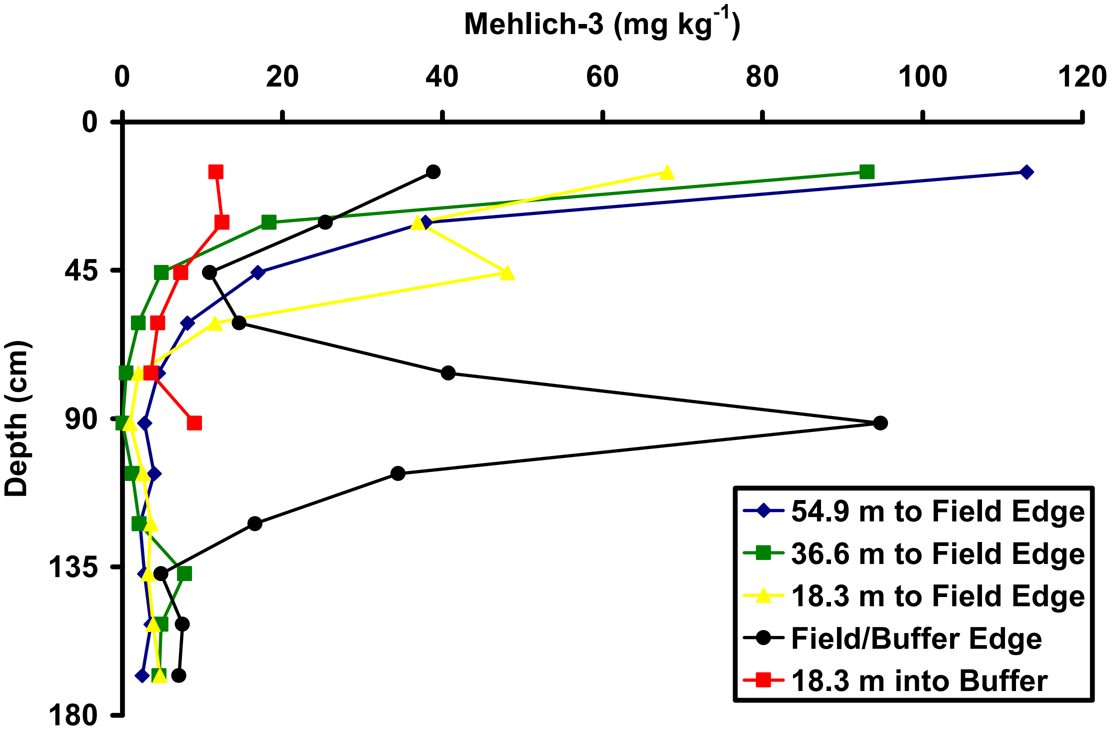

Figure 37. Site GG1 Lakeland series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

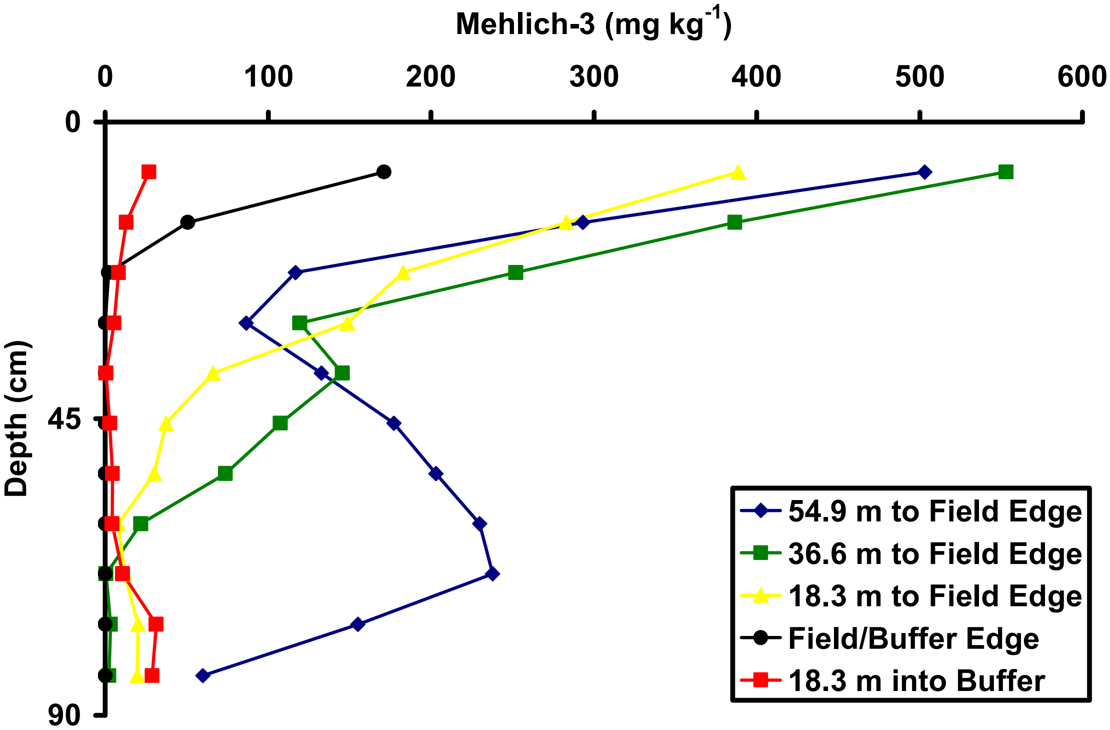

Figure 38. Site H1 Autryville series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

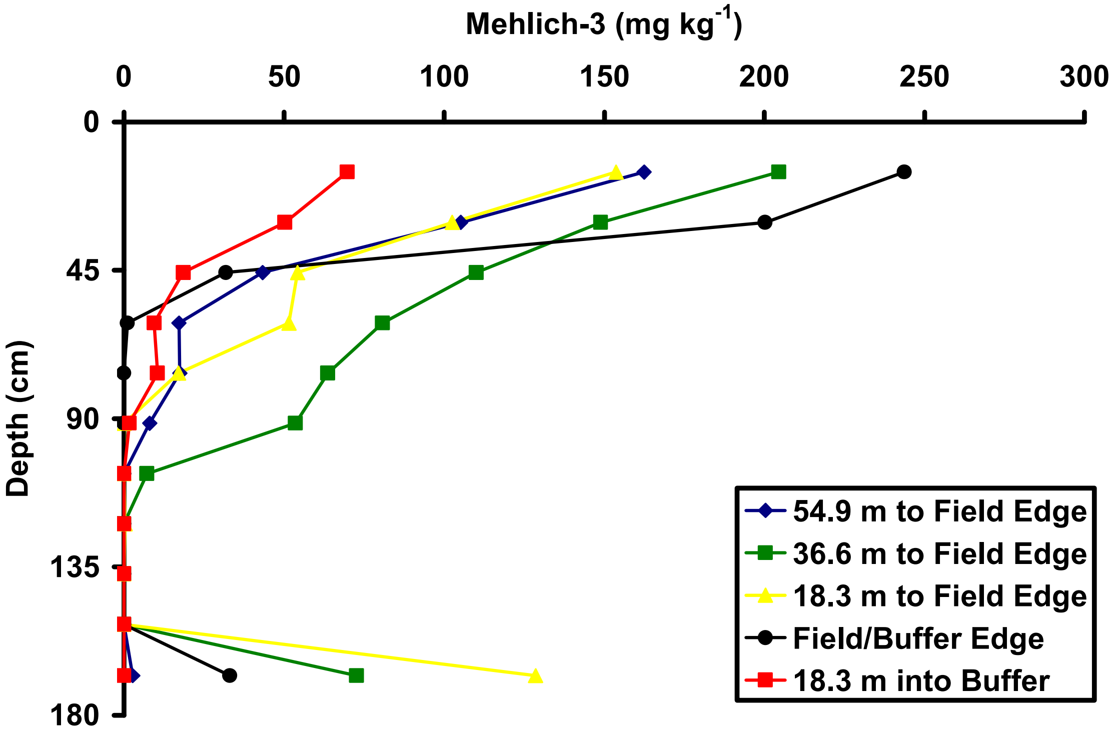

Figure 39. Site H2 Norfolk series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

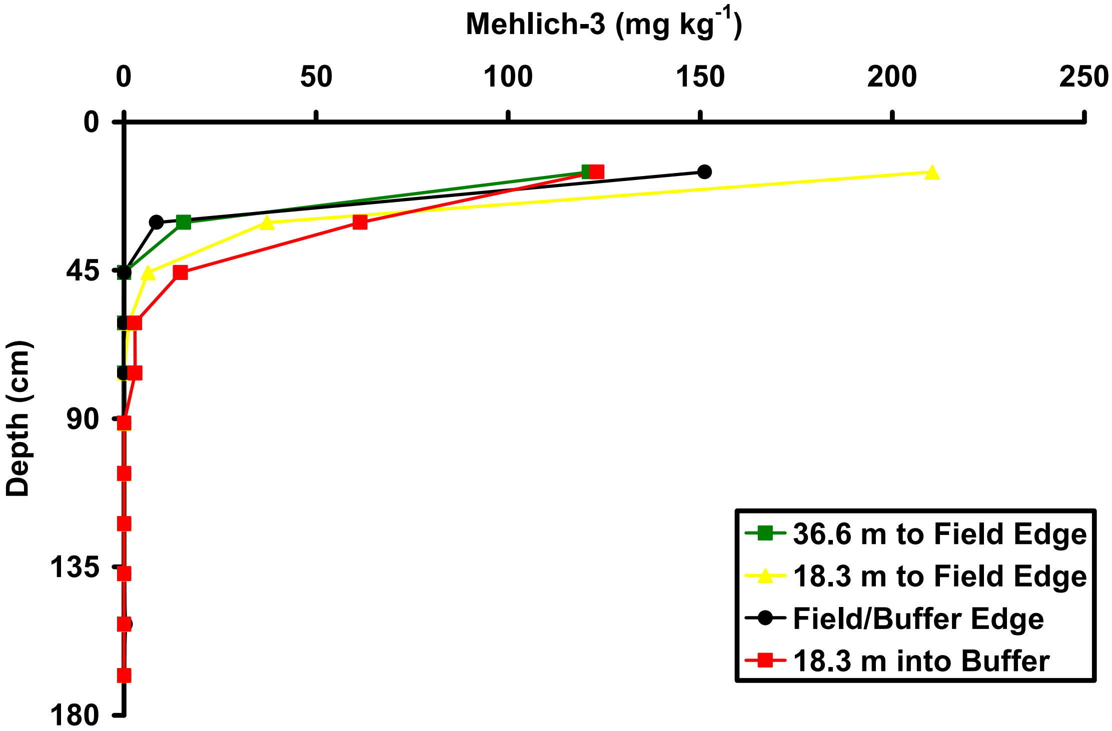

Figure 40. Site I1 Norfolk series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

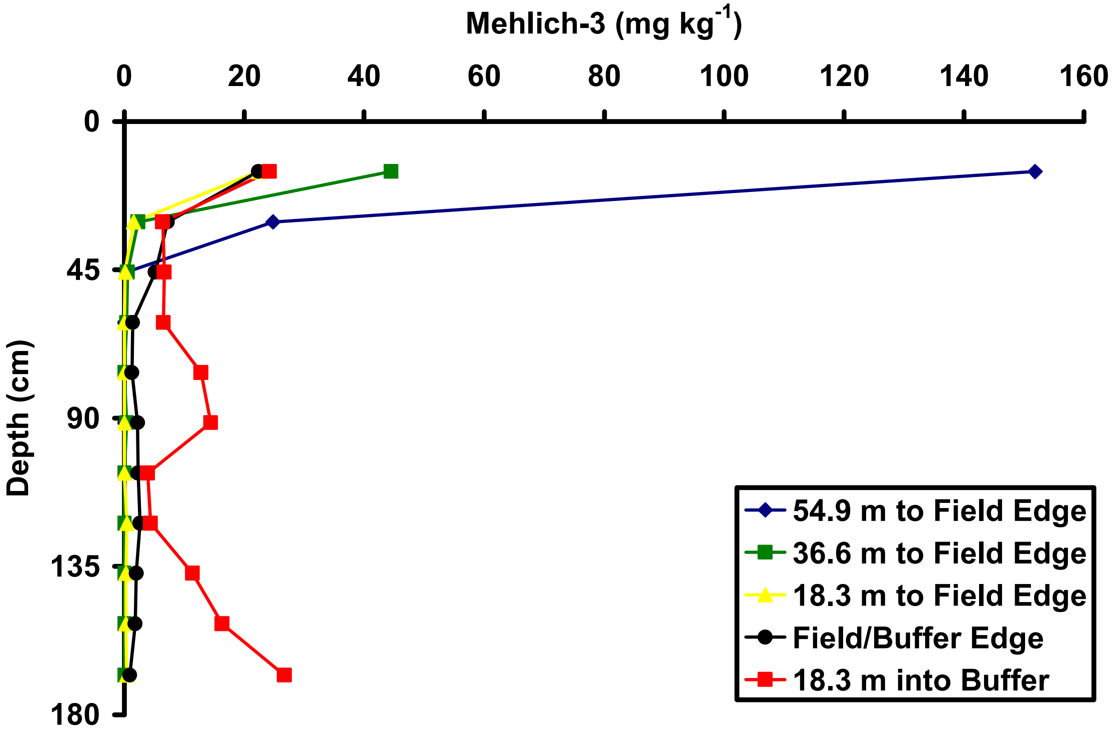

Figure 41. Site I2 Marvyn series Mehlich-3 phosphorus distribution by depth for soil cores collected at 54.9 m, 36.6 m, and 18.3 m from the field edge, at the field/buffer interface, and 18.3 m into the riparian buffer.

APPENDIX A

Table A-1. Analysis of variance of Mehlich-3 phosphorus distribution in the Goldsboro soil cores 1-5 collected from Site A1.

Depth (cm)	**Mehlich-3 P mg kg^{-1} Core 1**	**2**	**3**	**4^{buffer}**	**5**
15.2	286 a	196 a	294 a	137 a	-
30.5	259 a	66 b	133 b	81 a	-
47.8	159 ba	38 b	14 c	26 a	-
61.0	132 ba	18 b	0 c	38 a	-
76.2	88 b	8 b	0 c	10 a	-
91.4	36 b	1 b	0 c	9 a	-
106.7	5 b	3 b	0 c	-	-
122.0	0 b	1 b	1 c	-	-
137.2	0 b	0 b	0 c	-	-
152.4	0 b	0 b	0 c	-	-
167.8	0 b	0 b	0 c	-	-
LSD$_{\alpha=0.05}$	164	66	62	140	-

Table A-2. Analysis of variance of Mehlich-3 phosphorus concentrations in the Goldsboro series across soil cores 1-5 at each core sample depth collected at Site A1.

	Mehlich-3 P mg kg^{-1} Depth (cm)										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	286 a	259 a	159 a	132 a	88 a	36 a	5 a	0 a	0 a	0 a	0 a
2	196 a	66 b	38 a	18 ba	8 a	1 a	3 a	1 a	0 a	0 a	0 a
3	294 a	133 ba	14 a	0 b	0 a	0 a	0 a	1 a	0 a	0 a	0 a
4^{buffer}	137 a	81 b	26 a	38 ba	10 a	9 a	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-
LSD$_{\alpha=0.05}$	207	146	168	127	98	65	5	8	1	0	0

Table A-3. Analysis of variance of Mehlich-3 phosphorus distribution in the Lynchburg soil cores 1-5 collected from Site A2.

Depth cm	Mehlich-3 P $\mathrm{mg\ kg^{-1}}$ Core[a]				
	1	**2**	**3**	**4**	**5**
15.2	299 a	341 a	341 a	254 a	278 a
30.5	209 b	321 a	262 a	186 ba	141 ba
47.8	179 cb	174 b	139 b	93 bc	45 b
61.0	134 cd	116 cb	85 cb	46 c	24 b
76.2	86 ed	82 cb	75 cb	34 c	27 b
91.4	46 ef	80 cb	80 cb	21 c	-
106.7	36 ef	72 cb	76 cb	12 c	-
122.0	40 ef	53 c	47 cb	0 c	-
137.2	23 f	50 c	14 c	0 c	-
152.4	14 f	44 c	5 c	0 c	-
167.8	8 f	11 c	32 c	0 c	-
$\mathrm{LSD}_{\alpha=0.05}$	54	117	103	104	232

Table A-4. Analysis of variance of Mehlich-3 phosphorus concentrations in the Lynchburg series across soil cores 1-5 at each core sample depth collected at Site A2.

	Mehlich-3 P mg kg^{-1} Depth cm										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	299 a	209 a	179 a	134 a	86 a	46 ba	36 ba	40 a	23 ba	14 a	8 a
2	341 a	321 a	174 a	116 a	82 a	80 a	72 ba	53 a	50 a	44 a	11 a
3	341 a	262 a	139 ba	85 ba	75 ba	80 a	76 a	47 a	14 ba	5 a	32 a
4	254 a	186 a	93 ba	46 bc	34 bc	21 b	12 b	0 a	0 b	0 a	0 a
5	278 a	141 a	45 b	24 c	27 c	-	-	-	-	-	-
LSD$_{\alpha=0.05}$	287	197	105	57	46	44	63	53	36	54	80

Table A-5. Analysis of variance of Mehlich-3 phosphorus distribution in the Norfolk soil cores 1-5 collected from Site A3.

Depth cm	Mehlich-3 P mg kg^{-1} Core 1	2	3	4	5
15.2	155 a	191 ba	185 ba	127 edc	188 a
30.5	117 ba	189 ba	225 a	119 ed	206 a
47.8	81 ba	212 a	192 ba	140 bdc	198 a
61.0	79 ba	180 ba	139 ba	195 ba	150 a
76.2	57 ba	134 ba	82 b	219 a	171 a
91.4	46 b	75 ba	96 ba	188 bac	202 a
106.7	40 b	29 b	87 ba	141 bdc	172 a
122.0	36 b	31 ba	75 b	75 ef	206 a
137.2	19 b	19 b	91 ba	52 f	196 a
152.4	16 b	28 b	71 b	85 edf	132 a
167.8	30 b	15 b	77 b	50 f	102 a
LSD$_{\alpha=0.05}$	108	182	140	63	119

Table A-6. Analysis of variance of Mehlich-3 phosphorus concentrations in the Norfolk series across soil cores 1-5 at each core sample depth collected at Site A3.

	Mehlich-3 P **mg kg^{-1}** **Depth** **cm**										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	155 a	117 a	81 a	79 a	57 b	46 c	40 b	36 b	19 b	16 b	30 a
2	191 a	189 a	212 a	180 a	134 ba	75 c	29 b	31 b	19 b	28 ba	15 a
3	185 a	225 a	192 a	139 a	82 ba	96 bc	87 a	75 b	91 ba	71 ba	77 a
4	127 a	119 a	140 a	195 a	219 a	188 ab	141 a	75 b	52 b	85 ba	50 a
5	188 a	206 a	198 a	150 a	171 ba	202 a	172 a	206 a	196 a	132 a	102 a
LSD$_{\alpha=0.05}$	120	165	205	211	159	94	86	75	119	107	93

Table A-7. Analysis of variance of Mehlich-3 phosphorus distribution in the Autryville soil cores 1-5 collected from Site B1.

Depth (cm)	**Mehlich-3 P mg kg^{-1} Core 1**	**2**	**3**	**4**	**5**
15.2	323 a	229 a	196 a	255 a	347 a
30.5	234 b	154 b	245 a	185 a	169 ba
47.8	81 c	79 c	199 a	167 ba	29 ba
61.0	42 dc	50 dc	82 b	44 c	11 b
76.2	32 dc	42 dc	47 cb	13 c	14 b
91.4	7 dc	14 d	29 cb	23 c	19 b
106.7	3 d	9 d	20 cb	58 bc	8 b
122.0	1 d	7 d	9 c	64 bc	10 b
137.2	8 dc	7 d	7 c	15 c	-
152.4	3 d	3 d	7 c	10 c	-
167.8	2 d	2 d	14 c	1 c	-
LSD$_{\alpha=0.05}$	74	53	63	117	321

Table A-8. Analysis of variance of Mehlich-3 phosphorus concentrations in the Autryville series across soil cores 1-5 at each core sample depth collected at Site B1.

	Mehlich-3 P **mg kg^{-1}** **Depth** **(cm)**										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	323 a	234 a	81 bc	42 ba	32 ba	7 a	3 a	1 a	8 a	3 a	2 ba
2	229 a	154 a	79 bc	50 ba	42 a	14 a	9 a	7 a	7 a	3 a	2 ba
3	196 a	245 a	199 a	82 a	47 a	29 a	20 a	9 a	7 a	7 a	14 a
4	255 a	185 a	167 ba	44 ba	13 b	23 a	58 a	64 a	15 a	10 a	1 b
5	347 a	169 a	29 c	11 b	14 b	19 a	8 a	10 a	-	-	-
LSD$_{\alpha=0.05}$	294	134	114	44	28	36	113	123	27	17	12

Table A-9. Analysis of variance of Mehlich-3 phosphorus distribution in the Autryville soil cores 1-5 collected from Site B2.

	Mehlich-3 P mg kg^{-1} Core				
Depth (cm)	**1**	**2**	**3**	**4**	**5**
15.2	193 a	179 a	160 a	146 a	93 ba
30.5	204 a	182 a	146 a	127 a	105 a
47.8	160 ba	108 a	81 b	63 b	73 bac
61.0	118 bc	92 cb	47 c	49 b	37 bdc
76.2	103 c	87 cb	37 c	37 b	28 dc
91.4	91 dc	76 cbd	26 dc	41 b	8 d
106.7	51 de	50 ced	6 d	27 b	7 d
122.0	12 e	30 ed	5 d	16 b	8 d
137.2	5 e	18 e	5 d	10 b	6 d
152.4	6 e	13 e	4 d	8 b	6 d
167.8	6 e	6 e	6 d	10 b	5 d
LSD$_{\alpha=0.05}$	48	53	30	64	59

Table A-10. Analysis of variance of Mehlich-3 phosphorus concentrations in the Autryville series across soil cores 1-5 at each core sample depth collected at Site B2.

	Mehlich-3 P mg kg^{-1} Depth (cm)										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	193 a	204 a	160 a	118 a	103 a	91 a	51 a	12 a	5 a	6 a	6 a
2	179 a	182 a	108 ba	92 ba	87 ba	76 ba	50 a	30 a	18 a	13 a	6 a
3	160 ba	146 a	81 b	47 bc	37 bc	26 bc	6 a	5 a	5 a	4 a	6 a
4	146 ba	127 a	63 b	49 bc	37 bc	41 bac	27 a	16 a	10 a	8 a	10 a
5	93 b	105 a	73 b	37 c	28 c	8 c	7 a	8 a	6 a	6 a	5 a
$\text{LSD}_{\alpha=0.05}$	74	100	63	52	53	53	49	40	24	16	10

Table A-11. Analysis of variance of Mehlich-3 phosphorus distribution in the Wagram soil cores 1-5 collected from Site B3.

	Mehlich-3 P mg kg^{-1} Core				
Depth (cm)	**1**	**2**	**3**	**4**	**5**
15.2	121 a	148 a	55 a	163 a	13 a
30.5	19 b	78 b	4 b	44 b	10 ba
47.8	1 b	21 c	4 b	6 b	3 b
61.0	0 b	11 c	1 b	2 b	4 ba
76.2	0 b	3 c	0 c	3 b	3 b
91.4	0 b	2 c	0 c	3 b	3 b
106.7	0 b	2 c	0 c	1 b	2 b
122.0	0 b	2 c	0 c	0 b	-
137.2	0 b	2 c	0 c	0 b	-
152.4	0 b	2 c	0 c	1 b	-
167.8	0 b	4 c	0 c	0 b	-
LSD$_{\alpha=0.05}$	29	25	3	87	10

Table A-12. Analysis of variance of Mehlich-3 phosphorus concentrations in the Wagram series across soil cores 1-5 at each core sample depth collected at Site B3.

	Mehlich-3 P mg kg^{-1} Depth (cm)										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	121 ba	19 b	1 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 b
2	148 ba	78 a	21 a	11 a	3 a	2 a	2 a	2 a	2 a	2 a	4 a
3	55 ba	4 b	4 a	1 a	0 a	0 a	0 a	0 a	0 a	0 a	0 b
4	163 a	44 ba	6 a	2 a	3 a	3 a	1 a	0 a	0 a	1 a	0 b
5	13 b	10 b	3 a	4 a	3 a	3 a	2 a	-	-	-	-
LSD$_{\alpha=0.05}$	143	45	22	16	5	5	4	3	3	3	3

Table A-13. Analysis of variance of Mehlich-3 phosphorus distribution in the Autryville soil cores 1-5 collected from Site C1.

Depth (cm)	**Mehlich-3 P mg kg^{-1} Core 1**	**2**	**3**	**4**	**5**
15.2	196 ba	149 a	118 a	45 a	23 a
30.5	129 ba	63 b	20 b	10 a	24 a
47.8	24 ba	7 b	0 b	0 a	29 a
61.0	0 b	2 b	1 b	0 a	18 a
76.2	1 b	0 b	0 b	0 a	16 a
91.4	0 b	0 b	16 b	0 a	6 a
106.7	0 b	0 b	0 b	0 a	8 a
122.0	0 b	0 b	0 b	0 a	-
137.2	463 a	0 b	0 b	0 a	-
152.4	51 ba	0 b	0 b	0 a	-
167.8	91 ba	0 b	0 b	0 a	-
LSD$_{\alpha=0.05}$	447	71	20	54	67

Table A-14. Analysis of variance of Mehlich-3 phosphorus concentrations in the Autryville series across soil cores 1-5 at each core sample depth collected at Site C1.

						Mehlich-3 P mg kg^{-1} Depth (cm)					
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	196 a	129 a	24 a	0 a	1 b	0 a	0 b	0 a	463 a	51 a	91 a
2	149 a	63 ba	7 a	2 a	0 b	0 a	0 b	0 a	0 a	0 a	0 a
3	118 ba	20 ba	0 a	1 a	0 b	16 a	0 b	0 a	0 a	0 a	0 a
4	45 bc	10 b	0 a	0 a	0 b	0 a	0 b	0 a	0 a	0 a	0 a
5	23 c	24 ba	29 a	18 a	16 a	6 a	8 a	-	-	-	-
LSD$_{\alpha=0.05}$	86	110	47	26	3	33	0	0	1344	266	2111

Table A-15. Analysis of variance of Mehlich-3 phosphorus distribution in the Varina soil cores 1-5 collected from Site C2.

Depth (cm)	**Mehlich-3 P mg kg^{-1} Core 1**	**2**	**3**	**4**	**5**
15.2	438 a	475 a	383 a	243 a	100 a
30.5	285 b	241 b	231 b	125 bc	97 a
47.8	105 c	126 cd	136 cb	102 bc	119 a
61.0	55 dce	57 d	84 c	104 bc	102 a
76.2	41 dce	42 d	99 c	92 bc	85 a
91.4	34 de	53 d	146 cb	63 c	89 a
106.7	24 e	110 cd	156 cb	75 c	-
122.0	23 e	123 cd	159 cb	136 bc	-
137.2	29 de	112 cd	140 cb	145 bac	-
152.4	39 dce	190 cb	102 c	181 ba	-
167.8	96 dc	145 cbd	74 c	123 bc	-
LSD$_{\alpha=0.05}$	69	110	102	105	204

Table A-16. Analysis of variance of Mehlich-3 phosphorus concentrations in the Varina series across soil cores 1-5 at each core sample depth collected at Site C2.

	Mehlich-3 P mg kg^{-1} Depth (cm)										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	438 a	285 a	105 a	55 a	41 a	34 a	24 c	23 b	29 a	39 a	96 a
2	475 a	241 a	126 a	57 a	42 a	53 a	110 ba	123 ba	112 a	190 a	145 a
3	383 a	231 ba	136 a	84 a	99 a	146 a	156 a	159 a	140 a	102 a	74 a
4	243 b	125 bc	102 a	104 a	92 a	63 a	75 bc	136 ba	145 a	181 a	123 a
5	100 c	97 c	119 a	102 a	85 a	89 a	-	-	-	-	-
LSD$_{\alpha=0.05}$	103	107	116	100	101	132	54	114	139	187	78

Table A-17. Analysis of variance of Mehlich-3 phosphorus distribution in the Norfolk soil cores 1-5 collected from Site C3.

Depth (cm)	**Mehlich-3 P mg kg^{-1} Core 1**	**2**	**3**	**4**	**5**
15.2	252 a	186 a	132 a	87 a	26 a
30.5	16 b	26 b	28 b	42 b	11 ba
47.8	2 b	10 b	6 b	10 c	9 ba
61.0	0 b	2 b	2 b	6 c	12 ba
76.2	0 b	2 b	2 b	1 c	4 b
91.4	0 b	1 b	2 b	0 c	5 b
106.7	0 b	0 b	1 b	0 c	3 b
122.0	0 b	0 b	0 b	1 c	1 b
137.2	0 b	7 b	0 b	2 c	0 b
152.4	0 b	15 b	0 b	1 c	0 b
167.8	0 b	0 b	0 b	0 c	0 b
$LSD_{\alpha=0.05}$	26	41	47	29	19

Table A-18. Analysis of variance of Mehlich-3 phosphorus concentrations in the Norfolk series across soil cores 1-5 at each core sample depth collected at Site C3.

	Mehlich-3 P mg kg^{-1} Depth (cm)										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	252 a	16 a	2 a	0 a	0 a	0 b	0 a	0 a	0 a	0 a	0 a
2	186 ba	26 a	10 a	2 a	2 a	1 ba	0 a	0 a	7 a	15 a	0 a
3	132 b	28 a	6 a	2 a	2 a	2 ba	1 a	0 a	0 a	0 a	0 a
4	87 bc	42 a	10 a	6 a	1 a	0 b	0 a	1 a	2 a	1 a	0 a
5	26 c	11 a	9 a	12 a	4 a	5 a	3 a	1 a	0 a	0 a	0 a
LSD$_{\alpha=0.05}$	104	48	15	13	5	3	3	2	11	23	1

Table A-19. Analysis of variance of Mehlich-3 phosphorus distribution in the Marvyn soil cores 1-5 collected from Site C4.

	Mehlich-3 P				
	mg kg^{-1}				
Depth	**Core**				
(cm)	**1**	**2**	**3**	**4**	**5**
15.2	255 a	220 a	116 a	57 a	71 a
30.5	102 b	93 b	35 b	18 b	40 ba
47.8	69 cb	36 c	13 cb	8 b	13 b
61.0	63 cb	16 dc	10 cb	4 b	13 b
76.2	8 c	6 dc	12 cb	2 b	8 b
91.4	0 c	2 dc	3 c	0 b	2 b
106.7	0 c	1 dc	0 c	0 b	0 b
122.0	0 c	0 d	0 c	0 b	0 b
137.2	0 c	0 d	0 c	0 b	0 b
152.4	1 c	0 d	0 c	0 b	0 b
167.8	0 c	0 d	0 c	0 b	0 b
$LSD_{\alpha=0.05}$	87	36	26	24	42

Table A-20. Analysis of variance of Mehlich-3 phosphorus concentrations in the Marvyn series across soil cores 1-5 at each core sample depth collected at Site C4.

	Mehlich-3 P mg kg^{-1} Depth (cm)									
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	255 a	102 a	69 a	63 a	8 a	0 a	0 a	0 a	0 a	1 a	0 a
2	220 a	93 a	36 a	16 a	6 a	2 a	1 a	0 a	0 a	0 a	0 a
3	116 b	35 a	13 a	10 a	12 a	3 a	0 a	0 a	0 a	0 a	0 a
4	57 b	18 a	8 a	4 a	2 a	0 a	0 a	0 a	0 a	0 a	0 a
5	71 b	40 a	13 a	13 a	8 a	2 a	0 a	0 a	0 a	0 a	0 a
LSD$_{\alpha=0.05}$	78	84	88	85	21	6	1	0	1	1	0

Table A-21. Analysis of variance of Mehlich-3 phosphorus distribution in the Pantego soil cores 1-5 collected from Site D1.

Depth (cm)	**Mehlich-3 P $mg\ kg^{-1}$ Core 1**	**2**	**3**	**4**	**5**
15.2	84 a	71 dc	63 ba	103 ba	7 a
30.5	10 cb	28 dce	41 b	48 ba	0 b
47.8	4 c	12 e	26 b	28 b	1 b
61.0	5 c	8 e	17 b	20 b	0 b
76.2	7 cb	19 de	22 b	11 b	1 b
91.4	6 cb	34 dce	21 b	10 b	1 b
106.7	13 cb	80 c	25 b	16 b	-
122.0	25 cb	191 b	39 b	14 b	-
137.2	32 b	212 ba	56 b	41 ba	-
152.4	-	248 a	144 a	24 b	-
167.8	-	-	-	145 a	-
$LSD_{\alpha=0.05}$	27	56	83	108	5

Table A-22. Analysis of variance of Mehlich-3 phosphorus concentrations in the Pantego series across soil cores 1-5 at each core sample depth collected at Site D1.

	Mehlich-3 P mg kg^{-1} Depth (cm)									
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	84 a	10 a	4 a	5 bc	7 a	6 b	13 a	25 b	32 a	-	-
2	71 ba	28 a	12 a	8 bac	19 a	34 a	80 a	191 a	212 a	248 a	-
3	63 ba	41 a	26 a	17 ba	22 a	21 ba	25 a	39 b	56 a	144 a	-
4	103 a	48 a	28 a	20 a	11 a	10 b	16 a	14 b	41 a	24 a	145
5	7 b	0 a	1 a	0 c	1 a	1 b	-	-	-	-	-
LSD$_{\alpha=0.05}$	73	63	30	15	21	22	77	70	268	418	-

Table A-23. Analysis of variance of Mehlich-3 phosphorus distribution in the Ocilla soil cores 1-5 collected from Site F1.

Depth (cm)	**Mehlich-3 P mg kg^{-1} Core 1**	**2**	**3**	**4**	**5**
15.2	413 a	425 a	110 a	73 a	31 ba
30.5	377 a	320 a	83 ba	12 cbd	1 c
47.8	170 b	235 ba	49 bac	16 cd	7 bc
61.0	108 b	102 b	44 bc	11 d	9 bc
76.2	58 b	78 b	6 c	36 cb	14 bac
91.4	50 b	29 b	27 bc	36 cbd	16 bac
106.7	47 b	51 b	35 bc	37 cb	37 a
122.0	60 b	38 b	43 bc	33 cbd	16 bac
137.2	43 b	34 b	16 c	44 b	-
152.4	46 b	25 b	6 c	-	-
167.8	-	31 b	10 c	-	-
$LSD_{\alpha=0.05}$	158	215	62	25	26

Table A-24. Analysis of variance of Mehlich-3 phosphorus concentrations in the Ocilla series across soil cores 1-5 at each core sample depth collected at Site F1.

	Mehlich-3 P mg kg^{-1} Depth (cm)										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	413 a	377 a	170 ba	108 a	58 ba	50 a	47 a	60 a	43 a	46 a	-
2	425 a	320 a	235 a	102 ba	78 a	29 a	51 a	38 bac	34 a	25 a	31
3	110 b	83 b	49 ba	44 bc	6 c	27 a	35 a	43 ba	16 a	6 a	10
4	73 b	12 b	16 ba	11 c	36 bac	36 a	37 a	33 bc	44 a	-	-
5	31 b	1 b	7 b	9 c	14 bc	16 a	37 a	16 c	-	-	-
LSD$_{\alpha=0.05}$	169	171	222	63	50	50	32	24	31	59	-

Table A-25. Analysis of variance of Mehlich-3 phosphorus distribution in the Wagram soil cores 1-5 collected from Site G1.

Depth (cm)	**Mehlich-3 P mg kg^{-1} Core 1**	**2**	**3**	**4**	**5**
15.2	180 a	200 a	125 a	48 a	25 a
30.5	161 a	156 ba	55 b	15 b	20 a
47.8	163 a	104 bc	23 c	13 b	22 a
61.0	166 a	93 dc	14 dc	18 ba	15 a
76.2	119 b	50 dce	10 dc	23 ba	-
91.4	100 b	39 de	8 d	17 ba	-
106.7	87 cb	37 de	9 dc	11 b	-
122.0	47 cd	31 e	9 d	-	-
137.2	19 d	18 e	10 dc	-	-
152.4	13 d	8 e	-	-	-
167.8	19 d	9 e	-	-	-
LSD$_{\alpha=0.05}$	40	60	14	33	16

Table A-26. Analysis of variance of Mehlich-3 phosphorus concentrations in the Wagram series across soil cores 1-5 at each core sample depth collected at Site G1.

	Mehlich-3 P										
	mg kg^{-1}										
	Depth (cm)										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	180 a	161 a	163 a	166 a	119 a	100 a	87 a	47 a	19 a	13 a	19 a
2	200 a	156 a	104 b	93 b	50 b	39 b	37 ba	31 a	18 a	8 a	9 a
3	125 b	55 b	23 c	14 c	10 c	8 b	9 b	9 a	10 a	-	-
4	48 c	15 b	13 c	18 c	23 cb	17 b	11 b	-	-	-	-
5	25 c	20 b	22 c	15 c	-	-	-	-	-	-	-
LSD$_{\alpha=0.05}$	47	48	41	64	28	35	52	53	39	19	27

Table A-27. Analysis of variance of Mehlich-3 phosphorus distribution in the Lynn Haven soil cores 1-5 collected from Site G2.

Depth (cm)	**Mehlich-3 P mg kg^{-1} Core 1**	**2**	**3**	**4**	**5**
15.2	140 a	101 a	31 a	21 a	36 a
30.5	90 a	116 a	23 a	9 a	18 a
47.8	85 a	92 a	29 a	2 a	11 a
61.0	90 a	102 a	33 a	3 a	8 a
76.2	96 a	99 a	29 a	5 a	12 a
91.4	100 a	60 a	23 a	8 a	-
106.7	156 a	53 a	40 a	12 a	-
122.0	116 a	35 a	44 a	3 a	-
137.2	81 a	30 a	-	1 a	-
152.4	74 a	50 a	-	1 a	-
167.8	53 a	46 a	-	2 a	-
LSD$_{\alpha=0.05}$	261	207	54	20	44

Table A-28. Analysis of variance of Mehlich-3 phosphorus concentrations in the Lynn Haven series across soil cores 1-5 at each core sample depth collected at Site G2.

	Mehlich-3 P mg kg^{-1} Depth (cm)										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	140 a	90 a	85 a	90 ba	96 a	100 a	156 a	116 a	81	74	53
2	101 a	116 a	92 a	102 a	99 a	60 a	53 ba	35 a	30	50	46
3	31 a	23 a	29 ba	33 ba	29 a	23 a	40 ba	44 a	-	-	-
4	21 a	9 a	2 b	3 b	5 a	8 a	12 b	3 a	1	1	2
5	36 a	18 a	11 b	8 ba	12 a	-	-	-	-	-	-
LSD$_{\alpha=0.05}$	166	131	71	96	114	126	122	440	-	-	-

Table A-29. Analysis of variance of Mehlich-3 phosphorus distribution in the Lakeland soil cores 1-5 collected from Site GG1.

Depth (cm)	**Mehlich-3 P mg kg^{-1} Core 1**	**2**	**3**	**4**	**5**
15.2	113 a	93 a	68 a	39 ba	12 a
30.5	38 b	18 b	37 bac	25 ba	13 a
47.8	17 c	5 cb	48 ba	11 b	7 a
61.0	8 dc	2 c	12 bc	15 ba	4 a
76.2	4 dc	1 c	2 c	41 ba	4 a
91.4	3 dc	0 c	1 c	95 a	9 a
106.7	4 dc	1 c	3 c	35 ba	-
122.0	2 d	2 c	3 c	17 ba	-
137.2	3 dc	8 cb	3 c	5 b	-
152.4	4 dc	5 cb	4 c	7 b	-
167.8	2 d	5 cb	4 c	7 b	-
LSD$_{\alpha=0.05}$	15	15	39	82	22

Table A-30. Analysis of variance of Mehlich-3 phosphorus concentrations in the Lakeland series across soil cores 1-5 at each core sample depth collected at Site GG1.

	Mehlich-3 P mg kg^{-1} Depth (cm)										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	113 a	38 a	17 a	8 a	4 a	3 a	4 a	2 a	3 a	4 a	2 a
2	93 ba	18 a	5 a	2 a	1 a	0 a	1 a	2 a	8 a	5 a	5 a
3	68 bc	37 a	48 a	12 a	2 a	1 a	3 a	3 a	3 a	4 a	4 a
4	39 dc	25 a	11 a	15 a	41 a	95 a	35 a	17 a	5 a	7 a	7 a
5	12 d	13 a	7 a	4 a	4 a	9 a	-	-	-	-	-
LSD$_{\alpha=0.05}$	33	37	65	28	62	153	43	23	10	7	9

Table A-31. Analysis of variance of Mehlich-3 phosphorus distribution in the Autryville soil cores 1-5 collected from Site H1.

Depth (cm)	**Mehlich-3 P mg kg^{-1} Core 1**	**2**	**3**	**4**	**5**
15.2	503 a	553 a	388 a	171 a	27 bac
30.5	293 b	386 ba	283 ba	51 b	13 bac
47.8	117 fed	252 bc	183 bc	2 c	8 bac
61.0	86 fe	119 dc	149 dc	0 c	5 bac
76.2	133 cfed	146 dc	66 de	0 c	0 c
91.4	177 ced	108 dc	37 e	0 c	3 bc
106.7	203 cbd	74 d	30 e	0 c	4 bc
122.0	230 cb	22 d	8 e	0 c	4 bc
137.2	238 cb	1 d	12 e	0 c	11 bac
152.4	155 cfed	3 d	20 e	0 c	32 a
167.8	60 f	2 d	20 e	0 c	29 ba
LSD$_{\alpha=0.05}$	108	168	107	35	27

Table A-32. Analysis of variance of Mehlich-3 phosphorus concentrations in the Autryville series across soil cores 1-5 at each core sample depth collected at Site H1.

	Mehlich-3 P mg kg^{-1} Depth (cm)										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	503 ba	292 b	117 bc	86 bac	133 a	177 a	203 a	230 a	238 a	155 a	60 a
2	553 a	386 a	252 a	119 ba	146 a	108 ba	74 b	22 b	1 b	3 b	2 b
3	388 b	283 b	183 ba	149 a	66 a	37 b	30 b	8 b	12 b	20 b	20 ba
4	171 c	51 c	2 c	0 c	0 a	0 b	0 b	0 b	0 b	0 b	0 b
5	27 d	13 c	8 c	5 bc	0 a	3 b	4 b	4 b	11 b	32 b	29 ba
$\text{LSD}_{\alpha=0.05}$	144	87	115	117	163	122	125	35	104	106	51

Table A-33. Analysis of variance of Mehlich-3 phosphorus distribution in the Norfolk soil cores 1-5 collected from Site H2.

Depth (cm)	**Mehlich-3 P mg kg^{-1} Core 1**	**2**	**3**	**4**	**5**
15.2	162 a	193 a	199 a	313 a	70 a
30.5	105 b	168 a	116 b	241 b	50 a
47.8	43 c	124 ba	63 c	51 c	19 b
61.0	17 dc	101 bac	56 c	1 d	9 b
76.2	17 dc	71 bdc	17 d	0 d	10 b
91.4	8 d	43 bdc	0 d	0 d	2 b
106.7	0 d	45 bdc	0 d	0 d	0 b
122.0	0 d	6 dc	0 d	0 d	0 b
137.2	0 d	0 d	0 d	0 d	0 b
152.4	0 d	0 d	0 d	0 d	0 b
167.8	3 d	0 d	0 d	0 d	0 b
LSD$_{\alpha=0.05}$	28	97	37	43	30

Table A-34. Analysis of variance of Mehlich-3 phosphorus concentrations in the Norfolk series across soil cores 1-5 at each core sample depth collected at Site H2.

	Mehlich-3 P mg kg^{-1} Depth (cm)										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	162 b	105 bc	43 b	17 b	17 b	8 ba	0 a	0 a	0 a	0 a	3 a
2	193 b	168 ba	124 a	101 a	71 a	43 a	45 a	6 a	0 a	0 a	0 a
3	199 b	116 bc	63 ba	56 ba	17 b	0 b	0 a	0 a	0 a	0 a	0 a
4	313 a	241 a	51 ba	1 b	0 b	0 b	0 a	0 a	0 a	0 a	0 a
5	70 c	50 c	19 b	9 b	10 b	2 ba	0 a	0 a	0 a	0 a	0 a
LSD$_{\alpha=0.05}$	79	102	76	72	50	43	60	8	0	0	0

Table A-35. Analysis of variance of Mehlich-3 phosphorus distribution in the Norfolk soil cores 1-5 collected from Site I1.

	Mehlich-3 P mg kg^{-1} Core				
Depth (cm)	**1**	**2**	**3**	**4^{buffer}**	**5**
15.2	121 a	210 a	151 a	123 a	-
30.5	16 b	37 b	8 b	61 b	-
47.8	0 b	6 b	0 b	15 cb	-
61.0	0 b	1 b	0 b	3 c	-
76.2	0 b	0 b	0 b	3 c	-
91.4	0 b	0 b	0 b	0 c	-
106.7	0 b	0 b	0 b	0 c	-
122.0	0 b	0 b	0 b	0 c	-
137.2	0 b	0 b	0 b	0 c	-
152.4	0 b	0 b	0 b	0 c	-
167.8	0 b	0 b	0 b	0 c	-
LSD$_{\alpha=0.05}$	28	69	18	48	-

Table A-36. Analysis of variance of Mehlich-3 phosphorus concentrations in the Norfolk series across soil cores 1-5 at each core sample depth collected at Site I1.

	Mehlich-3 P mg kg^{-1} Depth (cm)										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	121 a	16 a	0 b	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a
2	210 a	37 a	6 ba	1 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a
3	151 a	8 a	0 b	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a
4$^{\text{buffer}}$	123 a	61 a	15 a	3 a	3 a	0 a	0 a	0 a	0 a	0 a	0 a
5	-	-	-	-	-	-	-	-	-	-	-
LSD$_{\alpha=0.05}$	128	73	12	3	3	0	0	0	0	0	0

Table A-37. Analysis of variance of Mehlich-3 phosphorus distribution in the Marvyn soil cores 1-5 collected from Site I2.

Depth (cm)	**Mehlich-3 P mg kg^{-1} Core 1**	**2**	**3**	**4**	**5**
15.2	152 a	45 a	22 a	22 a	24 a
30.5	25 b	2 b	1 b	7 b	6 a
47.8	0 b	1 b	0 b	5 b	7 a
61.0	0 b	0 b	0 b	1 b	6 a
76.2	0 b	0 b	0 b	1 b	13 a
91.4	0 b	0 b	0 b	2 b	14 a
106.7	0 b	0 b	0 b	2 b	4 a
122.0	0 b	0 b	0 b	3 b	4 a
137.2	0 b	0 b	0 b	2 b	11 a
152.4	0 b	0 b	0 b	2 b	16 a
167.8	0 b	0 b	0 b	1 b	27 a
LSD$_{\alpha=0.05}$	50	16	8	7	30

Table A-38. Analysis of variance of Mehlich-3 phosphorus concentrations in the Marvyn series across soil cores 1-5 at each core sample depth collected at Site I2.

	Mehlich-3 P mg kg^{-1} Depth (cm)										
Core	**15.2**	**30.5**	**47.8**	**61.0**	**76.2**	**91.4**	**106.7**	**122.0**	**137.2**	**152.4**	**167.8**
1	152 a	25 a	0 b	0 b	0 b	0 b	0 a	0 a	0 b	0 a	0 a
2	45 b	2 b	1 b	0 b	0 b	0 b	0 a	0 a	0 b	0 a	0 a
3	22 b	1 b	0 b	0 b	0 b	0 b	0 a	0 a	0 b	0 a	0 a
4	22 b	7 b	5 a	1 b	1 b	2 b	2 a	3 a	2 ba	2 a	1 a
5	24 b	6 b	7 a	6 a	13 a	14 a	4 a	4 a	11 a	16 a	27 a
LSD$_{\alpha=0.05}$	83	17	4	5	7	6	5	6	10	23	38

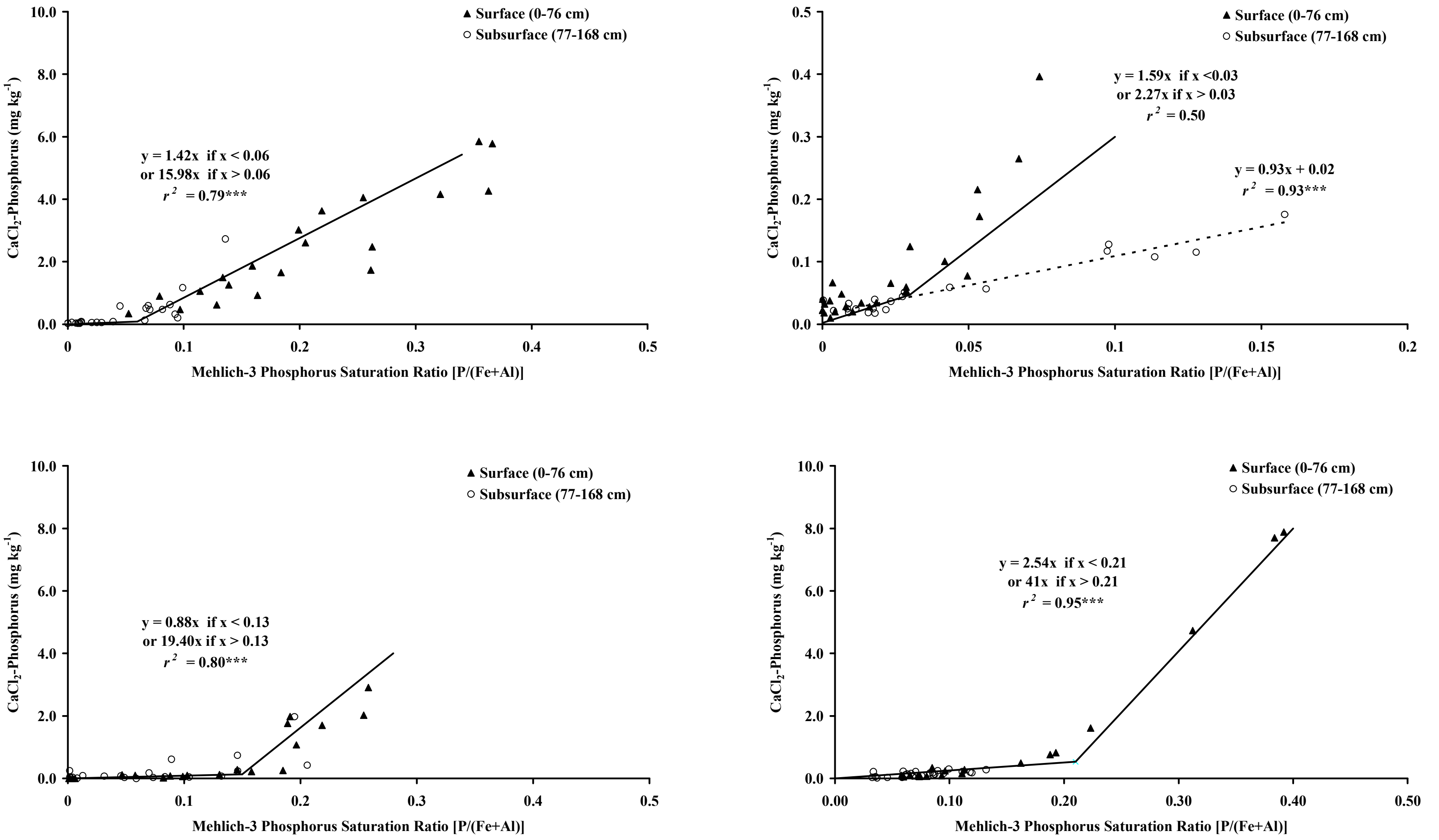

Figure A-1. The CaCl$_2$-P concentrations as a function of Mehlich-3 phosphorus saturation ratios for the Lynchburg loamy fine sand (top left), Pantego loam (top right), Lynn Haven fine sand (bottom left), and Varina loamy sand (bottom right).

Table 1. Particle size analysis and the corresponding soil texture with depth (cm) of the Lynchburg, Lynn Haven, and Pantego soils in the field and riparian buffer.

	Soil							
	Lynchburg loamy fine sand				Lynn Haven fine sand			
	Location							
	Field		RB		Field		RB	
Depth	Sand, silt, clay	Texture[†]	Sand, silt, clay	Texture[†]	Sand, silt, clay	Texture[†]	Sand, silt, clay	Texture[†]
cm[‡]	%		%		%		%	
0-15	91, 6, 3	S	88, 10, 2	S	94, 3, 3	S	97, 0, 3	S
15-30	89, 8, 3	S	89, 10, 1	S	93, 3, 4	S	97, 1, 2	S
30-46	89, 8, 3	S	90, 9, 1	S	92, 3, 5	S	97, 0, 3	S
46-61	88, 8, 4	S	88, 8, 4	S	93, 2, 5	S	95, 2, 3	S
61-76	88, 8, 4	S	85, 7, 8	LS	94, 2, 4	S	98, 1, 1	S
76-91	86, 7, 7	LS			95, 1, 4	S		
91-107	82, 6, 11	LS			92, 3, 5	S		
107-122	77, 7, 16	SL			89, 6, 5	S		
122-137	74, 6, 20	SL			89, 6, 5	S		
137-152	72, 7, 20	SCL			91, 7, 2	S		
152-168	77, 6, 17	SL			89, 7, 5	S		

	Soil							
	Pantego loam				Varina sandy loam			
	Location							
	Field		RB		Field		RB	
Depth	Sand, silt, clay	Texture[†]	Sand, silt, clay	Texture[†]	Sand, silt, clay	Texture[†]	Sand, silt, clay	Texture[†]
cm[‡]	%		%		%		%	
0-15	87, 9, 4	S	70, 16, 14	SL	91, 6, 3	S	96, 0, 4	S
15-30	85, 9, 6	LS	61, 23, 16	SL	83, 15, 2	LS	93, 1, 6	S
30-46	85, 9, 6	LS	55, 25, 20	SL	88, 10, 2	S	81, 9, 11	SL
46-61	85, 8, 7	LS	54, 25, 21	SCL	91, 7, 2	S	78, 7, 15	SL
61-76	85, 8, 7	LS	53, 27, 20	SCL	85, 12, 3	LS	88, 7, 5	S
76-91	83, 8, 9	LS	58, 23, 19	SL	79, 15, 6	LS	93, 4, 3	S
91-107	87, 7, 6	LS			65, 15, 20	SL		
107-122	87, 6, 7	LS			59, 8, 33	SCL		
122-137	86, 6, 8	LS			65, 11, 24	SCL		
137-152	87, 5, 8	LS			70, 9, 21	SCL		
152-168	91, 2, 7	S			40, 12, 48	C		

[†] S, sand; LS, loamy sand; SL, sandy loam; SCL, sandy clay loam;

[‡] Combined across all field core samples.