EVALUATING AGRICULTURAL MANAGEMENT PRACTICES FOR REDUCING PHOSPHORUS LOSSES FROM GRASSLANDS RECEIVING MANURE

by

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(Under the Direction of Miguel L. Cabrera)

ABSTRACT

Poultry and dairy production are important aspects of the agricultural economy in the Southern Piedmont of Georgia. Manures associated with this production are typically surface-applied to pastures as an economic fertilizer for forages. However, nutrients such as phosphorus (P) applied in manures may contribute to agricultural nonpoint pollution through contamination of surface runoff. This has potential to accelerate eutrophication of surface waters, which can harm aquatic life and complicate the water treatment process. Given that surface-applied manures can contribute to P in runoff, a study was conducted to examine agricultural management strategies to reduce export of P from grasslands with applied manures. Following application of either broiler litter or dairy slurry at the plot-scale in the first objective of the study, core aeration was shown to have the greatest potential for reducing P losses in runoff compared to discontinuous slit aeration with tines, continuous-furrow disk aeration, and a control of no aeration. The second objective, conducted at the field-scale, determined that continuous-furrow knife aeration was effective in reducing runoff volume (22%) and export of total P (18%) and dissolved reactive P (41%) compared to a control on well-drained soils and less effective on fields with more poorly-drained soils or a relatively high seasonal water table. In the third objective, the use of on-farm, field-scale runoff data determined that the Georgia P Index was well-suited for estimating the risk of edge-of-field P losses from fields under pasture or hay management in the Southern Piedmont. Furthermore, nutrient source (broiler litter, dairy slurry, inorganic N, and no amendments), forage system (hay or pasture), and year were significant factors affecting edge-of-field P losses. Results from this study suggest that core and continuous-furrow knife aeration procedures may have a widespread impact in reducing the levels of P exported from pastures receiving broiler litter in the Southern Piedmont. Additionally, the impact of agricultural management practices on P export from pasture and hay systems can be effectively modeled by farmers using the Georgia P Index, especially for farms with a low or medium risk of P export.

INDEX WORDS: Phosphorus, grassland, pasture, management practices, mechanical aeration, P index, runoff, poultry litter, dairy slurry.

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INTRODUCTION

The poultry and dairy industries are important components of agricultural production in the Southern Piedmont of Georgia. Manures associated with this production are typically surface-applied to pastures as an economic fertilizer for forages. However, this surface application of manures may lead to surface runoff contamination with P as well as to P accumulation at the soil surface (Kuykendall et al., 1999). Such agricultural nonpoint pollution has the potential to accelerate eutrophication of surface waters (Carpenter et al., 1998; Hubbard et al., 2004; Sharpley and Rekolainen, 1997). Eutrophication can lead to algal blooms, which, after dying, reduce dissolved oxygen levels, kill fish, reduce biodiversity, and otherwise reduce the suitability of waters for use by humans and wildlife. In terms of drinking water, following blooms of *cyanobacteria* there is potential for contamination of drinking waters with carcinogenic chlorination by-products such as trihalomethanes during the water treatment process (Kotak et al., 1993; Palmstrom et al., 1988). Additionally, a metabolite of actinomycetes and blue-green algae called geosmin can give water an unpleasant earthy smell following algal blooms, which is very expensive to chemically remove from drinking waters (Moore et al., 2006).

Land management strategies are needed to reduce the amount of available P transported to surface waters from manure-fertilized grasslands. One strategy is incorporation of manures into the soil (Bundy et al., 2001; Little et al., 2005; Shah et al., 2004b) to facilitate binding of P with soil minerals and to reduce the amount of nutrients remaining at the soil surface where they are susceptible to transport in runoff. Nichols et al. (1994) incorporated poultry litter on tall fescue plots using shallow (2.5 cm) rotary tillage, but subsequent P export in runoff was no different than with surface-applied litter, perhaps due to the shallow incorporation by tillage. Disturbance of the soil surface by tillage, regardless of depth, may lead to negative impacts on forage production as well as a higher risk of P transport due to erosion vulnerability. A potential solution is partial soil disturbance or banding of manures into the soil, which has been reported to reduce nutrient loss (Ross et al., 1979; Thompson et al., 1987).

Mechanical aeration partially disturbs the soil surface and has generally not reduced forage productivity (Burgess et al., 2000; Chen et al., 2001; Malhi et al., 2000; Pote et al., 2003; Shah et al., 2004a). Several types of aeration implements have been used to disturb or puncture the soil surface in grasslands. Types of aeration created by these implements may include discontinuous slit aeration by knives or tines (Bittman et al., 2005; Franklin et al., 2006; Franklin et al., 2007; Harrigan et al., 2006; Shah et al., 2004a; van Vliet et al., 2006), continuous-furrow aeration by knives or disks (Burgess et al., 2000; Little et al., 2005; Pote et al., 2003; Ross et al., 1979; Thompson et al., 1987), or core aeration by cylindrical cores (Callahan et al., 1998; Hartwiger and O'Brien, 2001; Kraft et al., 2004). All have potential to partially incorporate applied manures, to allow for more P adsorption to soil minerals, increase infiltration by breaking the soil surface, and to slow runoff flow by increasing the roughness of the landscape. While past grassland research on mechanical aeration of the soil surface to reduce P losses is limited, it offers an experimental basis for analyzing various aeration treatments, which in turn will allow for utilization and conservation of available nutrients while sustaining environmental quality.

To predict the impact of management practices on losses of P from agriculture, several states have developed models which can be used by farmers and agricultural professionals to minimize P losses and better utilize available nutrients (Lemunyon and Gilbert, 1993; Sharpley et al., 2003). As such, the Georgia P Index (Cabrera et al., 2002; Gaskin et al., 2005) was developed to estimate the risk of bioavailable P loss from agricultural land to surface waters considering sources of P, transport mechanisms, and management practices. Given the limited nature of available data of runoff P from varying agricultural management practices in Southern Piedmont grasslands, data collected on-farm at the field-scale will be useful to examine how field management and landscape affect soil P levels and edge-of-field losses of P in runoff. Additionally, a comparison of measured losses of runoff P to risk ratings for P loss calculated by the Georgia P Index will be useful for farmers and agricultural professionals using this nutrient management tool to prevent excessive export of P from agricultural fields.

The objective of this dissertation research is to evaluate agricultural management practices for reducing phosphorus losses from grasslands receiving manure. Specific objectives are (1) to determine the effectiveness of three mechanical aeration treatments and a control treatment (aeration with cylindrical cores, continuous-furrow no-till disk aeration perpendicular to the slope, slit aeration with tines, and no aeration treatment) in reducing the loss of P in surface runoff from grasslands with three manure treatments (broiler litter, dairy slurry, and no manure) under simulated rainfall at the plot-scale, (2) to examine the effect of continuous-furrow knife aeration perpendicular to the slope on runoff volume and the export of P from grazed field plots with applied broiler litter using a paired-watershed approach, and (3) to use data collected on-farm at the field-scale to examine how field management and landscape morphology impact soil P levels and edge-of-field losses of P in runoff and to compare measured losses of runoff P to risk ratings for P loss calculated by the Georgia P Index.

References

Bittman, S., L.J.P. van Vliet, C.G. Kowalenko, S. McGinn, D.E. Hunt, and F. Bounaix. 2005. Surface-banding liquid manure over aeration slots: A new low-disturbance method for reducing ammonia emissions and improving yield of perennial grasses. Agron. J. 97:1304-1313.

Bundy, L.G., T.W. Andraski, and J.M. Powell. 2001. Management practice effects on phosphorus losses in runoff in corn production systems. J. Environ. Qual. 30:1822-1828.

Burgess, C.P., R. Chapman, P.L. Singleton, and E.R. Thom. 2000. Shallow mechanical loosening of a soil under dairy cattle grazing: Effects on soil and pasture. N. Z. J. Agric. Res. 43:279-290.

Cabrera, M.L., D.H. Franklin, G.H. Harris, V.H. Jones, H.A. Kuykendall, D.E. Radcliffe, L.M. Risse, and C.C. Truman. 2002. The Georgia Phosphorus Index. Cooperative Extension Service, Publication Distribution Center, University of Georgia, Athens, GA. 4pp.

Callahan, L.M., W.L. Sanders, J.M. Parham, C.A. Harper, L.D. Lester, and E.R. McDonald. 1998. Cultural and chemical controls of thatch and their influence on rootzone nutrients in a bentgrass green. Crop Sci. 38:181-187.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Applic. 8:559-568.

Chen, Y., Q. Zhang, and D.S. Petkau. 2001. Evaluation of different techniques for liquid manure application on grassland. Appl. Eng. Ag. 17:489-496.

Franklin, D.H., M.L. Cabrera, and V.H. Calvert. 2006. Fertilizer source and soil aeration effects on runoff volume and quality. Soil Sci. Soc. Am. J. 70:84-89.

Franklin, D.H., M.L. Cabrera, L.T. West, V.H. Calvert, and J.A. Rema. 2007. Aerating grasslands: Effects on runoff and phosphorus losses from applied broiler litter. J. Environ. Qual. 36:208-215.

Gaskin, J.W., K. Harris, M.L. Cabrera, and L.M. Risse. 2005. Using the Georgia P-Index to identify high risk management of poultry litter, *In* K. J. Hatcher, ed. Proc. of the 2005 Georgia Water Resources Conference, Athens, GA. 25-27 April 2005.

Harrigan, T.M., B.B. Bailey, W.J. Northcott, A.N. Kravchenko, and C.A.M. Laboski. 2006. Field performance of a low-disturbance, rolling-tine, dribble-bar manure applicator. Appl. Eng. Agric. 22:33-38.

Hartwiger, C., and P. O'Brien. 2001. Core aeration by the numbers. USGA Green Sect. 39:8-9.

Hubbard, R.K., G.L. Newton, and G.M. Hill. 2004. Water quality and the grazing animal. J. Anim. Sci. 82:E255-263.

Kotak, B.G., S.L. Kenefick, D.L. Fritz, C.G. Rousseaux, E.E. Prepas, and S.E. Hrudey. 1993. Occurrence and toxicological evaluation of cyanobacterial toxins in Alberta lakes and farm dugouts. Water Res. 27:495–506.

Kraft, R.W., S.J. Keeley, and K. Su. 2004. Conversion of fairway-height perennial ryegrass turf to Kentucky bluegrass without nonselective herbicides. Agron. J. 96:576-579.

Kuykendall, H.A., M.L. Cabrera, and C.S. Hoveland. 1999. Stocking method effects on nutrient runoff from pastures fertilized with broiler litter. J. Environ. Qual. 28:1886-1890.

Lemunyon, J.L., and R.G. Gilbert. 1993. The concept and need for a phosphorus assessment tool. J. Prod. Agric. 6:483-486.

Little, J.L., D.R. Bennett, and J.J. Miller. 2005. Nutrient and sediment losses under simulated rainfall following manure incorporation by different methods. J. Environ. Qual. 34:1883-1895.

Malhi, S.S., K. Heier, K. Nielsen, W.E. Davies, and K.S. Gill. 2000. Efficacy of pasture rejuvenation through mechanical aeration or N fertilization. Can. J. Plant Sci. 80:813-815.

Moore, P.A., Jr., B.C. Joern, D.R. Edwards, C.W. Wood, and T.C. Daniel. 2006. Effects of manure amendments on environmental and production problems, p. 759-776 *In* Animal agriculture and the environment: National center for manure and animal waste management white papers. ASABE. Pub. 913C0306, St. Joseph, Michigan.

Nichols, D.J., T.C. Daniel, and D.R. Edwards. 1994. Nutrient runoff from pasture after incorporation of poultry litter or inorganic fertilizer. Soil Sci. Soc. Am. J. 58:1224-1228.

Palmstrom, N.S., R.E. Carlson, and G.D. Cooke. 1988. Potential links between eutrophication and formation of carcinogens in drinking water. Lake Reservoir Manage. 4:1-15.

Pote, D.H., P.A. Moore, Jr., K. Buddington, F.X. Han, W.L. Kingery, and G.E. Aiken. 2003. Water-quality effects of incorporating poultry litter into perennial grassland soils. J. Environ. Qual. 32:2392-2398.

Ross, I.J., S. Sizemore, J.P. Bowden, and C.T. Haan. 1979. Quality of runoff from land receiving surface application and injection of liquid dairy manure. Trans. ASAE 22:1058-1062.

Shah, S.B., J.L. Miller, and T.J. Basden. 2004a. Mechanical aeration and liquid dairy manure application impacts on grassland runoff water quality and yield. Trans. ASAE 47:777-788.

Shah, S.B., S.A. Gartin, D.K. Bhumbla, M.D. Shamblin, and H.N. Boone. 2004b. Runoff water quality impacts of different turkey litter application methods. Appl. Eng. Agric. 20:207-210.

Sharpley, A.N., and S. Rekolainen. 1997. Phosphorus in agriculture and its environmental implications, *In* H. Tunney, et al., eds. Phosphorus losses from soil to water. CAB International, Cambridge, UK.

Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A. Moore, Jr., and G. Mullins. 2003. Development of phosphorus indices for nutrient management planning strategies in the United States. J. Soil Water Conserv. 58:137-160.

Thompson, R.B., J.C. Ryden, and D.R. Lockyer. 1987. Fate of nitrogen in cattle slurry following surface application or injection to grassland. J. Soil Sci. 38:689-700.

van Vliet, L.J.P., S. Bittman, G. Derksen, and C.G. Kowalenko. 2006. Aerating grassland before manure application reduces runoff nutrient loads in a high rainfall environment. J. Environ. Qual. 35:903-911.

CHAPTER 1

LITERATURE REVIEW

Eutrophication

Eutrophication is a process by which the addition of nutrients (primarily phosphorus (P) and nitrogen) to an aquatic system accelerates aquatic plant growth thereby depleting dissolved oxygen and producing an environment unfavorable for aquatic life. In freshwaters, controlling inputs of P is critical to controlling eutrophication (Sharpley and Rekolainen, 1997). The most visible consequence of eutrophication is the excessive growth of algae and other aquatic weeds. This aquatic vegetation not only physically disrupts use of water bodies, it causes further problems when the vegetation begins to decompose. The decomposition process reduces the dissolved oxygen level in the water, which can kill fish and other aquatic life (Carpenter et al., 1998). Reducing dissolved oxygen levels below that required for living organisms is termed hypoxia, which has become a problem in seasonally stratified coastal ecosystems such as the Chesapeake Bay (Boesch et al., 2001). Of further ecological concern, there is a great potential for loss of aquatic biodiversity when eutrophication occurs (Seehausen et al., 1997). Certain algae can also be toxic to humans, livestock, and wildlife when they release toxins into freshwaters or when harvested fish and shellfish transfer the toxins to humans. Of particular concern following blooms of *cyanobacteria* is the contamination of drinking waters with carcinogenic chlorination by-products such as trihalomethanes formed by the interactions with organic matter during the water treatment process (Kotak et al., 1993; Palmstrom et al., 1988). Additionally, a metabolite of actinomycetes and blue-green algae called geosmin can give water an unpleasant earthy smell following algal blooms, which is very expensive to chemically remove from drinking waters (Moore et al., 2006). While there is a potential direct threat to human health if water with elevated nitrate (NO_3^-) levels is consumed, P is not considered a direct threat and no drinking water standards have been established for P by the USEPA (Carpenter et al., 1998; USEPA, 2003; USEPA, 2007).

There are many potential sources of nutrients such as P to surface waters. These include industry, development, agriculture, landscaping, and natural ecosystems. Sources of nutrients are either point or nonpoint sources. While point sources discharge nutrients directly into water bodies and are relatively easy to monitor and regulate, nonpoint sources are typically more difficult to control because they are more likely to be discontinuous and develop from large land areas. This discontinuity occurs because nonpoint source transport tends to be related to rainfall events and nonpoint sources tend to vary temporally and spatially.

Agricultural nonpoint pollution is reported to be the primary source of nonpoint nutrients in the United States (USEPA, 1996). Inorganic fertilizers can be an important contributor to eutrophication, though the primary focus of the studies in this dissertation is on land application of livestock manures. Manures are typically applied to agricultural crops at a rate that will meet the N requirements of the crop. Crops typically require from 5 to 10 kg of available N per kg of available P (Lander et al., 1998). However, manures typically have a much lower N to P ratio, such as 2.2 kg N per kg P for broiler litter (Sims and Wolf, 1994). In this case, applied P is disproportionately high leading to an accumulation of P in the soil, making it vulnerable to transport during storm events either in particulate or dissolved form. Due to a high concentration of broiler production in the Southern Piedmont, there is a regional accumulation of P on some areas of the landscape.

Southern Piedmont

The Southern Piedmont covers parts of Virginia, North Carolina, South Carolina, Georgia, and Alabama, occupying a 15.3-million ha land area. With a mild and humid climate, rainfall in the region is relatively high (110 to 140 cm yr^{-1}), with autumn typically the driest season (Franzluebbers et al., 2002; Stuedemann and Seman, 1998). Combined with an elevation range from 120 to 450 m, the hazard of erosion is considered severe.

Soils in the Southern Piedmont are primarily Ultisols and are considered to be highly eroded. Residual parent materials of upland soils are granite, gneiss, and schists. In areas with little erosion, surface soil horizons are typically loamy sands to sandy loams. However, with erosion and tillage, subsoil horizons with greater clay content become incorporated with the surface soil, and consequently lower the rate of infiltration (Stuedemann and Seman, 1998). Soils are typically low in available P, but applied P is fixed rapidly into particulate form when exposed to clay minerals (Anderson et al., 1996; Stuedemann and Seman, 1998), allowing P to accumulate at the surface where it is susceptible to transport during rainfall events.

Poultry and, to a lesser extent, dairy production are important agricultural industries in the Southern Piedmont region of Georgia. As such, a large amount of waste is generated. The waste product of broiler production is termed 'litter', which is typically a mixture of excreta, feathers, bedding materials (typically wood shavings), and waste feed (Moore et al., 1995). Dairy waste is generally in a liquid form and stored in lagoons that collect waste washed from barns and holding areas which house the dairy cows. Most of these wastes are applied to pasture land as good agronomic practice, but most P in pastured systems is recycled by the grazing animals, and little is removed. Such practices can increase the amount of available P in runoff (Kuykendall et al., 1999). Stuedemann and Seman (1998) estimated total annual P production in the Southern Piedmont to be 16.3 million kg P from poultry production, and 2.5 million kg P from dairy production. While poultry wastes are more abundant than dairy wastes, dairy wastes may be more vulnerable to transport in runoff following land application because they are in a liquid form and thus can increase surface soil water content, making runoff more likely if rain events occur soon after application.

Impacts of Manure Management

There has been a large amount of research examining the potential water quality impacts of manure applications in agricultural situations. As one might expect, both timing (in relation to rainfall events) and rate of manure applications can influence runoff water quality. In South Carolina, McLeod and Hegg (1984) examined runoff water quality from tall fescue pasture with dairy manure, poultry litter, or municipal sludge applied at a target rate of 112 kg N ha^{-1}. Simulated rainfall was applied and runoff sampled at 1, 7, 14, and 21 d after manure or fertilizer applications. Concentration of total P in runoff from poultry litter averaged 12 mg P L^{-1} at 1 d and was reduced to 5 mg P L^{-1} at 7 d. Concentration of total P in runoff from dairy manure was initially 8 mg P L^{-1} and was reduced to 7 mg P L^{-1} at 7 d.

In Arkansas, Sauer et al. (1999) compared nutrient runoff from grazing animal depositions to that from application of poultry litter. Dairy feces and urine generally produced smaller levels of nutrients in runoff than did poultry litter or a combination of the two. This reduction was likely due to a smaller application rate of dairy manure as cattle stocking densities were simulated to be representative of typical northwest Arkansas pastures. Upon application of simulated rainfall one day after manure applications, 22% (13.5 mg P L^{-1}) of soluble reactive P in applied poultry litter was transported in runoff (determined by the automated ascorbic acid method) as compared to 15% (0.79 mg P L^{-1}) of soluble reactive P from dairy feces and urine.

When rainfall was applied two weeks afterwards, 2% (1.2 mg P L^{-1}) of applied soluble reactive P from poultry litter and 5% (0.24 mg P L^{-1}) of applied soluble reactive P from dairy feces and urine was transported in runoff.

Bingham et al. (1980) reported less total P when runoff events occurred 3 d after poultry waste application than when runoff events occurred directly afterwards. Similarly, Kleinman and Sharpley (2003) evaluated P losses in runoff from dairy, layer poultry, and swine manure over successive rainfall events in Pennsylvania. They reported that water extractable P in manures was related to runoff P loss at only higher manure application rates. Below 75 kg total P ha^{-1}, no relationship was reported between water extractable P in the applied manures and P concentration in runoff. In terms of timing of rainfall events following manure application, at rates containing greater than 50 kg total P ha^{-1}, dissolved reactive P (DRP) and total P (TP) concentrations decreased significantly with successive rainfall events (3, 10, and 24 d following application). The researchers suggested that P indices could be changed to reflect that applied manure may influence runoff P concentration for a limited time. Pierson et al. (2001) suggested that dissolved reactive P losses were limited if runoff did not occur soon after application of poultry litter.

Mechanical Aeration

Mechanical aeration of waste-amended soils is a management practice that may help to reduce P transport to surface waters. There are several mechanical treatments of the soil surface which have potential to increase infiltration and binding of applied P with clay minerals. Of these, three types will be examined here. The first includes treatments that involve spikes or tines, where slits or small holes are punched into the soil surface in a discontinuous manner. A second category uses disks or knives to disrupt the soil surface in a series of continuous, parallel furrows. A third technique of mechanical treatment, commonly used for aeration of turf grasses, involves the removal of cylindrical cores from the soil surface. There is limited research on the effect of these mechanical treatments generally, and their impact on reducing the amount of P in surface runoff specifically.

<u>Discontinuous slit aeration</u>

In Mississippi, Ingram et al. (2000) examined the impacts of slit aeration with an Aer-Way^{TM} aerator on soil compaction on bahiagrass (*Paspalum notatum* L.) pastures and bermudagrass (*Cynodon dactylon* (L.) Pers.) hayfields. The researchers hypothesized that slit aeration could increase infiltration in soils compacted due to grazing pressure and intensive past cultivation. However, the researchers found no significant differences in temporal soil penetration resistance or soil moisture contents following aeration treatments, and reported greater localized compaction at the bottom of the aeration slits. The researchers did not attempt to measure infiltration or runoff on the aerated sites.

In West Virginia, Shah et al. (2004) also examined the impacts of slit aeration with an Aer-Way^{TM} aerator (15-cm depth, 0º offset) on a well-drained silt loam soil (Alfisol), but with applied dairy slurry. Over six simulated rain events, aeration reduced concentrations of total P (13%) and dissolved reactive P (29%) in runoff at $p \leq 0.11$. Similarly, mass TP export was reduced by 37% and DRP by 47%. In another study involving applied dairy slurry, van Vliet et al. (2006) reported that slit aeration with an Aer-Way^{TM} machine (14-cm depth, rotating at 2.5º offset) reduced annual runoff volumes on grasslands by 47 to 81% and total suspended solids (TSS) export by 48 to 69% on somewhat poorly-drained (imperfectly-drained) silt loam (alluvial Inceptisol). Total P export was reduced by 25 to 75% and DRP export was reduced by 60% to 96%.

Two studies in Georgia, one at the plot-scale with simulated rainfall and one at the field-scale with natural rainfall, examined the impacts of slit aeration on runoff volumes and nutrient export. At the plot-scale, while only significant at $p = 0.16$, there was a 27% decrease in runoff volume from slit aerated plots (Aer-Way^{TM} aerator, 6-cm depth, 0º offset) compared to non-aerated plots on a moderately well-drained Ultisol (Franklin et al., 2006). Mass export of DRP and TP were unaffected by aeration treatment. This lack of impact may be because slit aeration was done parallel to the slope rather than perpendicular to the slope. At the field-scale on well-drained soils (Ultisols), slit aeration with an Aer-Way^{TM} machine (10- to 12-cm depth, 0º offset) significantly reduced both runoff volume and DRP export by 35% (Franklin et al., 2007). However, this was not the case on poorly-drained soils (Ultisols and Alfisols), as slit aeration increased runoff volume and P export.

In Alberta, Canada, Malhi et al. (2000) examined the impact of mechanical aeration on pasture rejuvenation using an Aer-Way^{TM} aerator with a series of knives penetrating to a 15-cm depth. Aeration did not impact forage yield of smooth bromegrass (*Bromus inermis* Leyss)—Kentucky bluegrass (*Poa pratensis* L.) mixtures or alfalfa (*Medicago sativa* L.)—smooth bromegrass mixtures on any of the sites studied. Similarly, Gordon et al. (2000) examined forage yields under aeration using a similar Aer-Way^{TM} aerator in Nova Scotia, Canada. Forages were dominated by timothy (*Phleum pratense* L.). Of the eleven on-farm fields studied, there was an observed decrease in forage dry matter yield on nine fields. The researchers suggested that the reduction in yields may have been due to increased compaction due to machine traffic associated with aeration or physical damage to the plants caused by the aeration. On average, forage yields were reduced 9.4% from aerated fields in the first harvest following manure application.

Continuous-furrow disk or knife aeration

Disk aeration utilizes methods similar to 'no-till' or conservation tillage seeding of crops, which disrupts the soil surface in a series of parallel rows. Though there are no studies examining the impact of no-till disk aeration on grasslands, Little et al. (2005) examined different manure incorporation methods on a clay loam soil (Mollisol) in Alberta, Canada. Utilizing a single pass of a double-disk (10- to 15-cm depth; parallel to the slope) as one of the treatments, the researchers reported a 14% reduction in TP losses from applied beef cattle manures compared to no incorporation.

Using an aeration technique that also created a series of parallel rows, although using aeration shanks (knives) rather than disks, Burgess et al. (2000) examined impacts of aeration on ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) pasture in New Zealand. The shanks were placed 50-cm apart and pulled through the soil at a 22-cm depth. While the pasture yield, botanical composition, and root length of forages were unaffected by aeration treatment, there was a decrease in the amount of bare ground and an increase in dry root weight of the forages. By decreasing the amount of bare soil exposed to raindrop impact and increasing root mass, there is potential for reduced runoff rates and increased infiltration.

On a silt loam (Ultisol) in Arkansas, Pote et al. (2003) examined the impacts of a continuous-furrow aeration technique (8-cm depth, 20-cm spacing). Aeration furrows were created by using a steel blade to slice the soil surface, spanning the width of the plots. The researchers reported that DRP concentrations in runoff were lower from plots with poultry litter incorporated into aeration furrows than from plots with surface-applied poultry litter, and were actually no greater than plots with no litter application. However, aerated plots with surface-applied poultry litter generally did not produce smaller concentrations of DRP in runoff than did those plots without aeration. Results for TP in runoff were similar as most P transported was in a dissolved form, typical for runoff from perennial grasslands. This research indicates the importance of good contact of applied poultry litter with the soil in order to reduce levels of DRP in runoff.

Core aeration

Research is lacking on the impact of core aeration on P export in runoff. This mechanical treatment involves pulling cylindrical cores from the soil surface. There is however, some research on core aeration in turf grass situations to reduce thatch and increase nutrient retention (Callahan et al., 1998; Hartwiger and O'Brien, 2001; Kraft et al., 2004). There is a potential that runoff from core-aerated land may transport more sediment than undisturbed soil because the cores are removed from the soil and are placed on top of the soil surface, where bare soil of the cores is exposed to rainfall impact. However, this method may also result in reduced localized compaction compared to slit aeration given that plugs are pulled from the soil, rather than the soil being pressed open.

Phosphorus Indices

In order to better manage agricultural P, 47 states have adopted a "P indexing" approach which ranks sites according to potential vulnerability for losses of P (Lemunyon and Gilbert, 1993; Sharpley et al., 2003). Generally, the P indexing approach to P management is achieved by accounting for P-source factors and P-transport factors. Source factors include soil test P (STP) and type and rate of fertilizer or manure applications, whereas transport factors include runoff, erosion, leaching, and proximity to streams. Other modifying factors include soil texture, pH, P sorption capacity, flooding frequency, and various conservation factors (Sharpley et al., 2003). More recently, the concept of "critical source areas" has influenced P risk assessment by demonstrating that certain areas of a given field or landscape often have a disproportionate impact on P export. Critical source areas are those hydrologically active areas which exhibit hydrologic connectivity to the drainage network (transport factors) and have relatively high P-source factors (Gburek and Sharpley, 1998; Gburek et al., 2000; Pionke et al., 2000; Sharpley et al., 2001).

There have been three major changes to the P index since it was originally developed (Lemunyon and Gilbert, 1993; Sharpley et al., 2003). The first change that has been adopted in many states is that the index is calculated using the factors in a multiplicative rather than an additive fashion. This represents an improvement because it more realistically accounts for interacting factors, such as STP and runoff. Using the multiplicative index calculation, sites with high levels of STP will not necessarily generate highly vulnerable P index values unless there is also potential for runoff to occur. A second improvement involves the inclusion of transport factors reflecting the distance of the field to surface waters. This factor allows for consideration of the probability of P from a given site being exported to surface waters during a given event. The third improvement involves the continuous, open-ended scaling of factors such as STP, erosion, and P application rate. This can prevent small changes in one factor from having a disproportionate and unrealistic impact on the final P index rating (Sharpley et al., 2003).

As such, the Georgia P Index (Cabrera et al., 2002; Gaskin et al., 2005) was developed to estimate the risk of bioavailable P loss from agricultural land to surface waters considering P-source factors, P-transport factors, as well as management practices which may impact P export. Potential export of bioavailable P is divided into three loss pathways: (1) soluble P in runoff, (2) particulate P in surface runoff, and (3) soluble P in leachate. Within each pathway, P-source factors (STP, inorganic fertilizer P, or organic fertilizer P) are adjusted according to management practices and summed to obtain a source risk rating. Similarly, transport risk ratings are determined using factors such as risk of runoff, risk of sediment loss, and risk of leaching, respectively for the three pathways. Additional factors, such as vegetative buffer widths and depth to water table are also considered. Risk ratings for each transport pathway are summed, and a numerical P index value is determined in order to place a field within four categories (low, medium, high, or very high) of risk for export of bioavailable P to surface waters. Unlike the P management approach in 3 states, the majority of U.S. states (including Georgia) do not use P indexing to attempt to quantify losses of P from agricultural fields.

Leytem et al. (2003) calculated P index ratings for 272 fields in Delaware and reported that the majority of fields were in the "low" risk category, with only 28% of fields indicating that P-based management would be required. The authors contrasted this with the finding that 55% of all fields evaluated had "excessive" soil test P values and that approximately 14% of fields in the "low" rating category had unsustainable levels of soil erosion. Field-scale validation of P index risk rating was suggested as an important step for further research.

Some studies have attempted to compare P index estimates of field P export vulnerability to either simulated or measured P export. Veith et al. (2005) compared P index values computed using the Pennsylvania P Index for 22 agricultural fields under field crop management to total P loss calculated by SWAT (Soil and Water Assessment Tool). The correlation between predicted values from the two assessment tools was significant at $p = 0.002$, with 73% of fields ranked similarly by the two tools. Of the remaining fields, half were under-predicted and half over-predicted by SWAT. The authors also made note of the important point that SWAT is a continuous model driven by day-to-day management and climate impacts while the P index gives an annual field assessment based on management and average estimates of runoff and erosion.

Given this, the congruence of P loss estimates between the two assessment tools, while designed to meet differing needs of differing users, does suggest that the P index can accurately rank and identify the probability of P export from assessed fields.

In the Southern Plains area of Oklahoma and Texas, Sharpley (1995) evaluated 30 watersheds, the majority of which were less than 5 ha, and compared the original Lemunyon and Gilbert (1993) P field index values to measured values of total P export over 16 years. Watersheds included both cropping and grassland management, as well as both P fertilized and unfertilized management. The author reported a close logarithmic relationship between measured losses of total P and P index ratings [P Index = -5.7 + 6.3log(total P loss); $r^2 = 0.70$].

In Arkansas, Delaune et al. (2004) measured annual P losses from two 0.4-ha watersheds with untreated poultry litter applied annually to one plot and alum-treated poultry litter applied to the second. The authors compared the range of P index values over 6 years of management to actual annual P losses from the field watersheds. The P index was rather successful in estimating the risk of P losses from these two field watersheds, as shown by a strong linear relationship ($r^2 = 0.83$, $p < 0.0001$).

Using six cultivated and four pasture watersheds ranging from 3 to 20.8 ha in the Texas Blackland Prarie (predominance of Vertisols), Harmel et al. (2006) compared estimated P loss potentials determined from the Texas, Arkansas, and Iowa P Indices to measured P losses. Risk ratings and measured P losses were compared over three years, one fallow year and two years with annual poultry litter applications. With the Texas P Index, there was a significant ($p = 0.014$) linear relationship between measured loads of total P and the Texas P Index ratings in the fallow year, no significant relationship in the first year of litter application, and a significant ($p = 0.022$) linear relationship in the second year of litter application. The authors suggested that unusually high erosion from grazed pastures in the first year of litter application (that was difficult to represent in the Texas P Index) was a contributing factor to the lack of a relationship between the two values, and a contributor to a better performance of the index on cultivated fields. For all three years combined, the relationship between the Texas P Index and measured losses of total P was significant at $p = 0.001$. The Arkansas P Index had particular difficulty in estimating the risk of P loss from fields with no applied P and from cultivated fields. The authors suggested that this was not surprising as it was designed for pastures with applied poultry litter and minimal erosion. The Iowa P Index, though designed for cropland and pastures in the Midwest, fared especially well given a significant relationship to measured losses of total P in each of the three study years with both land uses. In general, all three P indices were more highly correlated with dissolved P loads and concentrations than with total P and particulate P loads or concentrations. On pastured watersheds, dissolved P concentrations were well correlated with all three P index ratings: $r^2 = 0.86$, 0.90, and 0.84 for the Texas, Iowa, and Arkansas Indices, respectively. The authors suggested that variation in soil erosion was a limitation of the three indices in that variation in annual soil erosion can introduce substantial error into ratings of the risk of P export.

Given the limited nature of available data of runoff P from varying agricultural management practices in Southern Piedmont grasslands, data collected on-farm at the field-scale will be useful to examine how field management and landscape affect soil P levels and edge-of-field losses of P in runoff. Additionally, a comparison of measured losses of runoff P to risk ratings for P loss calculated by the Georgia P Index will be useful for farmers and agricultural professionals using this nutrient management tool to prevent excessive export of P from agricultural fields.

References

Anderson, S.J., K.J. Steyer, and K.E. Sanders. 1996. Effect of colloidal goethite and kaolinite on colorimetric phosphate analysis. J. Environ. Qual. 25:1332-1338.

Bingham, S.C., P.W. Westerman, and M.R. Overcash. 1980. Effect of grass buffer zone length in reducing the pollution from land application areas. Trans. ASAE 23:330-335.

Boesch, D.F., R.B. Brinsfield, and R.E. Magnien. 2001. Chesapeake Bay eutrophication: Scientific understanding, ecosystem restoration, and challenges for agriculture. J. Environ. Qual. 30:303-320.

Burgess, C.P., R. Chapman, P.L. Singleton, and E.R. Thom. 2000. Shallow mechanical loosening of a soil under dairy cattle grazing: Effects on soil and pasture. N. Z. J. Agric. Res. 43:279-290.

Cabrera, M.L., D.H. Franklin, G.H. Harris, V.H. Jones, H.A. Kuykendall, D.E. Radcliffe, L.M. Risse, and C.C. Truman. 2002. The Georgia Phosphorus Index. Cooperative Extension Service, Publication Distribution Center, University of Georgia, Athens, GA. 4pp.

Callahan, L.M., W.L. Sanders, J.M. Parham, C.A. Harper, L.D. Lester, and E.R. McDonald. 1998. Cultural and chemical controls of thatch and their influence on rootzone nutrients in a bentgrass green. Crop Sci. 38:181-187.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Applic. 8:559-568.

DeLaune, P.B., P.A. Moore, Jr., D.K. Carman, A.N. Sharpley, B.E. Haggard, and T.C. Daniel. 2004. Evaluation of the phosphorus source component in the phosphorus index for pastures. J. Environ. Qual. 33:2192-2200.

Franklin, D.H., M.L. Cabrera, and V.H. Calvert. 2006. Fertilizer source and soil aeration effects on runoff volume and quality. Soil Sci. Soc. Am. J. 70:84-89.

Franklin, D.H., M.L. Cabrera, L.T. West, V.H. Calvert, and J.A. Rema. 2007. Aerating grasslands: Effects on runoff and phosphorus losses from applied broiler litter. J. Environ. Qual. 36:208-215.

Franzluebbers, A.J., J.A. Stuedemann, and S.R. Wilkinson. 2002. Bermudagrass management in the Southern Piedmont USA. II. Soil phosphorus. Soil Sci. Soc. Am. J. 66:291-298.

Gaskin, J.W., K. Harris, M.L. Cabrera, and L.M. Risse. 2005. Using the Georgia P-Index to identify high risk management of poultry litter, *In* K. J. Hatcher, ed. Proc. of the 2005 Georgia Water Resources Conference, Athens, GA. 25-27 April 2005.

Gburek, W.J., and A.N. Sharpley. 1998. Hydrologic controls on phosphorus loss from upland agricultural watersheds. J. Environ. Qual. 27:267-277.

Gburek, W.J., A.N. Sharpley, L. Heathwaite, and G.J. Folmar. 2000. Phosphorus management at the watershed scale: a modification of the phosphorus index. J. Environ. Qual. 29:130-144.

Gordon, R., G. Patterson, T. Harz, V. Rodd, and J. MacLeod. 2000. Soil aeration for dairy manure spreading on forage: effects on ammonia volatilisation and yield. Can. J. Soil Sci. 80:319-326.

Harmel, D., S. Potter, P. Casebolt, K. Reckhow, C. Green, and R. Haney. 2006. Compilation of measured nutrient load data for agricultural land uses in the United States. J. Am. Water Resour. Assoc. 42:1163-1178.

Hartwiger, C., and P. O'Brien. 2001. Core aeration by the numbers. USGA Green Sect. 39:8-9.

Ingram, D.M., D.E. Pettry, R.E. Switzer, C.H. Hovermale, B. Johnson, and N.C. Edwards, Jr. 2000. Technical Bulletin 220: Influence of spike-tooth aeration on permanent pastures in Mississippi. Office of Agricultural Communications, Mississippi State Univ., Starkville.

Kleinman, P.J.A., and A.N. Sharpley. 2003. Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events. J. Environ. Qual. 32:1072-1081.

Kotak, B.G., S.L. Kenefick, D.L. Fritz, C.G. Rousseaux, E.E. Prepas, and S.E. Hrudey. 1993. Occurrence and toxicological evaluation of cyanobacterial toxins in Alberta lakes and farm dugouts. Water Res. 27:495–506.

Kraft, R.W., S.J. Keeley, and K. Su. 2004. Conversion of fairway-height perennial ryegrass turf to Kentucky bluegrass without nonselective herbicides. Agron. J. 96:576-579.

Kuykendall, H.A., M.L. Cabrera, C.S. Hoveland, M.A. McCann, and L.T. West. 1999. Stocking method effects on nutrient runoff from pastures fertilized with broiler litter. J. Environ. Qual. 28:1886-1890.

Lander, C.H., D. Moffitt, and K. Alt. 1998. Nutrients available from livestock manure relative to crop growth requirements. Resource Assessment and Strategic Planning Working Paper 98-1, USDA-NRCS. Available at: http://www.nrcs.usda.gov/technical/land/pubs/nlweb.html.

Lemunyon, J.L., and R.G. Gilbert. 1993. The concept and need for a phosphorus assessment tool. J. Prod. Agric. 6:483-486.

Leytem, A.B., J.T. Sims, and F.J. Coale. 2003. On-farm evaluation of a phosphorus site index for Delaware. J. Soil Water Conserv. 58:89-97.

Little, J.L., D.R. Bennett, and J.J. Miller. 2005. Nutrient and sediment losses under simulated rainfall following manure incorporation by different methods. J. Environ. Qual. 34:1883-1895.

Malhi, S.S., K. Heier, K. Nielsen, W.E. Davies, and K.S. Gill. 2000. Efficacy of pasture rejuvenation through mechanical aeration or N fertilization. Can. J. Plant Sci. 80:813-815.

McLeod, R.V., and R.O. Hegg. 1984. Pasture runoff quality from application of inorganic and organic nitrogen sources. J. Environ. Qual. 13:122-126.

Moore, P.A., Jr., T.C. Daniel, A.N. Sharpley, and C.W. Wood. 1995. Poultry manure management: Environmentally sound options. J. Soil Water Conserv. 50.:321-327.

Moore, P.A., Jr., B.C. Joern, D.R. Edwards, C.W. Wood, and T.C. Daniel. 2006. Effects of manure amendments on environmental and production problems, p. 759-776 *In* Animal agriculture and the environment: National center for manure and animal waste management white papers. ASABE. Pub. 913C0306, St. Joseph, Michigan.

Palmstrom, N.S., R.E. Carlson, and G.D. Cooke. 1988. Potential links between eutrophication and formation of carcinogens in drinking water. Lake Reservoir Manage. 4:1-15.

Pierson, S.T., M.L. Cabrera, G.K. Evanylo, H.A. Kuykendall, C.S. Hoveland, M.A. McCann, and L.T. West. 2001. Phosphorus and ammonium concentrations in surface runoff from grasslands fertilized with broiler litter. J. Environ. Qual. 30:1784-789.

Pionke, H.B., W.J. Gburek, and A.N. Sharpley. 2000. Critical source area controls on water quality in an agricultural watershed located in the Chesapeake Basin. Ecol. Eng. 14:325-335.

Pote, D.H., P.A. Moore, Jr., K. Buddington, F.X. Han, W.L. Kingery, and G.E. Aiken. 2003. Water-quality effects of incorporating poultry litter into perennial grassland soils. J. Environ. Qual. 32:2392-2398.

Sauer, T.J., T.C. Daniel, P.A. Moore, Jr., K.P. Coffey, D.J. Nichols, and C.P. West. 1999. Poultry litter and grazing animal waste effects on runoff water quality. J. Environ. Qual. 28:860-865.

Seehausen, O., J.J.M.v. Alphen, and F. Witte. 1997. Cichlid fish diversity threatened by eutrophication that curbs sexual selection. Science 277:1808-1811.

Shah, S.B., J.L. Miller, and T.J. Basden. 2004. Mechanical aeration and liquid dairy manure application impacts on grassland runoff water quality and yield. Trans. ASAE 47:777-788.

Sharpley, A.N. 1995. Identifying sites vulnerable to phosphorus loss in agricultural runoff. J. Environ. Qual. 24:947-951.

Sharpley, A.N., and S. Rekolainen. 1997. Phosphorus in agriculture and its environmental implications, *In* H. Tunney, et al., eds. Phosphorus losses from soil to water. CAB International, Cambridge, UK.

Sharpley, A.N., R.W. McDowell, J.L. Weld, and P.J.A. Kleinman. 2001. Assessing site vulnerability to phosphorus loss in an agricultural watershed. J. Environ. Qual. 30:2026-2036.

Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A. Moore, Jr., and G. Mullins. 2003. Development of phosphorus indices for nutrient management planning strategies in the United States. J. Soil Water Conserv. 58:137-160.

Sims, J.T., and D.C. Wolf. 1994. Poultry waste management: Agricultural and environmental issues. Adv. Agron. 52:1–83.

Stuedemann, J.A., and D.H. Seman. 1998. State of agriculture in the Southern Piedmont, p. 2.1-2.21, *In* D. H. Franklin, ed. Nutrient cycles in the Southern Piedmont: A workbook for managing nutrients at the watershed scale.

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

USEPA. 2003. National Primary Drinking Water Standards. EPA 816-F-03-016. USEPA, Office of Water (4606M). U.S. Gov. Print. Office, Washington, DC.

USEPA. 2007. Drinking water contaminants [Online] http://www.epa.gov/safewater/contaminants/index.html (posted 10 Sept 2007; verified 25 Nov 2007).

van Vliet, L.J.P., S. Bittman, G. Derksen, and C.G. Kowalenko. 2006. Aerating grassland before manure application reduces runoff nutrient loads in a high rainfall environment. J. Environ. Qual. 35:903-911.

Veith, T.L., A.N. Sharpley, J.L. Weld, and W.J. Gburek. 2005. Comparison of measured and simulated phosphorus losses with indexed site vulnerability. Trans. ASAE 48:557-565.

CHAPTER 2

EVALUATING AERATION TECHNIQUES FOR DECREASING PHOSPHORUS EXPORT FROM GRASSLANDS RECEIVING MANURE[1]

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ABSTRACT

Given that surface-applied manures can contribute to phosphorus (P) in runoff, a study was conducted to examine mechanical aeration of grasslands for reducing P transport by increasing infiltration of rainfall and binding of P with soil minerals. The effects of three aeration treatments and a control (aeration with cores, continuous-furrow “no-till” disk aeration perpendicular to the slope, slit aeration with tines, and no aeration treatment) on the export of total suspended solids (TSS), total Kjeldahl P (TKP), total dissolved P (TDP), dissolved reactive P (DRP), and bioavailable P (BAP) in runoff from grasslands with three manure treatments (broiler litter, dairy slurry, and no manure) were examined before and after simulated compaction by cattle. Plots (0.75 x 2 m) were established on a Cecil soil series with mixed tall fescue (*Festuca arundinacea* Schreb.)-bermudagrass (*Cynodon dactylon* (L.) Pers.) vegetation on 8 to 12% slopes. Manures were applied at a target rate of 30 kg P ha^{-1} and simulated rainfall applied at a rate of 85 mm h^{-1}. Although the impact of aeration type on P export varied before and after simulated compaction, overall results indicated that core aeration has the greatest potential for reducing P losses. Export of TKP was reduced by 55%, TDP by 62%, DRP by 61%, total BAP by 54%, and dissolved BAP by 57% on core-aerated plots with applied broiler litter as compared to the control ($p < 0.05$). Core and no-till disk aeration also showed potential for reducing P export from applied dairy slurry ($p < 0.10$). Given that Cecil soil is common in pastures receiving broiler litter in the Southern Piedmont, results indicate that pairing core aeration of these pastures with litter application could have a widespread impact on surface water quality.

INTRODUCTION

The poultry and dairy industries are significant components of agricultural production in the Southern Piedmont, USA. In this region, manures associated with these industries are typically surface-applied to pastures as a fertilizer. Phosphorus in surface applied manures can accumulate at the soil surface and be transported to surface waters in agricultural runoff (Kuykendall et al., 1999). Additionally, P associated with agricultural nonpoint pollution has the potential to contribute to eutrophication of surface waters (Carpenter et al., 1998; Hubbard et al., 2004; Sharpley and Rekolainen, 1997).

Agricultural professionals have developed several strategies to reduce the amount of available P transported to surface waters. One strategy is incorporation of manures into the soil (Bundy et al., 2001; Little et al., 2005; Shah et al., 2004b) to facilitate binding of P with soil minerals and to reduce the amount of nutrients remaining at the soil surface where they are susceptible to transport in runoff. Nichols et al. (1994) incorporated poultry litter on tall fescue plots using shallow (2.5 cm) rotary tillage, but subsequent P export in runoff was no different than surface-applied litter, perhaps due to the shallow incorporation by tillage. Disturbance of the soil surface by tillage, regardless of depth, may lead to negative impacts on forage production as well as a higher risk of P transport due to erosion vulnerability. A potential solution is partial soil disturbance or banding of manures into the soil, which has been reported to reduce nutrient loss (Ross et al., 1979; Thompson et al., 1987).

Mechanical aeration partially disturbs the soil surface and has generally not reduced forage productivity (Burgess et al., 2000; Chen et al., 2001; Malhi et al., 2000; Pote et al., 2003; Shah et al., 2004a). Several types of aeration implements have been used to disturb or puncture the soil surface in grasslands. Types of aeration created by these implements may include slit aeration by tines (Bittman et al., 2005; Franklin et al., 2006; Franklin et al., 2007; Harrigan et al., 2006; Shah et al., 2004a; van Vliet et al., 2006), continuous-furrow aeration using no-till disks or knives (Little et al., 2005; Pote et al., 2003), or core aeration by cylindrical cores (Callahan et al., 1998; Hartwiger and O'Brien, 2001; Kraft et al., 2004). All have potential to partially incorporate applied manures, allow for more P adsorption to soil minerals, increase infiltration by breaking the soil surface, and slow runoff flow by increasing the roughness of the landscape.

In West Virginia, Shah et al. (2004a) examined the impacts of slit aeration (15-cm depth, 0º offset) on a well-drained silt loam soil (Alfisol), but with applied dairy slurry. Over six simulated rain events, aeration reduced concentrations of total P (TP) by 13% and dissolved reactive P (DRP) by 29% in runoff at $p \leq 0.11$. Similarly, mass TP export was reduced by 37% and DRP by 47%. In another study involving applied dairy slurry, van Vliet et al. (2006) reported that slit aeration (14-cm depth, rotating at 2.5º offset) reduced annual runoff volumes on grasslands by 47 to 81% and total suspended solids (TSS) export by 48 to 69% on somewhat poorly-drained silt loam (alluvial Inceptisol). Total P export was reduced by 25 to 75% and DRP export was reduced by 60 to 96%.

Two studies in Georgia, one at the plot-scale with simulated rainfall and one at the field-scale with natural rainfall, examined the impacts of slit aeration on runoff volumes and nutrient export. At the plot-scale, while only significant at $p = 0.16$, there was a 27% decrease in runoff volume from slit aerated plots (6-cm depth, 0º offset) compared to non-aerated plots on a moderately well-drained Ultisol (Franklin et al., 2006). Mass export of DRP and TP were unaffected by aeration treatment. This lack of impact may be because slit aeration was done parallel to the slope rather than perpendicular to the slope. At the field-scale on well-drained soils (Ultisols), slit aeration (10- to 12-cm depth, 0º offset) significantly reduced runoff volume and DRP export (Franklin et al., 2007). However, this was not the case on poorly-drained soils (Ultisols and Alfisols), as slit aeration increased runoff volume and P export.

Disk aeration utilizes methods similar to 'no-till' or conservation tillage seeding of crops, which disrupts the soil surface in a series of parallel continuous furrows. Though there are no studies examining the impact of no-till disk aeration on grasslands, Little et al. (2005) examined different manure incorporation methods on a clay loam soil (Mollisol) in Alberta, Canada. Utilizing a single pass of a double-disk (10- to 15-cm depth; parallel to the slope) as one of the treatments, the researchers reported a 14% reduction in TP losses from applied beef cattle manures compared to no incorporation.

On a silt loam (Ultisol) in Arkansas, Pote et al. (2003) examined the impacts of a similar continuous-furrow aeration technique (8-cm depth). Aeration furrows were created by using a steel blade to slice the soil surface, spanning the width of the plots. The researchers reported that DRP concentrations in runoff were lower from plots with poultry litter incorporated into aeration slits than from plots with surface-applied poultry litter, and were actually no higher than plots with no litter application. However, aerated plots with surface-applied poultry litter generally did not produce lower concentrations of DRP in runoff than did those plots without aeration.

Research is lacking on the impact of core aeration on P export in runoff. This mechanical treatment involves pulling cylindrical cores from the soil surface. There is however, some research on core aeration in turf grass situations to reduce thatch and increase nutrient retention (Callahan et al., 1998; Hartwiger and O'Brien, 2001; Kraft et al., 2004). There is a potential that runoff from core-aerated land may transport more sediment than undisturbed soil because the cores are removed from the soil and are placed on top of the soil surface, where bare soil of the cores is exposed to rainfall impact. However, this method may also result in reduced localized compaction compared to slit aeration given that plugs are pulled from the soil, rather than the soil being pressed open.

While some studies have specifically examined the potential of mechanical aeration to reduce runoff volume, suspended solids, and/or nutrient export from grasslands (Franklin et al., 2006; Franklin et al., 2007; Pote et al., 2003; Shah et al., 2004a; van Vliet et al., 2006), no studies have directly compared mechanical aeration implements (core, slit, disk) under purely well-drained soil conditions before and after soil compaction. However, past work does offer an experimental basis for analyzing various aeration treatments, which in turn will allow for utilization of available nutrients while sustaining environmental quality.

One important aspect of analyzing export of P from agricultural land is an examination of the fractions of P present in runoff. Total Kjeldahl P (TKP) is a measure of the total amount of P present in runoff, including sediment and particulate-bound inorganic and organic P as well as dissolved inorganic and organic P. Total dissolved P (TDP) is a measure of the total dissolved inorganic and organic P present. Dissolved reactive P determines the fraction of P that can be determined colorimetrically under the molybdate blue reaction (Murphy and Riley, 1962), and it is largely representative of the dissolved inorganic (orthophosphate) fraction of P. As such, the difference between DRP and TDP represents dissolved organic P. The fraction of bioavailable P (BAP) in runoff is considered to be a more specific estimate of the potential environmental impact of transported P in aquatic sytems (Sharpley et al., 1992) and has been estimated using FeO-coated papers (Myers et al., 1997; Robinson et al., 1994; Sharpley, 1993). This method can be applied to unfiltered runoff samples to estimate the total BAP (TBAP) present in runoff, or applied to filtered samples to estimate the amount of BAP in a dissolved form (DBAP).

The objective of this study was to determine the effectiveness of three mechanical aeration treatments and a control treatment (aeration with cylindrical cores, continuous-furrow no-till disk aeration perpendicular to the slope, slit aeration with tines, and no aeration treatment) in reducing the loss of P in surface runoff from grasslands with three manure treatments (broiler litter, dairy slurry, and no manure) under simulated rainfall at the plot-scale, both before and after simulated compaction by cattle.

MATERIALS AND METHODS

Plot Establishment

In the summer of 2004, forty-eight plots (0.75 x 2 m) were established on a Cecil coarse sandy loam soil (fine, kaolinitic, thermic, Typic Kanhapludult) with mixed tall fescue-bermudagrass vegetation on 8 to 12% slopes in Oconee County, Georgia, USA (33º 47' N, 83º 23' W, elevation 225 m). Experimental plots were delineated with galvanized sheet metal (23-cm width) placed into the ground to a depth of 18 cm. Prior to all rainfall simulations, forages on plots were harvested to a 10-cm stubble height to standardize forage canopy height and determine forage herbage mass (dried at 65ºC for 48 h).

Rainfall Simulations to Establish Blocks

Simulated rainfall was applied to plots (all forages at 10-cm stubble height) at a rate of 85 mm h^{-1} until 30 min of runoff had occurred in order to evaluate baseline conditions of runoff from plots. For all rainfall events, the duration of rainfall required to produce 30-min of runoff averaged 56 min. Given this time period, the rainfall rate of 85 mm h^{-1} represents an approximate 1-in-50-yr return period for a 1-h rainfall in Oconee County (Hershfield, 1961). Histograms were used to identify frequency distributions of baseline runoff volumes. Using these histograms, plots were classified into four blocks: each with three aeration treatments and a control (aeration with cylindrical cores, no-till disk aeration perpendicular to the slope, slit aeration with tines, and no aeration treatment) factorially combined with three manure treatments (broiler litter, dairy manure, and no manure). The four aeration (including the control) and three manure treatments (4 x 3) were randomly applied to the twelve plots within each of the four blocks (48 plots).

Mechanical Aeration

Plots were aerated using an aeration device fashioned by attaching cores, tines, or metal flashing (disk aeration) to rows on a metal plate and pushing the implement into the soil. While commercially-available cores and tines were employed in fabrication of aeration devices, they did not simulate the motion or rotation that would have occurred if actual field-scale aeration equipment were utilized. This experiment was done at the plot-scale using rainfall simulation where hydrologic inputs on multiple manures aerated with different implements could be controlled and replicates could be increased. The core aeration implements (BEFCO Inc., Rocky Mount, NC) were approximately 11 cm long, producing a hole with an approximate diameter of 2-cm. The tine implements (AerWay®, Wylie, TX) were 20 cm long, and produced a tapered, wedge-shaped slit with an approximate 1.5 by 6 cm opening at the soil surface. Galvanized 11-gauge metal flashing was used to simulate no-till disk aeration. Each aeration implement was inserted to a depth of 8 cm and impacted a similar-sized surface area of the plot (200 cm^2), with a total of nine aerated rows running perpendicular to the slope on each plot.

Manure Treatments and P Assay

Immediately following each aeration treatment, plots were fertilized with manure treatments at a target rate of 30 kg P ha^{-1} (each application) according to preliminary analysis by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Actual rates of application determined in subsequent lab analyses differed slightly from these estimates (Table 2.1). All broiler litter was dried (65ºC) and ground before application to ensure consistent nutrient application to plots. Samples of applied manures were analyzed for TKP by Kjeldahl digestion (Baker and Thompson, 1992), and for molybdate reactive P (MRP) by shaking 20 g of broiler litter in 4 L of deionized water for 4 h, then filtering (0.45 µm) and analyzing the filtrate according to the molybdate blue method (Murphy and Riley, 1962). Dissolved reactive P in dairy slurry was determined by filtering (0.45 µm) the slurry and similarly analyzing the filtrate. Total dissolved P (TDP) in both broiler litter and dairy slurry was determined by Kjeldahl digestion of the filtered extracts (USEPA, 1979). Manure pH was determined using a pH electrode, with broiler litter mixed with deionized water at a ratio of 1:5 (weight basis).

Following this first aeration and manure application in January 2005, rainfall simulations were conducted using the same methods as during the baseline rainfall simulation. Runoff samples were collected at 5-min intervals until 30 min of runoff had occurred. All runoff during the first 30 min of runoff was collected to determine runoff volumes between each sampling time.

In June 2005, plots were compacted using methods described by Clary (1995) to simulate compaction resulting from cattle hoof action in grazed pastures. Ten locations on each plot were compacted, each with an area of 100 cm^2. Compaction was intended to simulate that which would result under light grazing by cattle, not compaction of the entire area as would be expected in heavy use areas (Butler et al., 2006). Following the compaction in June 2005, plots were again aerated and manure treatments applied before this rainfall simulation, using the same methods as in January 2005. Rainfall was measured using rain gauges at the plot surface during each simulated rainfall event in order to verify rainfall rate applied. Herein "PreCmpct" and "PostCmpct" will refer to the January 2005 and June 2005 rainfall events, respectively.

Laboratory Analysis of Runoff and Soils

Unfiltered runoff samples were analyzed colorimetrically for TKP following a Kjeldahl digestion (USEPA, 1979), and for TBAP using FeO-coated paper circles as described by Myers et al. (1997). Samples were filtered (0.45 µm) to determine concentration of TSS and subsequent filtrate analyzed for DRP by the molybdate blue method (Murphy and Riley, 1962), TDP by the Kjeldahl method, and DBAP as described above for TBAP. Samples collected at 5-min intervals represented point estimates of concentrations and were plotted versus cumulative runoff volume. The points were joined with straight lines and the areas under the lines integrated according to the trapezoid rule to determine cumulative mass of TSS and forms of P exported during 30-min of runoff.

Immediately before rainfall simulations (following manure applications), three soil cores (1.75-cm internal diameter) extracted from a 0- to 2-cm depth and two cores extracted from a 0- to 5-cm depth were obtained from each plot. In each plot, soil cores were combined into a composite sample by depth. The sample taken at the 0- to 5-cm depth was then divided into two subsamples. One sample was air-dried and sieved (< 2 mm), while the second was placed in a soil tin and dried at 105ºC for 48 h to determine gravimetric soil moisture content. The air-dried, sieved sample was analyzed for Mehlich-I soil test P (STP) using methods described by Mehlich (1953) and for water soluble P (WSP) by shaking 1 g of soil with 25 mL of deionized water for 1 h, then filtering (0.45 µm) and analyzing the filtrate according to the molybdate blue method (Murphy and Riley, 1962).

Statistical Analysis

Runoff volume and export of TSS, TKP, TDP, DRP, TBAP, and DBAP in runoff were examined using the PROC GLM procedure (SAS Institute, 1994) with baseline runoff volume used as covariate in the analysis. If the main effect of aeration type was significant ($p < 0.10$), means were separated using the LSMEANS procedure with the PDIFF option. Differences between means were considered significant at $p < 0.10$. Considering that the focus of this manuscript is the evaluation of P export from grasslands aerated with different mechanical aeration implements and not on the variation in P export between manure treatments, differences in runoff constituents as related to aeration were examined by manure treatment. This was also important considering the variation in the amount of P applied between manure treatments (broiler litter, dairy slurry, and no manure), and in the case of application of the liquid dairy slurry, associated addition of water to plots.

RESULTS AND DISCUSSION

Soil Properties

At 0- to 2-cm and 0- to 5-cm depths, STP averaged 36 and 22 mg P kg^{-1} and WSP averaged 20 and 9 mg P kg^{-1}, respectively, at the baseline event (Table 2.2). For both rainfall events following manure applications (PreCmpct and PostCmpct), mean STP was not significantly related to aeration type for any manure treatment ($p > 0.10$). Although STP and WSP had increased rather substantially from the baseline event to the PostCmpct event (Table 2.2), values were relatively low compared to many fields with a history of manure applications, where STP levels above 100 mg kg^{-1} are common (Franklin et al., 2007). Soil moisture levels were notably lower at the PostCmpct rainfall event (June) than at the PreCmpct event (January), for all manure treatments (Table 2.3). Considering the differing seasons of these two events, it is important to note that seasonal effects such as dominance of tall fescue (January) or bermudagrass (June) and a difference in soil moisture content may have also played a role in the different relationships observed between aeration implements and the control at these two rainfall events. Because of this difference PreCmpct and PostCmpct results will be presented separately.

Runoff Volume

Although there was a general trend of lower runoff volume with core aeration as compared to non-aerated control plots, aeration type was not significantly related to runoff volume with either applied broiler litter, dairy slurry, or the control when both rain events were combined in the analysis (Tables 2.4, 2.5, and 2.6). At the PreCmpct event, mean runoff volume from core aeration with applied broiler litter was 27% lower than from non-aerated control plots, a difference in rainfall capture that could be agronomically important but was not large enough to be statistically significant in this study ($p = 0.15$ for main effect of aeration type; Table 2.7). At the PostCmpct event, mean runoff volume was increased 59% with no-till disk aeration compared to the control ($p < 0.05$; Table 2.7), whereas mean runoff volume from core aeration was similar to the control. The trend observed under core aeration may largely be due to the aeration process which pulls soil cores from the soil surface, rather than forcing implements into the soil. This localized soil compaction in slit and no-till disk aeration, caused by the aeration implements pushing into the soil, may have prevented an increase in infiltration with slit and no-till disk aeration.

The lack of an impact of slit aeration on runoff volume was somewhat surprising given the results of van Vliet et al. (2006) and Franklin et al. (2006; 2007). While the results of van

Vliet et al. (2006) may be partially explained by the use of a slit aerator rotating at an angle, which likely would have created a greater soil disturbance than the method utilized in our study, differing soil types and associated drainage class and permeability properties may also explain the differences among these studies.

Total Suspended Solids

When either broiler litter or dairy slurry was applied, there was generally no effect of aeration type on export of TSS when data from both rainfall events were combined in the analysis (Tables 2.4 and 2.5). Our findings differ from those of van Vliet et al. (2006) who reported reductions in mean TSS export of 48 to 69% with slit aeration and applied dairy slurry. The different results reported in our study may be due to differing soil types. Nevertheless, we may have made a type 2 statistical error (accepting the null hypothesis of no difference between means, when it is actually false) while testing TSS export with slit aeration after dairy slurry was applied. In this case, there was a trend of 23 to 28% lower TSS export compared to the control (Table 2.8).

However, when no manures were applied, mean TSS export was greatest under core aeration at the PreCmpct event (Table 2.8). This was likely due to the core aeration technique, which removed soil cores and placed them at the soil surface where vulnerable to export in runoff. This increase should be considered in the design of best management practices. If manures are not applied, core aeration may result in greater erosion or sediment export.

Total Kjeldahl Phosphorus

With applied broiler litter, both aeration type and event were significantly related to mass export of TKP when data from both rainfall events were combined in the analysis ($p < 0.05$; Table 2.4). At the PreCmpct event, core aeration reduced mean TKP export by 57% compared to no aeration (Fig. 2.1a). Mean TKP export from no-till disk and slit aeration was also less than that from the control, with reductions of 25% and 28%, respectively. Relative to the control, TKP export at the PostCmpct event was 50% lower from core aeration (Fig. 2.1b), which was similar to the reduction by core aeration in the PreCmpct event. However, this reduction was not significant at the PostCmpct event ($p = 0.13$ for the main effect of aeration type).

With applied dairy slurry, aeration type was not significantly related to TKP export at the PreCmpct event (Fig. 2.2a). However, at the PostCmpct event there was a 52% reduction in TKP export with core aeration and a 58% reduction with no-till disk aeration ($p < 0.10$ for the main effect of aeration type; Fig. 2.2b). When no manure was applied (manure control plots) aeration did not significantly impact P export (Table 2.6). Mean values of P export when no manure was applied showed that rather low levels of P export can be attributed to soil P in this study, even with the exposure of soil particles associated with mechanical aeration (Fig. 2.3a, 2.3b).

While core aeration was shown to be effective in reducing TKP export if either broiler litter or dairy slurry were applied, its relative effectiveness varied depending on rain event (PreCmpct vs. PostCmpct) and type of applied manure. Past research has also shown an inconsistent impact of mechanical aeration on TP export. With slit aeration followed by dairy slurry application, Shah et al. (2004a) reported reductions in TP export of 37% and van Vliet et al. (2006) reported that slit aeration reduced TP export by 25 to 75%. Franklin et al. (2006) reported that mass export of TKP was unaffected by aeration treatment with applied broiler litter.

<u>Total Dissolved Phosphorus</u>

Similar to export of TKP, TDP export was most affected by aeration type with applied broiler litter (Tables 2.4, 2.5, and 2.6). In the case of applied broiler litter, core aeration reduced mean TDP export by 66%, no-till disk aeration reduced export by 35%, and slit aeration reduced export by 27% compared to the control at the PreCmpct event (Fig. 2.1a). Export was similar to the control for all aeration treatments at the PostCmpct event (Fig. 2.1b). With applied broiler litter at the PreCmpct event, mean TDP export under core and no-till disk aeration was 69% and 78% of TKP export, respectively, both significantly less than the 90% under the aeration control with applied broiler litter (Fig. 2.1a). This indicates that reduction in P with mechanical aeration may be in large part due to adsorption of dissolved P to soil exposed by the aeration process, especially by the core implements. This is further supported by the increase in TSS export observed from core aeration when no manures were applied, as discussed in the previous section. Core aeration may also be more effective than other aeration types at slowing overland runoff flow, in that the extracted cores may act as flow impediments at the soil surface.

Dissolved Reactive Phosphorus

Aeration type was significantly related to DRP export with both applied broiler litter ($p < 0.05$; Table 2.4) and dairy slurry ($p < 0.10$; Table 2.5) when data from both rainfall events were combined in the analysis. Similar to TKP export with applied broiler litter, core aeration decreased DRP export by 66% compared to the control at the PreCmpct event (Fig. 2.1a). Likewise, no-till disk aeration and slit aeration significantly decreased DRP export compared to the control by 34% and 28%, respectively. The greater effectiveness of core aeration may be due to the increased volume of soil particles exposed when cores are placed on the soil surface, resulting in greater adsorption of P to soil minerals. This implies that increasing STP levels may limit the effectiveness of core aeration for decreasing P losses. It should also be pointed out that if the P sorption capacity of a given soil has been met for the volume of soil exposed (11 x 2 cm core) these cores could then serve as a P source rather than a sink, possibly increasing P losses from high-P soils.

With applied dairy slurry, DRP export was similar under all aeration types at the PreCmpct event (Fig. 2.2a). At the PostCmpct event, DRP export was reduced 47% by core aeration and 55% by no-till disk aeration ($p < 0.10$ for the main effect of aeration type; Fig. 2.2b). The lack of an impact on P export observed with slit aeration and applied dairy slurry is somewhat surprising given that both Shah et al. (2004a) and van Vliet et al. (2006) reported reductions in DRP export from applied dairy slurry when fields were slit aerated. The difference may be related to the soils present in these studies, as one was conducted on an alluvial Inceptisol with a silt loam surface soil and the other conducted on a well-drained Alfisol with a silt loam surface soil. The highly eroded Ultisol in our study, is likely less able to accommodate a high volume of applied dairy slurry due to slower rates of infiltration and is more likely to be slightly compacted by the slit aeration procedure than the soils in either the Shah et al. (2004a) or van Vliet et al. (2006) study.

<u>Bioavailable Phosphorus</u>

Similar to other P constituents in runoff, BAP was generally only related to aeration type when broiler litter was applied (Table 2.4). At the PreCmpct event, TBAP export was 58% lower than the control when plots were aerated with cores (Fig. 2.1a). Likewise, DBAP was 64% lower than the control under core aeration at the PreCmpct event with applied broiler litter. Differing from the effect on TBAP export, no-till disk and slit aeration reduced DBAP export compared to the control by 29% and 27%, respectively. At the PostCmpct event, both TBAP and DBAP export were increased by no-till disk aeration, though unaffected by either core or slit aeration (Fig. 2.1b). For all aeration treatments with applied broiler litter, the percentage of TKP represented as TBAP and DBAP averaged 75% and 55%, respectively.

With applied dairy slurry, aeration did have a significant impact on TBAP export at the PostCmpct event ($p < 0.10$ for the main effect of aeration type; Fig. 2.2b), but not for the PreCmpct event. In this case, core and no-till disk aeration decreased mean TBAP export by 49% and 56%, respectively, which is quite similar to impacts on mean DRP export. No previous studies that examined nutrient export from aeration specifically reported on BAP losses, making it difficult to gain a greater perspective of results reported here. However, the reductions observed in our study help to demonstrate the effectiveness of core aeration in reducing the export of P readily available to algae.

Forage Herbage Mass

Forage herbage production was examined by using the herbage mass from plots at the initial harvest as a covariate in comparing aeration type to herbage mass following aeration and manure application. When broiler litter was applied, aeration type was not significantly related to biomass production ($p = 0.11$; data not shown). Though this main effect of aeration type was not determined to be significant, mean herbage mass from core aerated plots when broiler litter was applied did differ from the control ($p < 0.10$). Forage dry matter production on core aerated plots with applied broiler litter was 2,215 kg ha^{-1} compared to 1,633 kg ha^{-1} on control plots. Aeration type was not significantly related to forage herbage production with applied dairy slurry or when no manures were applied. Results here are typical of other studies which have examined forage production with aeration, in that yields were either unaffected, slightly increased, or slightly decreased with aeration (Burgess et al., 2000; Chen et al., 2001; Malhi et al., 2000; Pote et al., 2003; Shah et al., 2004a). Variation in results among studies is likely due to differences in forage species and soil properties affecting the impact of mechanical aeration, such as drainage and bulk density.

CONCLUSIONS

The effectiveness of core aeration may be largely attributable to binding of P to exposed soil minerals and given that there is potential for increased export of TSS from core aerated fields, core aeration should only be conducted on soils with further P sorption capacity. Management practices that help to control TSS transport may enhance the effectiveness of core aeration. Specifically, vegetative filter strips have been shown to be very effective tools for controlling TSS exports from agricultural fields (Blanco-Canqui et al., 2006; Chaubey et al., 1995; Daniels and Gilliam, 1996). With relatively large reductions in TDP observed under core (66%) and to a lesser extent no-till disk aeration (35%) and slit aeration (27%) at the PreCmpct event, additional control of P associated with transported solids (20 to 30% of TKP export) could further reduce environmental risks associated with broiler litter application.

Results presented here suggest that aeration, specifically core aeration of relatively low-P soils, has potential to reduce P export from surface-applied manures, but further research is needed to determine the effects on high-P soils. Given that Cecil soil is common in pastures receiving broiler litter in the Southern Piedmont, core aeration could have a widespread impact on water quality in the Southern Piedmont region. An important consideration of the potential impact of mechanical aeration seems to be soil type and associated drainage class, permeability, and resistance to compaction. While studies have shown the potential of slit aeration to reduce nutrient losses from both alluvial Inceptisols and well-drained Alfisols with applied dairy slurry (Shah et al., 2004a; van Vliet et al., 2006) and well-drained Ultisols with applied poultry litter

(Franklin et al., 2007), aeration has been shown to be less effective in other situations. The efficacy of core aeration in the Southern Piedmont seems to be largely due to exposing a greater surface area of soil minerals to bind P and prevent its export in runoff, as well as the lack of localized compaction when aeration implements enter the soil.

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REFERENCES

Baker, W.H., and T.L. Thompson. 1992. Determination of total nitrogen in plant samples by Kjeldahl, p. 14-17, *In* C. O. Plank, ed. Plant analysis reference procedures for the southern region of the United States. Southern Coop. Ser. Bull. 368. University of Georgia, Athens, GA.

Bittman, S., L.J.P. van Vliet, C.G. Kowalenko, S. McGinn, D.E. Hunt, and F. Bounaix. 2005. Surface-banding liquid manure over aeration slots: A new low-disturbance method for reducing ammonia emissions and improving yield of perennial grasses. Agron. J. 97:1304-1313.

Blanco-Canqui, H., C.J. Gantzer, and S.H. Anderson. 2006. Performance of grass barriers and filter strips under interrill and concentrated flow. J. Environ. Qual. 35:1969-1974.

Bundy, L.G., T.W. Andraski, and J.M. Powell. 2001. Management practice effects on phosphorus losses in runoff in corn production systems. J. Environ. Qual. 30:1822-1828.

Burgess, C.P., R. Chapman, P.L. Singleton, and E.R. Thom. 2000. Shallow mechanical loosening of a soil under dairy cattle grazing: Effects on soil and pasture. N. Z. J. Agric. Res. 43:279-290.

Butler, D.M., D.H. Franklin, N.N. Ranells, M.H. Poore, and J.T. Green, Jr. 2006. Ground cover impacts on sediment and phosphorus export from manured riparian pasture. J. Environ. Qual. 35:2178-2185.

Callahan, L.M., W.L. Sanders, J.M. Parham, C.A. Harper, L.D. Lester, and E.R. McDonald. 1998. Cultural and chemical controls of thatch and their influence on rootzone nutrients in a bentgrass green. Crop Sci. 38:181-187.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Applic. 8:559-568.

Chaubey, I., D.R. Edwards, T.C. Daniel, P.A. Moore, Jr., and D.J. Nichols. 1995. Effectiveness of vegetative filter strips in controlling losses of surface-applied poultry litter constituents. Trans. ASAE 38:1687-1692.

Chen, Y., Q. Zhang, and D.S. Petkau. 2001. Evaluation of different techniques for liquid manure application on grassland. Appl. Eng. Ag. 17:489-496.

Clary, W.P. 1995. Vegetation and soil responses to grazing simulation on riparian meadows. J. Range Manage. 48:18-25.

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.

Franklin, D.H., M.L. Cabrera, and V.H. Calvert. 2006. Fertilizer source and soil aeration effects on runoff volume and quality. Soil Sci. Soc. Am. J. 70:84-89.

Franklin, D.H., M.L. Cabrera, L.T. West, V.H. Calvert, and J.A. Rema. 2007. Aerating grasslands: Effects on runoff and phosphorus losses from applied broiler litter. J. Environ. Qual. 36:208-215.

Harrigan, T.M., B.B. Bailey, W.J. Northcott, A.N. Kravchenko, and C.A.M. Laboski. 2006. Field performance of a low-disturbance, rolling-tine, dribble-bar manure applicator. Appl. Eng. Agric. 22:33-38.

Hartwiger, C., and P. O'Brien. 2001. Core aeration by the numbers. USGA Green Sect. 39:8-9.

Hershfield, D.M. 1961. Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years. Weather Bureau Technical Paper No. 40. U.S. Weather Bureau, Washington, DC.

Hubbard, R.K., G.L. Newton, and G.M. Hill. 2004. Water quality and the grazing animal. J. Anim. Sci. 82:E255-263.

Kraft, R.W., S.J. Keeley, and K. Su. 2004. Conversion of fairway-height perennial ryegrass turf to Kentucky bluegrass without nonselective herbicides. Agron. J. 96:576-579.

Kuykendall, H.A., M.L. Cabrera, and C.S. Hoveland. 1999. Stocking method effects on nutrient runoff from pastures fertilized with broiler litter. J. Environ. Qual. 28:1886-1890.

Little, J.L., D.R. Bennett, and J.J. Miller. 2005. Nutrient and sediment losses under simulated rainfall following manure incorporation by different methods. J. Environ. Qual. 34:1883-1895.

Malhi, S.S., K. Heier, K. Nielsen, W.E. Davies, and K.S. Gill. 2000. Efficacy of pasture rejuvenation through mechanical aeration or N fertilization. Can. J. Plant Sci. 80:813-815.

Mehlich, A. 1953. Determination of P, K, Ca, Mg, and NH_4. North Carolina Soil Test Div. (Mimeo), Raleigh, NC.

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

Myers, R.G., G.M. Pierzynski, and S.J. Thien. 1997. Iron oxide sink method for extracting soil phosphorus: Paper preparation and use. Soil Sci. Soc. Am. J. 61:1400-1407.

Nichols, D.J., T.C. Daniel, and D.R. Edwards. 1994. Nutrient runoff from pasture after incorporation of poultry litter or inorganic fertilizer. Soil Sci. Soc. Am. J. 58:1224-1228.

Pote, D.H., P.A. Moore, Jr., K. Buddington, F.X. Han, W.L. Kingery, and G.E. Aiken. 2003. Water-quality effects of incorporating poultry litter into perennial grassland soils. J. Environ. Qual. 32:2392-2398.

Robinson, J.S., A.N. Sharpley, and S.J. Smith. 1994. Development of a method to determine bioavailable phosphorus loss in agricultural runoff. Agric. Ecosyst. Environ. 47:287-297.

Ross, I.J., S. Sizemore, J.P. Bowden, and C.T. Haan. 1979. Quality of runoff from land receiving surface application and injection of liquid dairy manure. Trans. ASAE 22:1058-1062.

SAS Institute. 1994. SAS/STAT User's guide, Version 8. 2nd ed. SAS, Cary, NC.

Shah, S.B., J.L. Miller, and T.J. Basden. 2004a. Mechanical aeration and liquid dairy manure application impacts on grassland runoff water quality and yield. Trans. ASAE 47:777-788.

Shah, S.B., S.A. Gartin, D.K. Bhumbla, M.D. Shamblin, and H.N. Boone. 2004b. Runoff water quality impacts of different turkey litter application methods. Appl. Eng. Agric. 20:207-210.

Sharpley, A.N. 1993. An innovative approach to estimate bioavailable phosphorus in agricultural runoff using iron oxide-impregnated paper. J. Environ. Qual. 22:597-601.

Sharpley, A.N., and S. Rekolainen. 1997. Phosphorus in agriculture and its environmental implications, *In* H. Tunney, et al., eds. Phosphorus losses from soil to water. CAB International, Cambridge, UK.

Sharpley, A.N., S.J. Smith, O.R. Jones, W.A. Berg, and G.A. Coleman. 1992. The transport of bioavailable phosphorus in agricultural runoff. J. Environ. Qual. 21:30-35.

Thompson, R.B., J.C. Ryden, and D.R. Lockyer. 1987. Fate of nitrogen in cattle slurry following surface application or injection to grassland. J. Soil Sci. 38:689-700.

USEPA. 1979. Methods for chemical analysis of water and wastes. EPA-600/4-79-020. USEPA, Environmental monitoring and support laboratory, Cincinnati, OH.

van Vliet, L.J.P., S. Bittman, G. Derksen, and C.G. Kowalenko. 2006. Aerating grassland before manure application reduces runoff nutrient loads in a high rainfall environment. J. Environ. Qual. 35:903-911.

TABLES AND FIGURES

Table 2.1. Analysis of applied manures

	Amount applied (plot^{-1})	pH	TKP† (kg P ha^{-1})	TDP (kg P ha^{-1})	DRP (kg P ha^{-1})
Broiler Litter (Pre, PostCmpct)	321.7 g	6.4	24.3	15.5	14.9
Dairy Slurry (PreCmpct)	22.4 L	7.4	33.1	3.9	1.9
Dairy Slurry (PostCmpct)	17.6 L	7.5	27.2	2.6	1.4

†TKP=total Kjeldahl P, TDP=total dissolved P, DRP=dissolved reactive P

Table 2.2. Mehlich I soil test P (STP) and water soluble P (WSP) levels at each rain event according to nutrient source

	--------------------------------Rain event--------------------------------					
	Baseline	**PreCmpct**	**PostCmpct**	**Baseline**	**PreCmpct**	**PostCmpct**
	--------------------Sampling depth--------------------					
	----------0 to 2 cm----------			----------0 to 5 cm----------		
	---------------------------STP, mg P kg^{-1}---------------------------					
Broiler litter	32.8b†	48.3b	111.4a	24.2b	30.2b	47.4a
Dairy slurry	33.1c	59.1b	88.2a	18.5c	32.8b	47.2a
Control (none)	42.3	24.4	30.7	23.6	18.0	20.1
	---------------------------WSP, mg P kg^{-1}---------------------------					
Broiler litter	19.5c	33.8b	58.2a	8.9b	18.5a	17.2a
Dairy slurry	18.4c	45.5b	31.3a	8.2c	20.6b	13.4a
Control (none)	23.2	14.6	14.7	11.2	8.0	6.6

† Within manure treatments (rows) and sampling depths, means followed by the same letter or no letters are not significantly different ($p > 0.10$).

Table 2.3. Gravimetric soil moisture levels at each rain event according to nutrient source

	---------Rain event---------	
	PreCmpct	**PostCmpct**
	----Soil moisture (g g^{-1})----	
Broiler litter	0.318a†	0.157b
Dairy slurry	0.399a	0.261b
Control (none)	0.279a	0.155b

† Within manure treatments, soil moisture means followed by the same letter are not significantly different ($p > 0.10$).

Table 2.4. Analysis of Variance: Cumulative total runoff variables during 30 min of runoff with applied broiler litter

		Volume	TSS	TKP	TDP	DRP	TBAP	DBAP
Source	**DF**				***p*-values**			
Model	**8**	***	**	***	***	***	***	***
Hypothesis tests								
Baseline runoff	**1**	***	**	***	***	***	***	***
Aeration	**3**	‡	NS	*	**	**	*	*
Event	**1**	***	***	*	*	**	***	***
Aeration * event	**3**	NS	NS	NS	NS	NS	NS	NS
Residual	**23**							
Total	**31**							

‡, †, *, **, ***, represent $p < 0.15, 0.10, 0.05, 0.01, 0.001$ respectively; NS=not significant; DF=degrees of freedom

Table 2.5. Analysis of Variance: Cumulative total runoff variables during 30 min of runoff with applied dairy slurry

		Volume	TSS	TKP	TDP	DRP	TBAP	DBAP
Source	**DF**				***p*-values**			
Model	**8**	***	**	***	***	***	***	***
Hypothesis tests								
Baseline runoff	**1**	**	NS	*	*	*	*	NS
Aeration	**3**	NS	NS	NS	NS	†	NS	†
Event	**1**	***	***	***	***	***	***	***
Aeration * event	**3**	NS	NS	NS	NS	NS	NS	NS
Residual	**23**							
Total	**31**							

‡, †, *, **, ***, represent $p < 0.15, 0.10, 0.05, 0.01, 0.001$ respectively; NS=not significant; DF=degrees of freedom

Table 2.6. Analysis of Variance: Cumulative total runoff variables during 30 min of runoff without manure applications (control)

		Volume	TSS	TKP	TDP	DRP	TBAP	DBAP
Source	**DF**	------------------------------*p*-values------------------------------						
Model	**8**	***	***	NS	NS	*	NS	NS
Hypothesis tests								
Baseline runoff	**1**	***	**	*	*	NS	†	†
Aeration	**3**	NS	*	NS	NS	NS	NS	NS
Event	**1**	***	***	NS	**	***	NS	†
Aeration * event	**3**	NS	*	NS	NS	NS	NS	NS
Residual	23							
Total	**31**							

‡, †, *, **, ***, represent $p < 0.15$, 0.10, 0.05, 0.01, 0.001 respectively; NS=not significant; DF=degrees of freedom

Table 2.7. Mean runoff volume according to nutrient source and aeration type, before and after simulated compaction

	----------------PreCmpct----------------			----------------PostCmpct----------------		
	Broiler litter	**Dairy slurry**	**None**	**Broiler litter**	**Dairy slurry**	**None**
---Aeration type---	---------------------------------% of rainfall applied---------------------------------					
Core	23.9†	43.3	26.3	11.6b	13.1	9.2
No-till disk	28.2	52.9	33.3	19.7a	12.1	19.1
Slit	29.5	52.2	30.8	15.5ab	14.9	11.1
None (control)	33.8	50.7	26.1	12.4b	21.5	13.9

† Within columns, means followed by the same letter or no letters are not significantly different ($p > 0.10$).

Table 2.8. Mean export of total suspended solids (TSS) according to nutrient source and aeration type, before and after simulated compaction

	__________PreCmpct__________			__________PostCmpct__________		
	Broiler litter	**Dairy slurry**	**None**	**Broiler litter**	**Dairy slurry**	**None**
---Aeration type---	-------------------------------- kg TSS ha^{-1}---------------------------------					
Core	36.6†	235.1	58.2a	6.8ab	15.4	3.3
No-till disk	32.5	258.5	22.3b	9.7a	8.7	3.1
Slit	42.6	146.2	13.8b	5.0b	9.7	3.7
None (control)	44.7	189.5	24.3b	5.3b	13.5	3.0

† Within columns, means followed by the same letter or no letters are not significantly different ($p > 0.10$).

Fig. 2.1. Mean export of total Kjeldahl P (TKP), total dissolved P (TDP), dissolved reactive P (DRP), total bioavailable P (TBAP), and dissolved bioavailable P (DBAP) as affected by aeration type with applied broiler litter at (a) PreCmpct and (b) PostCmpct rain events (percentages indicate the proportion of TKP represented as TDP, DRP, TBAP, or DBAP; ‡, †, *, **, *** indicate main effect of aeration type at $p < 0.15, 0.1, 0.05, 0.01, 0.001$ respectively; § within each phosphorus fraction, means and percentages represented by the same letter or no letters are not significantly different ($p > 0.10$)).

Fig. 2.2. Mean export of total Kjeldahl P (TKP), total dissolved P (TDP), dissolved reactive P (DRP), total bioavailable P (TBAP), and dissolved bioavailable P (DBAP) as affected by aeration type with applied dairy slurry at (a) PreCmpct and (b) PostCmpct rain events (percentages indicate the proportion of TKP represented as TDP, DRP, TBAP, or DBAP; ‡, †, *, **, *** indicate main effect of aeration type at $p < 0.15, 0.1, 0.05, 0.01, 0.001$ respectively; § within each phosphorus fraction, means and percentages represented by the same letter or no letters are not significantly different ($p > 0.10$)).

Fig. 2.3. Mean export of total Kjeldahl P (TKP), total dissolved P (TDP), dissolved reactive P (DRP), total bioavailable P (TBAP), and dissolved bioavailable P (DBAP) as affected by aeration type with no manure application at (a) PreCmpct and (b) PostCmpct rain events (percentages indicate the proportion of TKP represented as TDP, DRP, TBAP, or DBAP; ‡, †, *, **, *** indicate main effect of aeration type at $p < 0.15, 0.1, 0.05, 0.01, 0.001$ respectively; § within each phosphorus fraction, means and percentages represented by the same letter or no letters are not significantly different ($p > 0.10$)).

Figure 2.1.

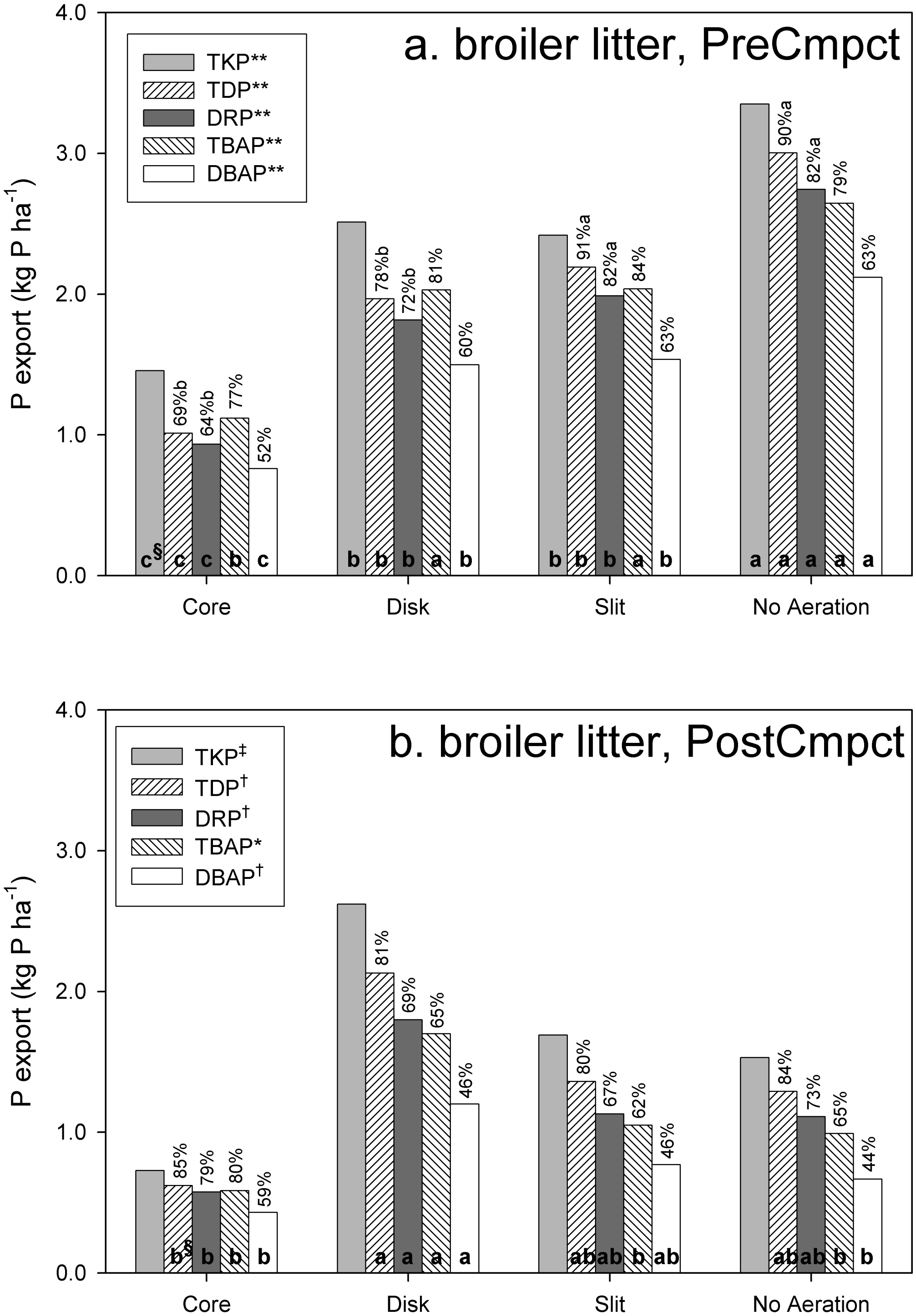
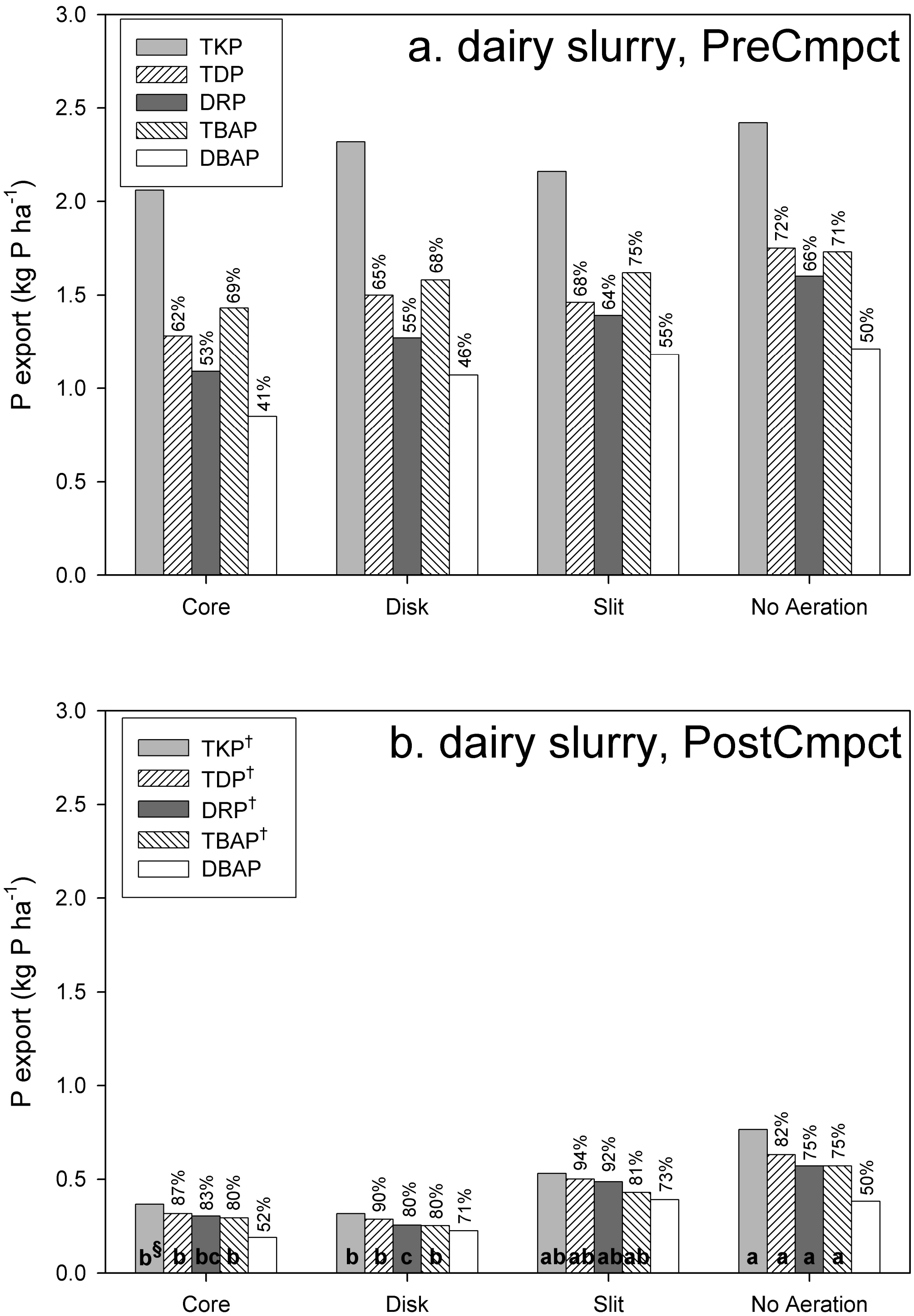
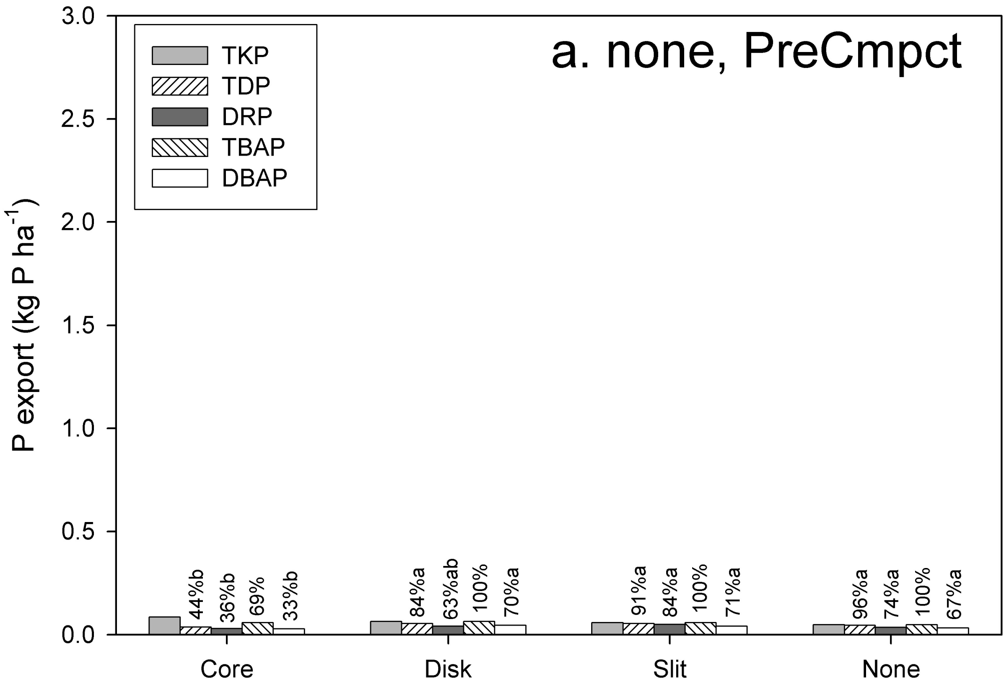

a. broiler litter, PreCmpct
TKP**
TDP**
DRP**
TBAP**
DBAP**
P export (kg P ha-1)
4.0
3.0
2.0
1.0
0.0
69%b
64%b
77%
52%
78%b
72%b
81%
60%
91%a
82%a
84%
63%
90%a
82%a
79%
63%
c§ c c b c
b b b a b
b b b a b
a a a a a
Core
Disk
Slit
No Aeration
b. broiler litter, PostCmpct
TKP‡
TDP†
DRP†
TBAP*
DBAP†
P export (kg P ha-1)
4.0
3.0
2.0
1.0
0.0
85%
79%
80%
59%
81%
69%
65%
46%
80%
67%
62%
46%
84%
73%
65%
44%
b§ b b b
a a a a
ab ab b ab
ab ab b b
Core
Disk
Slit
No Aeration

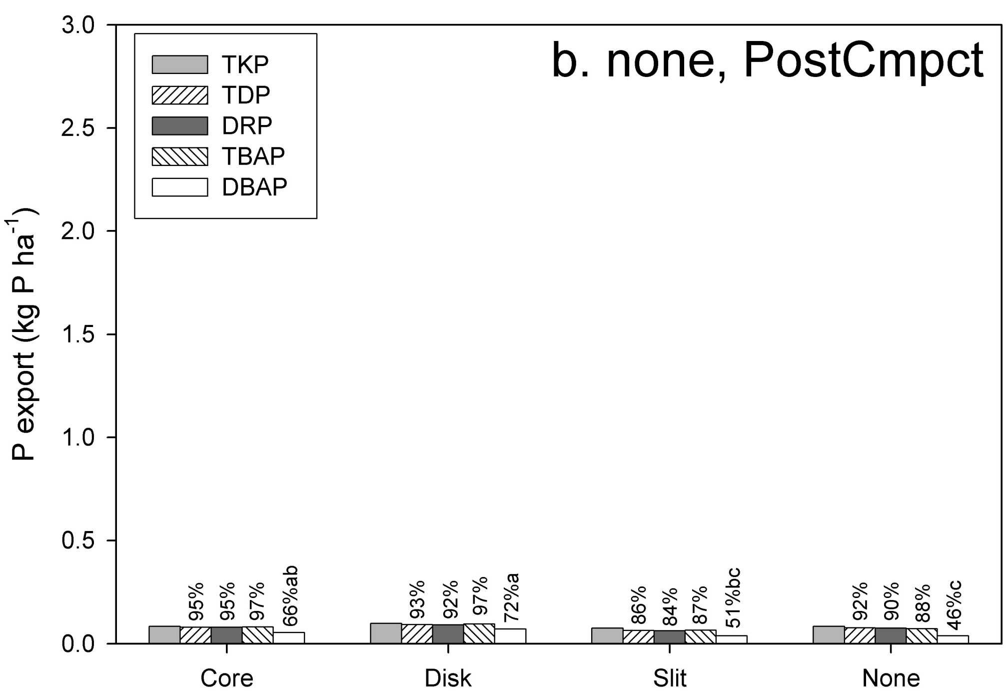
Figure 2.2.



a. dairy slurry, PreCmpct
TKP
TDP
DRP
TBAP
DBAP
P export (kg P ha-1)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
62%
53%
69%
41%
65%
55%
68%
46%
68%
64%
75%
55%
72%
66%
71%
50%
Core
Disk
Slit
No Aeration
b. dairy slurry, PostCmpct
TKP†
TDP†
DRP†
TBAP†
DBAP
P export (kg P ha-1)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
87%
83%
80%
52%
90%
80%
80%
71%
94%
92%
81%
73%
82%
75%
75%
50%
b§
b
bc
b
b
b
c
b
ab
ab
ab
ab
a
a
a
a
Core
Disk
Slit
No Aeration

Figure 2.3.


a. none, PreCmpct
TKP
TDP
DRP
TBAP
DBAP
P export (kg P ha^{-1})
3.0
2.5
2.0
1.5
1.0
0.5
0.0
44%b
36%b
69%
33%b
84%a
63%ab
100%
70%a
91%a
84%a
100%
71%a
96%a
74%a
100%
67%a
Core
Disk
Slit
None


b. none, PostCmpct
TKP
TDP
DRP
TBAP
DBAP
P export (kg P ha^{-1})
3.0
2.5
2.0
1.5
1.0
0.5
0.0
95%
95%
97%
66%ab
93%
92%
97%
72%a
86%
84%
87%
51%bc
92%
90%
88%
46%c
Core
Disk
Slit
None

CHAPTER 3

CONTINUOUS-FURROW KNIFE AERATION FOR DECREASING PHOSPHORUS EXPORT FROM GRASSLANDS RECEIVING POULTRY LITTER: A PAIRED-WATERSHED EVALUATION[1]

[1]Butler, D.M., D.H. Franklin, M.L. Cabrera, A.S. Tasistro, K. Xia, L.T. West, and V.H. Calvert. To be submitted to *J. Environ. Qual.*

ABSTRACT

Mechanical aeration has largely been promoted to alleviate soil compaction, increase rainfall infiltration, and to promote health of turf grasses or production of forage grasses. Additionally, there is potential for aeration to reduce losses of phosphorus (P) in runoff from grasslands with applied manures through increased infiltration, partial incorporation of applied manures, binding of P with soil minerals, and slowing of runoff flow through increased roughness of the soil surface. Nevertheless, there are few data which report the impact of aeration on P losses, especially at the field scale under natural rainfall. As such, a study was conducted to examine at the field scale under natural rainfall the impact of continuous-furrow knife aeration in reduction of P losses in runoff from broiler litter applied to tall fescue (*Festuca arundinacea* Schreb.)/bermudagrass (*Cynodon dactylon* L.) pastures. Six paired, bermed field watersheds were monitored by automatic sampling during rainfall events from 1995 to 1998 to develop calibration relationships between paired watersheds. One field of each pair was then aerated perpendicular to the slope and monitored during rainfall events from spring 2005 through fall 2007. Continuous-furrow knife aeration was most effective in reducing runoff volume (22%) and export of total P (18%) and dissolved reactive P (41%) on Field 2, predominantly characterized by moderately well-drained to well-drained soils. Continuous-furrow knife aeration was less effective on Field 6 (characterized by predominantly poorly-drained soils), and was not effective on Field 5 (dominated by moderately well-drained to well-drained soils, but relatively high seasonal water table). Results suggest that soil properties and density of concentrated flow areas in fields may be important determinants of the effectiveness of continuous-furrow knife aeration for reducing runoff volume and P export from pastures.

INTRODUCTION

Management of grasslands for improved rainfall infiltration and nutrient retention is an important aspect of maintaining forage productivity while preventing environmental degradation. In the Southern Piedmont (USA), the predominance of beef cattle-poultry grassland systems necessitates that grasslands be well-managed in order to prevent excessive nutrient losses following repeated applications of poultry litter. Repeated surface applications of poultry litter allows phosphorus (P) to accumulate at the soil surface where potentially vulnerable to export in runoff (Haygarth et al., 1998; Hooda et al., 2001; Kuykendall et al., 1999; Sharpley et al., 2001). Losses of P are especially problematic given the importance of P as a limiting nutrient in many aquatic systems (Carpenter et al., 1998; Sharpley and Rekolainen, 1997).

Whereas complete incorporation of manures into the soil by tillage has been reported to reduce nutrient losses in field crop situations (Bundy et al., 2001; Little et al., 2005), it is not as practical in perennial grassland systems where it may lead to negative impacts on forage production as well as a higher risk of P transport due to erosion vulnerability. Partial soil disturbance or banding of manures into the soil is a potential solution to these limitations and has been reported to reduce nutrient loss (Ross et al., 1979; Shah et al., 2004b; Thompson et al., 1987). However, banding or injecting manures into the soil also has potential shortcomings in that it is typically used with liquid manures, may cause soil compaction if heavy equipment is required, and does not result in even manure distribution in the field. Partial soil disturbance by mechanical aeration has potential to alleviate these shortcomings while reducing the environmental impact of surface applied manures. Mechanical aeration has potential to increase rainfall infiltration (reduce runoff volume) by breaking the soil surface and by slowing runoff flow through increased roughness of the landscape and to increase P retention (decrease P concentration in runoff) through partial incorporation of applied manures and greater P adsorption to soil minerals. Furthermore, mechanical aeration has generally been reported to not negatively impact forage productivity (Burgess et al., 2000; Chen et al., 2001; Malhi et al., 2000; Pote et al., 2003; Shah et al., 2004a). However, considering the great variety of potential aeration techniques, more research is needed to determine which techniques are most suited to varying environmental conditions and agricultural management practices. Mechanical aeration techniques must also strike a balance by creating a sufficient amount of soil disturbance to reduce runoff volume and nutrient export, while not being so severe that forage productivity, soil structure, and risk of erosion are negatively affected.

A wide variety of mechanical aeration implements have been used to disturb or puncture the soil surface in grasslands (Butler et al., 2008). Research has generally focused on the effectiveness of slit aeration (discontinuous) by tines or knives (Bittman et al., 2005; Franklin et al., 2006; Franklin et al., 2007; Harrigan et al., 2006; Pote et al., 2003; Shah et al., 2004a; van Vliet et al., 2006). Continuous-furrow aeration using disks or knives (Butler et al., 2008; Little et al., 2005; Pote et al., 2003) and core aeration (Butler et al., 2008) have also been examined to some extent. While several studies reported a reduction in runoff volume (Franklin et al., 2006; Franklin et al., 2007; van Vliet et al., 2006) or export of P (Butler et al., 2008; Franklin et al., 2007; Shah et al., 2004a; van Vliet et al., 2006) following aeration, some also reported no significant impact of mechanical aeration with surface-applied manures (Pote et al., 2003). Differences may largely be attributed to variation in soil properties, considering that Franklin et al. (2007) reported that aeration was most effective in moderately well-drained to well-drained soils for reduction in runoff volume and P export, but was less effective in more poorly-drained soils or soils with seasonally high water tables.

On the same field-scale paddocks that were used for our study and on adjacent small plots, Franklin et al. (2006; 2007) examined a discontinuous slit aeration technique for reduction in runoff volume and P export following broiler litter application. The researchers reported that at the plot-scale under simulated rainfall, though only significant at $p = 0.16$, there was a 27% decrease in runoff volume from slit aerated plots (6-cm depth, 0º offset) compared to non-aerated plots on a moderately well-drained Ultisol (Franklin et al., 2006). Mass export of dissolved reactive P (DRP) and total P (TP) were unaffected by aeration treatment. The researchers speculated that this lack of impact may have been because slit aeration was done parallel to the slope rather than perpendicular to the slope. Under natural rainfall at the field-scale on moderately well-drained to well-drained soils (Ultisols), discontinuous slit aeration (10- to 12-cm depth, 0º offset) significantly reduced runoff volume (35%) and DRP export (35%) (Franklin et al., 2007). However, this was not the case on poorly-drained soils and soils with seasonally-high water tables (Ultisols and Alfisols). Considering the lack of impact on some soils, investigation of a more drastic aeration technique (deeper with a greater surface area and volume of soil impacted) that also does not necessitate that farmers purchase expensive new equipment will be useful for suggesting management practices that reduce the risk of P export from pastures amended with poultry litter.

The objective of this study was to examine the effect of continuous-furrow knife aeration perpendicular to the slope on runoff volume and the export of TP and DRP from pastures with applied broiler litter using a paired-watershed approach.

MATERIALS AND METHODS

Six 0.8-ha field-scale watersheds located at the College of Agricultural and Environmental Sciences Central Georgia Research and Education Center (39°24’ N, 83°29’ W, elevation 150 m) were used to evaluate the impact of continuous-furrow knife aeration at the field plot scale under grazed conditions. Mixed tall fescue (*Festuca arundinacea* Schreb.)-bermudagrass (*Cynodon dactylon* L.) was the dominant forage on the plots and soils were classified as Altavista (fine-loamy, mixed, semiactive, thermic Aquic Hapludults), Cecil (fine, kaolinitic, thermic, Typic Kanhapludults), Helena (fine, mixed, semiactive, thermic Aquic Hapludults), and Sedgefield (fine, mixed, active, thermic Aquic Hapludults). Earthen berms (0.6 m high, 1.5 m wide) surrounding each plot directed surface runoff to a 0.45-m H-flume equipped with a SENIX ultrasonic sensor (SENIX Corporation, Burlington, VT) which measured depth of flow, and to a Coshocton wheel which sampled surface runoff. The pan of the Coshocton wheel held a composite sample of the last 1000 L of runoff which flowed through the flume. At pre-determined runoff volumes, samples were automatically collected from the Coshocton wheel pan and stored in an ISCO 3700FR refrigerated sampler (Isco Corporation, Lincoln, NE). Precipitation and runoff volume data were recorded with CR10 dataloggers (Campbell Scientific, Inc., Logan, UT).

Due to variability in the hydrology of these large field watersheds, fields were paired based on historic runoff volume data collected from 1995 through 1998 (Kuykendall et al., 1999). Runoff volume from each plot averaged 5.7, 9.3, 10.2, 10.8, 14.5, and 19.8 mm per event for Fields 1, 5, 2, 4, 3, and 6, respectively. As there were no differences in runoff volume between Fields 1, 2, 4, and 5 ($p > 0.05$), Fields 1 and 2 and Fields 4 and 5 were paired because they were adjacent to one another and had the most similar soils according to the soil map

(Franklin et al., 2007; Fig. 3.1). Fields 3 and 6 were paired considering that average runoff volumes per event did not differ. Calibration relationships were developed using the historic data from 1995 through 1998 for each watershed pair for runoff volume and P concentration and mass load.

The field watersheds were used for a similar study examining the impacts of a slit aeration technique from Oct. 2000 through 2002 (Franklin et al., 2007). Broiler litter was applied during the fall and spring of the study years as well as the first two years of the calibration period. During evaluation of continuous-furrow knife aeration in our study, broiler litter was applied to all fields on 28 Apr. 2005, 22 Nov. 2005, 9 May 2006, 31 Oct. 2006, and 7 Mar. 2007 (Table 3.1, 3.2). Litter was applied with a spreader equipped with load cells to accurately determine the amount of broiler litter applied to each field.

Samples of applied broiler litter were analyzed to determine the amounts of total N, total P, and water-soluble P. Total N and P were determined by Kjeldahl digestion (Baker and Thompson, 1992). Water-soluble P was determined by shaking 20 g of litter with 4 L of deionized water for 30 min at 120 oscillations per min, centrifuging, filtering (0.45-µm), then measuring P in the filtrate by the molybdate blue method (Murphy and Riley, 1962).

Immediately following broiler litter application, one field from each pair (2, 5, and 6) was aerated perpendicular to the slope by pulling 1.5-cm-wide ammonia-injection knives (Universal NH_3 knife, Shoup Manufacturing Co., Kankakee, IL) attached to a chisel-plow frame through the soil, with the other three fields (1, 3, 4) as nonaerated controls. This aeration technique produced continuous furrows of an average 10-cm depth with 27-cm spacing between furrows.

For the aerated fields, the area occupied by either well-drained or moderately well-drained soils was 63% in Field 2, 68% in Field 5, and 25% in Field 6 (Fig. 3.1). Soil samples

(1.75-cm internal diameter) were taken prior to applications of broiler litter from each plot at depths of 0 to 2 cm (20 cores), 0 to 5 cm (12 cores), and 0 to 15 cm (12 cores). Soil cores were composited for each field by depth, air-dried, sieved (< 2 mm), and then analyzed for Mehlich I P (Mehlich, 1953) and water-soluble P (WSP) by shaking 1 g of soil with 25 mL of deionized water for 1 h, then filtering (0.45 μm) and analyzing the filtrate according to the molybdate blue method (Murphy and Riley, 1962). Franklin et al. (2007) examined soil cores (3-cm internal diameter) to a depth of 1.4 m in transects from high to low elevation to describe soil profiles.

During each runoff event, automatic samplers took from 1 to 15 samples and cumulative runoff for each event was recorded by the CR10 datalogger (Campbell Scientific, Logan, UT) at each time a sample was taken. Unfiltered runoff samples were analyzed colorimetrically for TP following a Kjeldahl digestion according to USEPA method 351.2 (USEPA, 1979). Samples were filtered (0.45 μm) to determine concentration of total suspended solids and subsequent filtrate analyzed for DRP by the molybdate blue method (Murphy and Riley, 1962).

Concentrations of DRP and TP were integrated against cumulative runoff to determine total mass of DRP and TP loss. Integration was completed according to the trapezoid rule using the PROC EXPAND procedure (SAS Institute, 1994). Flow-weighted concentrations were determined by dividing total mass loss of runoff constituents by the total volume of surface runoff.

Results were analyzed by paired fields which were grouped according to similar historic runoff volumes, soil types, and proximity to one another. Runoff volumes and nutrient export from the each field aerated (or to be aerated) were regressed against runoff volumes and nutrient export from the corresponding paired field not aerated. The regression of data before aeration was compared to that of data following aeration using PROC GLM (SAS Institute, 1994).

In order to estimate density of drainage networks/areas of concentrated flow in each paddock, high resolution digital elevation models (DEMs) were created from global positioning system (GPS) measurements taken in the field. Points were collected by mounting a Leica Wild SR399E sensor (Leica Geosystems, Heerbrugg, Switzerland) with an AT302 antenna equipped with a CR 344 controller onto a utility vehicle. A 2-way radio system (Pacific Crest, Santa Clara, California) was used in order for real-time corrections to be made in the field. Kinematic sampling mode was utilized with measurement recorded automatically every 2 m, while following circular paths in the watershed at the width of the utility vehicle (~1 m). Horizontal precision was set to collect points at an error of 2 cm or less. In terms of accuracy for the elevation or vertical coordinate, Van Niel *et al.* (2004) suggested that the vertical error is approximately 2.5 times the horizontal. Yao and Clark (2000), however, suggested that vertical error from a global positioning system (GPS) receiver is 1.5 times the horizontal error. In this sense, it can be said that the vertical error in this experiment was less than 5 cm, at worst. The base station consisted of Leica Wild SR299 sensor and also a CR 344 controller assembled on a tripod. The base station was located less than 300 m from all plots.

Data points were loaded into Arc/Tools, a component of the Arc/GIS workstation, where a points coverage file was created. The coverage file was them imported in Arc/Map. In Arc/Map, ordinary kriging interpolation using a spherical semivariogram model was used to interpolate a surface based on the elevation of the collected data points. The hydrology functions in Arc/Map were then used to fill any sinks in this DEM. This function eliminates depressions of elevation which would otherwise prevent interpretation of flow paths from the DEM as the model would expect water to enter these sinks, but not exit. The direction of flow of each pixel and the flow accumulation (number of other pixels of cumulative flow which flow into a specified pixel) were then also determined. The results of the flow accumulation procedure were then used to determine the length of concentrated flow with pixels draining more than 500,000 and 100,000 pixels (Fig. 3.2). Concentrated flow lengths were then divided by plot area to determine the density of drainage networks for each plot (km ha^{-1}).

RESULTS

Throughout the study, mean Mehlich I soil P across all six paddocks ranged from a low of 178.9 (70.5) mg P kg^{-1} to a high of 257.1 (45.4) mg P kg^{-1} at 0 to 2.5 cm, 107.7 (39.6) mg P kg^{-1} to 196.5 (33.0) mg P kg^{-1} at 0 to 5 cm, and 53.5 (12.9) mg P kg^{-1} to 83.5 (17.9) mg P kg^{-1} at 0 to 15 cm (standard deviations given in parentheses; Table 3.3). Similarly, mean WSP ranged from a low of 53.4 (15.6) mg P kg^{-1} to a high of 83.1 (10.9) mg P kg^{-1} at 0 to 2.5 cm, 28.5 (7.3) mg P kg^{-1} to 49.2 (13.9) mg P kg^{-1} at 0 to 5 cm, and 7.3 (1.8) mg P kg^{-1} to 20.9 (4.4) mg P kg^{-1} at 0 to 15 cm.

Before the first litter application to the study paddocks, DRP concentrations in runoff averaged 0.45 mg P L^{-1} (Kuykendall et al., 1999). As such, high levels of DRP export in runoff led Franklin et al. (2007) to report that concentrations of DRP in runoff were likely controlled by P in applied broiler litter, not soil P levels. It is interesting, however, to note the slight buildup in soil P levels through the course of this study (Table 3.3).

Average annual precipitation throughout the study years from 2005 to 2007 was 963 mm, compared to 1037 mm from 1995 to 1998 (baseline period before aeration), and 1051 mm from 2001 to 2003 (during the slit aeration study period). Daily rainfall distribution was examined from 1995 through 2007 (Fig. 3.3). Soil moisture levels were recorded weekly during the second year of the study and varied widely, from a low of 0.03 g g^{-1} in May 2007 to a high of nearly 0.30 g g^{-1} in Nov. 2006 (data not shown).

Paired Fields One and Two

Runoff Volume

Using historic data before field aeration, the slope of the regression of runoff from Field 2 (to be aerated) against runoff volume from Field 1 (not aerated) was 1.86 (4. 3.3a; note line labeled “Before”). This indicates that Field 2 had approximately 1.86 times more runoff than Field 1 while under the same management. With continuous-furrow knife aeration on Field 2, the slope of the regression was significantly lowered ($p < 0.05$) from 1.86 to 1.40, while the intercept was unchanged (Fig. 3.4a; note line labeled “After”). The percentage reduction in slope of 22% in Field 2 indicates the percentage reduction in runoff volume following aeration treatment.

Amount of Phosphorus Loss

Similar to the impact on runoff volume, aeration also significantly impacted the loss of TP and DRP (Fig. 3.5a and 3.5b). The reduction in mass TP export is indicated by the decrease in regression slope from 2.25 before aeration to 1.84 following aeration ($p = 0.13$), a reduction of 18% (Fig. 3.5a). The effect on DRP loss was even greater, with the regression slope decreasing from 3.16 before aeration to 1.86 following aeration ($p < 0.001$; Fig. 3.5b), a reduction of 41%. However, there was no observed effect of aeration on flow-weighted concentrations (Fig. 3.5c and 3.5d).

Paired Fields Four and Five

Runoff Volume

There was no observed effect of aeration on runoff following aeration of Field 5 as the regression slopes and intercepts were remarkably similar before and after continuous-furrow aeration (Fig. 3.4b).

Amount of Phosphorus Loss

Similar to runoff volume, there was no observed effect of aeration on either TP or DRP losses or concentrations (Fig. 3.6). Regression lines were remarkably similar for the historic period as well as the period following aeration. A greater number of high volume rainfall events may have helped to confirm this lack of effect, as there were relatively few very heavy runoff events during the nearly three years of this study.

Paired Fields Three and Six

Runoff Volume

Following aeration, the slope of the regression was reduced from 1.02 to 0.73 ($p < 0.05$), a reduction of 28% (Fig. 3.4c). However, the r-squared value of the regression was just 0.59, with a small cluster of runoff events with comparatively low runoff from Field 3 in relation to Field 6 adding to the variability. This cluster of three runoff events occurred within a brief one-month period during the winter, Dec. 25, 2006 and Jan. 7 and 22, 2007.

Amount of Phosphorus Loss

The effect of aeration on losses of TP and DRP was also not overly clear (Fig. 3.7). For both TP and DRP, the slope of the regression line was significantly lower following aeration treatment ($p < 0.01$; Fig. 3.7a, 3.7b). However, the intercept was also larger following aeration treatment. This is likely due to the scattered nature of the data as indicated by the relatively low r-squared values for regression lines for the after aeration period.

DISCUSSION

Our results indicated that continuous-furrow knife aeration reduced runoff volume and P export in Paired Fields 1 and 2, had a marginal impact on Paired Fields 3 and 6, and was not effective on Paired Fields 4 and 5. These results are similar to those reported by Franklin et al. (2007) who examined runoff volumes and P losses following slit aeration (discontinuous) on the same field watersheds. The authors reported a similar reduction of runoff volume (35%) and DRP (35%) from Paired Fields 1 and 2, which is somewhat surprising given the more extensive nature of the continuous-furrow aeration technique compared to discontinuous slit aeration. However, differing from the results with continuous-furrow knife aeration where an 18% reduction in TP was observed, slit aeration did not reduce TP. This may have been due to P binding with runoff solids, which may have been increased by the slit aeration procedure. Field 2 is largely comprised of moderately well-drained (Altavista, 27%) to well-drained soils (Cecil, 36%; Fig 3.1) with redoximorphic features generally well below the start of the Bt horizon. Reduction in runoff volume may largely be due to the aeration procedure breaking the soil surface to allow for greater infiltration in these soils with good drainage, as well as the furrows created by the aeration procedure slowing overland flow to allow more time for infiltration.

While the lack of an observed effect of flow-weighted P concentrations from Paired Fields 1 and 2 may be due to the scattered nature of the data, it may also indicate that the decrease in runoff volume from aerated Field 2 may be the driving factor in decreased P losses. The greater impact of aeration on DRP losses does suggest, however, that increased binding of P with exposed soil minerals may be playing a role. Additionally, a potential increase in sediment associated P following continuous-furrow aeration may have prevented a greater reduction in TP as compared to DRP.

Continuous-furrow knife aeration was not found to have an impact on runoff volume or P export from Paired Fields 4 and 5. This also was very similar to results reported by Franklin et al. (2007) for discontinuous slit aeration. Field 5, the aerated field, is dominated by moderately well-drained to well-drained soils (68% of plot area) similar to Field 2, but the effect of aeration was quite different. Franklin et al. (2007) speculated that the lack of impact of aeration may have been due to shallower depths of redoximorphic features in Field 5, indicating shallower depths to the seasonal high water table.

Results in this study did differ somewhat from results reported by Franklin et al. (2007) for Paired Fields 3 and 6. With continuous-furrow knife aeration, results suggested that runoff volume and export of P were slightly reduced by aeration or not affected. However, with slit aeration, runoff volume and P export were increased by the procedure. Field 6 does differ from the other aerated fields in that 75% of the plot is comprised of poorly-drained soils. These soils may be especially prone to compaction, suggesting that continuous-furrow knife aeration created by pulling aeration knives through the soil may have caused less localized soil compaction than slit aeration where knives are pushed into the soil. However, even with continuous-furrow knife aeration, the tractor used to pull the aerator may have created compaction which may have prevented a greater effect of aeration on runoff and P losses.

Areas of concentrated flow within the paired field watersheds were also examined in order to explain differences observed with continuous-furrow aeration among the fields. In general, Paired Fields 4 and 5 had lower concentrated flow density than Paired Fields 1 and 2 or

Paired Fields 3 and 6 (Table 3.4; Fig. 3.2). Although with only three paired fields, it may not be wise to over-emphasize the results of concentrated flow density. However, it is interesting that plots with higher concentrated flow density did seem to have a greater response to continuous-furrow aeration. This is somewhat logical, considering the aeration procedure is more able to attenuate runoff and associated P when the aeration furrows interrupt a greater number of concentrated flow areas. In fields with a lower density of concentrated flow areas, runoff water and nutrients may be quickly exported from the field through a few channels of flow, which aeration may be less able to interrupt due to fewer interaction points of the concentrated flow area and the aeration procedure. Continuous-furrow knife aeration may be most effective at breaking up areas of concentrated flow, causing a greater interaction of runoff with the soil surface and leading to reduced risk of P export.

CONCLUSIONS

Results of our research, coupled with past studies of aeration techniques for reducing nutrient export from pastures with surface-applied manures, tend to reinforce the importance of soil properties and site conditions in determining the potential effectiveness of aeration. Continuous-furrow knife aeration was most effective in reducing runoff volume and P export from Paired Fields 1 and 2 which are dominated by moderately well-drained to well-drained soils, a seasonal high water table below the Bt horizon, and a higher density of concentrated flow areas relative to the other paired fields where aeration was less effective.

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REFERENCES

Baker, W.H., and T.L. Thompson. 1992. Determination of total nitrogen in plant samples by Kjeldahl, p. 14-17, *In* C. O. Plank, ed. Plant analysis reference procedures for the southern region of the United States. Southern Coop. Ser. Bull. 368. University of Georgia, Athens, GA.

Bittman, S., L.J.P. van Vliet, C.G. Kowalenko, S. McGinn, D.E. Hunt, and F. Bounaix. 2005. Surface-banding liquid manure over aeration slots: A new low-disturbance method for reducing ammonia emissions and improving yield of perennial grasses. Agron. J. 97:1304-1313.

Bundy, L.G., T.W. Andraski, and J.M. Powell. 2001. Management practice effects on phosphorus losses in runoff in corn production systems. J. Environ. Qual. 30:1822-1828.

Burgess, C.P., R. Chapman, P.L. Singleton, and E.R. Thom. 2000. Shallow mechanical loosening of a soil under dairy cattle grazing: Effects on soil and pasture. N. Z. J. Agric. Res. 43:279-290.

Butler, D.M., D.H. Franklin, M.L. Cabrera, A.S. Tasistro, K. Xia, and L.T. West. 2008. Evaluating aeration techniques for decreasing phosphorus export from grasslands receiving manure. J. Environ. Qual. *(accepted 18 Dec 2007)*.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Applic. 8:559-568.

Chen, Y., Q. Zhang, and D.S. Petkau. 2001. Evaluation of different techniques for liquid manure application on grassland. Appl. Eng. Ag. 17:489-496.

Franklin, D.H., M.L. Cabrera, and V.H. Calvert. 2006. Fertilizer source and soil aeration effects on runoff volume and quality. Soil Sci. Soc. Am. J. 70:84-89.

Franklin, D.H., M.L. Cabrera, L.T. West, V.H. Calvert, and J.A. Rema. 2007. Aerating grasslands: Effects on runoff and phosphorus losses from applied broiler litter. J. Environ. Qual. 36:208-215.

Harrigan, T.M., B.B. Bailey, W.J. Northcott, A.N. Kravchenko, and C.A.M. Laboski. 2006. Field performance of a low-disturbance, rolling-tine, dribble-bar manure applicator. Appl. Eng. Agric. 22:33-38.

Haygarth, P.M., L. Hepworth, and S.C. Jarvis. 1998. Forms of phosphorus transfer in hydrological pathways from soil under grazed grassland. Eur. J. Soil Sci. 49:65-72.

Hooda, P.S., V.W. Truesdale, A.C. Edwards, P.J.A. Withers, M.N. Aitken, A. Miller, and A.R. Rendell. 2001. Manuring and fertilization effects on phosphorus accumulation in soils and potential environmental implications. Advances in Environmental Research 5:13-21.

Kuykendall, H.A., M.L. Cabrera, C.S. Hoveland, M.A. McCann, and L.T. West. 1999. Stocking method effects on nutrient runoff from pastures fertilized with broiler litter. J. Environ. Qual. 28:1886-1890.

Little, J.L., D.R. Bennett, and J.J. Miller. 2005. Nutrient and sediment losses under simulated rainfall following manure incorporation by different methods. J. Environ. Qual. 34:1883-1895.

Malhi, S.S., K. Heier, K. Nielsen, W.E. Davies, and K.S. Gill. 2000. Efficacy of pasture rejuvenation through mechanical aeration or N fertilization. Can. J. Plant Sci. 80:813-815.

Mehlich, A. 1953. Determination of P, K, Ca, Mg, and NH_4. North Carolina Soil Test Div. (Mimeo), Raleigh, NC.

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

Pote, D.H., P.A. Moore, Jr., K. Buddington, F.X. Han, W.L. Kingery, and G.E. Aiken. 2003. Water-quality effects of incorporating poultry litter into perennial grassland soils. J. Environ. Qual. 32:2392-2398.

Ross, I.J., S. Sizemore, J.P. Bowden, and C.T. Haan. 1979. Quality of runoff from land receiving surface application and injection of liquid dairy manure. Trans. ASAE 22:1058-1062.

SAS Institute. 1994. SAS/STAT User's guide, Version 8. 2nd ed. SAS, Cary, NC.

Shah, S.B., J.L. Miller, and T.J. Basden. 2004a. Mechanical aeration and liquid dairy manure application impacts on grassland runoff water quality and yield. Trans. ASAE 47:777-788.

Shah, S.B., S.A. Gartin, D.K. Bhumbla, M.D. Shamblin, and H.N. Boone. 2004b. Runoff water quality impacts of different turkey litter application methods. Appl. Eng. Agric. 20:207-210.

Sharpley, A.N., and S. Rekolainen. 1997. Phosphorus in agriculture and its environmental implications, *In* H. Tunney, et al., eds. Phosphorus losses from soil to water. CAB International, Cambridge, UK.

Sharpley, A.N., R.W. McDowell, and P.J.A. Kleinman. 2001. Phosphorus loss from land to water: integrating agricultural and environmental management. Plant Soil 237:287-307.

Thompson, R.B., J.C. Ryden, and D.R. Lockyer. 1987. Fate of nitrogen in cattle slurry following surface application or injection to grassland. J. Soil Sci. 38:689-700.

USEPA. 1979. Methods for chemical analysis of water and wastes. EPA-600/4-79-020. USEPA, Environmental monitoring and support laboratory, Cincinnati, OH.

Van Niel, K.P., S.W. Laffan, and B.G. Lees. 2004. Effect of error in the DEM on environmental variables for predictive vegetation modelling. J. Veg. Sci. 15:747-756.

van Vliet, L.J.P., S. Bittman, G. Derksen, and C.G. Kowalenko. 2006. Aerating grassland before manure application reduces runoff nutrient loads in a high rainfall environment. J. Environ. Qual. 35:903-911.

Yao, H., and R.L. Clark. 2000. Evaluation of sub-meter and 2 to 5 meter accuracy GPS receivers to develop digital elevation models. Precis. Agric. 2:189-200.

TABLES AND FIGURES

Table 3.1. Timeline of field watershed management during continuous-furrow knife aeration treatments

Date	Event
2005	
28 Apr.	Litter application & aeration
14 Jun.	Hayed paddocks
1 Aug.	Began grazing
26 Aug.	Mowed paddocks
19 Sept.	Ended grazing
22 Nov.	Litter application & aeration
2006	
7 Mar.	Mowed paddocks
11 Apr.	Mowed paddocks
5 May	Began grazing
9 May	Ended grazing
	Litter application & aeration
30 Jun.	Began grazing
28 Jul.	Ended grazing
31 Oct.	Litter application & aeration
2007	
7 Mar.	Litter application & aeration
7 May	Began grazing
13 Aug.	Ended grazing
17 Aug	Mowed paddocks
7 Oct.	Mowed paddocks

Table 3.2. Broiler litter application dates and mean rates of total N, total P, and water-soluble P applied to field watersheds before aeration treatments and during slit aeration and continuous-furrow knife aeration treatments.

Date	Total N	Total P	Water-soluble P
	---------------------------kg ha^{-1}	---------------------------	
Before aeration			
16 Mar. 1995	267	102	16
30 Oct. 1995	267	112	22
5 Mar. 1996	502	174	30
25 Sept. 1996	260	103	29
During slit aeration			
11 Oct. 2000	148	92	13
19 Mar. 2001	150	75	11
19 Oct. 2001	169	92	12
14 Feb. 2002	141	81	8
23 Oct. 2002	175	90	12
During continuous-furrow aeration			
28 Apr. 2005	157	59	25
22 Nov. 2005	88	47	18
9 May 2006	149	70	20
31 Oct. 2006	153	72	16
7 Mar. 2007	161	47	15

Table 3.3. Mean Mehlich I soil test P and water-soluble P (WSP) on field watersheds during continuous-furrow knife aeration treatments.

	Sampling depth					
	0 to 2.5 cm	**0 to 5 cm**	**0 to 15 cm**	**0 to 2.5 cm**	**0 to 5 cm**	**0 to 15 cm**
Season	--------Mehlich I, mg P kg^{-1}---------			----------WSP, mg P kg^{-1}----------		
Fall 2005	**178.9 (70.5)**	**107.7 (39.6)**	**53.5 (12.9)**	**53.4 (15.6)**	**28.5 (7.3)**	**7.3 (1.8)**
Spring 2006	**243.3 (27.1)**	**177.1 (34.7)**	**72.3 (20.5)**	**83.1 (10.9)**	**49.2 (13.9)**	**20.9 (4.4)**
Fall 2006	**189.4 (100.7)**	**130.2 (86.4)**	**73.8 (58.7)**	**76.3 (16.0)**	**47.4 (7.6)**	**19.5 (2.8)**
Spring 2007	**257.1 (45.4)**	**196.5 (33.0)**	**83.5 (17.9)**	**69.6 (18.7)**	**43.0 (12.7)**	**13.3 (6.4)**

Table 3.4. Estimates of channelized flow density (flow length per field area) determined from digital elevation models for thresholds of greater than 500,000 and 100,000 pixels (4-cm^2 pixels)

	----Drainage threshold, pixels----	
	> 500,000	**> 100,000**
Field	--------Flow density, km ha^{-1}--------	
1	**0.85**	**1.93**
2	**0.87**	**1.96**
4	**0.69**	**1.48**
5	**0.71**	**1.64**
3	**0.77**	**1.78**
6	**0.88**	**1.79**

Fig. 3.1. Distribution of soil series: Cecil (fine, kaolinitic, thermic, Typic Kanhapludults), Altavista (fine-loamy, mixed, semiactive, thermic Aquic Hapludults), Helena (fine, mixed, semiactive, thermic Aquic Hapludults), and Sedgefield (fine, mixed, active, thermic Aquic Hapludults) as labeled on the map (shades of gray represent drainage classes (well-drained, moderately well-drained, and poorly-drained) for each field; Fields 2, 5, and 6 were aerated).

Fig. 3.2. Estimates of channelized flow density determined from digital elevation models for thresholds of greater than 500,000 and 100,000 pixels (4-cm^2 pixels).

Fig. 3.3. Rainfall distribution for entire study period from before aeration (1995 to 1998) to slit aeration (2001 to 2003) and continuous-furrow knife aeration (2005 to 2007). Amount of rainfall (mm) for each rainfall event is represented by a vertical bar.

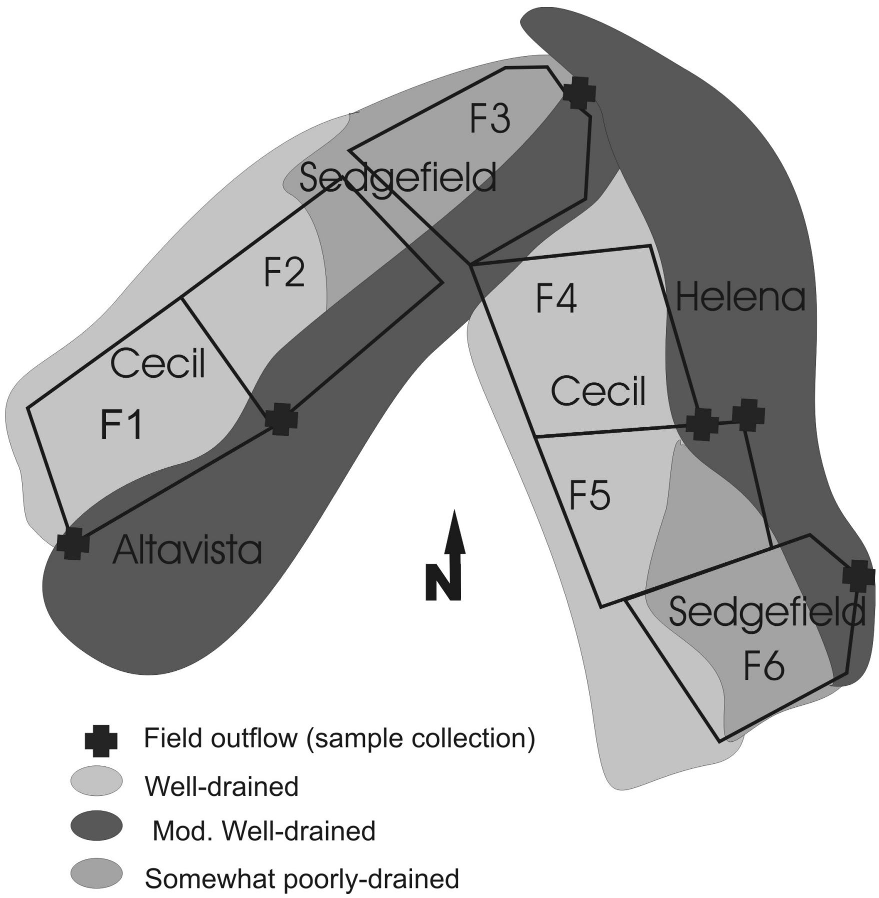
Fig. 3.4. Runoff volumes from continuous-furrow knife aerated (*y* axis) and nonaerated fields (*x* axis) “Before” any aeration period and “After” continuous-furrow knife aeration. (a) Fields 1 and 2, (b) Fields 4 and 5, and (c) Fields 3 and 6.

Fig. 3.5. Concentrations and mass losses of (a) and (c) total P (TP) and (b) and (d) dissolved reactive P (DRP) in runoff from Field 2 (aerated, *y* axis) and Field 1 (nonaerated, *x* axis) “Before” any aeration period and “After” continuous-furrow knife aeration.

Fig. 3.6. Concentrations and mass losses of (a) and (c) total P (TP) and (b) and (d) dissolved reactive P (DRP) in runoff from Field 5 (aerated, *y* axis) and Field 4 (nonaerated, *x* axis) “Before” any aeration period and “After” continuous-furrow knife aeration.

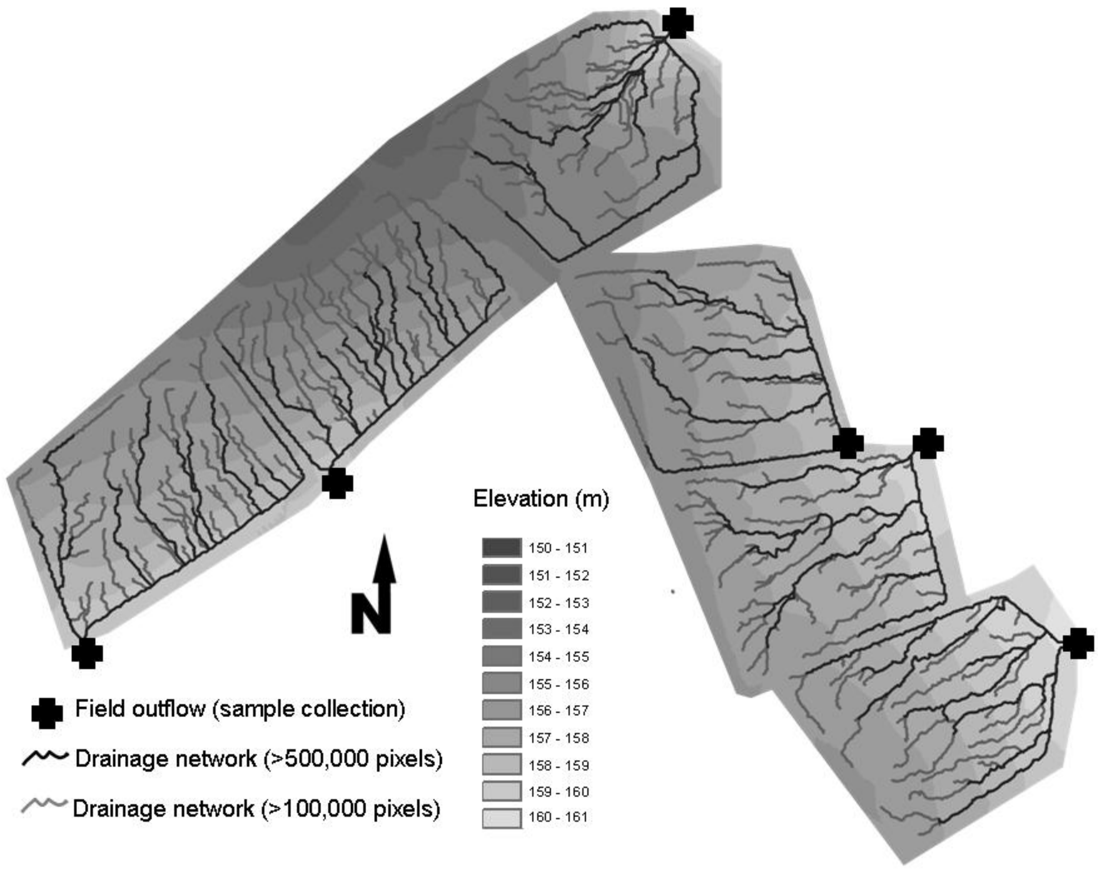
Fig. 3.7. Concentrations and mass losses of (a) and (c) total P (TP) and (b) and (d) dissolved reactive P (DRP) in runoff from Field 6 (aerated, *y* axis) and Field 3 (nonaerated, *x* axis) “Before” any aeration period and “After” continuous-furrow knife aeration.

Fig. 3.1



F3
Sedgefield
F2
Cecil
F1
Altavista
F4
Helena
Cecil
F5
Sedgefield
F6
N
Field outflow (sample collection)
Well-drained
Mod. Well-drained
Somewhat poorly-drained

Fig. 3.2.



Elevation (m)
150 - 151
151 - 152
152 - 153
153 - 154
154 - 155
155 - 156
156 - 157
157 - 158
158 - 159
159 - 160
160 - 161
N
Field outflow (sample collection)
Drainage network (>500,000 pixels)
Drainage network (>100,000 pixels)

Fig. 3.3.

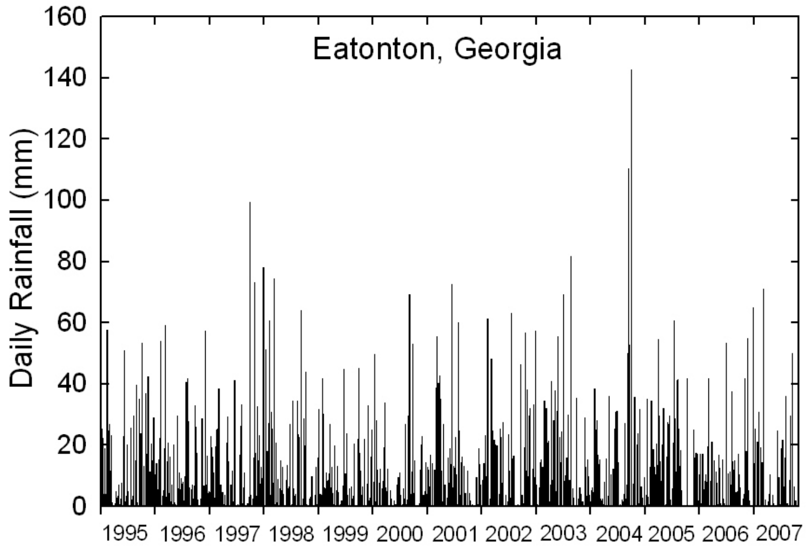

Eatonton, Georgia
Daily Rainfall (mm)
0
20
40
60
80
100
120
140
160
1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007

Fig. 3.4.

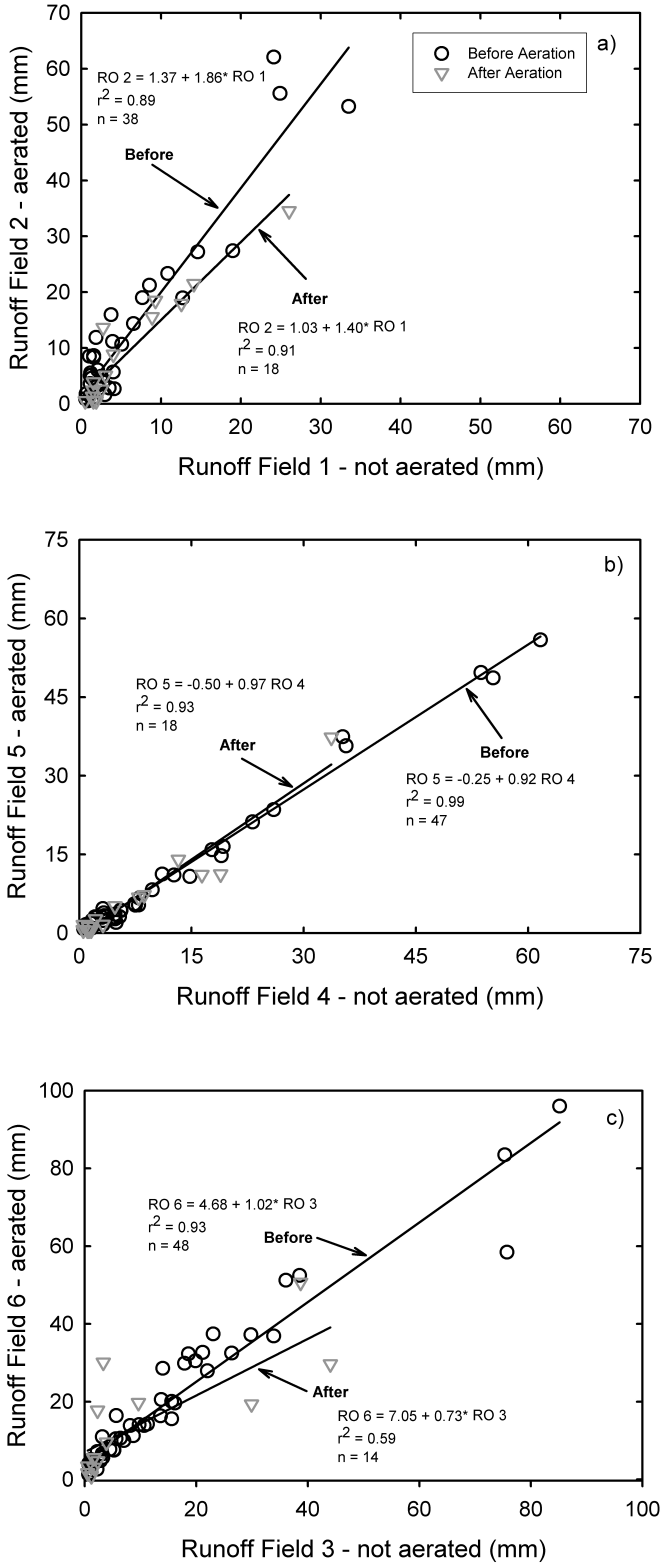
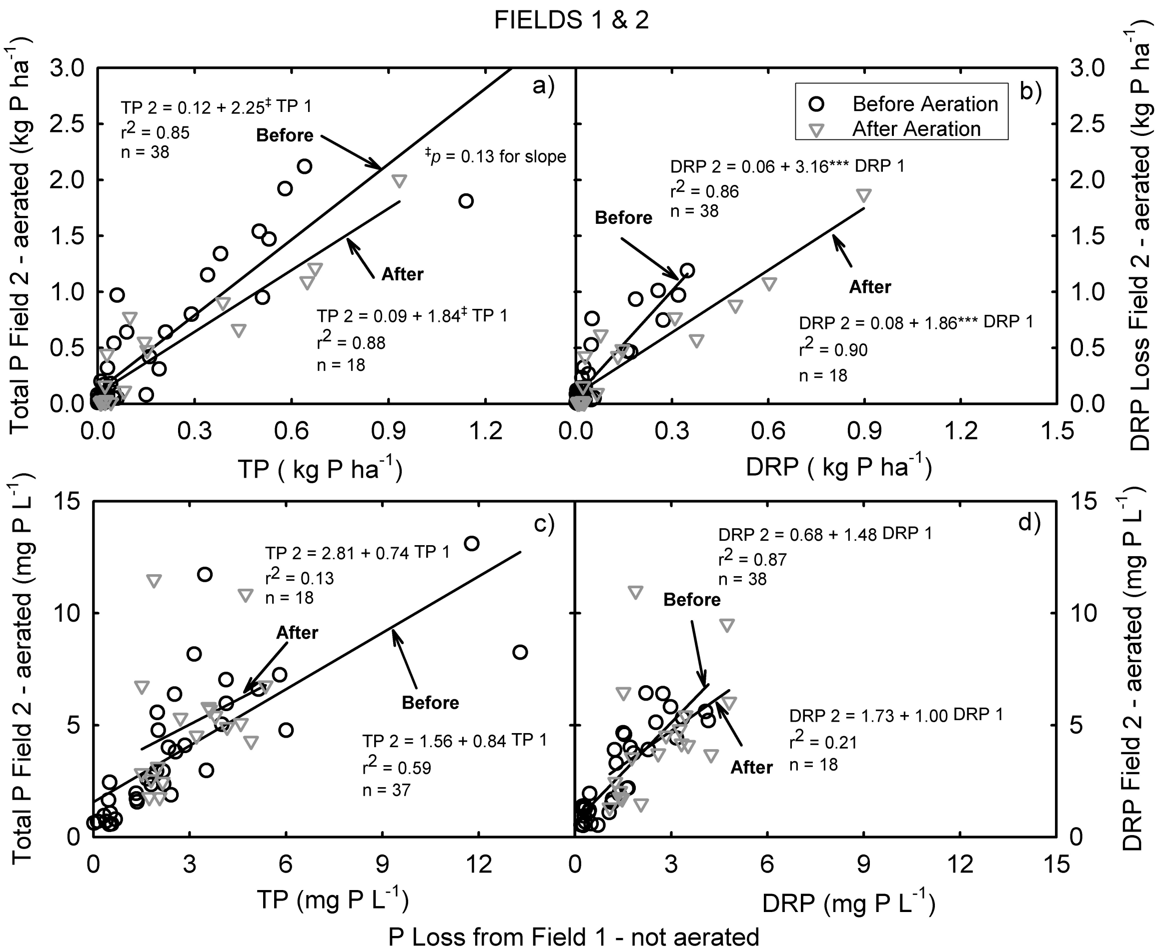
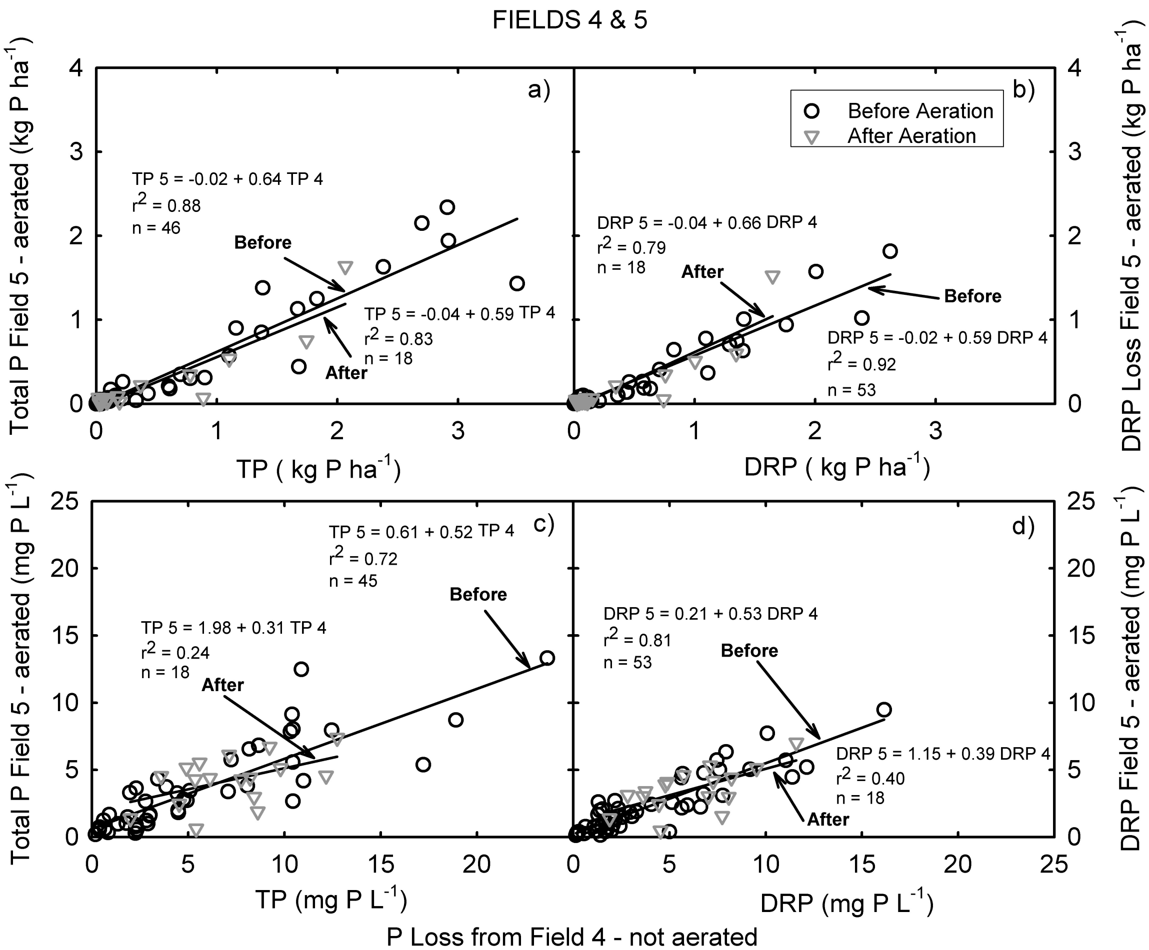

a)
Before Aeration
After Aeration
RO 2 = 1.37 + 1.86* RO 1
r2 = 0.89
n = 38
Before
After
RO 2 = 1.03 + 1.40* RO 1
r2 = 0.91
n = 18
Runoff Field 2 - aerated (mm)
Runoff Field 1 - not aerated (mm)
b)
RO 5 = -0.50 + 0.97 RO 4
r2 = 0.93
n = 18
After
Before
RO 5 = -0.25 + 0.92 RO 4
r2 = 0.99
n = 47
Runoff Field 5 - aerated (mm)
Runoff Field 4 - not aerated (mm)
c)
RO 6 = 4.68 + 1.02* RO 3
r2 = 0.93
n = 48
Before
After
RO 6 = 7.05 + 0.73* RO 3
r2 = 0.59
n = 14
Runoff Field 6 - aerated (mm)
Runoff Field 3 - not aerated (mm)

Fig. 3.5.



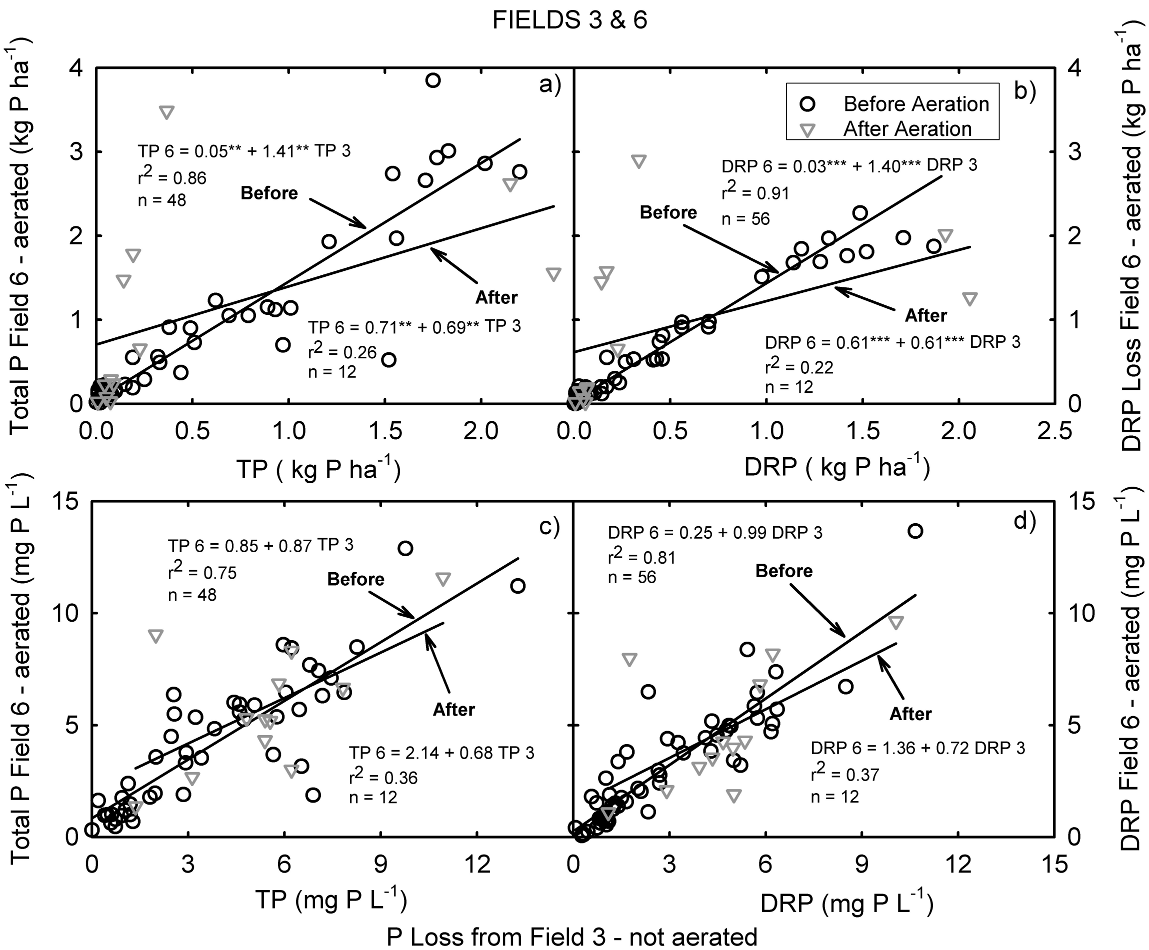
FIELDS 1 & 2
a)
TP 2 = 0.12 + 2.25‡ TP 1
r2 = 0.85
n = 38
Before
‡p = 0.13 for slope
After
TP 2 = 0.09 + 1.84‡ TP 1
r2 = 0.88
n = 18
b)
Before Aeration
After Aeration
DRP 2 = 0.06 + 3.16*** DRP 1
r2 = 0.86
n = 38
Before
After
DRP 2 = 0.08 + 1.86*** DRP 1
r2 = 0.90
n = 18
Total P Field 2 - aerated (kg P ha-1)
DRP Loss Field 2 - aerated (kg P ha-1)
TP (kg P ha-1)
DRP (kg P ha-1)
c)
TP 2 = 2.81 + 0.74 TP 1
r2 = 0.13
n = 18
After
Before
TP 2 = 1.56 + 0.84 TP 1
r2 = 0.59
n = 37
d)
DRP 2 = 0.68 + 1.48 DRP 1
r2 = 0.87
n = 38
Before
After
DRP 2 = 1.73 + 1.00 DRP 1
r2 = 0.21
n = 18
Total P Field 2 - aerated (mg P L-1)
DRP Field 2 - aerated (mg P L-1)
TP (mg P L-1)
DRP (mg P L-1)
P Loss from Field 1 - not aerated

Fig. 3.6.



FIELDS 4 & 5
a)
b)
Before Aeration
After Aeration
TP 5 = -0.02 + 0.64 TP 4
r2 = 0.88
n = 46
Before
TP 5 = -0.04 + 0.59 TP 4
r2 = 0.83
n = 18
After
DRP 5 = -0.04 + 0.66 DRP 4
r2 = 0.79
n = 18
After
Before
DRP 5 = -0.02 + 0.59 DRP 4
r2 = 0.92
n = 53
Total P Field 5 - aerated (kg P ha-1)
DRP Loss Field 5 - aerated (kg P ha-1)
TP (kg P ha-1)
DRP (kg P ha-1)
c)
d)
TP 5 = 0.61 + 0.52 TP 4
r2 = 0.72
n = 45
Before
TP 5 = 1.98 + 0.31 TP 4
r2 = 0.24
n = 18
After
DRP 5 = 0.21 + 0.53 DRP 4
r2 = 0.81
n = 53
Before
DRP 5 = 1.15 + 0.39 DRP 4
r2 = 0.40
n = 18
After
Total P Field 5 - aerated (mg P L-1)
DRP Field 5 - aerated (mg P L-1)
TP (mg P L-1)
DRP (mg P L-1)
P Loss from Field 4 - not aerated

Fig. 3.7.


FIELDS 3 & 6
Total P Field 6 - aerated (kg P ha-1)
DRP Loss Field 6 - aerated (kg P ha-1)
Total P Field 6 - aerated (mg P L-1)
DRP Field 6 - aerated (mg P L-1)
a)
b)
c)
d)
Before Aeration
After Aeration
TP 6 = 0.05** + 1.41** TP 3
r2 = 0.86
n = 48
TP 6 = 0.71** + 0.69** TP 3
r2 = 0.26
n = 12
DRP 6 = 0.03*** + 1.40*** DRP 3
r2 = 0.91
n = 56
DRP 6 = 0.61*** + 0.61*** DRP 3
r2 = 0.22
n = 12
TP 6 = 0.85 + 0.87 TP 3
r2 = 0.75
n = 48
TP 6 = 2.14 + 0.68 TP 3
r2 = 0.36
n = 12
DRP 6 = 0.25 + 0.99 DRP 3
r2 = 0.81
n = 56
DRP 6 = 1.36 + 0.72 DRP 3
r2 = 0.37
n = 12
Before
After
TP (kg P ha-1)
DRP (kg P ha-1)
TP (mg P L-1)
DRP (mg P L-1)
P Loss from Field 3 - not aerated

CHAPTER 4

ON-FARM, FIELD-SCALE RUNOFF AND SOIL PHOSPHORUS AS RELATED TO GRASSLAND MANAGEMENT, LANDSCAPE MORPHOLOGY, AND THE GEORGIA PHOSPHORUS INDEX[1]

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[1]Butler, D.M., D.H. Franklin, M.L. Cabrera, L.M. Risse, L.T. West, and J.W. Gaskin. To be submitted to J. Soil Water Conserv.

ABSTRACT

In order to better manage agricultural P, most states in the USA have adopted a “P indexing” approach which ranks fields according to potential vulnerability for losses of P. In Georgia, the Georgia P Index was developed to estimate the risk of bioavailable P loss from agricultural land to surface waters considering sources of P, transport mechanisms, and management practices. Given the limited nature of available data on runoff P from varying agricultural management practices, data collected on-farm at the field-scale will be useful in examining the performance of the Georgia P Index. As such, nine farm fields, managed as pasture or hay systems were outfitted with a total of 28 small in-field runoff collectors (SIRCs) and runoff P, soil P, and management practices were monitored from 2004 to 2007. Nutrient treatment of fields varied from those rich in P (broiler litter or dairy slurry) to those without P amendments (inorganic nitrogen (N) or no amendments). Data relating to nutrient applications, soil properties, soil P, slope, and cropping management were used as input values to determine a Georgia P Index value indicating the risk of P export from each field. Results indicated that levels of P export from fields corresponded well to risk ratings calculated by the Georgia P Index given that only 4% of observations produced DRP export greater than the level of risk calculated using the Georgia P Index. Measured P export was generally low to moderate (< 7 kg P ha^{-1} yr^{-1}) from fields rated as a low or medium risk of P export. Results also indicated that nutrient source (broiler litter, dairy slurry, inorganic N, and no amendments), forage system (hay or pasture), and year were significant factors affecting the risk of edge-of-field P losses.

INTRODUCTION

The Southern Piedmont, USA is dominated by beef cattle-poultry grassland systems. In these systems, nutrient imports in the form of fertilizers and poultry feed tend to be far greater than nutrient exports at both the farm scale and regional scale. Most generated wastes are applied to pasture land as good agronomic practice. Manures are typically applied at a rate that will meet the N requirements of the forage crop. Crops typically require from 5 to 10 kg of available N per kg of available P (Lander et al., 1998). However, manures typically have a much lower N to P ratio, such as 2.2 kg N per kg P for broiler litter (Sims and Wolf, 1994). In this case, applied P is disproportionately high leading to an accumulation of P in the soil, making it vulnerable to transport during storm events either in particulate or dissolved form.

In pastured systems, most P is recycled by the grazing animals and little is removed, which can increase the amount of available P in runoff (Kuykendall et al., 1999). The integration of haying into farming operations dominated by grazing in the Southern Piedmont may allow farmers to better balance nutrient imports and exports to their farms. For example, Mehlich I soil P has been shown to remain at a constant level with haying of bermudagrass, even when broiler litter was applied at excess rates of P (Franzluebbers et al., 2002). Similarly, Sigua et al. (2004) reported that when haying was paired with grazing, soil P levels remained constant. Additionally, cool-season forages such as annual ryegrass (*Lolium multiflorum* Lam.) have been shown to uptake a relatively high amount of P in comparison with several other forage species (Brink et al., 2001; Evers, 2002). Mikhailova et al. (2003) reported that intensively managed orchardgrass (*Dactylis glomerata* L.) or tall fescue (*Festuca arundinacea* Schreb.) can remove large quantities of P from manure-impacted soils (as much as 48.5 kg P ha^{-1} annually).

However, data is lacking on the impact of these integrated systems on P export in runoff from farms in the Southern Piedmont.

In order to better manage agricultural P, 47 states have adopted a “P indexing” approach which ranks sites according to potential vulnerability for losses of P (Sharpley et al., 2003). Generally, the P indexing approach to P management works by accounting for P-source factors and P-transport factors. Source factors include STP and fertilizer or manure applications, whereas transport factors include runoff, erosion, leaching, and proximity to streams. Other modifying factors may include soil texture, pH, P sorption capacity, flooding frequency, and various conservation factors (Sharpley et al., 2003).

The Georgia P Index (Cabrera et al., 2002; Gaskin et al., 2005) was developed to estimate the risk of bioavailable P loss from agricultural land to surface waters considering P-source factors, P-transport factors, as well as management practices which may impact P export. Potential export of bioavailable P is divided into three loss pathways: (1) soluble P in runoff, (2) particulate P in surface runoff, and (3) soluble P in leachate. Within each pathway, P-source factors (STP, inorganic fertilizer P, or organic fertilizer P) are adjusted according to management practices and summed to obtain a source risk rating. Similarly, transport risk ratings are determined using factors such as risk of runoff, risk of sediment loss, and risk of leaching, respectively for the three pathways. Additional factors, such as vegetative buffer widths and depth to water table are also considered. Risk ratings for each transport pathway are summed, and a numerical P index value is determined in order to place a field within four categories (low, medium, high, or very high) of risk for export of bioavailable P to surface waters. Unlike the P management approach in 3 states, the majority of U.S. states (including Georgia) do not use P indexing to attempt to quantify losses of P from agricultural fields.

Generally, there has not been extensive field-scale validation of P indices, though a few studies have examined the performance of the various P indices. Leytem et al. (2003) calculated P index ratings for 272 fields in Delaware and reported that the majority of fields were in the "low" risk category, with only 28% of fields indicating that P-based management would be required. The authors contrasted this with the finding that 55% of all fields evaluated had "excessive" soil test P values and that approximately 14% of fields in the "low" rating category had unsustainable levels of soil erosion. Veith et al. (2005) compared P index values computed using the Pennsylvania P Index for 22 agricultural fields under field crop management to total P loss calculated by SWAT (Soil and Water Assessment Tool). The correlation between predicted values from the two assessment tools was significant at $p = 0.002$, with 73% of fields ranked similarly by the two tools. Of the remaining fields, half were under-predicted and half over-predicted.

In the Southern Plains area of Oklahoma and Texas, Sharpley (1995) evaluated 30 watersheds, the majority of which were less than 5 ha, and compared the original Lemunyon and Gilbert (1993) P field index values to measured values of total P export over 16 years. Watersheds included both cropping and grassland management, as well as both P fertilized and unfertilized management. The author reported a close logarithmic relationship between measured losses of total P and P index ratings [P Index = -5.7 + 6.3log(total P loss); $r^2 = 0.70$]. In Arkansas, Delaune et al. (2004) measured annual P losses from two 0.4-ha watersheds with untreated poultry litter applied annually to one plot and alum-treated poultry litter applied to the second. The authors compared the range of P index values over 6 years of management to actual annual P losses from the field watersheds. The P index was rather successful in estimating the risk of P losses from these two field watersheds, as shown by a strong linear relationship (r^2 = 0.83, $p < 0.0001$).

Using six cultivated and four pasture watersheds ranging from 3 to 20.8 ha in the Texas Blackland Prarie (predominance of Vertisols), Harmel et al. (2006) compared estimated P loss potentials determined from the Texas, Arkansas, and Iowa P Indices to measured P losses. In general, all three P indices were more highly correlated with dissolved P loads and concentrations than with total P and particulate P loads or concentrations. On pastured watersheds, dissolved P concentrations were well correlated with all three P index ratings: r^2 = 0.86, 0.90, and 0.84 for the Texas, Iowa, and Arkansas Indices, respectively. The authors suggested that variation in soil erosion was a limitation of the three indices in that variation in annual soil erosion can introduce substantial error into ratings of the risk of P export.

Given the limited nature of available data of runoff P from varying agricultural management practices in Southern Piedmont grasslands, data collected on-farm at the field-scale will be useful to examine how field management and landscape affect soil P levels and edge-of-field losses of P in runoff. Additionally, a comparison of measured losses of runoff P to risk ratings for P loss calculated by the Georgia P Index will be useful for farmers and agricultural professionals using this nutrient management tool to prevent excessive export of P from agricultural fields.

MATERIALS AND METHODS

In 1998, 28 small in-field runoff collectors (SIRCs; Franklin et al., 2001) were placed in 9 farm fields in cooperation with private land owners in northeast Georgia to evaluate the effect of agricultural management practices on surface water quality. This study presents data collected on these fields from 2004 through 2007. Field management was classified into five categories: (A) unimproved tall fescue-common bermudagrass (*Cynodon dactylon* L.) pasture with manure or nutrient amendments, (B) hay fields with applied inorganic nitrogen (N), (C) unimproved tall fescue-common bermudagrass pasture with applied broiler litter, (D) hay systems with applied dairy slurry, and (E) hay systems with applied broiler litter (Table 4.1). Fields in management class B and E were transitioned from tall fescue-common bermudagrass to improved hay systems in either 2004 or 2005.

Beginning in late 2004 and continuing during the winter of each year for four years, soil cores (5-cm internal diameter) were taken to a 10 cm depth in triplicate at three points along a transect extending from the SIRC to the top of the hillslope of the contributing area (with point A at ~10 m in front of the SIRC, point C at ~10 m from the top of the hillslope of the contributing area, and point B taken halfway between points A and C). Soil samples were air-dried and sieved (< 2 mm) and then analyzed for Mehlich I soil P using methods described by Mehlich (1953). Resulting filtrate was analyzed according to the molybdate blue method (Murphy and Riley, 1962). A subsample was dried at 105ºC for 48 h to determine gravimetric soil moisture content.

Runoff was monitored throughout the study period and samples collected to determine concentrations of TP and DRP. Unfiltered runoff samples were analyzed colorimetrically for TP following a Kjeldahl digestion (USEPA, 1979). Samples were filtered (0.45 µm) and subsequent filtrate analyzed for DRP by the molybdate blue method (Murphy and Riley, 1962). Due to a large number of runoff events where the capacity of the SIRCs was exceeded, runoff was calculated using the curve number method. Curve numbers were determined by soil types and observations of management and cover at the fields throughout the study. In general, 2004 and

2005 had more large volume rainfall events and greater annual rainfall than 2006 and 2007 (Fig. 4.1A, 4.1B). Concentrations determined from field sampling were then multiplied by calculated runoff volumes to determine nutrient loads.

In order to determine the contributing area of each of the 28 SIRCs, high resolution digital elevation models (DEMs) were created from global positioning system (GPS) measurements taken in the field. Points were collected by mounting a Leica Wild SR399E sensor (Leica Geosystems, Heerbrugg, Switzerland) with an AT302 antenna equipped with a CR 344 controller onto a utility vehicle. A 2-way radio system (Pacific Crest, Santa Clara, California) was used in order for real-time corrections to be made in the field. Kinematic sampling mode was utilized with measurements recorded automatically every 2 m, while following circular paths in the watershed at the width of the utility vehicle (~1.5 m). Horizontal precision was set to collect points at an error of 4 cm or less. In terms of accuracy for the elevation or vertical coordinate, Van Niel *et al.* (2004) suggested that the vertical error is approximately 2.5 times the horizontal. Yao and Clark (2000), however, suggested that vertical error from a global positioning system (GPS) receiver is 1.5 times the horizontal error. In this sense, it can be said that the vertical error in this experiment was less than 10 cm, at worst. The base station consisted of Leica Wild SR299 sensor and also a CR 344 controller assembled on a tripod.

Data points were loaded into Arc/Tools, a component of the Arc/GIS workstation, where a point coverage file was created. The coverage file was then imported in Arc/Map. In Arc/Map, ordinary kriging interpolation using a spherical semivariogram model was used to interpolate a surface with 5 cm by 5 cm pixels based on the elevation of the collected data points. The hydrology functions in Arc/Map were then used to fill any sinks in this DEM. This function eliminates depressions of elevation which would otherwise prevent interpretation of flow paths from the DEM as the model would expect water to enter these sinks, but not exit. The direction of flow of each pixel (25-cm^2) and the flow accumulation (number of other pixels of cumulative flow which flow into a specified pixel) were then also determined. The results of the flow accumulation procedure were then used to determine the concentrated flow with pixels draining more than 25,000 pixels. Contributing areas were then calculated by assigning the pour points at the locations of the SIRCs and executing the Arc/Map watershed function. Drainage density was determined by calculating the total length of the concentrated flow paths in each contributing area and dividing by the contributing area (m m^{-2}).

Estimates of annual erosion were calculated by RUSLE2 (User's Reference Guide: Revised Universal Soil Loss Equation (RUSLE2), 2003) using corresponding climate, slope, soil properties, and management factors. Average slope and overland flow path length were calculated for each contributing area (Table 4.2). Overland flow path length as used in RUSLE2 is defined as length from the area where overland flow begins to a point where it is deposited in a gully or channel. For the purposes of this study, the deposition point will be considered as the location of the SIRC, making the overland flow path length the distance from the top of the hillslope to the location where sediments are deposited in the SIRC.

Management data was collected from each farm in order to calculate the risk of P losses for the contributing areas of each SIRC for each year using the Georgia P Index. Dates and rates of manure applications were determined in farmer interviews. Mean Mehlich I soil P for each collector and each year was used as the input for soil test P value (mean soil samples taken at points A, B, and C in each contributing area). Given that soil samples were taken in the winter of each season, the soil P value for 2004 was taken after any 2004 manure applications. In this case, the Georgia P Index was calculated without adding in applied manures for that year, as the applied manure P would be expected to be represented in the soil P value.

Soil P, applied manure P, Georgia P Index risk ratings, and mass export of DRP and TP were examined by field for each year. The influence of nutrient source (broiler litter, dairy slurry, inorganic N, or none), forage system (hay or pasture), year, slope, drainage density, soil P and relevant interactions on mass annual export of DRP and TP were examined using PROC GLM (SAS Institute, 1994). Soil P values and Georgia P Index values for each field were regressed against P loads and examined using PROC GLM. Adjusted means were separated using the pdiff option.

RESULTS AND DISCUSSION

Soil P

Soil P varied considerably at each field throughout the study (Fig. 4.2) and was significantly related to nutrient source (Table 4.3). While soil P was generally constant in each field throughout the study, there were some relatively high years on Fields E, H, and I (Fig. 4.2). This was somewhat surprising given no major management changes in these fields during those years. Higher soil P levels in 2007 in fields H and I may have been partially due to droughty weather, reducing both crop growth and the number of hay cuttings (and associated P removal).

The highest soil P values were observed from systems with applied broiler litter (Fig. 4.3). Soil P levels on fields with either applied dairy slurry, inorganic N, or no amendments did not differ. While this may be surprising, it is also important to note that just one field each was monitored with either applied dairy slurry or inorganic N.

Georgia P Index

The Georgia P Index was used to calculate the risk of P loss for the contributing areas of each SIRC (28) for each of the 4 years of the study. Applications of manure P (Fig. 4.4) were used as inputs along with soil, management, and landscape data collected. Averaged across field, risk ratings calculated by the P Index were predominantly in the low risk category (Fig. 4.5). The exceptions were generally fields under pasture management with applied broiler litter where medium risk ratings were more common, as well as one field under hay management with applied broiler litter. In these risk rating categories, no changes in management are suggested by the Georgia P Index. The slightly higher P Index risk ratings on fields under pasture management with applied broiler litter compared to fields under hay management with applied broiler litter are partly a result of larger curve number estimates and greater soil erosion estimates due to lower soil cover and associated impacts of grazing livestock.

P Export in Runoff

With annual export of DRP, the main effects of nutrient source ($p < 0.01$), forage ($p < 0.001$), and year ($p < 0.05$) were significant (Table 4.3). With annual TP export, main effects of nutrient source ($p < 0.01$), forage ($p < 0.001$), and year ($p < 0.05$) were likewise significant. For most fields, annual export of DRP was rather low (Fig. 4.6), near background levels associated with grazing of less than 1 kg P ha^{-1} yr^{-1} (Kuykendall et al., 1999). With applied broiler litter on pasture systems, average annual DRP export was in some cases greater than 4 kg P ha^{-1} yr^{-1} which is nearly as high as that reported by Pierson et al. (2001) for pastures in the Southern Piedmont receiving high rates of broiler litter application. Similarly, TP was generally highest from those fields under pasture management with applied broiler litter (Fig. 4.7). There was also a high export of TP from Field A in year 2004, which may have been a result of cattle loafing areas near the SIRCs combined with the high levels of rainfall observed that year.

As indicated in the multiple regression, the main effects of year, nutrient source, and forage system were significantly related to export of DRP. As related to year, DRP export was highest in 2004 and 2005 and lowest in 2006 and 2007 (Fig. 4.8). This was somewhat similar to precipitation patterns (Fig. 4.1B), though DRP export seems to have decreased by a larger percentage than did rainfall. With nutrient source, DRP export did not differ among fields with applied broiler litter, dairy slurry, or inorganic N (Fig. 4.9). Export of DRP from these three nutrient sources was greater than that from fields with no nutrient amendments. The relatively high level of DRP export from the field with inorganic N would seem to be related to higher soil P levels than those observed in fields with no nutrient amendments (Fig 4.2). This is likely due to historic broiler litter application to this field. When separated by forage system, export of DRP from pasture systems was significantly greater than that observed under hay management (Fig. 4.10). This is likely related to decreased cover in pasture systems as a result of grazing, as well as soil compaction and deposition of feces and urine by the grazing livestock in close proximity to the SIRC. Additionally, many of the SIRCs are placed at the field edge, where they are more likely to be shaded and thus are areas were cattle tend to congregate (Belsky et al., 1999). These lounging areas are often characterized by reduced forage ground cover, increased compaction, and higher numbers of feces and urine depositions.

Soil P values taken in the contributing area of each SIRC during each year were regressed against annual export of DRP and TP (data not shown). In this case, soil P levels were not significantly related to annual export of DRP or TP in runoff ($p > 0.1$). Additionally, soil P levels at points A, B, and C along the flow path length of the contributing area were each regressed against measured P export in runoff (data not shown). Somewhat surprisingly, soil P levels at point C were related to P export (p = 0.11), whereas soil P levels at points A and B were not. It is unclear why soils at point C seem to have a greater influence on P export in runoff.

Overall, these values of annual export of DRP and TP are rather low (< 4 kg P ha^{-1}) for pasture and hayfields in the Southern Piedmont region. While this may be partly due to the rather droughty conditions throughout this study, it is encouraging to note that the farm fields monitored during this study were not exporting large amounts of P out of the system.

Phosphorus Export as Compared to the Georgia P Index

The risk rating calculated for each SIRC and each year by the Georgia P Index was regressed against annual export of DRP (Fig. 4.11). This research focused on DRP rather than TP, as the Georgia P Index was developed to estimate the risk of bioavailable P losses (Cabrera et al., 2002), which is more closely represented by DRP than TP (Butler et al., 2008). Export of DRP in runoff was significantly related to Georgia P index values (p < 0.05), though the r^2 was rather low (0.03). This regression was also examined separately on fields without P amendments and fields with P amendments, though this did not improve the relationship.

Of the 112 observations of the Georgia P Index (28 SIRCs *x* 4 yr), 18 were calculated in the medium risk category (Georgia P Index value > 40, 16%) and 94 were calculated in the low risk category (84%). Of the 94 observations in the low risk category, all but 4 (96%) also exhibited what can be classified as low total annual export of DRP (< 4 kg P ha^{-1} yr^{-1}; Fig. 4.11). Of the 18 observations in the medium risk category, all but 1 (94%) exhibited low annual DRP export. The lone outlying observation with rather high annual DRP export (~16 kg P ha^{-1} yr^{-1}) is speculated to have resulted from cattle lounging and feeding in the area of the SIRC.

CONCLUSIONS

Results from the on-farm, field-scale data in this study suggested that the Georgia P Index worked well in classifying the risk of P export from the farms monitored. Monitored fields generally exhibited rather low to moderate levels of annual P export (< 7 kg P ha^{-1} yr^{-1}) and were classified by the Georgia P Index into low or medium risk categories that did not suggest a change in management to reduce the risk of P losses. In just 5 of 112 observations (4%), was the level of DRP export was greater than the risk rating calculated using the Georgia P Index. Results also indicated that nutrient source (broiler litter, dairy slurry, inorganic N, or no amendments), forage system (hay or pasture), and year were significant factors affecting edge-of-field P losses. Future research examining farms with a higher nutrient status that would place them in a higher category of risk for export of P would be useful in further examining the performance of the Georgia P Index in pastures and hayfields.

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REFERENCES

Belsky, A.J., A. Matzke, and S. Uselman. 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. J. Soil Water Conserv. 54:419-431.

Brink, G.E., G.A. Pederson, K.R. Sistani, and T.E. Fairbrother. 2001. Uptake of selected nutrients by temperate grasses and legumes. Agron. J. 93:887-890.

Butler, D.M., D.H. Franklin, M.L. Cabrera, A.S. Tasistro, K. Xia, and L.T. West. 2008. Evaluating aeration techniques for decreasing phosphorus export from grasslands receiving manure. J. Environ. Qual. *(accepted 18 Dec 2007)*.

Cabrera, M.L., D.H. Franklin, G.H. Harris, V.H. Jones, H.A. Kuykendall, D.E. Radcliffe, L.M. Risse, and C.C. Truman. 2002. The Georgia Phosphorus Index. Cooperative Extension Service, Publication Distribution Center, University of Georgia, Athens, GA. 4pp.

DeLaune, P.B., P.A. Moore, Jr., D.K. Carman, A.N. Sharpley, B.E. Haggard, and T.C. Daniel. 2004. Evaluation of the phosphorus source component in the phosphorus index for pastures. J. Environ. Qual. 33:2192-2200.

Evers, G.W. 2002. Ryegrass-bermudagrass production and nutrient uptake when combining nitrogen fertilizer with broiler litter. Agron. J. 94:905-910.

Franklin, D.H., M.L. Cabrera, J.L. Steiner, D.M. Endale, and W.P. Miller. 2001. Evaluation of percent flow captured by a small in-field runoff collector. Transactions of the ASAE 44:551-554.

Franzluebbers, A.J., J.A. Stuedemann, and S.R. Wilkinson. 2002. Bermudagrass management in the Southern Piedmont USA. II. Soil phosphorus. Soil Sci. Soc. Am. J. 66:291-298.

Gaskin, J.W., K. Harris, M.L. Cabrera, and L.M. Risse. 2005. Using the Georgia P-Index to identify high risk management of poultry litter, *In* K. J. Hatcher, ed. Proc. of the 2005 Georgia Water Resources Conference, Athens, GA. 25-27 April 2005.

Harmel, D., S. Potter, P. Casebolt, K. Reckhow, C. Green, and R. Haney. 2006. Compilation of measured nutrient load data for agricultural land uses in the United States. J. Am. Water Resour. Assoc. 42:1163-1178.

Kuykendall, H.A., M.L. Cabrera, C.S. Hoveland, M.A. McCann, and L.T. West. 1999. Stocking method effects on nutrient runoff from pastures fertilized with broiler litter. J. Environ. Qual. 28:1886-1890.

Lander, C.H., D. Moffitt, and K. Alt. 1998. Nutrients available from livestock manure relative to crop growth requirements. Resource Assessment and Strategic Planning Working Paper 98-1, USDA-NRCS. Available at: http://www.nrcs.usda.gov/technical/land/pubs/nlweb.html.

Lemunyon, J.L., and R.G. Gilbert. 1993. The concept and need for a phosphorus assessment tool. J. Prod. Agric. 6:483-486.

Leytem, A.B., J.T. Sims, and F.J. Coale. 2003. On-farm evaluation of a phosphorus site index for Delaware. J. Soil Water Conserv. 58:89-97.

Mehlich, A. 1953. Determination of P, K, Ca, Mg, and NH_4. North Carolina Soil Test Div. (Mimeo), Raleigh, NC.

Mikhailova, E.A., J.H. Cherney, and D.J.R. Cherney. 2003. Impact of phosphorus from dairy manure and commercial fertilizer on perennial grass forage production. J. Agron. Crop Sci. 189:367-375.

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

Pierson, S.T., M.L. Cabrera, G.K. Evanylo, H.A. Kuykendall, C.S. Hoveland, M.A. McCann, and L.T. West. 2001. Phosphorus and Ammonium Concentrations in Surface Runoff from Grasslands Fertilized with Broiler Litter. J Environ Qual 30:1784-1789.

SAS Institute. 1994. SAS/STAT User's guide, Version 8. 2nd ed. SAS, Cary, NC.

Sharpley, A.N. 1995. Identifying sites vulnerable to phosphorus loss in agricultural runoff. J. Environ. Qual. 24:947-951.

Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A. Moore, Jr., and G. Mullins. 2003. Development of phosphorus indices for nutrient management planning strategies in the United States. J. Soil Water Conserv. 58:137-160.

Sigua, G.C., M.J. Williams, and S.W. Coleman. 2004. Levels and changes of soil phosphorus in subtropical beef cattle pastures. Commun. Soil Sci. Plant Anal. 35:975-990.

Sims, J.T., and D.C. Wolf. 1994. Poultry waste management: Agricultural and environmental issues. Adv. Agron. 52:1–83.

USEPA. 1979. Methods for chemical analysis of water and wastes. EPA-600/4-79-020. USEPA, Environmental monitoring and support laboratory, Cincinnati, OH.

User's Reference Guide: Revised Universal Soil Loss Equation (RUSLE2). 2003. National Sedimentation Laboratory. USDA-ARS Oxford, MS.

Van Niel, K.P., S.W. Laffan, and B.G. Lees. 2004. Effect of error in the DEM on environmental variables for predictive vegetation modelling. J. Veg. Sci. 15:747-756.

Veith, T.L., A.N. Sharpley, J.L. Weld, and W.J. Gburek. 2005. Comparison of measured and simulated phosphorus losses with indexed site vulnerability. Trans. ASAE 48:557-565.

Yao, H., and R.L. Clark. 2000. Evaluation of sub-meter and 2 to 5 meter accuracy GPS receivers to develop digital elevation models. Precis. Agric. 2:189-200.

TABLES AND FIGURES

Table 4.1. Field characteristics and management

Field	**Management**	**Crop**†	**P amendments**	**Forage management**	**Number of SIRCs**
A	A	Unimproved pasture (TF-CB)	none	pasture	3
B	A	Unimproved pasture (TF-CB)	none	pasture	3
C	A	Unimproved pasture (TF-CB)	none	pasture	3
D	B	Improved hay (PM-CR; summer ’05)‡	none (inorganic N)	hay	3
E	C	Unimproved pasture (TF-CB)	broiler litter	pasture	4
F	C	Unimproved pasture (TF-CB)	broiler litter	pasture	3
G	D	Improved hay (HB-W-A; summer ‘05) §	dairy slurry	hay	3
H	E	Improved hay (HB-AR; summer ‘04)	broiler litter	hay	3
I	E	Improved hay (HB-AR; summer ‘05)	broiler litter	hay	3

† A=Alfalfa (*Medicago sativa* L.), AR=Annual Ryegrass (*Lolium multiflorum* Lam.), CR=Cereal Rye (Secale *cereale* L.), CB= Common Bermudagrass (*Cynodon dactylon* L.), HB=Hybrid Bermudagrass (*Cynodon dactylon* L.), PM=Pearl Millet (*Pennisetum glaucum* (L.) R. Br.), TF=Tall Fescue (*Festuca arundinacae* Schreb.), W=Wheat (*Triticum* spp.).

‡Fields D, H, and I converted from tall fescue-common bermudagrass hay on date indicated in parentheses.

§Upper 1/3 of contributing area of SIRC 3 in Field G is planted in alfalfa, converted from corn silage in summer ’05.

Table 4.2. Characteristics of contributing areas to each small in-field runoff collector (SIRC)

Field-SIRC	**Contributing area (ha)**	**Mean slope (%)**	**Flow path length† (m)**	**Drainage density ($m\ m^{-2}$)**
A-1	0.196	8.0	60.6	0.12
A-2	0.601	3.7	119.0	0.12
A-3	0.188	8.6	88.5	0.13
B-1	0.090	9.8	113.8	0.17
B-2	0.343	8.7	158.1	0.15
B-3	0.107	8.3	79.8	0.12
C-1	0.093	11.1	95.9	0.13
C-2	0.054	10.9	70.5	0.11
C-3	0.056	7.6	77.7	0.14
D-1	0.336	4.8	104.7	0.13
D-2	0.453	5.4	103.3	0.12
D-3	0.006	8.5	16.1	0.04
E-1	0.065	5.7	48.4	0.08
E-2	0.009	13.9	14.7	0.01
E-3	0.056	8.3	50.7	0.07
E-4	0.047	6.5	55.8	0.10
F-1	0.058	14.3	75.9	0.12
F-2	0.176	8.3	120.0	0.15
F-3	0.136	6.3	149.6	0.06
G-1	0.300	5.2	119.2	0.15
G-2	0.085	7.9	62.5	0.14
G-3	6.038	2.7	594.8	0.13
H-1	0.075	4.3	45.8	0.14
H-2	0.097	5.3	63.3	0.13
H-3	0.740	4.2	161.7	0.14
I-1	0.023	1.9	28.4	0.09
I-2	0.248	5.2	50.1	0.10
I-3	0.056	5.2	40.1	0.07

†Distance from top of hillslope to the small in-field runoff collector (SIRC)

Table 4.3. Analysis of variance for soil P, total P, and dissolved reactive P

	Soil P	DRP	TP
Source	-------------------***p*-values**------------------		
Model	***	***	***
Hypothesis tests			
Nutrient source	***	**	**
Forage	**NS**	***	***
Year	**NS**	**	**
Forage*Year	*	†	†
Nutr. Source * Year	**NS**	**NS**	**NS**
Soil P	**N/A**	**NS**	**NS**
Slope	***	**NS**	**NS**
Drainage Density	**NS**	**NS**	**NS**
Slope * Drainage Density	*	**NS**	**NS**

†, *, **, ***, represent $p < 0.10$, 0.05, 0.01, 0.001 respectively; NS=not significant; N/A=not applicable

Fig. 4.1. Daily precipitation (A) and yearly precipitation (B) for Watkinsville, GA from 2004 to 2007.

Fig. 4.2. Mean Mehlich I soil phosphorus (P) at each field from 2004 to 2007 (field management indicated on graph).

Fig. 4.3. Mean Mehlich I soil phosphorus (P) as affected by nutrient source (bars indicated by the same letter are not significantly different, $p > 0.05$).

Fig. 4.4. Mean manure phosphorus (P) applied to each field from 2004 to 2007 (field management indicated on graph).

Fig. 4.5. Mean Georgia Phosphorus (P) Index values for each field from 2004 to 2007 (field management indicated on graph).

Fig. 4.6. Mean annual dissolved reactive phosphorus (DRP) export from each field from 2004 to 2007 (field management indicated on graph).

Fig. 4.7. Mean annual total phosphorus (TP) export from each field from 2004 to 2007 (field management indicated on graph).

Fig. 4.8. Mean annual dissolved reactive phosphorus (DRP) export as affected by year (bars indicated by the same letter are not significantly different, $p > 0.05$)

Fig. 4.9. Mean annual dissolved reactive phosphorus (DRP) export as affected by nutrient source (bars indicated by the same letter are not significantly different, $p > 0.05$)

Fig. 4.10. Mean annual dissolved reactive phosphorus (DRP) export as affected by forage system (bars indicated by the same letter are not significantly different, $p > 0.05$)

Fig. 4.11. Mean annual dissolved reactive phosphorus (DRP) export as related to the Georgia P Index (dashed line at Georgia P Index value of 40 represents the separation between low and medium risk ratings; dashed line at Georgia P Index value of 75 represents separation between medium and high risk ratings; line at P export value of 4 kg P ha^{-1} represents upper limit of export values considered as “low”)

Fig. 4.1.

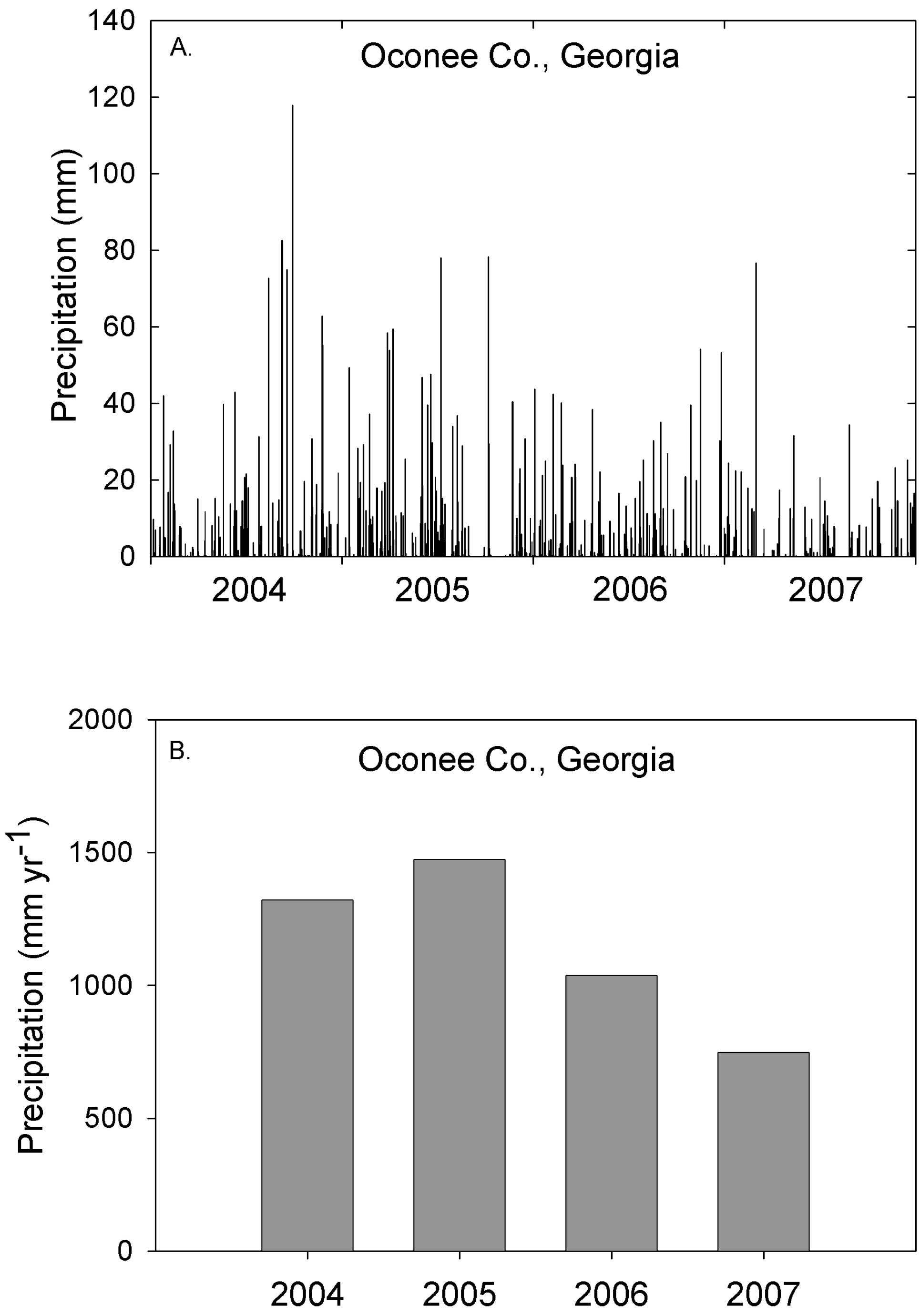
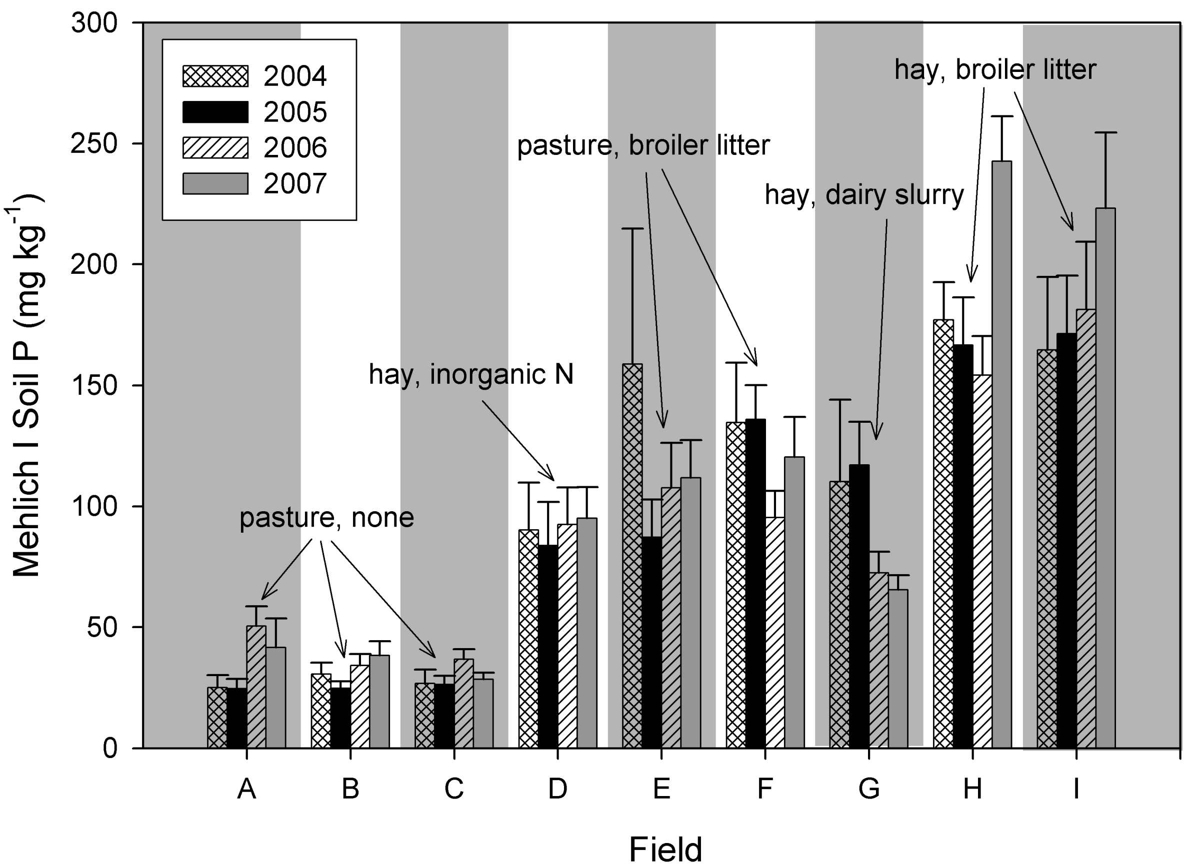

A.
Oconee Co., Georgia
Precipitation (mm)
0
20
40
60
80
100
120
140
2004
2005
2006
2007
B.
Oconee Co., Georgia
Precipitation (mm yr-1)
0
500
1000
1500
2000
2004
2005
2006
2007

Fig. 4.2.



300
250
200
150
100
50
0
Mehlich I Soil P (mg kg-1)
2004
2005
2006
2007
pasture, none
hay, inorganic N
pasture, broiler litter
hay, dairy slurry
hay, broiler litter
A
B
C
D
E
F
G
H
I
Field

Fig. 4.3.

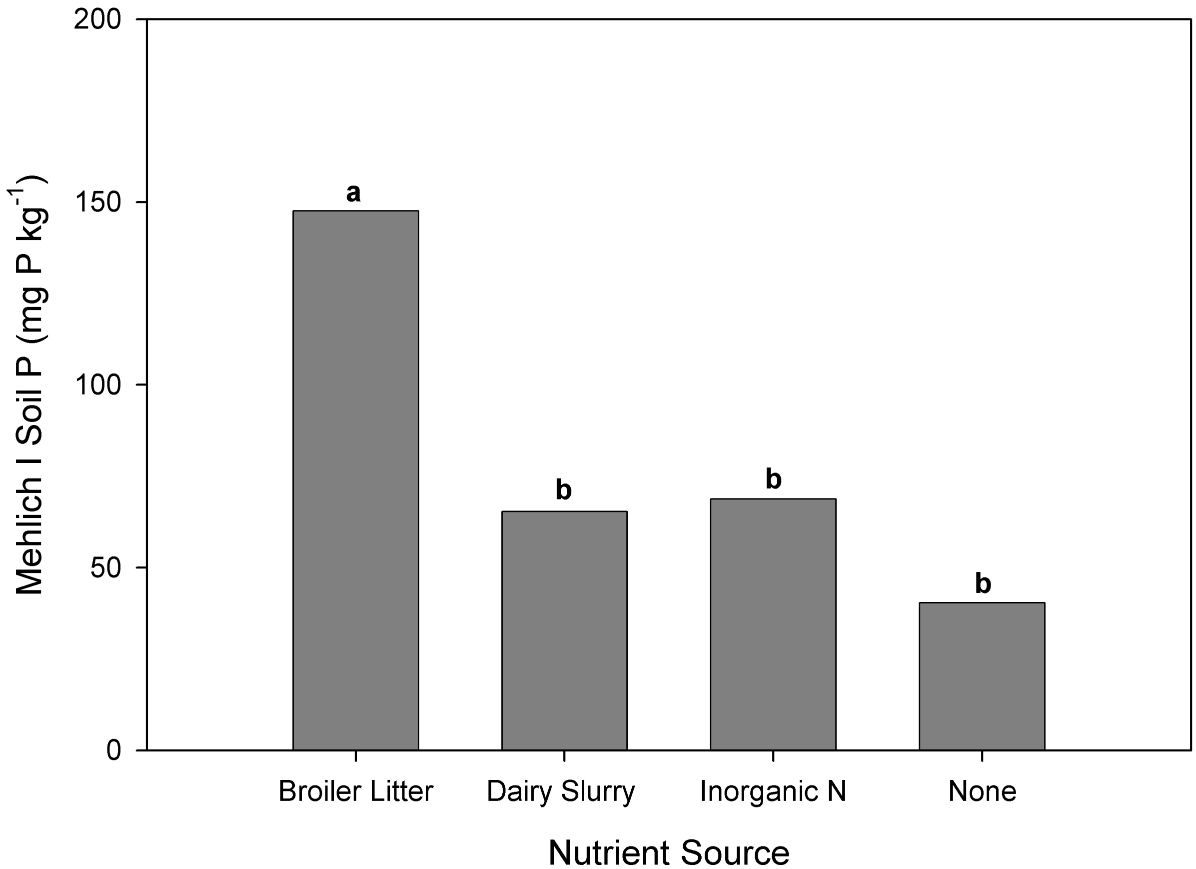
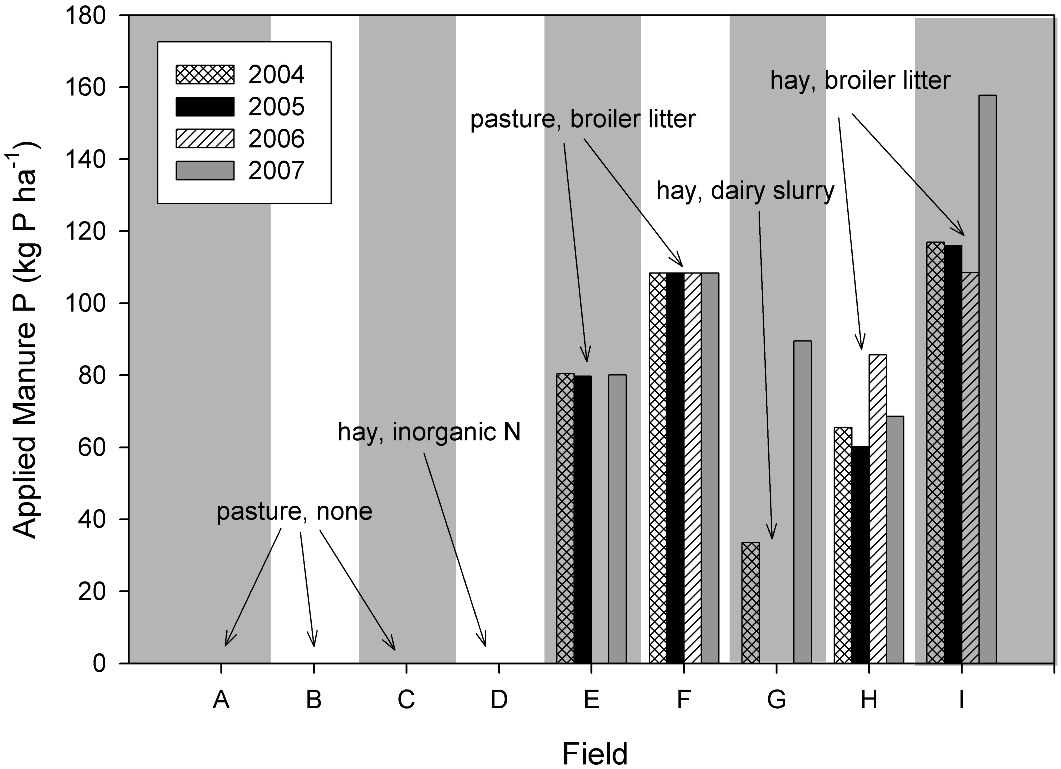
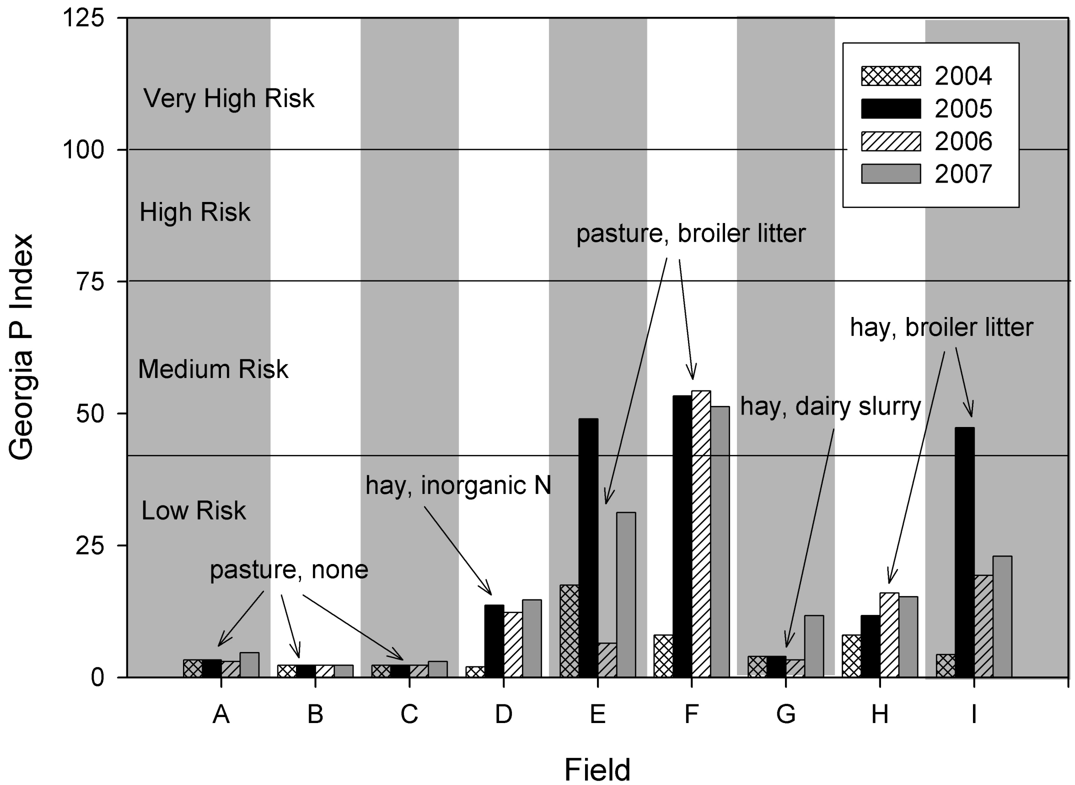

200
150
100
50
0
Mehlich I Soil P (mg P kg-1)
a
b
b
b
Broiler Litter
Dairy Slurry
Inorganic N
None
Nutrient Source

Fig. 4.4.



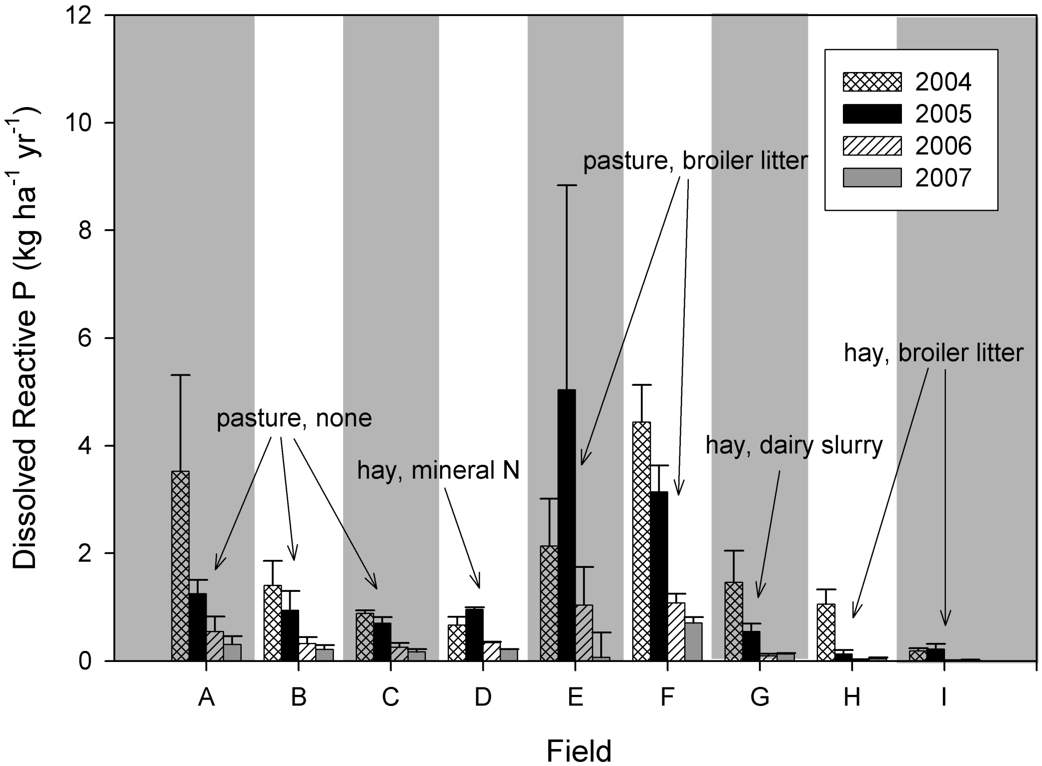
2004
2005
2006
2007
pasture, none
hay, inorganic N
pasture, broiler litter
hay, dairy slurry
hay, broiler litter
Applied Manure P (kg P ha-1)
180
160
140
120
100
80
60
40
20
0
A
B
C
D
E
F
G
H
I
Field

Fig. 4.5.



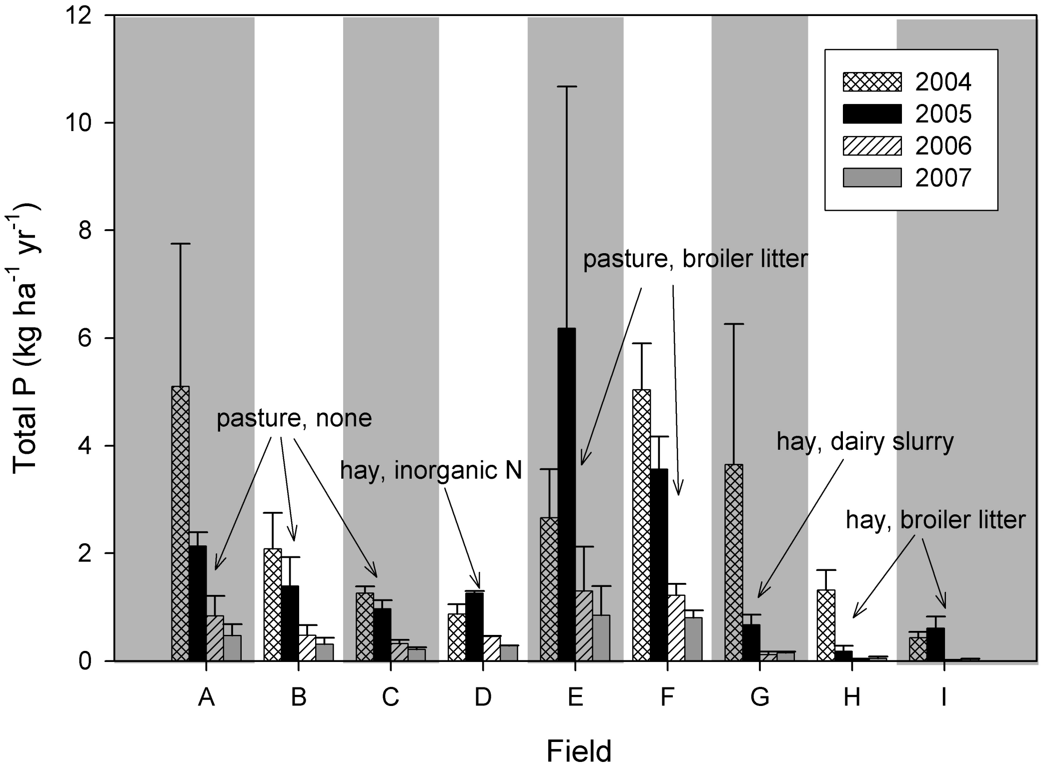
Georgia P Index
125
100
75
50
25
0
Very High Risk
High Risk
Medium Risk
Low Risk
2004
2005
2006
2007
pasture, broiler litter
hay, broiler litter
hay, dairy slurry
hay, inorganic N
pasture, none
A
B
C
D
E
F
G
H
I
Field

Fig. 4.6.



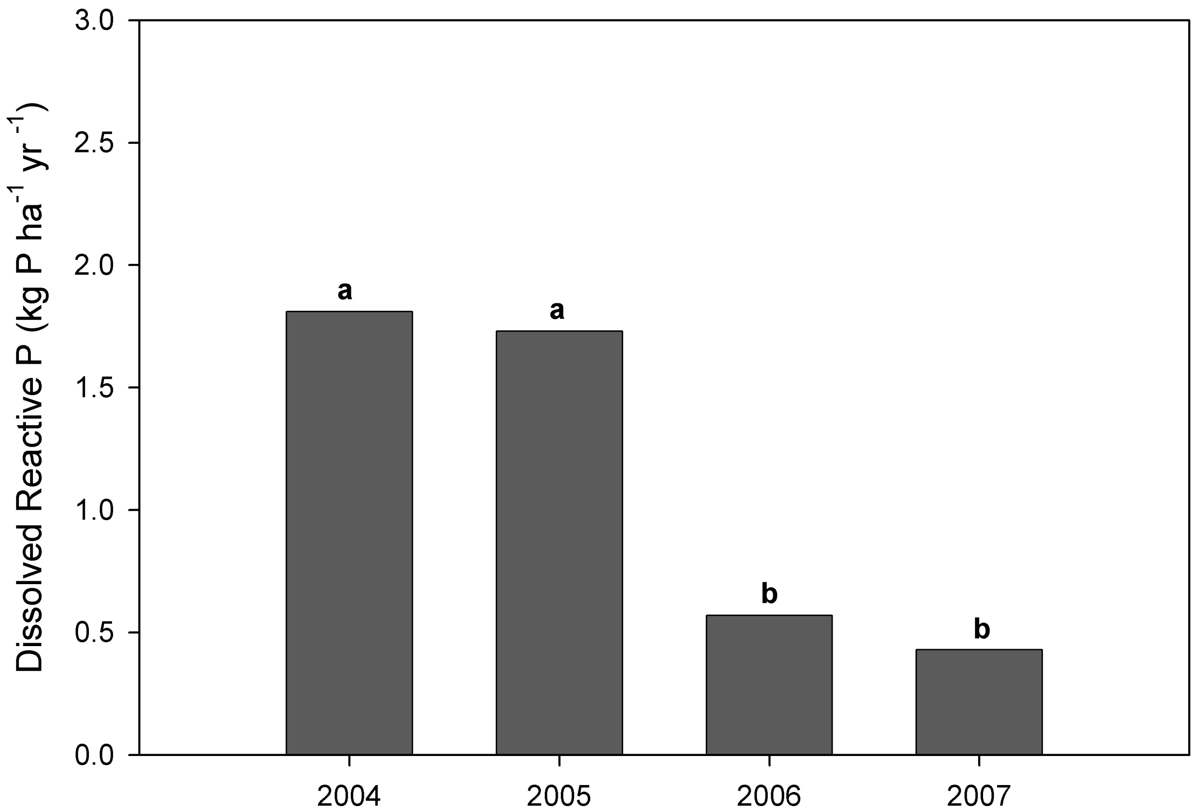
Dissolved Reactive P (kg ha^{-1} yr^{-1})
12
10
8
6
4
2
0
2004
2005
2006
2007
pasture, broiler litter
hay, broiler litter
pasture, none
hay, dairy slurry
hay, mineral N
A
B
C
D
E
F
G
H
I
Field

Fig. 4.7.



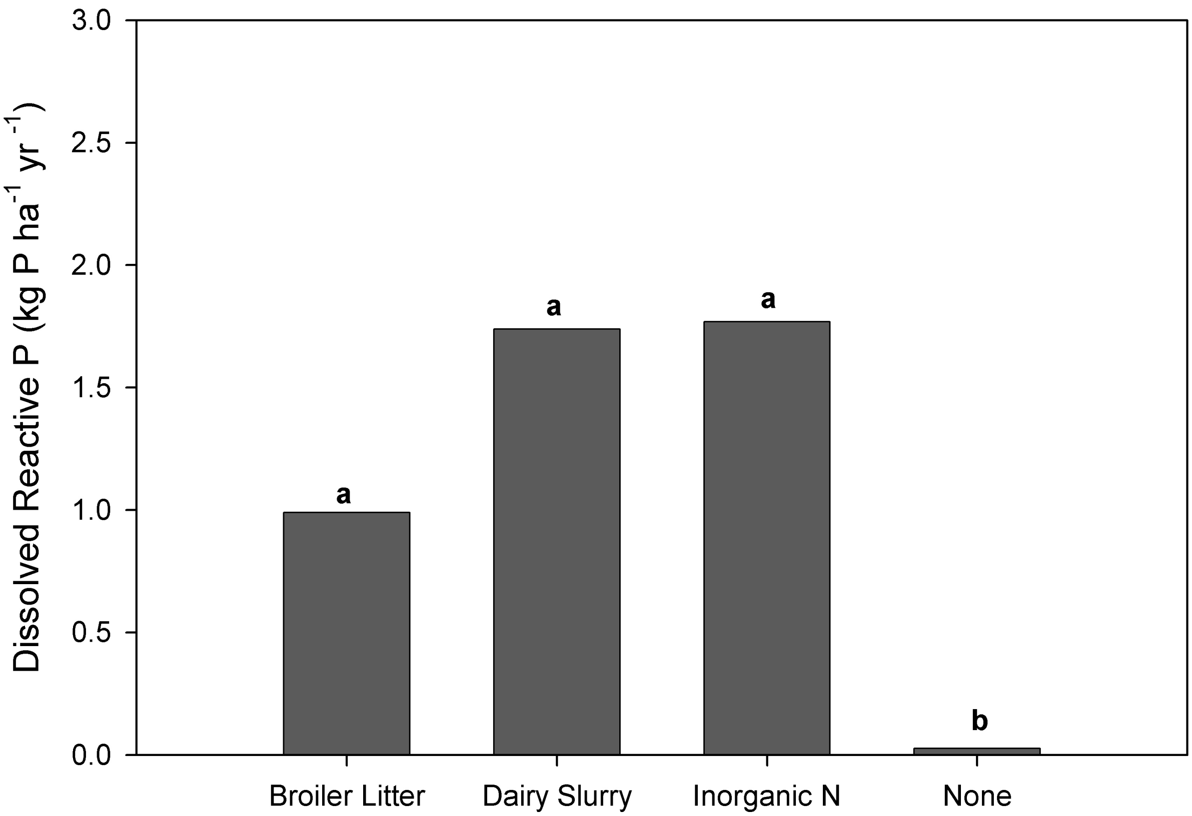
12
10
8
6
4
2
0
Total P (kg ha-1 yr-1)
2004
2005
2006
2007
pasture, broiler litter
pasture, none
hay, inorganic N
hay, dairy slurry
hay, broiler litter
A
B
C
D
E
F
G
H
I
Field

Fig 4.8.



Dissolved Reactive P (kg P ha-1 yr-1)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
a
a
b
b
2004
2005
2006
2007

Fig. 4.9.



3.0
2.5
2.0
1.5
1.0
0.5
0.0
Dissolved Reactive P (kg P ha^{-1} yr^{-1})
a
a
a
b
Broiler Litter
Dairy Slurry
Inorganic N
None

Fig. 4.10.

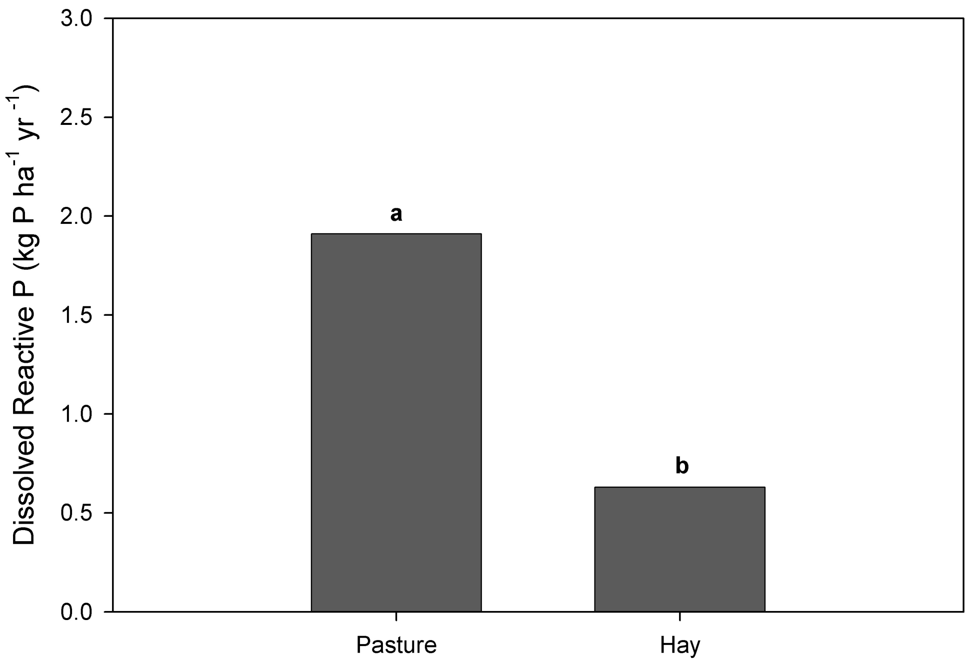
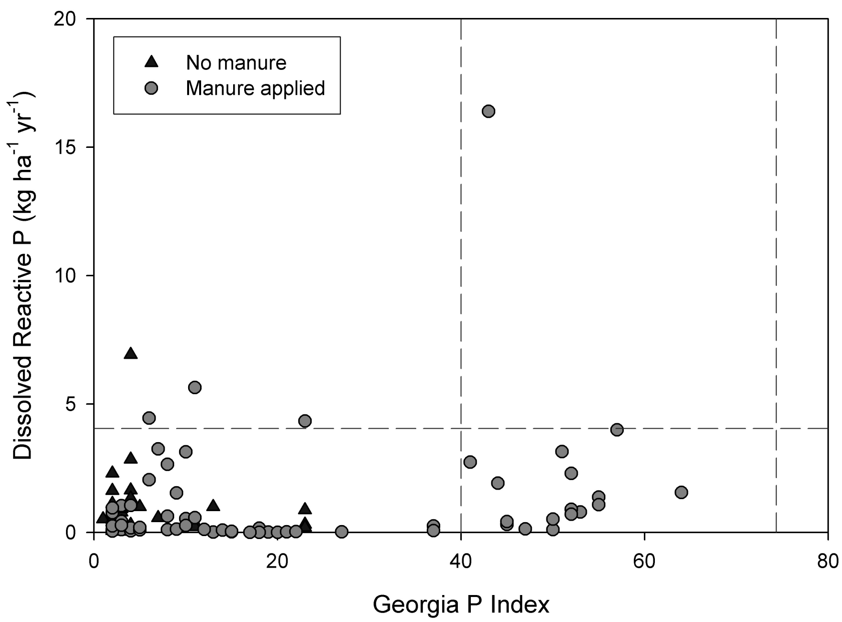

3.0
2.5
2.0
1.5
1.0
0.5
0.0
Dissolved Reactive P (kg P ha-1 yr -1)
a
b
Pasture
Hay

Fig. 4.11.


No manure
Manure applied
Dissolved Reactive P (kg ha^{-1} yr^{-1})
Georgia P Index
0
5
10
15
20
0
20
40
60
80

CHAPTER 5

CONCLUSIONS

Results presented here suggest that the effectiveness of core aeration for reducing export of P from pastures with applied manures may be largely attributable to binding of P to exposed soil minerals. Given that there is potential for increased export of total suspended solids (TSS) from core aerated fields, core aeration should only be conducted on soils with further P sorption capacity. Management practices such as vegetative buffer strips that help to control TSS transport may enhance the effectiveness of core aeration. With relatively large reductions in total dissolved P observed under core (66%) and to a lesser extent no-till disk aeration (35%) and slit aeration (27%), additional control of P associated with transported solids (20 to 30% of total P export) could further reduce environmental risks associated with broiler litter application.

The effectiveness of continuous-furrow knife aeration at the landscape scale was found to be closely related to soil properties and site conditions. Continuous-furrow knife aeration was most effective in reducing runoff volume (22%), total P (18%), and dissolved reactive P (DRP) export (41%) from landscapes dominated by moderately well-drained to well-drained soils, a seasonal-high water table below the Bt horizon, and a higher density of concentrated flow areas relative to landscapes where aeration was less effective. These results suggest that close examination of soil properties and drainage patterns in farm fields may allow farmers and professionals to determine areas where continuous-furrow knife aeration would have the greatest positive impact on water quality.

Results indicated that edge-of-field losses of P corresponded well to risk ratings calculated by the Georgia P Index given that only 4% of observations produced DRP export greater than the level of risk calculated using the Georgia P Index. Measured annual P export was generally low to moderate (< 7 kg P ha^{-1} yr^{-1}) from fields rated as a low or medium risk of P export. Results also indicated that nutrient source (broiler litter, dairy slurry, inorganic N, and no amendments), forage system (hay or pasture), and year were significant factors affecting the risk of edge-of-field P losses. On average, the lowest annual DRP export was observed from fields with no amendments, however, when looking at specific fields where no amendments were applied there were cases of higher DRP export due to cattle loafing. Fields managed as hay systems exhibited less than half the annual DRP export as those managed as pasture despite similar amounts of P applied in manures. Greater annual DRP export under pasture systems may have been at least partly due to proximity of collectors to shaded areas at field edges where grazing livestock are more likely to congregate. This suggests that it may be important to provide alternative shade sources for livestock that are located upstream and away from concentrated flow areas at field edges. Results from this study may be most useful for farmers and agricultural professionals working to prevent export of P from pastures and hayfields in the Southern Piedmont in order to maintain agricultural productivity and prevent environmental degradation.