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Aerating Grasslands: Effects on Runoff and Phosphorus Losses from Applied Broiler Litter

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ABSTRACT

Aeration has been promoted as improving infiltration of rainfall and extending grass or forage productivity, but research on the impact of this practice on P losses from grasslands has had mixed results. We designed a study to determine at the field scale, using a paired watershed approach, the impact of slit aeration on runoff volume and P losses in runoff from fescue (*Festuca arundinacea* Schreb.)/ bermudagrass (*Cynodon dactylon* L.) hay fields fertilized with broiler litter. Three pairs of 0.8-ha fields, each with similar soils (Typic Kanhapludults, Aquic Hapludults, and Aquultic Hapludalfs), were fertilized with broiler litter and monitored under similar management from 1995 through 1998, then one field in each pair received aeration treatment from 2001 through 2003. In the field with mostly well-drained soils, grassland aeration reduced surface runoff volume and mass losses of dissolved reactive P (DRP) in runoff by approximately 35%. In contrast, when poorly drained soils dominated, grassland aeration increased runoff volume (4.8 mm/runoff event) and mass losses of DRP and total P (0.25 kg TP ha^{-1} per runoff event). This implies that aeration of well-drained soils in the top poultry-producing counties of Georgia (0.2 million ha) could decrease dissolved phosphorus losses by more than 500 Mg P each year. This is not the case if soils are poorly drained.

To utilize natural resources efficiently, beneficial management is needed to condition the soil so as to reduce unnecessary losses of water and nutrients beyond the site or point of intended use. Improving rainfall infiltration and reducing overland flow can increase water supply to crops during droughty periods and retard flooding during periods of heavy rainfall. Management practices that reduce nutrient losses in runoff from grasslands are critical when applying broiler litter as a nutrient source (Kuykendall et al., 1999). Of particular importance is the reduction of P losses because of its influence on eutrophication in aquatic systems. Reducing P losses can be achieved by reducing the volume of runoff and/or reducing the concentration of P in runoff. Mechanical aeration of the soil is a practice that may accomplish these results while leaving much of the vegetation intact. Soil aerators are predominately slicers or plug-pullers, with slicer types being most common for agronomic uses and the type used in the studies discussed below. In the slicer type (slit aeration), tines are pushed into the soil to make elongated holes. Potential negative effects of these aerators are that the slicer may create compaction around the wall of the hole. Nevertheless, slit aeration may partially incorporate applied manures, increase contact between runoff water and soil (facilitating P adsorption by the soil), increase soil porosity, and increase surface roughness (increasing infiltration and reducing runoff). Environmental and agronomic benefits of aeration have been investigated, with most studies focusing on productivity or yields (Davies et al., 1989; Chen et al., 2001; Shah et al., 2004). In some cases, mechanical aeration did not increase yield when manures were applied (Malhi et al., 2000; Pote et al., 2001), while in other cases (Davies et al., 1989; Chen et al., 2001; Shah et al., 2004) forage yields were increased. A few studies have evaluated the effectiveness of aeration to reduce nutrient losses (Pote et al., 2003; Lau et al., 2003; Franklin et al., 2005) and have obtained different results as well.

When compared with nonaerated, Shah et al. (2004) reported that grasslands fertilized with liquid dairy manure and aerated had significant decreases in runoff volumes and mass losses of P, whereas Pote et al. (2003) reported no significant difference in runoff when aeration was used on grassed plots with surface-applied broiler litter. Both Bittman et al. (2005) and Shah et al. (2004) reported decreases in runoff volume from grasslands which had been moderately roughened using mechanical aeration.

Of the studies primarily focused on environmental impacts, most were conducted using simulated rainfall (Harrigan et al., 2004; Franklin et al., 2005), few were done with natural rainfall (Shah et al., 2004), and all were done at the small-plot scale. The results of these plot scale studies are useful because they indicate the potential change in magnitude that management practices can produce for reducing P losses. However, it is important to evaluate management practices at larger scales because environmental factors which influence water quality and runoff quantity can be quite variable across one soil classification unit, and often there are multiple soil units at the field scale. For example, Franklin et al. (2005) reported a threefold difference in runoff volume between landscape positions using small plots. Our objective was to determine, at the field scale, the environmental impacts of slit aeration on runoff volume and P losses in runoff from tall fescue-bermudagrass hay fields fertilized with broiler litter. We used the paired watershed approach and incorporated information about

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soil properties into our analysis so that the results would be applicable to a broad range of sites.

MATERIALS AND METHODS

This study was conducted in six 0.8-ha, tall fescue (*Festuca arundinacea* Schreb.)/bermudagrass (*Cynodon dactylon* L.) hayfields or field-scale watersheds, located at the College of Agricultural and Environmental Sciences Central Research and Education Center, near Eatonton, Georgia. The soil series present at the site were 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, Aquultic Hapludalfs). Each of the fields was surrounded by earthen berms that channeled the surface runoff to a 0.45-m flume, where it was automatically measured and subsampled by an ISCO 3700FR refrigerated sampler (Isco, Lincoln, NE).

Because of the inherent variability of large plots or fields, we used a paired watershed approach, pairing fields based on their propensity to generate surface runoff. To pair fields, we analyzed historic runoff volume data collected from 1995 through 1998, when all watersheds received similar treatment. Average runoff volumes per event were 5.7, 9.3, 10.2, 10.8, 14.5, and 19.8 mm for Fields 1, 5, 2, 4, 3, and 6, respectively. Because there were no significant differences ($p < 0.05$) between the first four fields (1, 2, 4, and 5) we chose to pair Fields 1 and 2 and Fields 4 and 5 because they were adjacent to one another and soil maps indicated that soils were most similar. We also paired Fields 3 and 6 because their average runoff volumes per event were not significantly different ($p < 0.05$) from each other. The historic data collected from 1995 through 1998 was then used to develop calibration relationships (runoff volume, P concentration, and P load) between the two watersheds in each pair.

During the calibration period, broiler litter applications were made to all fields in 1995 and 1996 (Table 1). During the aeration period, broiler litter was applied to all fields in 2000, 2001, and 2002 (Table 1). The broiler litter was applied with a spreader equipped with load cells so that the amounts delivered could be adequately determined.

Analysis of litter was done to determine the amount of total N, total P, and water-soluble P. Total N and total P in broiler litter were determined by Kjeldahl digestion (Baker and Thompson, 1992). Inorganic N was determined by shaking 20-g litter samples with 200 mL 1 *M* KCl for 30 min. A 30-mL subsample was taken from the 200-mL well-mixed sample, centrifuged, and 15 mL of the supernate was placed in a scintillation vial for measuring inorganic N in the extract by colorimetric procedures (Crooke and Simpson, 1971; Keeney and Nelson, 1982). Water-soluble P was determined by extracting 20 g of litter with 4 L of deionized water for 30 min in a reciprocating shaker at 120 oscillations per minute, centrifuging, filtering through a 0.45-μm filter, and measuring P in the filtrate by the molybdate blue method (Murphy and Riley, 1962).

Table 1. Dates and average rates of total N, total P, and water-soluble P applied with broiler litter to six field-scale plots before and during 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 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

Immediately after litter application, three of the fields (2, 5, 6) were treated with an AerWay 80Q aerator (10- to12-cm depth; 0° angle), whereas the other three fields (1, 3, 4) were left untreated as controls. The aeration was performed in a way such that the slits were predominantly perpendicular to the slope; the weights used on the aerator varied between 200 and 400 kg to ensure a consistent penetration of 10 to 12 cm. We used a 0° angle on the tines because in preliminary testing we observed that the next higher setting (2.5°) resulted in more vegetative damage than desired.

Pierson et al. (2001) identified the percentage of the area occupied by each soil series in the fields used. According to their data, the area occupied by well-drained and moderately well-drained soils in the aerated fields was 63% in Field 2 (36.1% Cecil and 27.3% Altavista), 68% in Field 5 (52% Cecil, 16% Helena), and 14.2% in Field 6 (Helena; Fig. 1). Twelve soil samples were collected from the upper 15 cm of each field at the beginning of the baseline period (November 1994), before the beginning of the aeration study (March 2000), and near the end of the aeration study (October 2002). The soil samples taken from each field were composited and analyzed for Mehlich I P (Mehlich, 1953). Soil cores (3-cm diam.) were also taken down to a depth of 1.4 m in transects from low to high elevations in each bermed field to describe soil profiles.

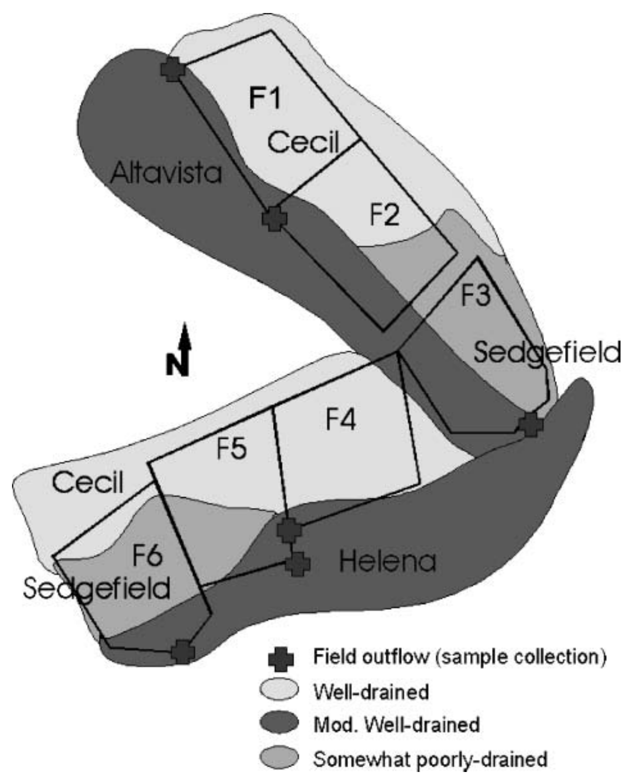

Fig. 1. Distribution of soil series: Cecil (fine, kaolinitic, thermic Typic Kanhapludults), Altavista (fine-loamy, mixed, semiactive, thermic Aquic Hapludults), Helena (fine, mixed, semiactive, thermic Aquic Hapludults), and Sedgefield (fine, mixed, active, thermic, Aquultic Hapludalfs) which are labeled on the map. Shades of gray represent drainage classes (well-drained, moderately, well-drained, and poorly drained) for each field (see legend on map). Aerated fields were Fields 2, 5, and 6.

Runoff volume was measured and sampled for each runoff event. Runoff samples were filtered through 0.45-μm cellulose-nitrate membranes, placed on ice in dark coolers, and transported to the analytical laboratory for analysis. Filtered samples were analyzed for dissolved reactive phosphorus (DRP) by the molybdate-blue method (Murphy and Riley, 1962) and unfiltered samples were analyzed for total Kjeldahl P (total P) by Kjeldahl digestion according to USEPA method 351.2 (USEPA, 1979).

The automatic samplers took from 1 to 13 samples in each runoff event, and cumulative runoff for the event was automatically recorded by a CR10 datalogger (Campbell Scientific, Logan, UT) at the time each sample was taken. The concentrations of DRP and total P were then integrated against cumulative runoff to calculate the total loss of DRP and total P during a runoff event. Integration was performed using Simpson's rule in MathCad 6.0 (MathSoft, Cambridge, MA). Flow-weighted concentrations of DRP and total P for each event were calculated by dividing the total loss of DRP or total P by the total volume of surface runoff.

RESULTS

Average annual rainfall was 1037 mm from 1995 through 1998 (baseline period before aeration) and 1051 mm from 2001 through 2003 (aeration period). Rainfall distribution from 1995 to 2003 is illustrated in Fig. 2. Mean soil P (Mehlich I) for the six fields, with standard deviations in parentheses, were 12.9 (3.8) mg P kg^{-1} in November 1994, 72.5 (16.0) mg P kg^{-1} in March 2000, and 102.6 (19.8) in October 2002. According to data from Schroeder et al. (2004) for similar Georgia soils, it takes about 300 mg P kg^{-1} as Mehlich III to obtain 1 mg DRP L^{-1} in runoff. The largest mean value of Mehlich I in our fields was 102.6 mg P kg^{-1}, which is approximately equivalent to 145 mg P kg^{-1} as Mehlich III (Shuman et al., 1988). Furthermore, the average DRP concentration in runoff from all six fields before the first broiler litter application in 1995 was 0.45 mg P L^{-1} (Kuykendall et al., 1999). Based on the magnitude of the DRP concentrations we measured (mean = 4.7 mg DRP L^{-1}), DRP in runoff from this study was likely controlled by the broiler litter applied, rather than by soil test P values.

Results will be presented by paired fields. As described in the Materials and Methods section, paired fields are grouped based on similar runoff volumes, similar soils, and proximity to one another.

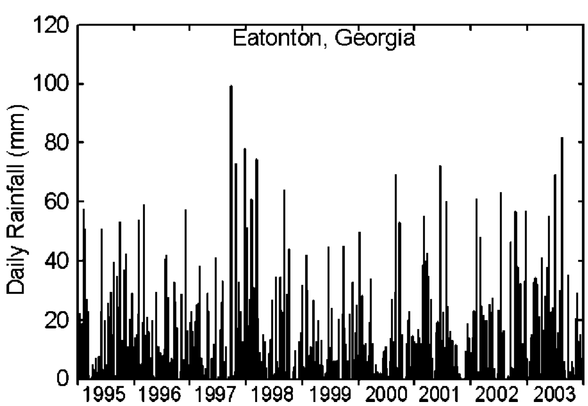

Fig. 2. Rainfall distributions by year for baseline (before aeration), 1995 through 1998 and for the period during aeration, 2001 through 2003. Amount of rainfall (mm) for each rainfall event is represented by a vertical bar.

Paired Fields One and Two

Runoff Volume

The slope of the regression of runoff volume from Field 2 (to be aerated) against runoff volume from Field 1 (not aerated) was 1.86 for the historic data collected when both fields had similar management (no aeration on either field–Fig. 3a; note line labeled "Before"). This indicated that in general, runoff volume in Field 2 tended to be about 1.86 times larger than runoff volume in Field 1 when both fields had the same management. When aeration was applied to Field 2, the slope of the regression significantly changed ($p < 0.01$) from 1.86 to 1.21, whereas the intercept did not change (Fig. 3a; note line labeled "After"), indicating that runoff volume tended to

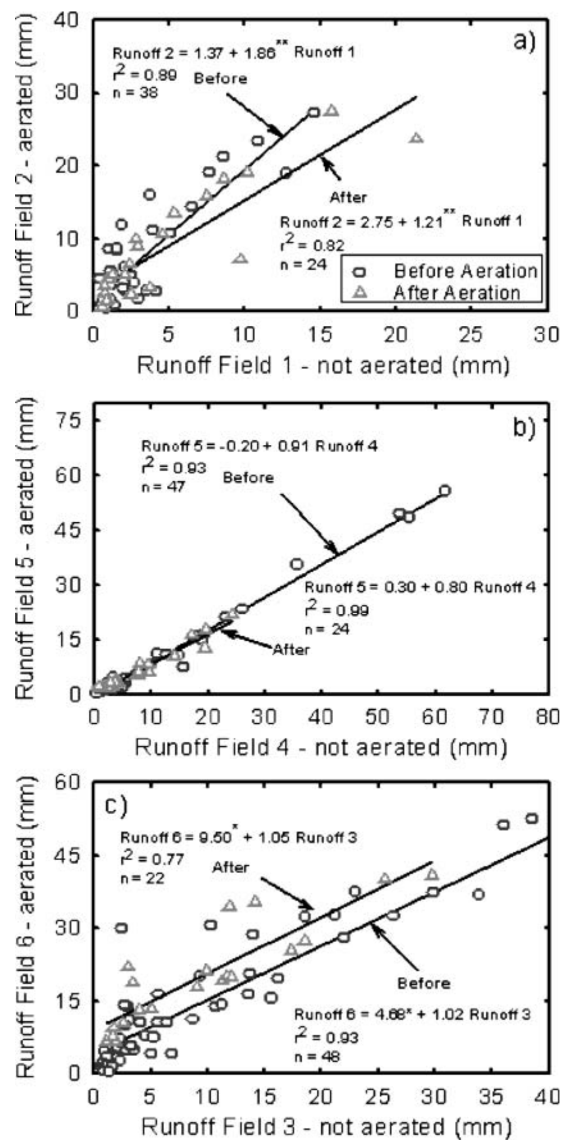

Fig. 3. Runoff volumes from aerated (*y* axis) and nonaerated fields (*x* axis) "Before" and "After" aerated periods. (a) Field 2; (b) Field 5; (c) Field 6.

decrease in Field 2, when compared with Field 1. The percentage of change in the slope [(1.86–1.21)/1.86 × 100 = 35%] can be interpreted as the percentage by which runoff volume was reduced by the aeration treatment. Thus, aeration reduced runoff volume by 35% in Field 2, which has 63% of its area occupied by moderately well-drained (Altavista, 27%) to well-drained soils (Cecil, 36%; Fig. 1). One possible reason for the reduction in runoff is that by potentially increasing surface area and porosity, aeration would increase infiltration and reduce surface runoff in soils that have good internal drainage. Results obtained in Field 2 agree with previous work performed with small plots on Altavista soil adjacent to Field 2, in which aeration reduced runoff volume by 27% at $p < 0.16$ (Franklin et al., 2005).

Amount of Phosphorus Loss

Dissolved P losses were reduced by aeration (Fig. 4b). Aeration showed a significant reduction of DRP concentration in runoff (Fig. 4d) from Field 2 ($p < 0.05$). This reduction was probably realized through adsorption of P by the soil as rainfall and runoff moved into the soil profile taking with it some of the DRP extracted from the surface-applied broiler litter during the rainfall event. Mass losses of DRP were also reduced as indicated by a reduction in the slope of the regression from 3.13 to 2.02 ("Before" and "After," respectively); this change in slope represents a 35% reduction in DRP loss (Fig. 4b). The reduction in mass loss of DRP was apparently caused by a reduction in runoff volume coupled with a reduction in DRP concentration.

Results for total P were different from those of DRP. In Field 2, aeration increased concentrations of total P in runoff (Fig. 4c, "After" slope 1.43 and "Before" slope 0.84) significantly ($p < 0.01$) but did not affect mass losses of total P (Fig. 4a). This increase in total P concentration was also observed in the other paired fields though it was never significant. A possible explanation for the observed increase in total P concentration may have been a greater amount of sediment P due to the disruption of the soil surface inherent in the aeration process. However, in Field 2, the increase in total P concentration was offset by the decrease observed in runoff volume, with no net effect on total loss of P.

Paired Fields Four and Five

Runoff Volume

Runoff volume was not significantly changed by aeration in Field 5 (Fig. 3b). There was, however, a trend ($p < 0.08$) for the intercept to be greater after aeration than before aeration (−0.2 "Before" and 0.3 "After"). The slopes for before and after aeration were very similar (0.91 for "Before" and 0.80 for "After"). This suggested a small increase in runoff which was noted because it

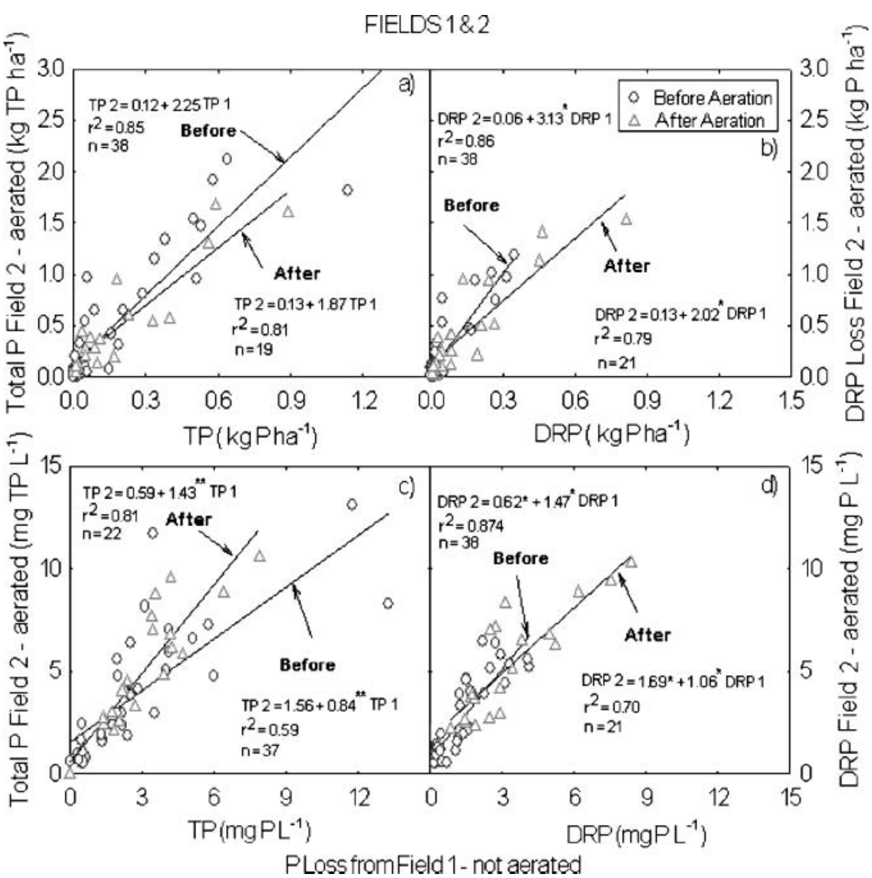

Fig. 4. Concentrations and mass losses of (a) and (c) total P and (b) and (d) DRP in runoff from Field 2 (aerated, *y* axis) and Field 1 (nonaerated, *x* axis) "Before" and "After" aerated periods.

agreed with runoff volume results observed in paired Fields 3 and 6 (the wetter sites).

Amount of Phosphorus Loss

No changes were noted for mass losses of either DRP or total P after aeration was performed on Field 5 (Fig. 5), although, concentrations of DRP were found to have a significantly larger slope after aeration than before aeration (0.75 vs. 0.53). An analysis of DRP concentrations relative to runoff volume indicated no significant correlations. However, the three highest DRP concentrations occurred during small runoff events. This resulted in small loads which may have led to a nonsignificant effect of aeration on total mass loss of DRP. This association of high DRP concentrations with small runoff volumes was not as apparent in the other aerated fields. This lack of difference in mass loss of DRP may or may not have held true if during the "After" aeration period, runoff volumes greater than 22 mm had been recorded in Field 5. Other potential explanations are given in the discussion section.

Paired Fields Three and Six

Runoff Volume

In Field 6, aeration increased the intercept of the regression (Fig. 3c) from 4.68 to 9.50 ($p < 0.05$), while the slopes remained similar. The larger intercept indicated an increase in runoff volume of approximately 4.8 mm in each rainfall event for the period during which aeration was applied to Field 6. Poorly drained soils covered 86% of the Field 6 and the other 14% was occupied by moderately well-drained soils.

Amount of Phosphorus Loss

Concentrations of DRP and total P showed no effect of aeration in Field 6 (Fig. 6c and 6d). Mass losses of both DRP and total P had larger intercepts for the time period after aeration had occurred (Fig. 6a and 6b), indicating an increase in DRP and total P losses which were apparently caused by an increase in runoff volume (Fig. 3). The increase in P losses after aeration was approximately 0.25 kg TP ha^{-1} (Fig. 6a), all of which appeared to be from dissolved reactive P (shift of 0.26 kg DRP ha^{-1}; Fig. 6b).

DISCUSSION

Soil aeration would be expected to partially incorporate the broiler litter and other manures applied, increase contact between runoff water and soil (facilitating P adsorption by the soil), increase soil porosity, and increase surface roughness (increasing infiltration and reducing runoff) in grasslands. As described in the results section, we found that aeration increased total P concentration in runoff from Field 2. The increase in total P concentration after aeration may have been caused by transport of soil particles left on the surface after the aeration procedure. That is, by exposing the soil at the surface (which was covered by grasses or residues before aeration), raindrop impact can more easily dislodge some soil and associated soil P where it is more easily transported. If reductions of runoff volume occur simultaneously with increases of

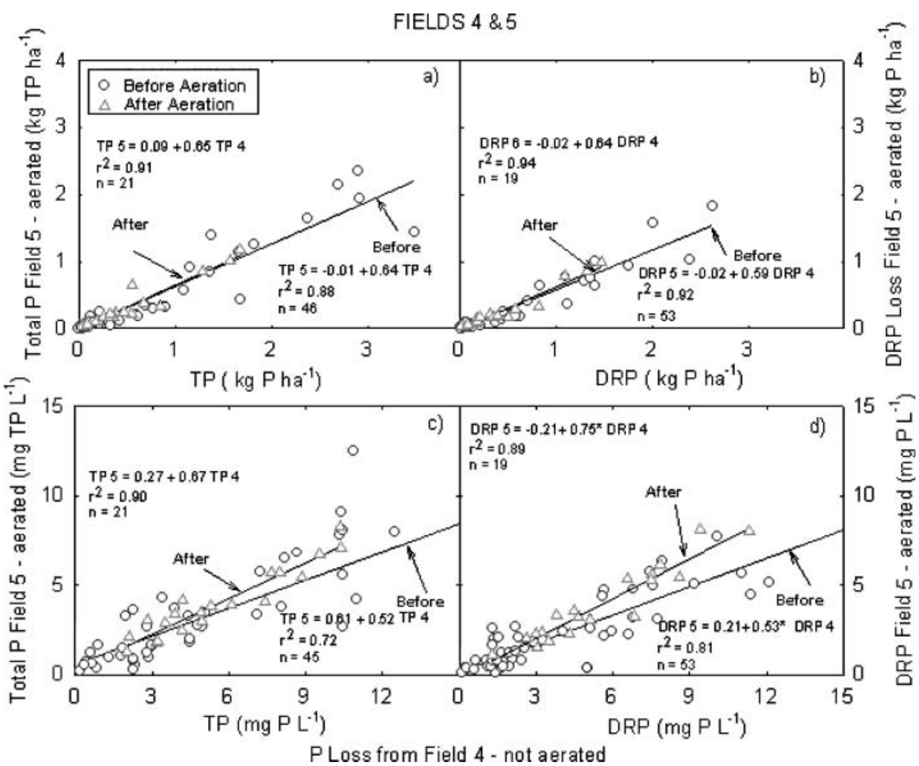

Fig. 5. Concentrations and mass losses of (a) and (c) total P and (b) and (d) DRP in runoff from Field 5 (aerated, *y* axis) and Field 4 (nonaerated, *x* axis) "Before" and "After" aerated periods.

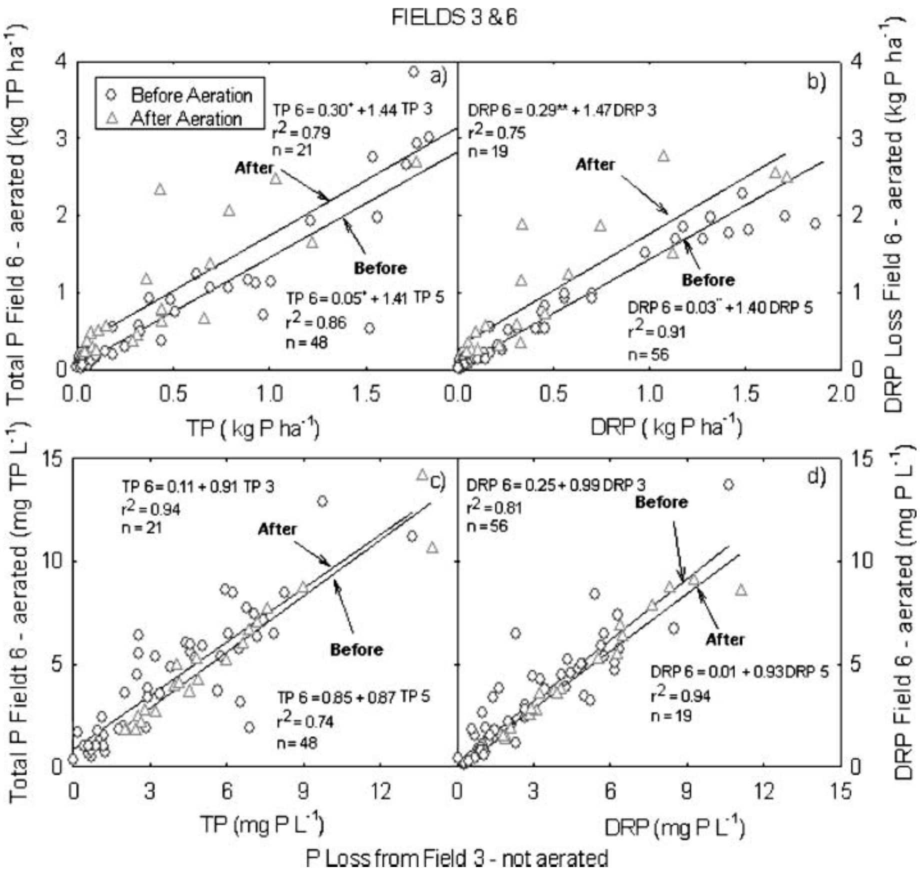

Fig. 6. Concentrations and mass losses of (a) and (c) total P and (b) and (d) DRP in runoff from Field 6 (aerated, *y* axis) and Field 3 (nonaerated, *x* axis) "Before" and "After" aerated periods.

total P concentrations, no net increase of mass losses of total P will be observed, as was the case for Field 2.

In this study, we had different results on each of the paired fields. Paired Fields 1 and 2 indicated that aeration reduced runoff volume and DRP losses; paired Fields 4 and 5 indicated that aeration had no effect on runoff volume, DRP, and total P losses; and paired Fields 3 and 6 indicated that aeration increased runoff volume, DRP, and total P losses. One might think that differences in soil texture may be the explanation for these varied results, but this is not the case because the surface soils (15 cm) in our fields had similar textures (sandy loam). In the studies of Shah et al. (2004) and Pote et al. (2003), soil textures were also similar (silt loam), yet Shah et al. (2004) found that aeration of orchardgrass (*Dactylis glomerata*) plots that received liquid dairy manure significantly reduced total P losses by 23 to 44%, whereas Pote et al. (2003) found that aeration of bermudagrass plots fertilized with broiler litter showed no effect on total P losses. In addition to having similar textures, Fields 2 and 5 were also characterized as having similar hydrologic properties, with the percentage of area in well-drained to moderately well-drained soils being 63% for Field 2 and 68% for Field 5. In spite of these similarities, the results were different for Fields 2 and 5.

Upon deeper inquiry we plotted elevation against hydrologically impeding soil morphological features and/or indicators (depth to Bt, depth to BC, and depth to redoximorphic features) to determine if these indicators may elucidate varied results between fields (Fig. 7). Most striking was the depth to redoximorphic features. Redoximorphic features have been considered to be an indicator of wetness or seasonal high water tables, which result in fluctuating reducing and oxidizing conditions.

In Field 2, where aeration reduced runoff volume and DRP losses, the start of the Bt horizon was at 20 cm but the redoximorphic features were not present until approximately 40 cm. In Field 5, at higher elevations the redoximorphic features were found at depths deeper than the start of the Bt horizon, whereas at lower elevations the redoximorphic features were found at shallower depths and coincided with the start of the Bt horizon (as in Field 6). In Field 6, redoximorphic features ran parallel to the start of the Bt horizon. It should be pointed out that all Bt horizons had similar clay contents. These observations suggested that the depth to redoximorphic features may be an important indicator as to when aeration may or may not be an effective strategy in reducing P losses while capturing more rainfall. It is yet unclear, at what depth or at what distance from point of concern the redoximorphic features would be most telling. Other implications are also suggested with the presence of redoximorphic features. Under flooded or reduced conditions, dissolved P can increase. This increase has been attributed to the reduction of ferric iron (Fe(III)) compounds. In Field 5, where aeration potentially increased infiltration in the upper

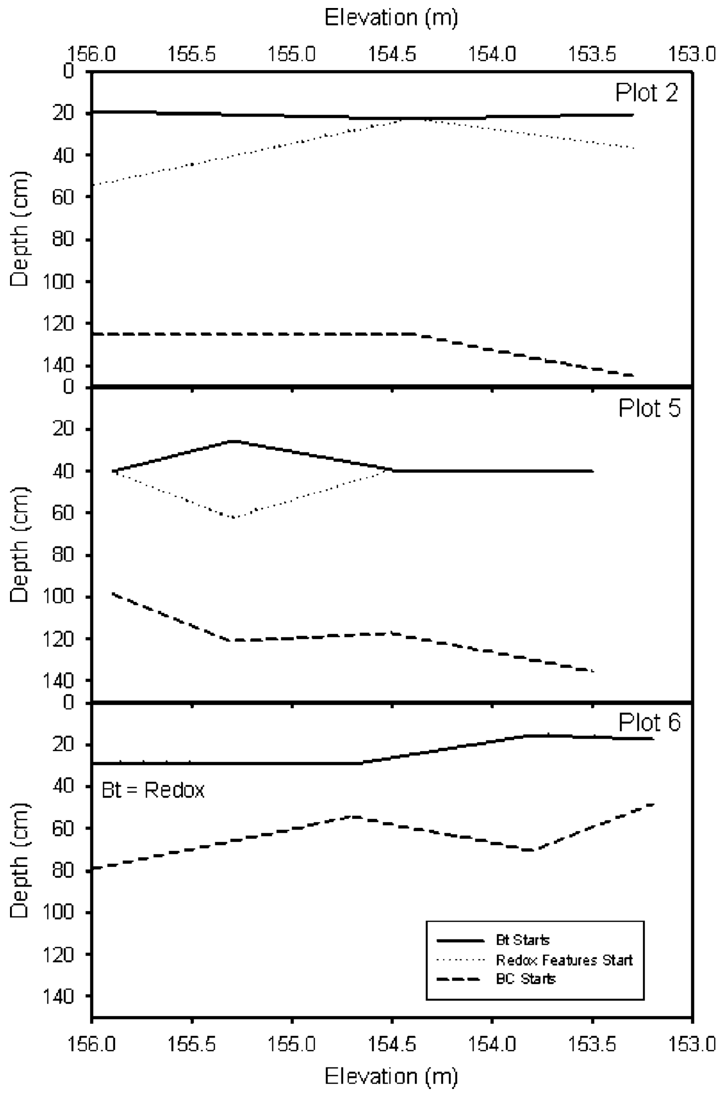

Fig. 7. Elevations (m) and depth of soil morphological features which could impede water drainage through the soil. The features include the start of the Bt horizon, the depth at which redoximorphic features first appear, and the depth at which the BC horizon begins.

portion of the field (as suggested by results in Field 2) this water may have moved laterally downhill ensuring saturation in the lower elevations of Field 5. We speculate that there was a decrease in runoff in the upper portion of the field and an increase in runoff in the lower portion of the field, resulting in a zero net balance in runoff volume. Under these saturated conditions in the lower portion of the field, P may have been released by the reductive dissolution of ferric hydroxides on which P was adsorbed, thereby increasing DRP concentrations.

It is unclear as to why aeration would increase runoff volume on poorly drained soils (Field 6), but it may have been related to soil compaction. Compaction could occur from either heavy tractor use or from cattle grazing. In this study, there was almost no grazing but there was tractor traffic from haying, spreading of broiler liter, and aerating operations. Compaction by tractor traffic during aeration is more likely on soils that tend to remain wet near the surface as was the case for soils in Field 6. This tendency for the soil to remain wet near the surface is shown by the fact that redoximorphic features in Field 6 coincided with the start of the Bt horizon and appeared at less than 20 cm from the surface at lower elevations (Fig. 7). Soil compaction in aerated Field 6 could have reduced infiltration, which in turn would translate into an increased volume of surface runoff.

CONCLUSIONS

Our results show that in a 0.8-ha field with 63% of its area occupied by well-drained (Cecil, 36%) to moderately well-drained (Altavista, 27%) soils, grassland aeration reduced surface runoff volume and losses of DRP in runoff by approximately 35%. In another field with 68% of its area occupied by well-drained (Cecil, 52%) and moderately well-drained (Helena, 16%) soils, grassland aeration did not affect runoff volume, total P, or DRP losses. In a third field with 86% of the area occupied by a poorly-drained soil (Sedgefield), aeration increased runoff volume and losses of DRP and total P. These results suggested that the effect of aeration is likely to vary depending on soil hydrological properties and that redoximorphic features may be indicative as to when aeration may reduce runoff and P losses. Thus, a thorough survey of the soils present in grassland would be desirable before aeration is used as a management practice to reduce P losses. Much additional work is still needed in this area of study. Questions still exist as to the effectiveness of aeration on heavily grazed pastures, the effects of the angle of the tines and degree of the disturbance of the soil, and the soil characteristics that could be used to estimate the impact of soil aeration.

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