Effects of Phosphorus Fertilization and Turfgrass Clipping Management on Phosphorus Runoff

Final Report

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Executive Summary

Phosphorus (P) enrichment of surface water and the role of home lawns as a source of P is a concern in many urban watersheds. A study was conducted on a silt loam soil with a 5% slope and high soil test P (27 mg kg^{-1} Bray P-1) to evaluate P fertilization and clipping management effects on P runoff from turfgrass (*Poa pratensis* L.). Phosphorus runoff was evaluated separately under frozen and non-frozen soil conditions. The study was conducted for five years following initiation of experimental treatments in Sept. 2004.

Four fertilizer treatments were compared: 1) no fertilizer, 2) nitrogen (N) + potassium (K) + 0xP, 3) N + K + 1xP, and 4) N + K + 3xP. Phosphorus rates were 21.3 (1xP) and 63.9 (3xP) kg ha^{-1} yr^{-1} the first year and 7.1 and 21.3 kg ha^{-1} yr^{-1} the following four years. Nitrogen and K were applied at recommended rates. The 1xP treatment in the first year was equivalent to the recommended P rate for turfgrass in Minnesota in the establishment year at the measured soil test level. The 1xP treatment in the following four years was typical of the amount of P commonly applied before the widespread availability of zero P turf fertilizers. Each fertilizer treatment was evaluated with clippings removed or clippings recycled back to the turf for a total of eight experimental treatments.

Data were collected for total P (TP) and reactive P (RP) concentrations in runoff, runoff depth, amounts of TP and RP transported in runoff, turfgrass growth and quality, P concentrations in plant tissue, P uptake, and soil test P levels (Bray P-1) at two soil depths. In the fourth and fifth years of the study TP measurements were not made and only RP was measured in runoff.

Soil test P in the 0- to 7.5-cm depth increased linearly with increasing P fertilizer application rate on all but the first soil sampling date in the first year of the study. Flow-weighted TP and RP concentrations in runoff increased linearly with increasing P fertilizer application rate in all five years of the study. These factors led to increases in annual P runoff losses as the P fertilizer rate increased in four of the five study years.

In the second year of the study, cumulative annual TP runoff was significantly greater for the no fertilizer treatment than for any of the treatments receiving fertilizer. Annual P runoff from the no fertilizer treatment was comparable to the 1xP treatment in the other four years of the study, even though it received no fertilizer P. These results were associated with consistently reduced growth and turf quality for the no fertilizer treatment and increases in runoff depth compared with the fertilized treatments in three of the five study years. Maintaining a dense, healthy stand of turf through practices such as adequate N and K fertilization can reduce P transport by reducing runoff depth. The no fertilizer treatment had soil test P levels in the 0- to 7.5-cm soil depth that were comparable to the 1xP rate and this was also a factor in the comparable amounts of P runoff. Reasons for the high soil test P in the no fertilizer treatment are unclear, but may be due to breakdown and degradation of the sod. Further research is needed to determine how soil test P is affected by fertilizer practices.

Returning rather than removing clippings led to some increases in soil test P levels and flow-weighted P concentrations in runoff, indicating that returned clippings are a potential source of P for runoff. However, under the conditions of this study, return of clippings did not lead to significant increases in P runoff. This suggests that modifying clipping management practices will not significantly affect P transport from turfgrass.

Over the five years of this study, 86% of the P transported in runoff occurred from snowmelt or rainfall runoff while the soil was frozen. In 2007, 81% of annual P runoff was from a single runoff event on frozen soil. Flow-weighted P concentrations were consistently higher in three of five years in frozen soil runoff than in runoff from non-frozen soil, but the fact that 78% of total runoff depth during the study was from frozen soil was probably the primary factor. A contributing factor in the treatments receiving P fertilizer was that one-third of the P was applied in Oct. Therefore, even on soils requiring P, fall application of P fertilizer to established turfgrass has a high runoff potential and should be avoided.

Tissue P concentrations increased linearly with increasing P application rate on all but one sampling date, and P uptake increased as the P rate increased in three of five years. However, in the presence of adequate N and K, the application of P fertilizer had no effect on turfgrass growth and quality in any year. These results, combined with those obtained for P runoff, indicate that on sites testing high in soil P, as used in this study, P runoff from lawns can be reduced without affecting turf quality by not applying P fertilizer.

Introduction

Accelerated eutrophication of surface waters due to phosphorus (P) loading from agricultural sources has been a concern for many years (Daniel et al., 1998). Similar concerns exist in urban environments and have led to regulations restricting P fertilizer application to turfgrass in the states of Minnesota (Rosen and Horgan, 2005) and Wisconsin (State of Wisconsin, 2009), and in Westchester County, New York (County of Westchester, 2009). Limited research has been conducted on P transport from home lawns to surface waters, but a need exists to evaluate the impact of lawns on water quality and the relative contribution of P fertilization practices. Until recently, almost all lawn fertilizers contained some P.

Several studies have looked at the effects of P fertilizer rate on P runoff from turfgrass. In bermudagrass [*Cynodon dactylon* (L.) Pers.] plots maintained similar to golf course fairways, Shuman (2002, 2004) found that the concentration and amount of soluble P in runoff from simulated rainfall were proportional to the P fertilizer rate at 4 and 24 h after fertilization, but not at 3 and 7 d. Easton and Petrovic (2004) reported that Kentucky bluegrass/perennial ryegrass (*Lolium perenne* L.) turf plots receiving fertilizers with higher P content generally had greater soluble P losses in runoff during establishment. In the second year, the non-fertilized control had P losses equivalent to the highest P rate and greater losses than all the other fertilizer treatments tested. Soldat et al. (2008) found higher P concentrations in runoff from Kentucky bluegrass/perennial ryegrass plots receiving P fertilizer than from plots not fertilized with P, but no significant differences in P mass losses.

Sod-forming grasses can reduce soil erosion and transport of P attached to soil particles (Gross et al., 1990; Gross et al., 1991). Grasses are frequently planted as buffer strips to filter runoff from adjoining cultivated land and are effective in removing both sediment bound and soluble P (Lee et al., 1999). Buffer strips are also planted in urban areas to control runoff and reduce P transport from paved surfaces and other land uses. Steinke et al. (2007) found similar P losses from buffer strips of Kentucky bluegrass and native prairie (mixed forb/grass) designed to modify runoff from pavement, even though the Kentucky bluegrass was fertilized with P and the native prairie was not fertilized. Non-fertilized buffer strips of bermudagrass bordering fertilized plots similar to golf course fairways reduced soluble P losses by 50 to 95% when simulated rainfall was applied to dry soil within 24 h after fertilization. However, when soil moisture was high and runoff volume was 5- to 15-fold greater, reductions in soluble P loss were only 0 to 25% (Cole et al., 1997).

Under some conditions, vegetation can be an important source of soluble P for transport. Sharpley et al. (1981) found that P leached from the living plant canopies of cotton (*Gossypium hirsutum*), sorghum (*Sorghum sudanense*), and soybean (*Glycine max.*) contributed 15 to 95% of the soluble P transported in runoff, depending on the P fertilizer rate and plant age. Leaching of soluble P from dead vegetation can be a much larger contributor to runoff P than soluble P from living vegetation. The amount of soluble P leaching from Kentucky bluegrass and annual ryegrass (*Lolium multiflorum* L.) increased following drying and freezing of harvested tissue (Timmons et al., 1970; Bechmann et al., 2005). Less than 1% of the total P was leached from fresh tissue, but 80 to 100% of total P was leached following drying and a series of freeze-thaw cycles. Kussow (2008) also found that drying and freezing increased the amount of P leaching from Kentucky bluegrass tissue. Runoff loss of soluble P was significantly higher from a perennial ryegrass winter cover crop than bare soil, but it was only 0.05% of the total P in the vegetation (Ulen, 1997). Leaching of soluble P from plant tissue may have management implications for controlling P losses from home lawns, where clippings can either be removed or recycled back to the turf.

Soluble P from vegetation may be most important when the majority of runoff occurs while the soil is frozen. Snowmelt runoff accounted for 80% of the total runoff and 82% of the total P loss from a native prairie in a 5-yr study in Minnesota (Timmons and Holt, 1977). Loss of P was strongly correlated with the amount of fall regrowth, which was consistent with leaching losses from vegetation being a major source of the P transported. Steinke et al. (2007) found that Kentucky bluegrass and native prairie buffer strips for controlling runoff and P transport from paved surfaces were effective during the growing season. However, overall they were relatively ineffective, because 80% of the runoff and the majority of the P loss occurred from snowmelt or rainfall when the soil was frozen. In a 5-yr study on Kentucky bluegrass maintained under home lawn conditions in WI, Kussow (2008) reported that 87% of annual runoff and 90% of soluble P losses occurred in the period from Dec. through Mar. In New York, 62% of the annual runoff from a Kentucky bluegrass/perennial ryegrass turf occurred during snowmelt or rainfall runoff on frozen soils, although the proportion of the annual P loss during this period was not reported (Easton and Petrovic, 2004). Additional research is needed on P runoff from home lawns when the soil is frozen over a wider geographic range.

Conflicting conclusions have been reported concerning the impact of home lawns on surface water quality. Shapiro and Pfannkuch (1973) studied a chain of eutrophic urban lakes and concluded that street sweeping to remove organic debris would reduce P loading from stormwater, but that removal of P from lawn fertilizers would "not materially reduce concentrations of P in runoff". Barten and Jahnke (1997) measured higher P concentrations in runoff from P fertilized lawns than unfertilized lawns, although they did not measure runoff volumes to determine the amounts of P transported. Waschbusch et al. (1999) used hydrologic data, along with measured P concentrations in runoff from various urban source areas, as inputs for an urban runoff model to estimate P loading into two urban lakes. They concluded that lawns and streets were responsible for most of the P transported to the lakes in runoff and that home lawns were the largest single source of both total and dissolved P.

In a comprehensive review of research on P transport in turfgrass ecosystems, Soldat and Petrovic (2008) concluded that P runoff losses from turfgrass are generally similar to pasture and grassland systems and lower than cultivated agricultural systems. Easton and Petrovic (2008) studied P loading rates from fertilized lawns, barren areas, and wooded areas in an urban watershed. They found that fertilized lawns had the highest dissolved P losses on shallow soils with low water storage and high runoff. On deeper soils with low runoff volumes, dissolved P losses from fertilized lawns were similar to or less than losses from barren and wooded areas. They concluded that fertilization reduced P losses compared with unfertilized land uses by improving plant growth and reducing runoff volumes. Fertilization included both N and P, so it was not possible to determine the role of P in these effects.

While a number of studies have reported P runoff impacts from turfgrass in various environments, we did not find a systematic study evaluating the effects of P fertilization rates that included appropriate controls (both an unfertilized control and a zero P control that received N). Therefore, the specific objectives of this study were to: 1) quantify P runoff following P fertilization of turfgrass maintained similar to a home lawn, 2) evaluate the effects of removing vs. recycling clippings on P runoff, and 3) assess the effects of P fertilization and clipping management on turf quality and growth.

Materials and Methods

Site Description

This study was conducted at the Turfgrass Research, Outreach, and Education Center on the St. Paul campus of the University of Minnesota. Plots were constructed on sloped land that was previously used as pasture. The soil is classified as a Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludoll) that is typical of soils in the Twin Cities metropolitan area. The site was prepared by stripping the original vegetation and grading to achieve a uniform slope of 5%. This moderate slope helped promote surface runoff and was typical of surrounding topography. Laser leveling occurred through use of a bulldozer for a 6-h period with no subsequent tillage.

Twenty-four individual plots were constructed by installing 10-cm plastic edging to a depth of 6 to 7 cm around the perimeter of each plot to contain runoff water. At the base of each plot, runoff water was funneled to a metal trough that was 15-cm wide by 122-cm long with a depth that sloped from 5-cm in the front to 10-cm in the back. Plot dimensions were 2.4 m by 7.3 m, but because of the funneling at the base of the plot the actual runoff area was approximately 17.1 m^2. A plastic tube at the base of the trough directed the runoff water to a 19-L plastic bucket, which was located within a larger 114-L container to catch any overflow runoff water.

Plots were sodded with a mixture of the Kentucky bluegrass cultivars Midnight II, Award, and Rugby II in Sept. 2003. The sod was grown on a silt loam soil and transported to the site with about 1.25 cm of adhering soil. All plots were uniformly managed during the first year. No fertilizer was applied and the sod, the base soil, and the runoff collection equipment were allowed to settle and equilibrate until experimental treatments were initiated in Sept. 2004. Before instituting treatments, soil samples were collected from the 0- to 7.5-cm and 7.5- to 15-cm depths of all 24 plots. Soil was air-dried, ground to pass through a 2-mm sieve, and analyzed by the University of Minnesota Soil Testing Laboratory using standard procedures recommended for the North Central U.S. (NCR-13, 1998): soil pH (1:1, soil:water – Watson and Brown, 1998), organic matter (loss by weight on ignition at 360°C for 2 h – Combs and Nathan, 1998), extractable P (Bray P-1, HCl + NH_4F extractant – Frank et al., 1998), and exchangeable K (ammonium acetate extractable – Warncke and Brown, 1998). Mean soil test values for the entire plot area are presented in Table 1.

Experimental Treatments

Four fertilizer treatments were evaluated in combination with two methods of clipping management, either clippings removed-from or clippings returned-to the plots. The experimental design was a randomized complete block with three replications. The fertilizer treatments were:

1) No fertilizer applied (control)
2) 0xP + N + K (no P applied)
3) 1xP + N + K (low P rate)
4) 3xP + N + K (high P rate)

Fertilizer was applied annually in May, Sept., and Oct. in three equal applications. Nitrogen and K rates of 146 kg N and 56 kg K ha^{-1} yr^{-1} were based on University of Minnesota Extension recommendations for home lawn and commercial turfgrass areas (Rosen et al., 2008). Nitrogen and K were applied at the same rates in all three years, but P rates in the first year were higher than in the following four years (Table 2). From Sept. 2004 through May 2005, the 1xP rate was 7.1 kg P ha^{-1} per application (21.3 kg P ha^{-1} yr^{-1}) and the 3xP rate was 21.3 kg P ha^{-1} per application (63.9 kg P ha^{-1} yr^{-1}). The 1xP rate was selected because it is the recommended P rate for the first year of turfgrass in Minnesota locations with Bray-P1 soil test levels >25 mg kg^{-1} (Rosen et al., 2008). The 3xP rate was selected because it was equivalent to the amount of P supplied by a 10-4.4-8.3 fertilizer (elemental P and K basis) when N is applied at the recommended rate for turfgrass. This was a common grade of fertilizer applied to home lawns in Minnesota before the enactment of the law restricting application of fertilizer P.

Beginning in Sept. 2005, P rates were reduced to 1/3 of the first year rates (Table 2). The 1xP rate was 2.37 kg P ha^{-1} per application (7.1 kg P ha^{-1} yr^{-1}) and the 3xP rate was 7.1 kg P ha^{-1} per application (21.3 kg P ha^{-1} yr^{-1}). The 1xP rate was selected because it is typical of the amount of P applied to established lawns with high P soil tests in the Twin Cities metropolitan area prior to the widespread availability of zero P turf fertilizers. It is equivalent to the amount of P supplied by a 27-1.3-2.5 fertilizer (elemental P and K basis) when N is applied at the recommended rate. The 3xP rate is an excessive application of P and simulated a fertilizer designed for a garden (10-4.4-8.3), but often used on lawns. No fertilizer P is recommended for established lawns in Minnesota with Bray-P1 soil tests >25 mg kg^{-1} as measured at this site (Rosen et al., 2008). The fertilizer recommendation for this site corresponds to the 0xP + N + K fertilizer treatment. Application rates of fertilizer P during all five years of the study are summarized in Table 2.

Nitrogen and K were applied as a 24-0-9.1 (elemental K basis) fertilizer (Professional Turf Fertilizer, Lesco Inc., Cleveland OH). The N source was 89.2% urea-N and 10.8% slow release N (polymer coated/sulfur coated urea). The K source was potassium chloride. Phosphorus was applied as triple superphosphate (0-20.1-0 on an elemental P basis). Fertilizer was applied using hand-held shakers in two directions to ensure uniform distribution and watered-in with a 0.64 cm irrigation. Plots were also irrigated twice in 2004 and once in 2005 to prevent turfgrass death, but irrigation amounts were never large enough to cause runoff. Plots were mowed as needed at 6.4 cm with a Toro Personal Pace mower (The Toro Company, Bloomington MN).

Analysis of Runoff Water

Samples of runoff water were collected year-around, including periods when snowmelt or rainfall runoff occurred while the soil was still frozen. After each runoff event, the runoff water was mixed, runoff volume from each plot was measured by pouring the water from the 19-L collection bucket into a graduated cylinder, and a sample was collected in a 125-ml high density polyethylene container. Samples were stored in a freezer until analysis. During large runoff events, volume measurements were made more than once in a 24-h period to avoid exceeding storage capacity of the runoff collectors. Samples for these events were collected from the initial filling of the 114-L overflow container. The container was emptied with a hand pump that measured water volume.

Runoff water was analyzed for reactive P [RP (<0.45 µm)] and total P [TP (unf)]. These descriptions for the forms of P in water followed recommendations of Haygarth and Sharpley (2000), who suggested operationally defined terminology based on the analytical method and size of filter used. The RP (<0.45 µm) concentration in runoff was measured colorimetrically by the molybdenum-blue method of Murphy and Riley (1962) after sample filtration through a 0.45 µm pore size, PVDF membrane filter (cat. #09-730-27, Fisher Scientific, Pittsburgh PA). In the first two years of the study, TP (unf) was determined by the same colorimetric method after nitric-perchloric acid digestion of homogenized, unfiltered samples (Amer. Public Health Assoc., 1998). In the third year of the study, TP (unf) was measured after nitric-sulfuric acid digestion (Amer. Public Health Assoc., 1998). Twenty samples were analyzed by both of these methods for comparison and the difference between them was less than 5% (data not shown). In the remainder of this paper, we abbreviate RP (<0.45 µm) as RP and TP (unf) as TP.

Mass losses of RP and TP from each plot were calculated from runoff volume and P concentration measurements. Concentrations of RP and TP from individual runoff events were converted to average flow-weighted concentrations by dividing the cumulative amount of P lost during a given time period by the cumulative runoff volume during the same period.

Turfgrass Growth and Quality

Turfgrass quality was evaluated five times each growing season at approximately monthly intervals between May and Oct. of 2005 through 2009. Quality was measured on a visual rating scale of 1 to 9 with a score of 9 being ideal, 6 being minimally acceptable, and 1 being complete death. Clippings were collected once in Oct. 2004 after initiating fertilizer treatments, four times in 2005, five times in 2006, twice in 2007, once in 2008, and twice in 2009 from a 0.5 m x 2.4 m sampling area in the middle of each plot. Sample fresh weights were measured; subsamples were collected for moisture determination; and in plots with the clippings returned treatment, the remainder of the sample was spread back onto the sampling area from which the clippings were obtained. Subsamples were dried in a 60°C oven and clipping dry weights were determined for each plot sampling area. Relative clipping dry matter production was used as a measure of growth for comparisons among treatments, since clippings were not collected the same number of times each year.

Tissue P Concentrations and P Uptake

The clippings used to determine turfgrass dry matter production were also used for measurement of tissue P concentrations. After drying, clippings were ground to pass through a 1-mm screen with a Wiley mill. Ground tissue was then dry ashed and total P was determined using an inductively coupled plasma (ICP) spectrometer (Munter et al., 1984). Phosphorus uptake was calculated by multiplying clipping dry weights by tissue P concentrations. Similar to dry matter production, relative P uptake was used for comparisons among treatments, since clippings were not collected the same number of times each year. In 2005, clippings were sampled five times for tissue P measurement, but dry weights and P uptake were only determined on four of these sampling dates.

Soil Test P

Soil from two depths was analyzed for differences among treatments and changes over time in levels of plant-available P. Soil samples from the 0- to 7.5-cm and 7.5- to 15-cm depths were collected in Sept. 2004 before the initiation of fertilizer treatments and in May and Oct. from 2005 to 2009. Soil was air-dried, ground to pass through a 2-mm sieve, and analyzed for extractable P by the Bray P-1 method (Frank et al., 1998). Bray P-1 provides an index of plant availability for soil P. Soil samples in May were always collected before fertilizer application and Oct. samples were always collected after fertilizer application.

Measurements from 2005 to 2009 were normalized, based on the Sept. 2004 soil tests, to adjust for initial differences in Bray P-1 levels among the plots before any fertilizer applications were made. The mean Bray P-1 value in Sept. 2004 of all 24 plots and the means for the three plots to be assigned to each of the eight fertilizer application x clipping management treatment combinations were calculated, the treatment means were subtracted from the overall mean, and these differences (positive or negative) were added to the Bray P-1 measurement for individual plots in 2005 to 2009. Normalization permitted more accurate comparisons among treatments, because it reflected changes in soil P over time without the confounding effects of differences in the initial soil test level.

Statistical Analysis

Runoff P concentrations, P runoff, and runoff depth data were analyzed by analysis of variance using a mixed effects model with year and season (frozen vs. non-frozen soil) treated as repeated measures (Littell et al., 2000). Soil test P was analyzed using year and time of sampling (May or Oct.) as repeated measures. Turf quality, clipping dry weights, P uptake, and total annual P runoff and annual runoff depth (frozen + non-frozen) were analyzed using year as the only repeated measure. For all repeated measures analysis, different covariance structures were fit to describe the correlation of the residual errors associated with each of the parameters studied. Tissue P concentrations were analyzed separately for each sampling date in each year and not by repeated measures analysis.

Due to factor interactions, effects of fertilizer application and clipping management were evaluated separately for individual years and for frozen vs. non-frozen soil conditions or different sampling dates within years. Comparisons between treatment means were made with individual t-tests at the 0.05 level of significance and the linear effect of P rate (trend analysis) was determined through orthogonal contrasts using the 0xP, 1xP, and 3xP treatments (Steel and Torrie, 1980). Statistical analysis was performed using SAS® statistical software (SAS 9.1.3, SAS Institute, Cary NC, 2002-2004) and Proc Mixed procedures (Littell et al., 1998 and Littell et al., 2006).

Results

Annual Precipitation and Runoff Losses

Total annual precipitation was 11% above the 30-yr average in 2005, 3% below average in 2006, 6% below average in 2007, 19% below average in 2008, and 20% below average for the first 10 months of 2009 (Table 3). Precipitation during frozen soil conditions was 10% of total precipitation in 2005, 6% of the total in 2006, 16% of the total in 2007, 15% of the total in 2008, and 16% of the total for the first 10 months of 2009. The number of runoff events from non-frozen soil was higher in years with greater amounts of precipitation, but a similar relationship did not occur on frozen soil. When the soil was frozen, a higher proportion of precipitation was lost as runoff. One-percent or less of the precipitation on non-frozen soil was converted to runoff, whereas 5 to 27% of precipitation was lost in frozen soil runoff.

Analysis of Variance and Data Presentation

A limited amount of data was collected in the fall of 2004 and it is presented for individual dates and time periods from Sept. to Dec. Analysis of variance for flow-weighted P concentrations in runoff, runoff depths, and P loss in runoff from 2005 to 2009 showed significant effects due to fertilizer application, season (frozen vs. non-frozen soil), and year (Table 4). The only significant effects of clipping management were interactions with fertilizer application and year for runoff depth. Significant fertilizer x season, fertilizer x year, season x year, and fertilizer x season x year interactions occurred for most of the variables studied. Due to the year effects and factor interactions, data are presented by year and for frozen vs. non-frozen soil conditions within each year.

Analysis of variance for turfgrass quality, clipping dry weights, and cumulative annual totals (frozen + non-frozen) for runoff depth and P transported in runoff did not include a season factor (Table 5). For all these data, there were significant fertilizer application and fertilizer x year effects. Clipping management had significant effects on turfgrass quality and clipping dry weights. Significant year effects occurred for total annual runoff depth and P transported in runoff. There were significant clipping management interactions with fertilizer application and year for runoff depth and a significant clipping x year interaction for turfgrass quality. These data are presented separately for each year of the study.

Analysis of variance for P concentrations in plant tissue and P uptake showed significant effects of fertilizer application on both variables (Table 6). Clipping management affected P uptake, but not tissue P concentrations. There were significant differences among years and among dates within years for P concentration, as well as significant fertilizer x date, clipping x date, and date x year interactions. There was a significant fertilizer x clipping x year interaction for P uptake. Tissue P concentrations are presented separately for each sampling date within years and P uptake is presented by year.

Analysis of variance for soil test P found significant differences among years and between May vs. Oct. sampling times within years for both soil depths (Table 7). Fertilizer application and clipping management had significant effects on soil test P in the 0- to 7.5-cm depth, although there were significant fertilizer x clipping, fertilizer x year, month x year, and fertilizer x month x year interactions. Fertilizer application and clipping management did not have significant overall effects on soil test P in the 7.5- to 15-cm depth, but there were significant fertilizer x year, clipping x month, clipping x year, and month x year interactions. Due to the year effects and factor interactions, soil test data are presented separately for each year and for May vs. Oct. sampling within years.

2004

Water samples were collected from a runoff event on Sept. 16, 2004, which was shortly before the initiation of experimental treatments. Reactive P concentrations in runoff were similar for all plots (Table 8). For TP, average P concentrations in runoff from the plots where the 1xP treatment would be applied were significantly greater than the future no fertilizer and 3xP plots. Flow-weighted RP and TP concentrations from four runoff events in Oct. showed a significant linear increase in concentration as the application rate of P fertilizer increased. After the soil was frozen, RP and TP concentrations for the single runoff event in Dec. were not affected by fertilizer application. Clipping management had no effect on P concentrations in runoff in 2004.

The amount of P transported in runoff was calculated for the Oct. runoff events (Table 8). Runoff depths were similar for all plots, so P runoff followed the same pattern as P concentrations. There was a significant linear increase in both RP and TP runoff as P fertilizer application rate increased. Clipping management had no effect on P runoff.

Tissue P concentrations were measured in Sept. and Oct. of 2004 and clipping dry weights and P uptake were determined for the Oct. sampling date (Table 9). On Sept. 30, there were no treatment effects on tissue P. On Oct. 18, after the second fertilizer application, tissue P concentrations increased significantly as P application rate increased. Tissue P, clipping dry weights, and P uptake were significantly greater for the 3xP treatment than the no fertilizer treatment. Clipping management had no effect on P concentrations, clipping dry weights, and P uptake in Sept. or Oct.

Soil tests in Sept. 2004 were before the initiation of fertilizer or clipping management treatments, but Bray P-1 results were analyzed by grouping plot measurements according to the future treatment that was going to be applied. This analysis found no significant differences in Bray P-1 levels among the future treatment locations in either the 0- to 7.5-cm or 7.5- to 15-cm depths (data not presented).

2005

Flow-weighted P Concentrations in Runoff

Mean annual flow-weighted P concentrations in runoff in 2005 were affected by P fertilizer application and whether the soil was frozen or non-frozen (Table 5). Clipping management had no significant effects on concentrations of TP or RP in runoff from either frozen or non-frozen soil. Reactive P concentrations were significantly higher in runoff from frozen soil than non-frozen soil. For TP, concentrations were consistently higher in frozen soil runoff, but the differences were not significant for the no fertilizer and 0xP treatments.

Phosphorus concentrations in runoff from the no fertilizer treatment were similar to those in both the 0xP and 1xP treatments, but significantly lower than those in the 3xP treatment. For treatments receiving fertilizer, trend analysis indicated significant linear increases in flow-weighted P concentrations with increasing P rate under both frozen and non-frozen soil conditions. This linear effect occurred for both TP and RP.

Runoff Depth

Runoff depths were significantly greater from frozen soil than non-frozen soil (Table 10). Neither fertilizer application nor clipping management had a significant effect on runoff depth from non-frozen soil. However, there were significant fertilizer application x clipping management interactions for frozen soil and total annual runoff depth. In both cases, the 0xP treatment had greater runoff depth from frozen soil than the other fertilizer treatments, but it was only higher when clippings were removed (data not presented).

Phosphorus Losses in Runoff

The amount of both TP and RP transported in runoff from frozen soil was significantly greater than the amount transported from non-frozen soil (Table 10). Clipping management had no effect, but fertilizer application had significant effects, on the amount of P lost in runoff. No differences occurred between the no fertilizer and 0xP treatments, but on frozen soil the 1xP and 3xP treatments had significantly greater TP and RP runoff than the no fertilizer treatment. Trend analysis indicated significant linear increases in P runoff with increasing P rate for TP and RP on both frozen and non-frozen soils.

Total P runoff losses in 2005 were equivalent to 2.3% of the total amount of P applied from Sept. 2004 to Aug. 2005 at the 3xP rate and 3.2% of the amount applied at the 1xP rate. This fertilizer application period was the annual interval when P applications were three times higher than in the ensuing two years of the study.

Turfgrass Growth and Quality

Turfgrass growth and quality were affected by both fertilizer application and clipping management in 2005 (Table 11). The no fertilizer treatment had a significantly lower quality rating, and significantly lower relative annual growth based on clipping dry weights, than any of the treatments receiving fertilizer. There were no quality or growth differences among the three fertilized treatments. Returning clippings significantly increased turf quality compared with clipping removal. Returning clippings increased growth compared with clipping removal in all three treatments receiving fertilizer, but not in the no fertilizer control (data not presented).

Tissue P Concentrations and P Uptake

On all five plant sampling dates in 2005, there was a significant linear increase in tissue P as the P fertilizer rate increased (Table 12). The no fertilizer treatment had higher tissue P concentrations on all dates than 0xP and 1xP, although not all differences were statistically significant. Clipping management generally had no effect on tissue P, except that on July 19 and Sept. 8 the no fertilizer treatment had the highest P concentrations when clippings were removed and the lowest P concentrations when clippings were returned (data not presented).

Fertilizer application and clipping management both had significant effects on P uptake (Table 13). The no fertilizer treatment had significantly lower P uptake than any of the fertilized treatments, and the 3xP fertilizer rate had significantly greater P uptake than all of the other treatments. Returning clippings generally increased P uptake compared with clipping removal, although there was a significant fertilizer x clipping management interaction for the 0xP and 1xP treatments. The 0xP treatment had significantly more P uptake than 1xP when clippings were removed, but significantly less P uptake than 1xP when clippings were returned (data not presented).

Soil Test P

Fertilizer application and clipping management had no significant effects on soil test P in the 0- to 7.5-cm soil depth in May of 2005, but there were significant treatment differences in Oct. (Table 14). Soil test P increased linearly with increasing P fertilizer application rate in Oct. Soil test P in Oct. was greater when clippings were returned than when they were removed for the 1xP and 3xP treatments, but not for the no fertilizer or 0xP treatments (Table 14 and Fig. 1). Fertilizer application and clipping management had no significant effects on soil test P in the 7.5- to 15-cm soil depth in either May or Oct. (Table 15).

2006

Flow-weighted P Concentrations in Runoff

Mean annual flow-weighted P concentrations in runoff in 2006 were affected by fertilizer application and frozen vs. non-frozen soil conditions, but not by clipping management (Table 16). Concentrations of TP and RP were always numerically higher in runoff from frozen soil than non-frozen soil, but many of the differences were not statistically significant. Total P concentrations were significantly higher for the 3xP treatment than the no fertilizer treatment in runoff from non-frozen soil. Trend analysis indicated significant linear increases in TP and RP concentrations with increasing P rate in runoff from non-frozen soil, but not from frozen soil.

Runoff Depth

Runoff depths were consistently greater from non-frozen soil than frozen soil, although not all differences were statistically significant (Table 16). The only significant effect of clipping management on runoff depth was a fertilizer application x clipping management interaction. Runoff depths from frozen soil were highest for the no fertilizer treatment when clippings were removed, but not when they were returned (data not presented). Runoff depths from frozen soil were similar for all fertilizer treatments, but runoff depths from non-frozen soil and total annual runoff depths were significantly higher for no fertilizer than any other treatment.

Phosphorus Losses in Runoff

The amount of both TP and RP transported in runoff from frozen soil was the same as the amount transported from non-frozen soil (Table 16). Fertilizer application treatments had no significant effect on P losses in runoff from frozen soil. However, the no fertilizer treatment resulted in significantly more TP and RP in runoff from non-frozen soil than any of the treatments receiving fertilizer. Cumulative annual losses of TP were also significantly higher for no fertilizer than any other treatment, but for RP cumulative annual losses for the no fertilizer treatment were only greater than 0xP treatment. There were no significant linear effects of P rate on P losses in runoff.

Cumulative annual TP losses were significantly greater when clippings were removed than returned. This was the cause of the significant clipping management x year interaction (Table 5), since TP losses were numerically lower when clippings were removed in 2005 (Table 10) and 2007 (Table 17). Total P runoff losses in 2006 were equivalent to 0.7% of the total annual amount of P applied at the 3xP rate and 2.3% of the amount applied at the 1xP rate.

Turfgrass Growth and Quality

Turfgrass growth and quality were affected by both fertilizer application and clipping management in 2006 (Table 11). The no fertilizer treatment had a significantly lower quality rating, and significantly lower relative annual growth based on clipping dry weights, than any of the treatments receiving fertilizer. There were no growth differences among the three fertilized treatments, but the 1xP treatment had a significantly lower quality rating than the 0xP treatment. Returning clippings significantly increased turf quality and clipping dry weights compared with clipping removal.

Tissue P Concentrations and P Uptake

On all five plant sampling dates in 2006, trend analysis showed a significant linear increase in tissue P as the P fertilizer rate increased (Table 12). The no fertilizer treatment tended to have the highest tissue P concentration, but not all of the differences compared with other treatments were statistically significant. Clipping management generally had no effect on tissue P.

Fertilizer application and clipping management both had significant effects on P uptake (Table 13). The no fertilizer treatment had significantly lower P uptake than all the other treatments and there was a significant linear increase in P uptake as the P application rate increased. Returning clippings significantly increased P uptake compared with clipping removal.

Soil Test P

Soil test P increased linearly with increasing P fertilizer application rate in the 0- to 7.5-cm soil depth in both May and Oct. of 2006 (Table 14). Soil test P tended to be greater when clippings were returned than when they were removed, but the difference was not significant (Table 14 and Fig. 1). Between Oct. 2005 and Oct. 2006, Bray P-1 levels increased by 17 to 23 mg P kg^{-1} soil in all treatments. In the 7.5- to 15-cm soil depth, soil test P increased linearly with increasing P fertilizer application rate in Oct. (Table 15). There was also a significant fertilizer application x clipping management interaction in Oct. Soil test P was greater when clippings were returned than removed for the no fertilizer and 1xP treatments, but there were no differences for the 0xP and 3xP treatments (Fig. 2).

2007

Flow-weighted P Concentrations in Runoff

Mean annual flow-weighted concentrations of TP and RP in 2007 were numerically higher in runoff from non-frozen soil than frozen soil, but only the difference in TP at the 1xP rate was statistically significant (Table 17). Total P and RP concentrations for the 3xP treatment were significantly higher than for the no fertilizer treatment in runoff from both frozen and non-frozen soil. For the 1xP treatment, runoff P concentrations were significantly higher than for the no fertilizer treatment in frozen soil runoff. Trend analysis indicated significant linear increases in flow-weighted TP and RP concentrations with increasing P rate in runoff from both frozen soil and non-frozen soil. Clipping management had no significant effects on P concentrations in runoff.

Runoff Depth

Runoff depth was significantly greater from frozen soil than from non-frozen soil for all fertilizer and clipping management treatments (Table 17). Runoff depths from frozen soil were comparable for all fertilizer application treatments. On non-frozen soil, the no fertilizer treatment resulted in significantly greater runoff depths than any of the treatments receiving fertilizer. Total annual runoff depth was significantly greater for the no fertilizer treatment than for the 0xP and 3xP treatments, but was similar to the 1xP treatment. Clipping management had no significant effect on runoff depth.

Phosphorus Losses in Runoff

For the 3xP treatment, the amount of TP and RP lost in runoff was significantly greater from frozen soil than non-frozen soil (Table 17). When clippings were returned, the amount of TP transported from frozen soil was significantly greater than the amount from non-frozen soil. There were no other significant differences in P losses between frozen and non-frozen soil.

Fertilizer treatment had no effect on TP runoff from non-frozen soil or RP runoff from frozen soil. The 3xP treatment resulted in significantly greater TP runoff losses from frozen soil and greater cumulative annual TP losses than the no fertilizer treatment. The 0xP treatment had significantly lower RP runoff from non-frozen soil and significantly lower cumulative annual RP runoff than the no fertilizer treatment. Trend analysis indicated a significant linear increase in TP runoff from frozen soil and cumulative annual TP runoff with increasing P rate. Total P runoff losses in 2007 were equivalent to 0.8% of the total annual amount of P applied at the 3xP rate and 1.4% of the amount applied at the 1xP rate.

Turfgrass Growth and Quality

The no fertilizer treatment had a significantly lower quality rating, and significantly lower relative annual growth based on clipping dry weights, than any of the treatments receiving fertilizer (Table 11). There were no growth differences among the three fertilized treatments, but the 1xP rate had a significantly lower quality rating than the 0xP and 3xP rates. Clipping management had no significant effects on turfgrass quality or growth.

Tissue P Concentrations and P Uptake

Phosphorus fertilization had significant effects on tissue P concentrations in 2007 (Table 12). On the July sampling date, the 0xP treatment had significantly lower tissue P than the 1xP or 3xP treatments. In August, there was a significant linear increase in tissue P as the P fertilizer rate increased. The no fertilizer treatment had P concentrations that were similar to the highest P rate on both dates. Clipping management had no effect on tissue P on either date.

The no fertilizer treatment had significantly lower P uptake than all of the fertilized treatments in 2007 (Table 13). Phosphorus uptake was similar for the three treatments receiving fertilizer. Clipping management had no significant effect on P uptake.

Soil Test P

Soil test P showed a significant linear increase with increasing P fertilizer application rate in the 0- to 7.5-cm soil depth on both the May and Oct. sampling dates (Table 14). Soil test P was numerically greater when clippings were returned than when they were removed, but the differences were not significant. Most of the difference occurred in the 1xP treatment (Fig. 1). In the 7.5- to 15-cm soil depth, the only effect of fertilizer application was that the 1xP treatment had significantly higher soil test P than the no fertilizer treatment in May (Table 15). On both sampling dates, soil test P in the 7.5- to 15-cm soil depth was significantly higher when clippings were returned than when they were removed. The majority of the difference occurred in the 1xP treatment (Fig. 2). Between Oct. 2006 and May 2007, Bray P-1 levels increased by 8 to 13 mg P kg^{-1} soil in all treatments, including the treatments where no fertilizer and no P fertilizer (0xP) was applied.

2008

Flow-weighted P Concentrations in Runoff

In runoff from both frozen and non-frozen soil in 2008, trend analysis showed a significant linear increase in flow-weighted RP concentrations as the P fertilizer rate increased (Table 18). Runoff from the no fertilizer treatment had significantly higher P concentrations than the 0xP treatment on frozen soil and significantly higher RP concentrations than both the 0xP and 1xP treatments on non-frozen soil. Flow-weighted RP concentrations were higher in runoff from frozen soil than in non-frozen soil runoff and most of the comparisons among individual treatments were statistically significant. Returning clippings significantly increased RP concentrations in runoff compared with clipping removal.

Runoff Depth

Annual runoff depth from frozen soil and total annual runoff depth were greater from the no fertilizer treatment than from the treatments receiving fertilizer, although the difference between no fertilizer and 1xP was not significant (Table 18). There were no differences in runoff depth among the fertilized treatments. Annual runoff from frozen soil and total annual runoff were significantly greater when clippings were removed than when they were returned. Fertilizer application and clipping management had no effect on runoff from non-frozen soil. Over 98% of total runoff in 2008 occurred while the soil was frozen.

Phosphorus Losses in Runoff

Trend analysis showed a significant linear increase in RP transported in runoff from both frozen and non-frozen soils as the P fertilizer rate increased (Table 18). The no fertilizer treatment had significantly greater RP runoff from frozen soil than the 0xP treatment and it was similar to the two treatments receiving P fertilizer. Most of the RP runoff was from frozen soil. Clipping management had no significant effect on RP runoff.

Turfgrass Growth and Quality

The no fertilizer treatment had a significantly lower quality rating, and significantly lower relative annual growth based on clipping dry weights, than any of the treatments receiving fertilizer (Table 19). There were no growth or quality differences among the three fertilized treatments. Clipping management had no effect on turfgrass quality, but returning clippings significantly increased growth compared with clipping removal.

Tissue P Concentrations and P Uptake

Trend analysis showed a significant linear increase in tissue P concentrations as the P fertilizer application rate increased (Table 12). The no fertilizer treatment had significantly lower tissue P concentrations than any of the treatments receiving fertilizer. There was a significant linear increase in P uptake as the P application rate increased (Table 13). The three treatments receiving fertilizer took up 15 to 25 times as much P as the no fertilizer treatment. Returning clippings significantly increased P uptake compared with clipping removal.

Soil Test P

Soil test P increased linearly with increasing P fertilizer application rate in the 0- to 7.5-cm soil depth in both May and Oct. of 2008 (Table 14). The no fertilizer treatment had soil test P levels that were similar to the 1xP rate. There were numerical increases in soil test P when clippings were returned compared with clipping removal, but the differences were not significant (Table 14 and Fig. 1). In the 7.5- to 15-cm soil depth, there was a trend in Oct. for a linear increase in soil test P with increasing P fertilizer application rate, but there were no significant differences among the fertilizer treatments on either sampling date (Table 15). Returning clippings significantly increased soil test P compared with clipping removal. The majority of the difference between clipping management treatments occurred at the 1xP fertilizer rate (Fig. 2).

2009

Flow-weighted P Concentrations in Runoff

Flow-weighted RP concentrations in runoff from both frozen and non-frozen soil in 2009 increased significantly as P application rate increased (Table 20). Concentrations were generally significantly greater in runoff from non-frozen soil than in frozen soil runoff. Returning clippings increased RP concentrations in frozen soil runoff compared with clipping removal, except for the 0xP treatment where RP was lower when clippings were returned (data not presented). A similar fertilizer x clipping interaction occurred on non-frozen soil where RP concentrations were higher when clippings were returned rather than removed for all treatments except the 3xP rate.

Runoff Depth

Fertilizer application and clipping management had no significant effects on runoff depth (Table 20). Runoff from frozen soil accounted for 99% of total annual runoff in 2009.

Phosphorus Losses in Runoff

Fertilizer application and clipping management had no effects on the small amounts of RP runoff from non-frozen soil (Table 20). For RP runoff from frozen soil and total annual RP runoff, trend analysis found significant linear increases as the P application rate increased. Reactive P runoff for the no fertilizer treatment was comparable to the 0xP and 1xP treatments, but significantly less than the 3xP treatment.

Turfgrass Growth and Quality

The no fertilizer treatment had a significantly lower quality rating, and significantly lower relative annual growth based on clipping dry weights, than any of the treatments receiving fertilizer (Table 19). There were no growth or quality differences among the three fertilized treatments. Clipping management had no effect on clipping dry weights, but returning clippings significantly increased turfgrass quality compared with clipping removal.

Tissue P Concentrations and P Uptake

Trend analysis showed significant linear increases in tissue P concentrations as the P fertilizer application rate increased on both sampling dates in 2009 (Table 12). On June 6, the no fertilizer treatment had tissue P concentrations comparable to the 0xP and 1xP application rates, but it was significantly lower than the 3xP treatment. On July 13, the no fertilizer treatment had tissue P concentrations comparable to the 1xP and 3xP application rates. Clipping management had no effect on tissue P on either sampling date. There was a significant linear increase in relative P uptake as the P application rate increased (Table 13). The no fertilizer treatment had significantly lower P uptake than any of the treatments receiving fertilizer. Returning clippings significantly increased P uptake compared with clipping removal.

Soil Test P

Soil test P increased linearly with increasing P fertilizer application rate in the 0- to 7.5-cm soil depth in both May and Oct. of 2009 (Table 14). The no fertilizer treatment had soil test P levels that were similar to the 1xP rate. Returning clippings significantly increased soil test P compared with clipping removal on both dates (Table 14 and Fig. 1).

In the 7.5- to 15-cm soil depth, trend analysis found that soil test P increased linearly with increasing P fertilizer application rate in both May and Oct. (Table 15). Soil test P for the no fertilizer treatment was similar to the 0xP and 1xP treatments. Returning clippings significantly increased soil test P compared with clipping removal in Oct., but clipping management effects were not significant in May (Table 15 and Fig. 2).

Discussion

Flow-weighted P Concentrations in Runoff

Frozen vs. non-frozen soil conditions affected mean annual flow-weighted P concentrations in runoff, but results were variable among years (Tables 10, 16-18, 20). Not all differences were statistically significant, but P concentrations were consistently higher in frozen soil runoff in 2005, 2006, and 2008. Runoff from non-frozen soil had higher P concentrations in 2007 and 2009, although 2009 measurements were based on a very small amount of runoff from non-frozen soil (Table 20). The largest differences were in 2005, when flow-weighted P concentrations were generally two- to three-times higher in runoff from frozen compared with non-frozen soil. The highest P concentrations of the study were in frozen soil runoff from the 3xP rate in 2005, which was probably due to the three-times higher P fertilizer rates in 2005 than in ensuing years (Table 2). One-third of the annual P rate was applied in Oct., so it was susceptible to winter runoff. Phosphorus concentrations in frozen soil runoff were about 50% lower for the 3xP treatment in 2006 to 2009 than in 2005.

In all five years of the study, trend analysis showed significant linear increases in flow-weighted P concentrations with increasing P fertilizer rate (Tables 8, 10, 16-18, 20). This included Oct. runoff events in 2004 that were about one month after the initiation of fertilizer treatments. The only measurements that did not show a linear P rate effect were TP and RP from frozen soil in 2006 and in a single runoff event in Dec. 2004. The absence of a rate effect on frozen soil runoff in 2006 was due to similar P concentrations for the 1xP and 3xP treatments, which were both higher than the 0xP treatment. In 2005 to 2007, flow-weighted P concentrations in runoff were similar for the no fertilizer treatment and the 0xP treatment that received N and K fertilizer. The same was true for runoff from non-frozen soil in 2009. For frozen soil runoff in 2009 and runoff from both frozen and non-frozen soil in 2008, P concentrations were significantly higher for the no fertilizer treatment than for the 0xP treatment.

Clipping management had inconsistent effects on flow-weighted P concentrations in runoff. Except for RP in Oct. 2004, concentrations were always numerically higher when clippings were returned rather than removed (Tables 8, 10, 16-18, 20). However, the only significant differences were for non-frozen soil runoff in 2008 and frozen soil runoff in 2008 and 2009.

Phosphorus concentrations in runoff reflect the potential for P losses. Higher P concentrations in frozen soil runoff than in runoff from non-frozen soil in three of the five study years suggest that leaching of P from decaying vegetation was a source of runoff P, as demonstrated in previous research by Timmons et al. (1970) and Bechmann et al. (2005). Returned clippings were also a source of runoff P, but the lack of consistently significant effects of clipping management on runoff P concentrations indicates that grass clippings supplied a small amount of plant tissue relative to the amount in turfgrass stems and leaves that died after the conclusion of the growing season. Higher P concentrations in frozen soil runoff also suggest that fall applications of P fertilizer can be a source of runoff P. The increases in runoff P concentrations as P application rate increased indicate that the amount of P fertilizer applied can be a determining factor in the amount of P available for runoff.

Runoff Depth

Runoff depths were affected by soil conditions (frozen vs. non-frozen), timing and amount of precipitation, and fertilizer treatment (Tables 3, 10, 16-18, 20). Runoff depths were much greater from frozen soil than non-frozen soil in four of the five study years. In those four years, 74 to 99% of total runoff depth occurred while the soil was frozen. Only one of six runoff events in 2007 occurred while the soil was frozen, but it accounted for 81% of total runoff depth. In 2006, only three of 12 runoff events and 32% of the total runoff depth occurred under frozen soil conditions. The difference in 2006 was that the amount of precipitation occurring while the soil was frozen was 46 mm, while there were 92 to 126 mm of precipitation on frozen soil in the other four years (Table 3).

Easton and Petrovic (2004) found that 62% of runoff from Kentucky bluegrass/perennial ryegrass turf was from frozen soil. In other studies on Kentucky bluegrass turf (Kussow, 2008), native prairie and Kentucky bluegrass buffer strips (Steinke et al., 2007), and native prairie (Timmons and Holt, 1977), 80 to 100% of runoff occurred while the soil was frozen.

Annual precipitation was highest in 2005 and lowest in 2008 and 2009 (Table 3). Total annual runoff depths generally followed the same pattern as annual precipitation, except that 2008 had the second highest runoff depth (Tables 10, 16-18, 20). The major effects of fertilizer application on runoff depth were that in 2006 and 2007 the no fertilizer treatment had significantly higher runoff depths from non-frozen soil than any of the treatments receiving fertilizer. The no fertilizer treatment also had the highest runoff depth from non-frozen soil in 2005, but the differences with the treatments receiving fertilizer were not significant. In 2008, the no fertilizer treatment had significantly higher runoff depths from frozen soil than any of the treatments receiving fertilizer. Higher runoff depths for the no fertilizer treatment were probably due to poorer turf quality and growth (Table 11). Easton and Petrovic (2004) also found that in the year after turf establishment the unfertilized control in their study had the highest runoff depth.

Annual runoff from frozen soil and total annual runoff were significantly greater when clippings were removed than when they were returned in 2008. This may have been due to non-decomposed clippings creating a barrier to runoff, but the lack of an effect on non-frozen soil or in any other year suggests that this result may be an aberration.

Phosphorus Losses in Runoff

Phosphorus losses in runoff from turfgrass were primarily affected by fertilizer application, frozen vs. non-frozen soil conditions, runoff depth, and turf quality and growth. The largest and most consistent effects on P losses in runoff were found in 2005 (Table 10). This was not surprising, because 2005 had the highest P fertilizer application rates. The amounts of precipitation (Table 3) and runoff depths (Tables 10, 16-18, 20) were also highest in 2005. About 39% of total runoff depth and 52% of P losses over the five years occurred in 2005.

Phosphorus fertilizer application rate significantly affected P runoff in 2004, 2005, 2007, 2008, and 2009, but not in 2006 (Tables 8, 10, 16-18, 20). About one month after the initiation of fertilizer treatments, trend analysis showed significant linear increases in TP and RP runoff with increasing P rate during Oct 2004 runoff events. Trend analysis in 2005 showed significant linear increases in TP and RP runoff with increasing P rate on both frozen and non-frozen soil. In 2007, there were significant linear increases in TP losses from frozen soil and in cumulative annual TP losses as P application rate increased. In 2008 and 2009, when only RP was measured, P runoff losses increased linearly with increasing P rate on frozen soil in both years and on non-frozen soil in 2008. These significant linear trends in P runoff paralleled significant linear P rate effects on flow-weighted P concentrations in runoff. Easton and Petrovic (2004) also found that using fertilizers with higher P content resulted in higher P runoff losses from turfgrass.

The higher P fertilizer rates in 2004 and 2005 could have had a carryover effect and influenced P runoff losses in following years. However, the fact that P runoff in 2006 was not affected by P rate suggests that the linear effects of P rate on P runoff from 2007 to 2009 were due to the P fertilizer applied in those years. Fewer differences between P rates were found using mean separation procedures than trend analysis. This may have been because the three replications used in the study were not enough to overcome variability among plots.

Differences in runoff depth were the main factor determining P runoff losses in 2006 (Table 16). Total P losses from non-frozen soil and cumulative annual total P losses were significantly greater for the no fertilizer treatment than for any of the treatments receiving fertilizer. These increases in P transport paralleled significant increases in runoff depth for the no fertilizer treatment (Table 16), as well as significant reductions in turf quality and growth (Table 11). Significantly greater runoff depth from the no fertilizer treatment on non-frozen soil in 2007 (Table `17) and frozen soil in 2008 (Table 18) also contributed to P runoff that was equal to or greater than the 3xP treatment. Easton and Petrovic (2004) found that in the year after turf establishment, the non-fertilized control in their study had the highest runoff depth and significantly greater P runoff loss than 9 of 10 fertilizer treatments.

Phosphorus runoff losses in 2005, 2008, and 2009 were significantly greater in runoff from frozen soil than in non-frozen soil runoff (Tables 10, 18, 20). Similar consistent numerical differences occurred in 2007, but P losses from frozen soil were only significantly greater at the 3xP rate (Table 17). Higher flow-weighted P concentrations and higher runoff depths were both important factors in greater P transport in frozen soil runoff in 2005 and 2008. In 2007, runoff depths were greater from frozen soil, but P concentrations were greater in non-frozen soil runoff. The single runoff event from frozen soil in 2007 accounted for 74% of annual TP losses due to high runoff depth. In 2009, P concentrations were greater in runoff from non-frozen soil, but P runoff was much higher from frozen soil due to 100-times greater runoff depths.

There were no significant differences between P runoff from frozen soil and P runoff from non-frozen soil in 2006 (Table 16). This may have been due to the fact that the amount of precipitation while the soil was frozen was lower than in other years (Table 3). This was the only year of the study when runoff depths from frozen soil were lower than runoff depths from non-frozen soil. Removing rather than returning clippings significantly increased cumulative annual TP runoff in 2006, but clipping management had no significant effects on P runoff in other years. Kussow (2008) also measured an increase in P runoff when clippings were removed rather than returned, but the difference was not statistically significant. Clipping management, therefore, does not appear to be a major factor in P runoff from turfgrass.

The results of this study support other research showing that winter snowmelt events and spring rainfall on frozen ground are important, and in many years dominant, parts of annual nutrient export from turfgrass and native prairie in northern climates (Kussow, 2008; Steinke et al., 2007; Timmons and Holt, 1977). In our study, 86% of P runoff losses over the five years occurred during winter and early spring when the soil was still frozen.

Reactive P comprised 72% of the TP runoff in 2005, 70% in 2006, and 77% in 2007. This is consistent with low erosion rates from turfgrass and limited transport of soil-bound P (Gross et al., 1990). In their review of research on P transport in turfgrass ecosystems, Soldat and Petrovic (2008) found that in plot-scale studies where runoff was collected from natural precipitation events, annual P loads ranged from 0.26 to 2.1 kg ha^{-1} yr^{-1}. This range included measurements of both TP and RP. In our 5-yr study, the range of runoff P losses was 0.06 to 1.47 kg ha^{-1} yr^{-1} for TP and 0.05 to 1.15 kg ha^{-1} yr^{-1} for RP. These results are comparable, but the range extends lower, than the range reported by Soldat and Petrovic (2008).

Turfgrass Quality and Growth

In the presence of N and K, turfgrass quality and growth were not affected by P fertilizer application (Tables 9, 11, 19). These results support the recommendation that there is no benefit from applying P fertilizer to established turf when soil P is in the adequate soil test range. This study cannot distinguish between the effects of N and K in improving turf quality and growth, although regular N applications are usually necessary for establishing and maintaining high quality turf (Turner and Hummel, 1992). Soil tests showed a need for K, so K may also have played a role.

As expected, turf quality and growth were significantly reduced when no fertilizer was applied (Tables 9, 11, 19). For the single clipping harvest in Oct. 2004, which was one month after the initiation of fertilizer treatments, dry weights were numerically lowest for the no fertilizer treatment, but not significantly different from 0xP or 1xP. Annual means for the five years from 2005 to 2009, however, found that the no fertilizer treatment always had significantly lower clipping dry weights than any of the fertilizer treatments and that growth was always similar for three treatments receiving fertilizer. Turf quality ratings for the no fertilizer treatment decreased from 3.7 in 2005 to 1.7 in 2008, although they increased back to 2.6 in 2009. Quality ratings increased slightly for all three fertilized treatments and ranged from 5.5 to 6.3 during the five years. The 1xP treatment was significantly lower than 0xP in 2006 and significantly lower than both 0xP and 3xP in 2007. These differences between the three fertilized treatments ranged from 0.4 to 0.7 units, which may not be meaningful on the nine point quality scale.

Clipping management significantly affected turf quality and growth. In 2005, 2006, and 2009, the quality rating increased by 0.3 to 0.6 units when clippings were returned. This small increase may not be very meaningful, but in 2005, 2006, and 2008 relative growth increased by 26 to 68% when clippings were returned rather than removed. This may have been due to the recycling of nutrients in the clippings.

Compared with the fertilized treatments, the significant reductions in turf quality and growth for the no fertilizer treatment were associated with significantly greater runoff depths from non-frozen soil in 2006 and 2007 (Tables 6 and 7). This is consistent with other research showing that a dense stand of turfgrass reduces water runoff (Gross et al., 1991; Easton and Petrovic, 2004). As indicated by the turf quality ratings and growth differences, the no fertilizer treatment resulted in reduced turf density, greater weed growth, more area with exposed soil, and more dead grass and weed tissue than the fertilized treatments.

Increases in runoff increase the potential for P transport. The results of this research indicate that maintenance of a healthy stand of turf is an important factor regulating runoff from lawns and other turfgrass areas. Poor turf quality can lead to higher amounts of runoff, which can increase the potential for P losses even where no P fertilizer has been applied.

Tissue P Concentrations and P Uptake

As expected, P fertilizer application had significant effects on tissue P concentrations and P uptake. There were no fertilizer effects on tissue P concentrations on the first sampling date in Sept. 2004, which was two weeks after the initiation of fertilizer treatments, but by the second sampling date about three weeks later there was a significant linear increase in tissue P as the P application rate increased (Table 9). This was soon after the second fertilizer application. Over the next five years, there were significant linear increases in tissue P concentration as the P fertilizer rate increased on all but one sampling date (Table 12). On that date, P concentrations were significantly higher for the 1xP and 3xP treatments than for the 0xP treatment, but they were comparable to each other. The no fertilizer treatment usually had tissue P concentrations that were similar to the 3xP fertilizer treatment. This was probably due to the much lower plant growth for the no fertilizer treatment compared with the fertilized treatments (Tables 9, 11, 19). Growth was limited by a factor other than P, since P concentrations for all treatments were always within or higher than the adequate range of 0.27 to 0.40% found in field test plots of Kentucky bluegrass (Mills and Jones, 1996). Growth was probably limited by inadequate N in the no fertilizer treatment, which led to increased concentration of P in plant tissue. Clipping management had no effect on tissue P concentrations.

The 3xP treatment had the greatest P uptake (P concentration x plant dry weight) in Oct. 2004 and it was significantly greater than the no fertilizer treatment (Table 9). This was due to differences in both P concentration and plant growth. Over the five full years of the study from 2005 to 2009, P uptake was significantly lower for the no fertilizer treatment than for any of the treatments receiving fertilizer (Table 13). Total P uptake was limited by the poor growth in the no fertilizer treatment (Tables 11 and 19). The 3xP treatment had significantly greater P uptake than the 0xP and 1xP treatments in 2005, 2006, and 2009, and the 0xP treatment in 2008. This was primarily due to greater tissue P concentrations at the high P fertilizer rate (Table 12). Returning clippings significantly increased P uptake compared with clipping removal in 2005, 2006, 2008, and 2009. This was due to significantly greater growth in those years when clippings were returned. Returning clippings significantly increased RP concentrations in runoff from frozen soil in 2008 and 2009 and from non-frozen soil in 2008 (Tables 18 and 20), suggesting that the total amount of P recycled in clippings can potentially affect P runoff.

Soil Test P

Soil test P in the 0- to 7.5-cm depth was strongly affected by the rate of P applied to the fertilized treatments. It increased linearly with increasing P application rate on every sampling date from Oct. 2005 to Oct. 2009 (Table 14). There was a similar trend on the first sampling date in May 2005, but it was not significant. Increases in soil test P as the P fertilizer rate increased were generally consistent with the magnitude of P losses in runoff.

Although not all differences were significant, soil test P in the 0- to 7.5-cm depth was consistently greater for the no fertilizer treatment than the 0xP treatment. Neither of these treatments received any P fertilizer, so the reason for these differences is unclear. The no fertilizer treatment generally had soil test P levels that were comparable to the 1xP treatment. The greater growth in the fertilized treatments (Tables 11 and 19) may have contributed to these results. Less P was contained in the biomass (roots, stems, and leaves) of the no fertilizer treatment, so more of the P in this system was in the soil and available to raise soil test P. The deterioration in turf quality in the no fertilizer treatment may also have released P through decomposition of parts of the sod as turf cover decreased.

Soil test P in the 7.5- to 15-cm depth was generally similar for all four fertilizer application treatments from 2005 to 2008 (Table 15). The only significant differences were a linear increase in soil test P with increasing P application rate in Oct. 2006 and greater soil test P for the 1xP treatment in May 2007 than for the no fertilizer treatment. In the final year of the study in May and Oct. of 2009, there were significant linear increases in soil test P with increasing P fertilizer application rate. This suggests deeper movement into the soil of surface-applied P by 2009. There was a trend for a linear rate effect in Oct. 2008, and the 3xP treatment had significantly higher soil test P than the no fertilizer treatment on both sampling dates in 2009. Contrary to the 0- to 7.5-cm soil depth, the no fertilizer and 0xP treatments always had comparable soil test P levels.

Clipping management had significant, but inconsistent, effects on soil test P in both soil depths (Tables 14-15 and Figs. 1-2). In the 0- to 7.5-cm depth, soil test P was always numerically greater when clippings were returned than removed, but the differences were only significant in Oct. 2005 and May and Oct. 2009. The most consistent differences were for the 1xP fertilizer rate. In the 7.5- to 15-cm depth, soil test P was significantly greater when clippings were returned than removed in 2007, 2008, and Oct. 2009. The majority of these differences also occurred for the 1xP fertilizer rate, although it is not clear why clipping management effects were greater in this treatment. These results suggest that under some circumstances removing clippings can remove a significant amount of P from a turfgrass system. Returning clippings may provide a potential source of soil P for runoff, although in this study increases in P runoff were not observed when clippings were returned (Tables 8, 10, 16, 17, 18, and 20).

There were large increases in soil test P in the 0- to 7.5-cm depth of all treatments between Oct. 2005 and Oct. 2006 (Table 14 and Fig. 1). These increases ranged from 17 to 23 mg P kg^{-1} of soil. Application of P fertilizer could explain increases for the 1xP and 3xP treatments, but it is not clear why the no fertilizer and 0xP treatments that received no P fertilizer had similar increases in soil test P. A possible explanation could be that the sod and the soil attached to it had been well fertilized and supplied large amounts of organic P that broke down and released P in the first two years of the study. Testing of the sod and soil before installation was not done, so this possibility cannot be confirmed. Soil test P increased by 8 to 13 mg P kg^{-1} of soil in the 7.5- to 15-cm soil depth of all treatments between Oct. 2006 and May 2007, so it appears that some of the increased P in the surface layer moved deeper into the soil during that time period (Table 15 and Fig. 2). More research is needed to help explain the soil P increase when no P fertilizer was applied. In addition, longer term studies are needed to determine the extent of soil P draw down in turf systems when P fertilizer is not applied.

Conclusions

Phosphorus transport in runoff from turfgrass was affected by frozen vs. non-frozen soil conditions, runoff depth, turf growth and quality, soil test P levels, and P fertilizer application rate. Returning clippings led to some increases in soil test P levels and flow-weighted P concentrations in runoff, compared with clipping removal, but under the conditions of this study the return of clippings did not lead to increases in P runoff. This suggests that modifying clipping management practices will not significantly affect P transport from turfgrass.

Over the five years of this study, 78% of total runoff depth and 86% of the P transported in runoff occurred while the soil was frozen. Therefore, even on soils requiring P, fall application of P fertilizer to established turfgrass would have a high runoff potential. Runoff depths increased in three of five years as turf quality and growth declined in the no fertilizer treatment, resulting in increased P runoff losses even when no P fertilizer was applied. Consequently, maintaining a dense, healthy stand of turf can reduce P transport by reducing runoff depth. Soil test P levels, flow-weighted P concentrations in runoff, and the potential for P runoff losses generally increased as the P application rate increased. In four of five years, increasing the amount of P fertilizer applied resulted in greater annual runoff losses of P. Applying P fertilizer increased tissue P concentrations and P uptake, but did not improve turf growth or quality when adequate N and K were applied. On sites testing high in soil P, as used in this study, P runoff from lawns can be reduced without affecting turf quality by not applying P fertilizer.

Further Research Needs

More research is needed to help explain the soil P increase that occurred when no P fertilizer was applied. Reasons for the high soil test P in the no fertilizer treatment are unclear, but one possibility is P release due to breakdown and degradation of the sod. Research to test this possibility could provide useful information about sources of P for runoff, because laying sod is a very common method of establishing turf. In addition, longer term studies are needed to determine how soil test P is affected by fertilizer practices and the extent of soil P draw down in turf systems when P fertilizer is not applied. This five-year study showed initial changes in soil P from different P fertilizer practices, but was too short to identify long-term patterns.

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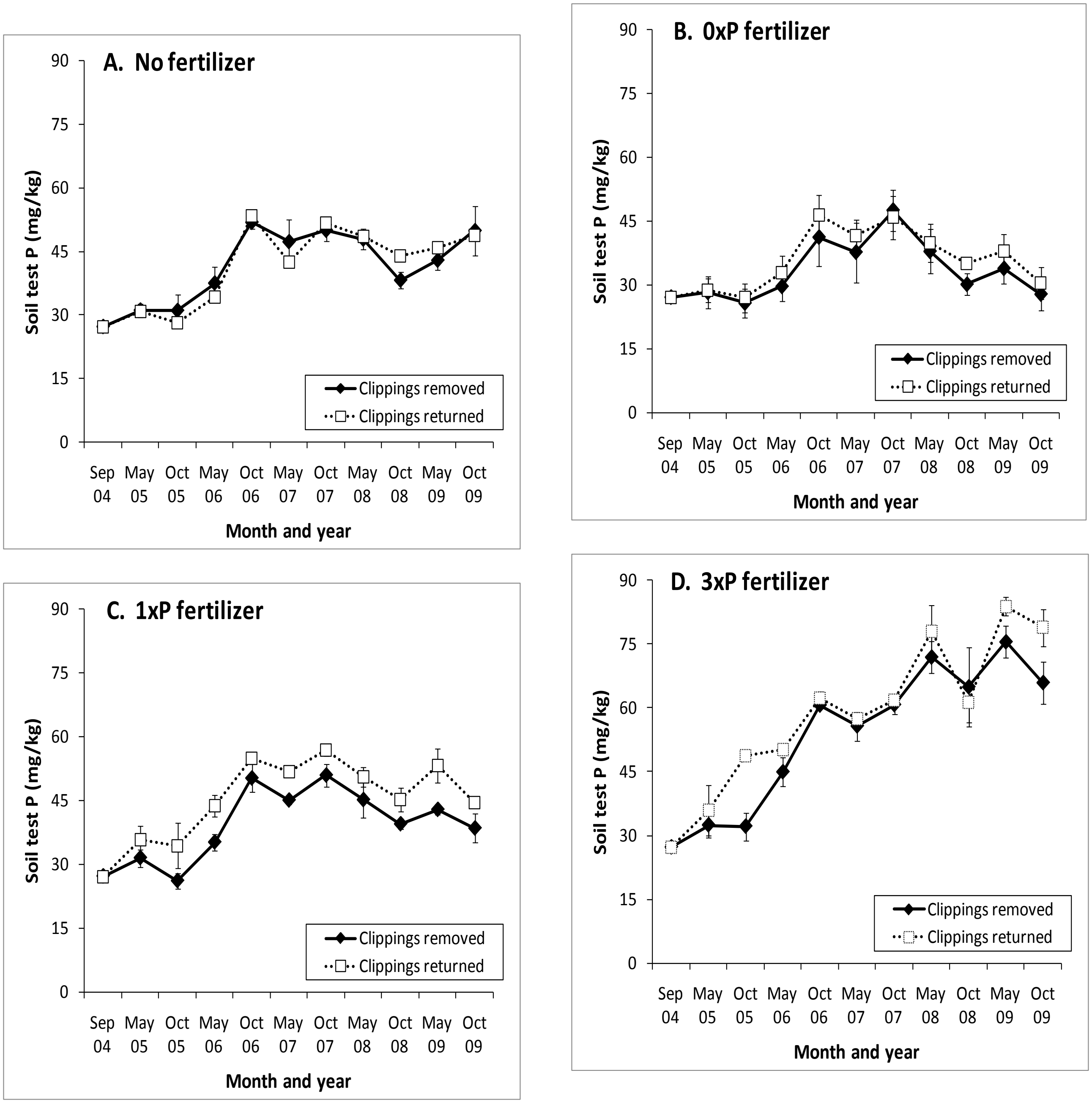

Figure 1. Soil test P (Bray P-1) from 2004 to 2009 in the 0- to 7.5-cm soil depth for clippings removed vs. clippings returned in each of the four fertilizer treatments: A. No fertilizer, B. 0xP+N+K, C. 1xP+N+K, D. 3xP+N+K. The Sept. sampling date was before the initiation of fertilizer or clipping management treatments. Vertical bars are standard errors.

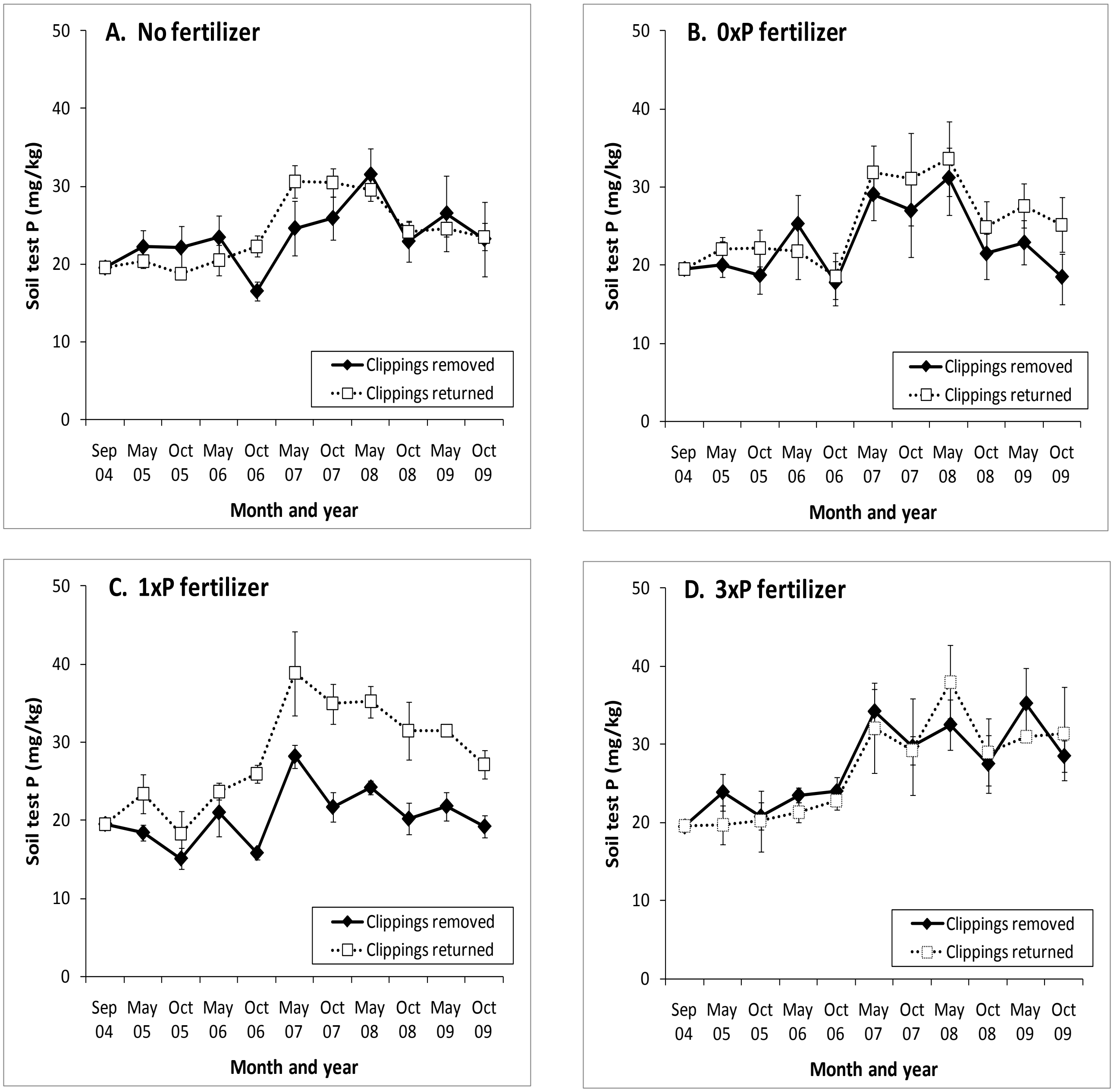

Figure 2. Soil test P (Bray P-1) from 2004 to 2009 in the 7.5- to 15-cm soil depth for clippings removed vs. clippings returned in each of the four fertilizer treatments: A. No fertilizer, B. 0xP+N+K, C. 1xP+N+K, D. 3xP+N+K. The Sept. sampling date was before the initiation of fertilizer or clipping management treatments. Vertical bars are standard errors.

Table 1. Soil test results from the experimental plot area before the initiation of fertilizer treatments in Sept. 2004.

Soil depth (cm)	pH	Organic matter (%)	Phosphorus (mg kg^{-1})	Potassium (mg kg^{-1})
0-7.5	6.8 ± 0.2†	4.4 ± 0.7	27 ± 8	115 ± 21
7.5-15	7.0 ± 0.2	2.9 ± 0.6	20 ± 5	87 ± 17

†Mean ± the standard deviation of 24 samples.

Table 2. Timing and rate of P application for the four fertilizer treatments. Each fertilizer treatment was used in combination with two clipping management treatments, either clippings removed or clippings returned, for a total of eight experimental treatments.

Fertilizer Treatment		Timing of phosphorus application																
		2004		2005			2006			2007			2008			2009		
		Sept	Oct	May	Sept	Oct	May	Sept	Oct	May	Sept	Oct	May	Sept	Oct	May	Sept	Oct
		---------- P application rate (kg P ha^{-1}) ----------																
1	No fertilizer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0xP, N+K†	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1xP, N+K	7.1	7.1	7.1	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37
4	3xP, N+K	21.3	21.3	21.3	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1

†Annual N rate was 146 kg N ha^{-1} and annual K rate was 56 kg K ha^{-1}.

Table 3. Precipitation amounts, number of runoff events, and the amount of runoff as a percentage of precipitation during frozen and non-frozen soil conditions in 2005 to 2009.

Year	Precipitation amount†			Number of runoff events			Runoff as a percentage of precipitation		
	Frozen soil	Non-frozen soil	Total	Frozen soil	Non-frozen soil	Total	Frozen soil	Non-frozen soil	Total
	-------------------- mm --------------------						-------------------- % --------------------		
2005	92	825	917	9	10	19	27.0	1.1	3.7
2006	46	758	804	3	9	12	8.3	1.1	1.5
2007	126	655	781	1	5	6	5.2	0.2	1.0
2008	101	568	669	6	2	8	24.9	0.1	3.8
2009‡	95	505	600	3	2	5	8.0	0.1	1.3

†30-yr mean annual precipitation = 828 mm yr^{-1}.
‡Data for 2009 are from Jan. 1 to Oct. 31.

Table 4. Analysis of variance table for flow-weighted P concentrations in runoff, runoff depth, and the amount of P transported in runoff during different seasons of the year (frozen vs. non-frozen soil conditions).

Source of variation[1]	Df	Response variable				
		Total P concentration	Reactive P concentration	Runoff depth	Total P runoff	Reactive P runoff
		---------------------------- Significance level of factor effects ----------------------------------				
Fertilizer application	3	**	**	*	**	**
Clipping management	1	NS	NS	NS	NS	NS
Season	1	**	**	**	**	**
Year	2	*	*	**	**	**
Fertilizer x clipping	3	NS	NS	*	NS	NS
Fertilizer x season	3	NS	*	*	**	**
Fertilizer x year	6	*	**	**	**	**
Season x year	2	**	**	**	**	**
Fertilizer x clipping x yr	6	NS	NS	**	NS	NS
Fertilizer x season x yr	6	*	*	NS	**	**

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.
[1]The interactions clipping x season, clipping x year, fertilizer x clipping x season, clipping x season x year, and fertilizer x clipping x season x year were not significant for any variable at the 0.05 probability level.

Table 5. Analysis of variance table for cumulative annual runoff depth, cumulative annual amount of P transported in runoff, and turfgrass quality and growth (data not separated by season).

Source of variation	Df	Response variable: Runoff depth	Total P runoff	Reactive P runoff	Turfgrass quality	Clipping dry weight
		----------------------- Significance level of factor effects -----------------------------				
Fertilizer application	3	*	**	**	**	**
Clipping management	1	NS	NS	NS	*	**
Year	2	**	**	**	NS	NS
Fertilizer x clipping	3	*	NS	NS	NS	NS
Fertilizer x year	6	*	**	**	**	*
Clipping x year	2	NS	**	NS	**	NS
Fertilizer x clipping x yr	6	*	NS	NS	NS	NS

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.

Table 6. Analysis of variance for P concentrations in plant tissue and relative P uptake.

Source of variation†	df	Plant P Concentration	Plant P Uptake
		Significance level of factor effects	
Fertilizer application	3	**	**
Clipping management	1	NS	**
Date	4	**	---‡
Year	2	**	NS
Fertilizer x clipping	3	NS	NS
Fertilizer x date	12	**	---
Fertilizer x year	6	NS	NS
Clipping x date	4	*	---
Clipping x year	2	NS	NS
Date x year	5	**	---
Fertilizer x clipping x year	6	NS	*

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.

†The interactions fertilizer x clipping x date, fertilizer x date x year, clipping x date x year, and fertilizer x clipping x date x year were not significant for any variable at the 0.05 probability level.

‡Analyzed on a cumulative basis and not for individual harvest dates.

Table 7. Analysis of variance for plant-available, soil test P at two soil depths.

Source of variation†	df	Soil test P‡	
		0 to 7.5 cm	7.5 to 15 cm
		Significance level of factor effects	
Fertilizer application	3	**	NS
Clipping management	1	*	NS
Month	1	*	**
Year	4	**	**
Fertilizer x clipping	3	NS	NS
Fertilizer x month	3	NS	NS
Fertilizer x year	12	**	*
Clipping x month	1	NS	*
Clipping x year	4	NS	*
Month x year	3	**	**
Fertilizer x month x year	12	*	NS

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.

†The interactions fertilizer x clipping x month, fertilizer x clipping x year, clipping x month x year, fertilizer x clipping x month x year were not significant for any variable at the 0.05 probability level.

‡Bray P-1 soil test.

Table 8. Effects of fertilizer application and clipping management on P concentrations in runoff, runoff depth, and P runoff in the fall of 2004.

Main effects†	P concentration						Runoff depth	P runoff	
	9/16†		10/3 to 10/29‡		12/7§		10/3 to 10/29		
	Reactive P	Total P	Reactive P	Total P	Reactive P	Total P		Reactive P	Total P
	---------- mg L^{-1} ----------						mm	---------- kg ha^{-1} ----------	
Fertilizer application									
No fertilizer	0.83a¶	0.88b	0.95b	2.27b	1.95a	3.19a	0.51a	0.0017b	0.0039b
0xP, N+K	0.81a	1.09ab	0.92b	1.87b	2.35a	4.52a	0.60a	0.0020b	0.0061b
1xP, N+K	0.79a	1.41a	1.63ab	3.10ab	1.26a	3.24a	0.53a	0.0038b	0.0074b
3xP, N+K	0.80a	0.87b	2.88a	4.70a	1.90a	3.57a	0.41a	0.0093a	0.0220a
Clipping management									
Removed	0.80	1.04	1.75	2.71	1.46	2.70	0.43	0.0042	0.0072
Returned	0.82	1.08	1.45	3.26	2.12	4.26	0.41	0.0042	0.0042
Significance#	NS	NS	NS	NS	NS	NS	NS	NS	NS
Fertilizer x clipping	NS	NS	NS	NS	NS	NS	NS	NS	NS
Orthogonal contrast									
Linear P rate††	NS	NS	*	*	NS	NS	NS	*	*

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.
†Before the initiation of fertilizer and clipping management treatments.
‡Flow-weighted P concentrations of four runoff events during non-frozen soil conditions.
§Frozen soil conditions.
¶Means within columns for fertilizer application treatments that are followed by different letters are significantly different at the 0.05 probability level.
#Significance level for comparison of clippings Removed vs. Returned.
††Linear P rate = (0xP, 1xP, 3xP).

Table 9. Effects of fertilizer application and clipping management on tissue P concentrations, clipping dry weights, and P uptake in the fall of 2004.

Main effects	P concentration		Dry weight	P uptake
	9/30	10/18	10/18	10/18
	-------------- % ---------------		---------------- kg/ha ----------------	
Fertilizer application				
No fertilizer	0.42a†	0.35b	45.1b	0.16b
0xP, N+K	0.38a	0.34b	64.8ab	0.22ab
1xP, N+K	0.40a	0.38ab	54.7ab	0.21ab
3xP, N+K	0.40a	0.41a	72.9a	0.30a
Clipping management				
Removed	0.40	0.37	62.5	0.23
Returned	0.40	0.37	56.3	0.21
Significance‡	NS	NS	NS	NS
Interaction				
Fertilizer x clipping	NS	NS	NS	NS
Orthogonal contrast				
Linear P rate§	NS	**	NS	NS

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.
†Means within columns for fertilizer application treatments that are followed by different letters are significantly different at the 0.05 probability level.
‡Significance level for comparison of clippings Removed vs. Returned.
§Linear P rate = (0xP, 1xP, 3xP).

Table 10. Effects of fertilizer application, clipping management, and frozen vs. non-frozen soil conditions on mean annual flow-weighted P concentrations in runoff, annual runoff depth, and annual P runoff in 2005.

	Mean annual flow-weighted P concentration				Annual runoff depth			Annual P runoff					
	Total P		Reactive P					Total P			Reactive P		
Main effects†	Frozen soil	Non-Frozen soil	Frozen soil	Non-Frozen soil	Frozen soil	Non-Frozen soil	Annual total	Frozen soil	Non-Frozen soil	Annual total	Frozen soil	Non-Frozen soil	Annual total
	-------------------- mg L^{-1} --------------------				------------- mm -------------			-------------------------------- kg ha^{-1} --------------------------------					
Fertilizer application													
No fertilizer	1.77bc‡	1.11b	1.28bc*§	0.54b	22.0b**	10.6a	32.6ab	0.38c**	0.11b	0.49b	0.27c**	0.05bc	0.33b
0xP, N+K	1.55c	0.92b	0.99c*	0.37b	28.9a**	8.1a	36.9a	0.44bc**	0.08b	0.51b	0.28c**	0.03c	0.31b
1xP, N+K	2.46b**	1.26b	1.87b**	0.62b	23.3b**	8.3a	31.6b	0.58b**	0.10b	0.68b	0.44b**	0.05b	0.49b
3xP, N+K	4.98a**	2.03a	3.95a**	1.30a	25.3ab**	8.1a	33.4ab	1.31a**	0.16a	1.47a	1.05a**	0.10a	1.15a
Clipping management													
Removed	2.66**	1.19	2.02**	0.62	25.7**	8.1	33.9	0.67**	0.10	0.77	0.51**	0.05	0.56
Returned	2.72**	1.47	2.03**	0.80	24.0**	9.4	33.4	0.68**	0.13	0.81	0.51**	0.07	0.58
Significance¶	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Orthogonal contrast													
Linear P rate#	**	**	**	**	NS	NS	NS	**	**	**	**	**	**

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.
†The main effects interaction (fertilizer application x clipping management) was significant at the 0.05 probability level for annual runoff depth from frozen soil and total annual runoff depth, but was not significant for any of the other variables.
‡Means within columns for fertilizer application treatments that are followed by different letters are significantly different at the 0.05 probability level.
§Where the symbols * and ** appear to the right of a mean value under a "Frozen soil" column heading, they indicate the significance level for the comparison with the "Non-frozen soil" mean in the adjacent column to the right; where there is no symbol, the comparison is non-significant.
¶Significance level for comparison of clippings Removed vs. Returned.
#Linear P rate = (0xP, 1xP, 3xP).

Table 11. Mean annual turf quality ratings, and relative annual growth based on clipping dry weights, from 2005 to 2007.

	2005		2006		2007	
Main effects†	Quality	Clipping DW	Quality	Clipping DW	Quality	Clipping DW
Fertilizer application	1-9, 9=best	% maximum	1-9, 9=best	% maximum	1-9, 9=best	% maximum
No fertilizer	3.7b‡	24.5b	2.7c	9.2b	2.0c	31.8b
0xP, N+K	5.6a	78.4a	6.0a	82.8a	6.0a	92.1a
1xP, N+K	5.5a	73.5a	5.6b	82.0a	5.6b	85.3a
3xP, N+K	5.7a	78.0a	5.9ab	92.1a	6.3a	88.5a
Clipping management						
Removed	5.0	52.3	4.9	59.0	5.1	70.1
Returned	5.3	74.9	5.3	74.1	4.9	78.2
Significance§	*	**	**	*	NS	NS
Orthogonal contrast						
Linear P rate¶	NS	NS	NS	NS	NS	NS

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.

†The main effects interaction (fertilizer application x clipping management) was significant at the 0.01 probability level for clipping dry weight in 2005, but was not significant at the 0.05 probability level for quality or for dry weight in any other year.

‡ Means within columns for fertilizer application treatments that are followed by different letters are significantly different at the 0.05 probability level.

§Significance level for comparison of clippings Removed vs. Returned.

¶Linear P rate = (0xP, 1xP, 3xP).

Table 12. Effects of fertilizer application and clipping management on P concentrations in turfgrass tissue, 2005-2009.

	Tissue P concentration														
	2005					2006					2007		2008	2009	
Main effects	5/30	6/8	7/19	9/8	9/27	5/16	5/26	6/29	8/9	9/26	7/10	8/30	10/31	6/1	7/13
	%														
Fertilizer application															
No fertilizer	0.41b†	0.46a	0.38ab	0.57ab	0.59a	0.43ab	0.46a	0.40a	0.61a	0.59a	0.45a	0.55a	0.28c	0.32b	0.33a
0xP, N+K	0.36c	0.38b	0.34c	0.52c	0.50b	0.38b	0.37c	0.35b	0.46c	0.45c	0.36b	0.47b	0.31b	0.32b	0.27b
1xP, N+K	0.36c	0.41b	0.36bc	0.54bc	0.52b	0.39ab	0.41b	0.36ab	0.49bc	0.45c	0.44a	0.49b	0.34ab	0.34b	0.29ab
3xP, N+K	0.44a	0.49a	0.41a	0.61a	0.60a	0.44a	0.44ab	0.40a	0.55ab	0.51b	0.42a	0.54a	0.36a	0.42a	0.33a
Clipping management															
Removed	0.41	0.43	0.38	0.55	0.54	0.40	0.42	0.37	0.52	0.50	0.43	0.51	0.33	0.35	0.30
Returned	0.37	0.43	0.37	0.57	0.57	0.42	0.42	0.38	0.54	0.50	0.40	0.51	0.32	0.35	0.31
Significance‡	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction															
Fertilizer x clipping	NS	NS	*	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Orthogonal contrast															
Linear P rate§	**	**	**	**	**	**	**	**	**	**	NS	*	**	**	*

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.
†Means within columns for fertilizer application treatments that are followed by different letters are significantly different at the 0.05 probability level.
‡Significance level for comparison of clippings Removed vs. Returned.
§Linear P rate = (0xP, 1xP, 3xP).

Table 13. Effects of fertilizer application and clipping management on relative P uptake by turfgrass, 2005-2009.

Main effects	P uptake 2005	2006	2007	2008	2009
	---------------------------------- % of maximum ----------------------------------				
Fertilizer application					
No fertilizer	25.8c†	9.1c	34.0b	3.2c	20.3c
0xP, N+K	74.9b	70.7b	81.3a	49.0b	65.6b
1xP, N+K	73.7b	78.3b	80.9a	56.9ab	59.5b
3xP, N+K	89.9a	94.2a	89.9a	74.5a	89.1a
Clipping management					
Removed	57.1	54.3	67.1	34.4	50.3
Returned	75.0	71.9	76.0	57.3	67.0
Significance‡	**	**	NS	**	*
Interaction					
Fertilizer x clipping	*	NS	NS	NS	NS
Orthogonal contrast					
Linear P rate§	NS	*	NS	*	*

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.
†Means within columns for fertilizer application treatments that are followed by different letters are significantly different at the 0.05 probability level.
‡Significance level for comparison of clippings Removed vs. Returned.
§Linear P rate = (0xP, 1xP, 3xP).

Table 14. Effects of fertilizer application and clipping management on plant-available, soil test P concentrations in the 0- to 7.5-cm soil depth, 2005-2009.

Main effects	Soil test P†									
	2005		2006		2007		2008		2009	
	May	Oct	May	Oct	May	Oct	May	Oct	May	Oct
	mg/kg									
Fertilizer application										
No fertilizer	31.0a‡	29.6b	35.8bc	52.6b	44.9bc	50.8bc	48.2b	41.0b	44.4b	49.4b
0xP, N+K	28.5a	26.4b	31.3c	43.9c	39.6c	46.7c	38.9c	32.7c	35.9c	29.2d
1xP, N+K	33.6a	30.2b	39.5b	52.6b	48.4b	53.9b	47.9b	42.4b	48.0b	41.5c
3xP, N+K	34.2a	40.4a	47.6a	61.4a	56.6a	61.3a	75.9a	63.1a	79.7a	72.4a
Clipping management										
Removed	30.8	28.8	36.8	51.0	46.4	52.3	50.7	43.2	48.8	45.5
Returned	32.8	34.6	40.3	54.2	48.3	54.0	54.7	46.4	55.2	50.7
Significance§	NS	*	NS	NS	NS	NS	NS	NS	*	*
Interaction										
Fertilizer x clipping	NS	*	NS	NS	NS	NS	NS	NS	NS	NS
Orthogonal contrast										
Linear P rate¶	NS	**	**	**	**	**	**	**	**	**

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.
†Bray P-1 soil test.
‡Means within columns for fertilizer application treatments that are followed by different letters are significantly different at the 0.05 probability level.
§Significance level for comparison of clippings Removed vs. Returned.
¶Linear P rate = (0xP, 1xP, 3xP).

Table 15. Effects of fertilizer application and clipping management on plant-available, soil test P concentrations in the 7.5- to 15-cm soil depth, 2005-2009.

	Soil test P†									
	2005		2006		2007		2008		2009	
Main effects	May	Oct	May	Oct	May	Oct	May	Oct	May	Oct
	------ mg/kg ------									
Fertilizer application										
No fertilizer	21.2a‡	20.4a	22.0a	19.4ab	27.6b	28.2a	30.5a	23.5a	25.5b	23.4b
0xP, N+K	21.0a	20.5a	23.5a	18.2b	30.5ab	29.0a	32.4a	23.2a	25.2b	21.9b
1xP, N+K	20.9a	16.7a	22.3a	20.9ab	33.5a	28.3a	29.7a	25.8a	26.7b	23.2b
3xP, N+K	21.8a	20.5a	22.4a	23.4a	33.2ab	29.5a	35.3a	28.3a	35.1a	29.9a
Clipping management										
Removed	21.1	19.2	23.3	18.5	29.0	26.1	29.8	23.0	26.6	22.3
Returned	21.3	19.9	21.8	22.4	33.4	31.4	34.1	27.4	28.6	26.8
Significance§	NS	NS	NS	NS	*	*	*	*	NS	*
Interaction										
Fertilizer x clipping	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
Orthogonal contrast										
Linear P rate¶	NS	NS	NS	*	NS	NS	NS	NS	*	*

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.
†Bray P-1 soil test.
‡Means within columns for fertilizer application treatments that are followed by different letters are significantly different at the 0.05 probability level.
§Significance level for comparison of clippings Removed vs. Returned.
¶Linear P rate = (0xP, 1xP, 3xP).

Table 16. Effects of fertilizer application, clipping management, and frozen vs. non-frozen soil conditions on mean annual flow-weighted P concentrations in runoff, annual runoff depth, and annual P runoff in 2006.

Main effects†	Mean annual flow-weighted P concentration: Total P, Frozen soil	Total P, Non-Frozen soil	Reactive P, Frozen soil	Reactive P, Non-Frozen soil	Annual runoff depth: Frozen soil	Non-Frozen soil	Annual total	Annual P runoff: Total P, Frozen soil	Total P, Non-Frozen soil	Total P, Annual total	Reactive P, Frozen soil	Reactive P, Non-Frozen soil	Reactive P, Annual total
	------------------- mg L^{-1} -------------------				------------- mm -------------			------------------------------- kg ha^{-1} -------------------------------					
Fertilizer application													
No fertilizer	2.23ab‡**§	0.98b	1.33ab	0.86ab	4.8a**	14.2a	18.9a	0.10a	0.12a	0.22a	0.06a	0.11a	0.17a
0xP, N+K	1.67b	1.00b	0.75b	0.60b	2.4a*	7.0b	9.4b	0.04a	0.06b	0.10b	0.02a	0.04b	0.06b
1xP, N+K	2.89a**	1.17b	1.71a**	0.78b	4.5a	7.1b	11.5b	0.10a	0.06b	0.16b	0.06a	0.05b	0.10ab
3xP, N+K	2.46ab	2.14a	1.65a	1.32a	3.8a	4.3b	8.1b	0.10a	0.05b	0.15b	0.07a	0.04b	0.11ab
Clipping management													
Removed	2.24*	1.06	1.34*	0.79	4.4**	10.0	14.4	0.10	0.09	0.19	0.06	0.07	0.13
Returned	2.38	1.58	1.38	0.98	3.2	6.3	9.5	0.07	0.06	0.12	0.04	0.05	0.08
Significance¶	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
Orthogonal contrast													
Linear P rate#	NS	**	NS	**	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.
†The main effects interaction (fertilizer application x clipping management) was significant at the 0.05 probability level for annual runoff depth from frozen soil, but was not significant for any other variable.
‡Means within columns for fertilizer application treatments that are followed by different letters are significantly different at the 0.05 probability level.
§Where the symbols * and ** appear to the right of a mean value under a "Frozen soil" column heading, they indicate the significance level for the comparison with the "Non-frozen soil" mean in the adjacent column to the right; where there is no symbol, the comparison is non-significant.
¶Significance level for comparison of clippings Removed vs. Returned.
#Linear P rate = (0xP, 1xP, 3xP).

Table 17. Effects of fertilizer application, clipping management, and frozen vs. non-frozen soil conditions on mean annual flow-weighted P concentrations in runoff, annual runoff depth, and annual P runoff in 2007.

	Mean annual flow-weighted P concentration				Annual runoff depth			Annual P runoff					
	Total P		Reactive P					Total P			Reactive P		
Main effects†	Frozen soil	Non-Frozen soil	Frozen soil	Non-Frozen soil	Frozen soil	Non-Frozen soil	Annual total	Frozen soil	Non-Frozen soil	Annual total	Frozen soil	Non-Frozen soil	Annual total
	-------------------- $mg\ L^{-1}$ --------------------				------------- mm -------------			-------------------------------- $kg\ ha^{-1}$ --------------------------------					
Fertilizer application													
No fertilizer	0.95b‡	1.08c	0.85b	0.83b	7.1a*§	3.3a	10.4a	0.07b	0.04a	0.11b	0.06a	0.03a	0.09a
0xP, N+K	0.75b	1.17c	0.62b	0.82b	6.3a*	0.9b	7.3b	0.05b	0.01a	0.06b	0.04a	0.01b	0.05b
1xP, N+K	1.16b*	2.12b	1.01ab	1.47a	7.1a*	1.1b	8.3ab	0.08b	0.02a	0.10b	0.07a	0.02ab	0.09a
3xP, N+K	2.54a	3.17a	1.64a	1.85a	5.9a*	0.5b	6.5b	0.14a*	0.02a	0.16a	0.10a*	0.01b	0.10a
Clipping management													
Removed	1.09	1.61	0.93	1.08	6.0*	1.8	8.0	0.06	0.03	0.10	0.06	0.02	0.08
Returned	1.49	2.16	1.06	1.40	7.1**	1.2	8.2	0.11*	0.03	0.13	0.08	0.02	0.09
Significance¶	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Orthogonal contrast													
Linear P rate#	**	**	*	**	NS	NS	NS	*	NS	**	NS	NS	NS

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.
†The main effects interaction (fertilizer application x clipping management) was not significant for any variable at the 0.05 probability level.
‡Means within columns for fertilizer application treatments that are followed by different letters are significantly different at the 0.05 probability level.
§Where the symbols * and ** appear to the right of a mean value under a "Frozen soil" column heading, they indicate the significance level for the comparison with the "Non-frozen soil" mean in the adjacent column to the right; where there is no symbol, the comparison is non-significant.
¶Significance level for comparison of clippings Removed vs. Returned.
#Linear P rate = (0xP, 1xP, 3xP).

Table 18. Effects of fertilizer application, clipping management, and frozen vs. non-frozen soil conditions on mean annual flow-weighted reactive P concentrations in runoff, annual runoff depth, and annual reactive P runoff in 2008.

Main effects	Mean annual flow-weighted reactive P concentration		Annual runoff depth			Annual reactive P runoff		
	Frozen soil	Non-Frozen soil	Frozen soil	Non-Frozen soil	Annual total	Frozen soil	Non-Frozen soil	Annual total
	-------------- $mg\ L^{-1}$ -------------		------------------------ mm ------------------------			----------------------- $kg\ ha^{-1}$ -----------------------		
Fertilizer application								
No fertilizer	1.26b†, *‡	0.88b	31.5a, *	0.3a	31.8a	0.40a, *	0.002b	0.40a
0xP, N+K	0.68c	0.54c	22.5b, *	0.3a	22.7b	0.15b, *	0.001b	0.15b
1xP, N+K	1.41b, *	0.61c	25.7ab, *	0.5a	26.2ab	0.32a, *	0.003ab	0.33a
3xP, N+K	2.35a, *	1.39a	20.6b, *	0.6a	21.2b	0.47a, *	0.007a	0.48a
Clipping management								
Removed	1.26*	0.71	28.5	0.5	29.0	0.36	0.003	0.36
Returned	1.59*	1.01	21.7	0.4	22.1	0.32	0.003	0.32
Significance§	*	*	*	NS	*	NS	NS	NS
Fertilizer x clipping	NS	NS	NS	NS	NS	NS	NS	NS
Orthogonal contrast								
Linear P rate¶	**	**	NS	NS	NS	**	**	**

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.
†Means within columns for fertilizer application treatments that are followed by different letters are significantly different at the 0.05 probability level.
‡Where the symbols * and ** appear to the right of a mean value under a "Frozen soil" column heading, they indicate the significance level for the comparison with the "Non-frozen soil" mean in the adjacent column to the right; where there is no symbol, the comparison is non-significant.
§Significance level for comparison of clippings Removed vs. Returned.
¶Linear P rate = (0xP, 1xP, 3xP).

Table 19. Mean annual turf quality ratings, and relative annual growth based on clipping dry weights, in 2008 and 2009.

	2008		2009	
Main effects	Quality	Clipping DW	Quality	Clipping DW
Fertilizer application	1-9, 9=best	% maximum	1-9, 9=best	% maximum
No fertilizer	1.7b†	4.3b	2.6b	10.9b
0xP, N+K	5.8a	58.5a	6.0a	94.3a
1xP, N+K	5.8a	62.0a	6.0a	80.3a
3xP, N+K	6.0a	75.6a	6.2a	97.4a
Clipping management				
Removed	4.7	37.4	4.9	71.8
Returned	5.0	62.8	5.5	69.6
Significance‡	NS	**	*	NS
Interaction				
Fertilizer x clipping	NS	NS	NS	NS
Orthogonal contrast				
Linear P rate§	NS	NS	NS	NS

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.
†Means within columns for fertilizer application treatments that are followed by different letters are significantly different at the 0.05 probability level.
‡Significance level for comparison of clippings Removed vs. Returned.
§Linear P rate = (0xP, 1xP, 3xP).

Table 20. Effects of fertilizer application, clipping management, and frozen vs. non-frozen soil conditions on mean annual flow-weighted reactive P concentrations in runoff, annual runoff depth, and annual reactive P runoff in 2009.

Main effects	Mean annual flow-weighted reactive P concentration		Annual runoff depth			Annual reactive P runoff		
	Frozen soil	Non-Frozen soil	Frozen soil	Non-Frozen soil	Annual total	Frozen soil	Non-Frozen soil	Annual total
	-------------- $mg\ L^{-1}$ -------------		------------------------ mm ------------------------			----------------------- $kg\ ha^{-1}$ ----------------------		
Fertilizer application								
No fertilizer	1.53b†	1.55b	7.1a, **‡	0.05a	7.2a	0.11b, **	0.0004a	0.11b
0xP, N+K	0.67c, *	1.88b	7.7a, **	0.09a	7.8a	0.06b, **	0.0012a	0.06b
1xP, N+K	1.28b, *	1.89b	7.6a, **	0.07a	7.6a	0.10b, **	0.0014a	0.10b
3xP, N+K	2.64a, *	3.27a	8.2a, **	0.04a	8.3a	0.22a, **	0.0008a	0.22a
Clipping management								
Removed	1.36*	2.15	7.5**	0.07	7.7	0.11**	0.0009	0.11
Returned	1.70*	2.20	7.7**	0.06	7.9	0.13**	0.0011	0.13
Significance§	*	NS	NS	NS	NS	NS	NS	NS
Fertilizer x clipping	*	*	NS	NS	NS	NS	NS	NS
Orthogonal contrast								
Linear P rate¶	**	*	NS	NS	NS	**	NS	**

NS = non-significant; *, ** = significant at the 0.05 and 0.01 probability levels, respectively.
†Means within columns for fertilizer application treatments that are followed by different letters are significantly different at the 0.05 probability level.
‡Where the symbols * and ** appear to the right of a mean value under a "Frozen soil" column heading, they indicate the significance level for the comparison with the "Non-frozen soil" mean in the adjacent column to the right; where there is no symbol, the comparison is non-significant.
§Significance level for comparison of clippings Removed vs. Returned.
¶Linear P rate = (0xP, 1xP, 3xP).