Phosphorus runoff potential of different sources of manure applied to fescue pastures in Virginia

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Abstract

Version 2.0 of the P Index for Virginia uses coefficients describing the risk of P losses for different manure sources applied to fescue pasture that have not been verified on Virginian soils. In the first experiment, four sources of manure (dairy slurry, piggery waste, beef solids, and poultry litter) and triple superphosphate (TSP) were applied iso-nitrogenously to pasture plots (1.5 m^2, 10% slope) with 31 ppm Mehlich 1-P soil test. The P treatments were amended in spring at a rate of 62.7 kg P_2O_5/ha and compared against a no-P-amended control. Forage was cut and removed monthly (n=5). Five rainfall simulations (65-70 mm/h) were conducted at three occasions (June, August, and October); the soil moisture was below field capacity at two events. Continuous surface runoff was collected for 30 min from each plot in accordance with the protocol of the National P Research Project. Data were statistically analyzed using Proc Mixed of SAS with rain event or cutting used as the repeated measure. Runoff concentrations of total P (TP) and dissolved reactive P (DRP) did not vary by treatment. The control showed less TP (0.126 mg/l) and DRP (0.068 mg/l) concentration than all other treatments (ranges 0.190 to 0.249 mg TP/l and 0.129 to 0.182 mg DRP/l) in runoff during the first event (40 d after treatment). The control had the lowest (0.118 mg/l) and TSP the highest (0.248 mg/l) TP concentration during the second event 24 h later. Samples taken at 5-min intervals during the second simulation showed a significant decrease in TP and DRP concentrations over time for all treatments but the control. Treatments did not affect edge-of-the-field losses of TP, DRP, or TKN. Soil test P and water-extractable P measured after the fifth and final rainfall simulation did not correlate to P concentrations in runoff. Forage yields and their N and P concentrations were not impacted. Results indicated a decreasing impact of manure, spring-applied to fescue pasture, on runoff P concentrations throughout the season. Highest TP concentrations were found during the first pair of simulated rainfalls from the TSP treatment. In a second experiment, indoor runoff boxes were used to simulate management intensive rotational grazing. Commercial fertilizer TSP and manure application increased runoff TP concentration from 0.146 mg/l to 0.245 mg/l and DRP concentration from 0.105 mg/l to 0.183 mg/l. Runoff P did not differ between organic or inorganic P treatments, possibly due to the small area of the boxes. However, application of manure increased runoff TKN overall, with a linear decrease as the time increased between application and rain simulation.

Keywords: Phosphorus Index, surface runoff, fescue pasture, manure application

Dedication

I would like to dedicate this work to our dear Grandfather Alois Flögel. You taught me everything in my younger years, from driving tractor, when I couldn't even reach the pedals, to building fences, growing crops and veggies, etc, etc. I'll never forget playing soccer in your back garden or watching sports with you on TV, especially Boris Becker's first Wimbledon win… But most of all, you taught us how to live the simple life and cared for us with so much love. My sibs and I miss you very much and we love you dearly.

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I guess I'm given the chance here to thank all the people who have helped me along the way and made me the person I am today. So I'll make use of it! First of all, I'd like to express my thankfulness for the opportunities I've had in general. Sometimes I have to step back and just realize where I am at today, how I got here (probably by own bone-head and in avoidance of 'doing the ordinary'), and from where I started the voyage… I've had many possibilities opened up to me, and I definitely did not choose the easiest one(s). But I was given the opportunity to leave my home and find my luck wherever. Two generations back, my grandparents and their folks only had one choice (well, maybe two: East front or west front) and never could return back home, and it is hard to believe (and very sad as well!) that the majority of the people in today's 'sophisticated' world don't have a fraction of the choices and chances that I have had and enjoyed over the years. I'm certain I have to consider myself *very* lucky and I can't believe I've made it this far. Someone must have been watching out for me, and I don't think I made His life always easy….

Anyway, I like to start out with my appreciation for my parents. You probably did not always quite understand what I was doing (and why, but neither did I!!), but without your support, I wouldn't have made it! Thank you! I also want to thank my grandparents for their aid and love and my aunt Karin for always having an open ear for my problems…

I'd like to express my appreciation for my friends back home-home. It's always nice to come back once a year and feel as if I've never left at all. And after being friends for so long, it must be forever… The same goes for my 'P-town heroes': Brian and Kim, Jon and Tammy, the Arbuckle family, Dan and Nikki, Chris, the Sheets' etc. You made me feel home away from home… Special thanks to Deb, I wouldn't have made it through the first year without you!!! Guess you are somewhat responsible for all this…. Thanks to my friends Ben and Jessica for giving me a roof to sleep under and a bed to sleep in when I come home. I also appreciated working for Robert and Peggy Webb and with the whole crew at Summit Farms, and for Randy and

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I almost have to feel sorry for Dr. McGilliard for trying to teach a 'dyslexic statstitician' (me) how to do simple stats – Thank you! I feel like I'm the most thorough scientist now…. I also appreciated all the input from Dr. Stallings. And I for sure wouldn't have been updated on any business, if it wasn't for the hallway patrol in the person of Dr. Pearson!! I enjoyed the more or less heated discussions we had going on…. To Dr. Barnes, thanks for the opportunity to TA for you twice, I learnt a lot, and hopefully, I never have to wash a darn udder again… Thanks for the free flight! Thanks to 'Prof.' Winston for his M&M supply (I'll for sure make it through any Michigan winter now!!), and to Dr. Herbein, who always had an open ear for any question! In addition, Dr. Akers has been a great department head, as the whole faculty here has been a pleasure to work with and for! And you know that Julie and Cindy are holding it all together! (Sometimes I think they run the show, too…)

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And last but not least (wow, this has gotten pretty extensive!), I enjoyed all the nightly phone conversations over the last couple of years, Kimberly (☺), good luck back in WI and may your dreams come true! Finally, I am sorry, if I have missed anyone in particular, but thank you to all the innumerous people with whom I have shared memorable moments and who have walked the path of life with me at a certain time.

I am excited about the future and things to come! - Marcus

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Chapter 1 : Introduction

BACKGROUND

Phosphorus (P) is a highly reactive element that never occurs in its elemental form in nature. Naturally, P is part of the mineral apatite ($Ca_5[F|(PO_4)_3]$). Weathering of apatite forms water-soluble phosphates (WSP) or ortho-phosphates including hydrogen and dihydrogen phosphate ($HPO_4^{=}$ and $H_2PO_4^{-}$). These represent the forms of P taken up by plants. Due to its high reactivity, P quickly binds to metals like Fe^{++} and Al^{+++} as part of clay minerals or oxides. Additionally, P occurs in, chelates to, and is slowly released from decaying organic matter as organic-P, leaving very little P dissolved in the soil solution at any given point.

Because of its chemistry, leaching of P is negligible in most soils and P tends to accumulate in surface soil layers (Cook, 1988; Kleinman et al., 2003). Exceptions may arise in soils with low P adsorption capacity, porous soils with large macrophores, or on tiled land (Kleinman et al., 2003). Soils do not have an unlimited buffering capacity for P, which is dependant on soil pH, clay concentration, and type of clay. Naturally, P concentrations in soils are inherently low and are a limiting factor for plant growth and development and crop production, as P is an essential element for all living organisms. Today, uncultivated soils, like the ones found in the tropics, are still deficient in P (BLW, 2004).

Along with the Green Revolution after World War II came the usage of inorganic P fertilizers. This increased the overall – including P – fertility of cropped soils and optimized crop production. As a consequence of the Green Revolution, manure was not the only fertilizer available to farmers anymore, enhancing the separation and regionalization of crop and livestock production.

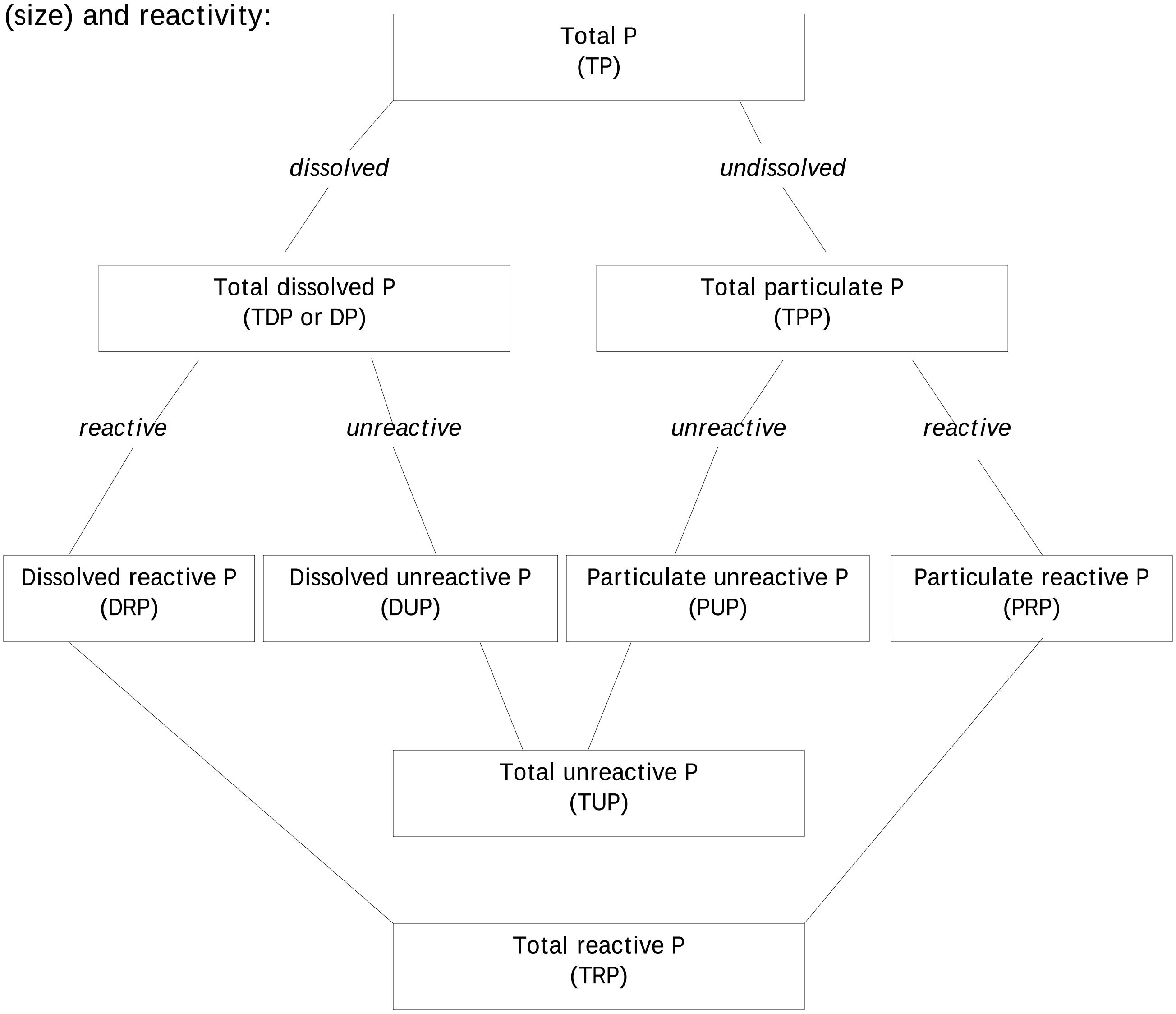
Today, most grains used in livestock rations are imported from grain producing states (Lanyon, 2000). Although grains contain similar concentrations of P compared to home-grown forages (Macgregor, 1994), their main P compound (phytic acid) is not (monogastrics) or only partially (ruminants) digestible (NRC, 2001). Conversely to current P feeding recommendations, P is still significantly overfed to dairy cows (*Bos* *spp*) (Dou et al., 2003; Knowlton et al., 2004), beef cattle, swine (*Sus scrofa domesticus*), and poultry (*Gallus gallus domesticus*) (Knowlton et al., 2004). All livestock species rid themselves of indigestible and excess P in feces or excrements (Knowlton et al., 2004). Phosphorus fed above requirements consequently increases the P concentration in manure directly.

Importing P within feedstuffs from grain-producing areas has led to a net accumulation of P on livestock producing farms (Lanyon, 2000), since manure and litter are not exported, but usually applied on adjacent fields. In an effort to minimize purchased commercial fertilizer and/or to reduce transport cost of manure hauling (Henry and Seagraves, 1960), manure and litter have been spread on the basis of the nitrogen (N) needs of a crop or were just deposited as waste products on fields.

To make matters worse, from the time of harvest of nutrients in a crop to their re-application as manure to agricultural fields, the N:P ratio has significantly dropped (Adeli and Varco, 2001). Nitrogen is readily taken up, transformed, and/or volatilized as ammonia, whereas P stays stable in non-gaseous forms in manure and soil. Additionally, the N:P ratio can be severely lowered if inorganic or mineral P is added to rations above and beyond animal needs. Consequently, manure applications based on N-needs of a crop with consideration of N-losses supply more P to the soil than is removed by the crop (Ribaudo et al., 2004). This has led to excessive concentrations of P in some agricultural soils.

High P concentrations in soils do not lead to toxicities in plants or animals per se, although P is known to tie up zinc, leading to symptoms of zinc deficiency in plants (Schulte, 2004). However, P can accelerate eutrophication in water bodies, especially in fresh water bodies, where P is usually the most limiting element for algae growth (Carpenter et al., 1998). According to the US Environmental Protection Agency (USEPA), anthropogenic eutrophication is the main reason of impaired water quality (USEPA, 1996). The Forest Service of the US Department of Agriculture (USDA, 1991) states that in 1985 roughly 60% of impaired lakes and rivers <u>assessed</u> for nonpoint source (NPS) pollution in the US resulted from agricultural impacts. Overall, water quality impairments in estuaries, lakes, and rivers were to 45%, 76%, and 65%, respectively, the result of NPS pollution.

Phosphorus in water is described in different ways according to its solubility (size) and reactivity:



(Adapted from Soil & Water Conservation Society of Metro Halifax, CA)

For the following discussion, only TP, DP, PP, and DRP will be of importance. Some studies report DP as part of TP mainly to describe sediment-bound P. It seems noteworthy that the physical distinction of P fractions in dissolved and undissolved by usage of a 0.45 µm filter is rather arbitrary and a matter of convenience and comparability between studies (Hart et al., 2004), but does not imply or relate to its bioavailability. Dissolved reactive P describes the readily available form of P, e.g. for algae growth, and should be used more correctly instead of DP.

There are three possible ways for P to reach surface waters from agricultural fields. Phosphorus may be lost via subsurface flow/leaching of DP, surface flow of DP, or attachment to eroded particles (sediment or particulate P). As mentioned above, leaching or subsurface flow of P is generally low, as P-deficient subsoils adsorb P (Daniel et al., 1994). The P concentration in and the P adsorption or buffering capacity of a soil directly influence P loss to surface flow. Surface flow of DP is naturally low, as P can readily form insoluble bonds, but steady, since rain water induces dissolution, desorption, and extraction of P from soil surfaces (Sharpley, 1985). Several studies have shown a close relationship between surface soil P concentration and P concentrations in surface runoff (Pote et al., 1999; Kleinman et al., 2002; Vadas et al., 2005). The concentration of P in runoff is linear to the percent of clay in the sediment transported. Most P (>80%) is lost in small events with an accumulative sediment loss of 50% (Quinton, 2001). Techniques that limit soil erosion also reduce PP in surface flow. Generally, erodability and runoff volume of an area increase with increasing slope (Fleming and Cox, 1996). Bioavailability of PP varies from 10% to 90% (Daniel et al., 1998), since it has to be desorbed and dissolved, thus PP provides a long-term source of potentially bioavailable P (Daniel et al., 1994).

The DP:TP ratio increases as vegetation filters out sediments and consequently decreases TP through reduction of PP. As a result, the distance to a stream and the ground cover along the way influence the DP:TP ratio of the surface runoff reaching flowing waters. In addition, fertilizer applications, increasing rates of P mineralization, and decaying of organic matter during spring and summer increase the DP:TP ratio (Cook, 1988). Consequently, surface runoff from hayground, pasture, or vegetative or filter strips usually harbors fewer sediment, but higher concentrations of DP, than runoff from row crops or fallow soil (Daniel et al., 1994). Hart et al. (2004) stressed the point that best management practices (BMP) implemented to reduce TP concentration in runoff will increase the DP:TP ratio. It is also known that the DP:TP ratio can change quickly from the time runoff is initiated upon reaching a stream and beyond. Cook (1988) detected that surface runoff from pasture contained 65% of TP in the dissolved form, whereas more than 85% of TP transported in the stream was particulate. Sharpley et al. (2002) linked the drop in DP:TP in streams and lakes to fluvial hydraulics. Researchers have speculated that initial DP concentration in runoff, because of its high reactivity, binds readily to sediments during overland flow (Hart et al., 2004). In contrast, Sharpley et al. (2002) presented evidence that adsorption and/or desorption of P either did not occur (or, more likely, was in a net-balance) or that adsorption/desorption of P happened prior to surface flow.

The transport of P from soils to (ultimately) the oceans is a natural process, as most mined P ores are deposits from sediments from prehistoric ages. The amount of P that is inevitably lost without anthropogenic activities is known as background loss. In 1980, background losses contributed 28% to the 2.66 x 10^6t of non-point source P (USDA, 1991).

PHOSPHORUS FLOW IN AND FROM PASTURES

According to a USDA report using data from 1997, livestock excreted 3.8 x 10^6 t of P nationwide, of which non-confined animals contributed 54% (Kellogg et al., 2000). Johnes et al. (1996) made the assumptions from a survey study in England that 95, 85, and 90% of cattle, swine, and poultry manures, respectively, are re-applied to land; the authors did not elaborate on the remaining waste. The amount of manure from confined animals applied to pasture, hayground, or rangeland is unknown. Approximately 55% of all agricultural land or 34% of the overall landmass in the US are classified as pasture, hayland, and rangeland (Vesterby and Krupa, 1997). Consequently, runoff potentials from these areas can have a major impact on overall P contributions to impaired waters.

Understanding the effect of ‘pastures’ on the volume of runoff and its concentrations of nutrients is also important given the fact that grass-based areas are recommended as BMPs to increase water infiltration and reduce sediment and nutrient losses, e.g. as riparian buffers, filter strips, in strip cropping, or in waterways (Hansen et al., 2002; Blanco-Canqui et al., 2004). In addition, the type and intensity of management of a pasture play a role, as runoff from unimproved pasture (Rangeland) in Australia only harbored slightly more TP than runoff from forest, and significantly less than intensively grazed pasture (Young et al., 1996).

In pastures, the species grown, canopy height and percent ground cover (Haan et al., 2005) influence the impact of raindrops on the soil, decreasing surface sealing (Daniel et al., 1993). The sward density, type (bunch versus sod forming grass), and rooting habits influence the flow- and infiltration rate of overland flow. Plant physiological differences, such as C3 versus C4 species and evapotranspiration rates, could lead to seasonal differences due to changing ground cover. Self-Davis et al. (2003) investigated these parameters among five grass species. They found that tall fescue cv. Kentucky-31 (*Festuca arundinacea* Schreb.) had the most ground cover after harvest (84%), when compared to Alamo switchgrass (*Panicum virgatum* L.), Caucasian bluestem (*Bothriochloa caucasia* (Trin.) C.E. Hubbard), Greenfield bermudagrass (*Cynodon dactylon* (L.) Pers.), and Pete eastern gamagrass (*Tripsacum dactyloides* (L.) L.). The tall fescue cultivar also had the highest water infiltration rate, probably due to the lowest soil moisture concentration in the upper 35 cm of the soil, and reduced surface flow by at least 44% in all seasons, when compared to the other four grasses. Contrary, Volaire and Lelièvre (2001) discovered that cultivars of orchard grass or cocksfoot (*Dactylis glomerata* L.) were able to retrieve water at lower soil potential than tall fescue cv. Centurion. The authors attributed drought resistance of tall fescue to its ability to develop a deeper rooting system than orchard grass. Attributes may not depend on a specific genus or species, but more so on individual cultivars.

Pastures created less runoff volume than tilled cropland, as it takes more time for surface runoff to occur from pastures (Daniel et al., 1993). The same study found that the concentrations of DRP in runoff from tall fescue pastures were about five fold higher than from cropland. The authors attributed this phenomenon to a dilution effect in tilled systems, vegetative cover, and the release of ortho-phosphates from decaying organic matter, which accumulates on the surface of undisturbed soils. Water extractable P from the soil correlated very weakly to DRP in the runoff water mainly because of very little runoff volume from some plots (Daniel et al., 1993).

Furthermore, applications of commercial P fertilizers created a sudden spike of P concentration in runoff, which declined over the following weeks (Sharpley and Syers, 1976). Hart et al. (2004) reviewed literature where the effect of commercial P applications to pastures on runoff P concentration persisted from 20 d to longer than one year.

It has been suggested that topography and location of pastures might impact the volume of surface runoff. Pastures are frequently found in hilly regions, which are more susceptible to tread damage and erosion and have lower infiltration rates and higher overland flow velocities due to the slope. In addition, pastures are often located at higher altitudes with increased rain intensity. All these factors may contribute to unpredictable DP:TP ratios (Hart et al., 2004).

Runoff after poultry litter applications

DeLaune et al. (2004b) detected a significant correlation between Mehlich-3 soil test P (STP) and DRP in collected runoff from pasture. After application of poultry litter, DRP concentrations in the runoff correlated poorly to STP, but significantly to the amount of DRP provided by the litter. Other studies confirmed the overriding effect of litter applications over STP on DRP concentrations in overland flow (Sauer et al., 2000; DeLaune et al, 2004a).

The application rate of litter has a significant impact on the amount of nutrients lost to surface flow, regardless of rain intensity, as noted by Edwards and Daniel (1993b). Independent from application rate of litter, a rain intensity of 50 mm/h 24 hours after litter application caused 2.2 – 2.5% of the TP applied to be lost to overland flow, whereas 100 mm/h rain resulted in the loss of 5.8 – 7.3% TP (Edwards and Daniel, 1993b). Total P and DRP lost in successive rain events after the first event are significantly lower (Penn et al., 2004). The length of drying time after amendment application (4 – 14 days) to a pasture had no significant effects on the concentrations of TP and DRP in runoff water (Edwards et al., 1994). One explanation suggested by Harmel et al. (2004) is the lower contact area of litter with the soil compared to manures containing more moisture.

Runoff from management intensive rotational grazed pasture

Grazing dairies, once the only means of supplying summer feed, almost disappeared with technological advances for feed and milk production, but have been re-juvenated as a low-input, cost-minimizing way of milk production (Bargo et al., 2002). In addition, access to pasture for ruminants is required for the production of organic milk and meat (USDA-AMS, undated). Today, pastured beef and dairy cattle are often fed using management intensive rotational grazing (MIRG) systems to maximize pasture production, in contrast to traditional, continuously grazed pasture systems. A switch from continuous to MIRG along with an increase of sward height after grazing from 5 to 10 cm reduced P loss in runoff by 65% (Haan et al., 2005). According to a survey by Groover (1998) 50% of all dairy farms in Virginia grazed their cows in some form; 11% utilized fresh paddocks at least every fourth day. Two thirds of all dairies in Virginia responded to the survey. In 1999, 22% of dairy farms in Wisconsin utilized MIRG defined as rotating their milking cows to a new paddock at least once a week (Undersander et al., 2002).

Mundy et al. (2003) compared the runoff constituents from pasture grazed by different stocking densities of lactating dairy cows. Total P and DRP concentrations for the two lower stocking densities (111 and 208 vs. 375 cows/ha for 6.5 h) were actually less compared to mechanically harvested pasture (TP: 1.0 mg/l vs. 1.5 mg/l; DRP: 0.9 mg/l vs. 1.5 mg/l), when the paddocks were flood-irrigated immediately after defoliation. At consecutive irrigations at day 7, 14, and 21, only the TP concentration at 7d for the highest stocking density differed. The authors concluded that P loss to runoff was a function of defoliation rather than defecation (Mundy et al., 2003).

Fleming and Cox (1998) collected runoff from a catchment under MIRG over a three-year period in South Australia. More than 98% of P loss occurred in surface runoff. The annual amount of P lost correlated to the annual runoff volume, which in turn was dependant on annual precipitation (= soil moisture), steepness of slope, and soil texture. Overall P loss for the driest year was practically nil; measured P was almost 100% in dissolved form. The other two years showed a low DP:TP ratio at the start of the rainy season (early winter). This ratio increased to almost 1 at the end of the rainy season in early spring. Seemingly, PP was exhausted over the season (Fleming and Cox, 1998).

Haan et al. (2005) reported that the highest amounts of sediment and P were lost from grazed pastures in Iowa during the wet season in late spring, when soil moisture was above field capacity. Soluble P concentrations and DP:TP were highest during summer runoff events (0.33 mg PO_4-P/L and 77%, respectively), intermediate in spring (0.23 mg/L and 69%), and low in autumn (0.13 mg/L and 41%) and early spring (0.08 mg/L and 21%). The authors did not elaborate on the occurrence of snowmelt. Total surface runoff volume accumulated to 26, 6, 15, and 14% of the total rainfall for the respective seasons. Slope steepness and length, as well as increasing soil erosion during wet seasons due to treading damage by grazing cattle might be responsible for changing DP:TP ratios (Hart et al., 2004). The same group attributed high DP:TP ratios during or immediately after dry spells to soluble P leached from plants, decreased plant uptake of P, or lysed soil microbes.

Runoff after application of dairy slurry and solid cattle manure

Surprisingly, there is very little literature available that deals with applications of dairy slurry or solid cattle manure to grassland in North America. Most scientific work in this area has been done in Europe. Unfortunately, the methods used in European studies do not resemble methods used in the US to measure P losses in overland flow. Studies are therefore only partially and cautiously comparable. Additionally, especially in the case of chemical and physical processes involving P in soils, results might differ, because of differences in soil type, climate, etc. (Hart et al., 2004).

Heathwaite and coworkers (1998) designed a study on steep (15 - 20% slopes) grassland to compare the effects on water quality of application of (unspecified) liquid cattle slurry and solid cattle manure to commercial fertilizer. Unfortunately, the application rates were not balanced for nutrients, but applied to the maximum weight/volume allowed by UK regulations (slurry 69 kg P/ha, solid 118 kg P/ha, and ammonium phosphate 100 kg P/ha). An irrigation gun simulated rainfall at a rate of 22 mm/h for 35 min on 4 consecutive days.

The inorganic fertilizer treatment resulted in much higher TP concentration in the runoff (15.3 mg P/L) as compared to slurry (0.82 mg P/L) and solids (1.76 mg P/L). Of the TP applied, only 0.3 to 0.4% of the slurry and solids P and 3.8% of the inorganic P were lost, probably due to the less intense simulated rain applied. Almost all of the

TP in runoff from the plots with solids applied was non-DRP; about two-thirds of the runoff from the slurry and inorganic treatments and 94% of the control were in the reactive form. A 10 m buffer strip at the end of the slope retained 98% of the runoff TP from the inorganic fertilizer treatment, but 88% of the TP in the runoff were DRP. The buffer strip only reduced TP losses from slurry by <10%, and unexpectedly and unexplainably decreased DRP as a proportion of TP (Heathwaite et al., 1998).

Misselbrook et al. (1994) applied cattle slurry and farm yard manure (28.4% DM) at the same rates as the study conducted by Heathwaite et al. (1998). The slurry was applied twice, once in the fall and again in spring and the solids were applied in the fall. The rates resulted in 15 and 20 kg P/ha for the slurry and 70 kg P/ha for the solids. Natural runoff for four months following the autumn applications accounted for 62% of the precipitation. The second application of slurry was made on soil at field capacity and was followed by a rainstorm within 24 h. The collected runoff for the next 47 d accounted for 84% of the total rainfall.

Again, as in Heathwaite et al. (1998), losses of P were small overall. During the winter season, 0.36 kg P/ha were lost from the slurry treatment and 0.98 kg P/ha from the solid treatment, as compared to 0.38 kg P/ha from the control. The losses were 0.82, 0.32, and 0.14 kg P/ha, respectively, for the 47 d after the second application of slurry. Unfortunately, the article only states maximum concentrations for P in the runoff, and compares those to a cited limit by UK/EU regulations of 0.05 mg/L. This approach neglects the dilution factor over a runoff event. The lower rain intensities used in these studies, as compared to studies conducted in North America, seem to result in minute P losses to overland flow.

Runoff after application of piggery waste

Westerman et al. (1985) showed that TP concentration in runoff from pasture increased with the application rate of swine slurry. These findings were confirmed by Edwards and Daniel (1993a), who also reported that DP:TP ratio under a one-year storm (50 mm/h) 24 h after treatment was 1, when piggery manure was applied at two different rates (19 and 38 kg P/ha) to fescue plots. The control treatment yielded a 0.7 DP:TP ratio while the manure ratio of DP:TP was 0.35. The results for a 10-yr storm (100 mm/h) showed lower TP and DP concentrations in the runoff of both treatments, probably due to a dilution effect. The DP:TP ratio was slightly lower at 0.8 – 0.9 for all three treatments. There were no significant differences in total amounts of TP and DP lost among the two rates. However, the more frequent storm (50 mm/h) removed 8% and 20% of the applied TP and DP, respectively, whereas 13% of TP and 31% of DP was lost in the intense rain (100mm/h). Again, a higher fraction of DP than PP was flushed from the pasture.

Edwards and Daniel (1993a, c) cited previous work by Westerman and Overcash (1980), where P concentration in surface runoff decreased up to 90% when a simulated storm occurred 3 d after the application of piggery waste compared to an immediate event. This might be the result of intensive soil-manure contact, unlike poultry litter. Edwards and Daniel (1993c) applied piggery waste to fescue plots at a rate of 45.5 kg TP/ha; 1.4 times the typical N removal rate of fescue grass. Runoff was collected at simulated rain events of 50 mm/h at d 4, 7, and 14. Contrary to cited results from Westerman and Overcash (1980), no differences in drying time after application was found. Phosphorus supplied from swine slurry, therefore, might be adsorbed by soil particles within a couple of days.

A high application of slurry seemed to seal the soil, when runoff occurred quicklier and yielded more volume in the study of Edwards and Daniel (1993a), where rain simulation occurred 24 h after manure application. The same scientists did not find a similar effect in a follow-up study (Edwards and Daniel, 1993c), when rain was simulated more than 3 d after spreading the slurry. A sealing effect of slurry is possible immediately after its amendment, leading to a reduced infiltration rate and increased overland flow.

AGRICULTURE IN THE SHENANDOAH VALLEY, VIRGINIA

The Shenandoah Valley in northwestern Virginia is a narrow valley nestled between the Blue Ridge Mountains in the east and the Alleghany Mountains and Shenandoah Mountains in the West. Its perimeters follow the course of the Shenandoah River, which feeds into the Potomac River, and ultimately into the Chesapeake Bay. Deep and fertile alluvial soils with high clay concentration, on which row crops in rotation with hay crops are grown, seam streams and rivers. With increasing distance to rivers and streams, residual soils in the region become shallower above limestone and dolomite bedrock, resulting in use as permanent pastures and haygrounds for beef cattle operations (Gaidos, 1997).

According to the latest agricultural census, over 9000 farms on over 500,000 ha of land, housing more than 500,000 head of cattle are located in Virginia's Shenandoah Valley (USDA, 2002). This represents about one third of the whole state population of cattle. Additionally, over 300 x 10^6 birds are produced yearly (mostly broilers and turkeys), making the Valley the leading poultry producing area in Virginia. The enormous mass of manure and litter produced there has to be land-applied carefully, since the sloping landscape and the shallowness of the soils give potential to nutrient losses via leaching, runoff, and erosion (Gaidos, 1997).

Soil phosphorus concentration in soils predominant in the Shenandoah Valley

The preponderance of livestock production in Virginia is concentrated in specific areas like the Shenandoah Valley, while a majority of the grain fed to livestock is imported from outside these areas (Gaidos, 1997). This practice has led to an accumulation of P in soils throughout the Valley. Brosius et al. (1999) analyzed soil samples taken to a depth of 25 mm from 28 fields in Rockingham County, the county in the Valley with the highest cattle and poultry density per cultivated land area. Eighty four percent of the samples ranged 'High' and 'Very High' in accordance with Virginia Tech's soil test classes (High = 18 – 55 ppm Mehlich 1-P and Very High >55 ppm). On average, 64% of TP was water-soluble, leading to the conclusion that the soils may have been nearly saturated with P. These results are in concert with unpublished data from the Virginia Soil Testing Laboratory accumulated from 1997 – 1998, where 71% of samples (n=179) from the same county had Mehlich 1-P > 18 ppm. Mullins (2003) reported that 11 of 13 soil samples from fields frequently covered with litter in the Valley ranked 'High' or 'Very High', averaging 354 ppm Mehlich 1-P. In that study, simulated rainfall was applied at a rate of 63 mm/h for 30 min after continuous runoff occurred from 3 m^2 plots, following the established protocol from the National P Runoff Project (2001). The surface runoff from these sites contained P in the range from 0.2 to 5.7 ppm. Concentrations of DRP in the runoff correlated strongly to STP concentrations (Mullins, 2003).

PHOSPHORUS INDEX IN THE U.S.

In an effort to lower P input to surface waters, especially the Chesapeake Bay, Virginia and other states within the watershed of the Bay have proposed and are implementing P based nutrient management plans.

Several scientists formed a P discussion group in 1990, which developed into an official USDA Information Exchange Group three years later. The Southern-Extension-Research-Activity (SERA-17) resulted from this group under the patronage of the Cooperative States Research, Education, and Extension Service (CSREES). SERA-17 serves as an information basis for agencies and lawmakers and recommends BMPs for restricting P loss to surface waters (SERA-17, 2005). In addition, the National P Research Project as a workgroup of SERA-17 was founded to "develop a scientific basis for recommendations to manage phosphorus […] in a sustainable manner within agricultural operations" (USDA-ARS, 2006). SERA-17 oversees and coordinates P research and education to industrial groups in the South.

Lemunyon and Gilbert (1993) proposed a P assessment tool – or Phosphorus Index – to evaluate sites based upon their vulnerability to P loss to water bodies. Furthermore, the P Index identifies factors impacting this vulnerability and management practices to either reduce P losses from the site and/or prevent P from reaching water bodies.

More practically, a P Index provides a simple tool to evaluate specific sites for their P loss potential and to determine BMPs to reduce these losses on site. The initial P Index, as described by Lemunyon and Gilbert (1993) ranked eight weighted site parameters, as erosion, STP, runoff class, and type (P_i vs. P_{org}), rate, and application method, in classes from 0 (none) to 5 (very high). Since then, the P Index has been expanded and refined. New parameters include timing of manure applications, use of biosolids, subsurface flow of water (drainage), etc. (USDA-ARS, 2003). Overall, P Indices should not be used for estimating actual P losses in runoff (Maguire et al., 2006), but for evaluating sites for their relative risk of P losses.

For the most part, individual states have established and are implementing their own version of a P Index. When comparing P Indices from different states, it seems as if states having trouble with eutrophication of water bodies, like Virginia (Chesapeake Bay) or Arkansas (Eucha-Spavinaw watershed) utilize more enhanced P Indices. Research on P dynamics in those regions may be more funded because of the P problematic. Although a P Index in its general form could be used in areas larger than regions, specific P dynamics are localized and depend on soil type, climate, precipitation, general management practices etc. (DeLaune et al., 2004b). Therefore, most weighting factors and coefficients used in the P index have been, are, or will be tested in each individual state, or on an even smaller region, as Virginia is divided into three zones having different P Index restrictions (Wolfe et al., 2005).

Phosphorus Index for Virginia

In 2005, version 2.0 of a P Index for Virginia was released (Wolfe et al., 2005). It is based on data collected specifically from benchmark soils in Virginia, which is split into the Ridge and Valley, the Piedmont and Middle and Upper Costal Plain, and Eastern Shore and Lower Costal Plain regions. More detailed, this P Index is based equally on three risk factors: Erosion, runoff, and subsurface. The erosion risk factor includes edge-of-the-field soil loss, as determined by RUSLE2, and a sediment delivery factor, which estimates the portion of the sediment loss that reaches flowing water. In addition, a sediment TP factor is calculated on the basis of STP, land use, and region. The runoff risk factor accounts for runoff from the field, which itself is influenced by the hydrology of the soil, the crop grown, and conservation practices implemented, like no-till or strip-cropping. Furthermore, a runoff delivery factor estimates the portion of runoff water that will ultimately be reaching a stream. The last factor accounts for DRP in the runoff based on the soil test and fertilizer applications. A management factor in form of the DRP concentration in the applied fertilizer is added on to the runoff risk factor. Lastly, the subsurface risk factor accounts for P loss in subsurface drainage and is dependant on the soil infiltration rate, rainfall, runoff (or infiltration), and the amount of evapotranspiration. In the

Virginia P Index the soil texture and drainage and a subsurface DRP factor describes the subsurface risk factor (Wolfe et al., 2005).

P Index = Erosion risk factor + Runoff risk factor + Subsurface risk factor

Erosion risk factor = Edge-of-the-field soil loss x Sediment P delivery factor x Sediment TP factor

Runoff risk factor = Runoff from field x Runoff P delivery factor x Runoff DRP factor + Applied fertilizer DRP factor

Subsurface risk factor = Percolation x Soil texture/drainage factor x Subsurface DRP factor

Several states, including Virginia, have proposed and put into law a P based nutrient management plan for certain enterprises depending on animal units on site or STP concentration on farmed land. In Virginia, these plans allow only the application of manure on the basis of crop removal over a 3 yr period, if STP analyzes above 55 ppm Mehlich 1-P. Above 65% of P saturation of a given soil, P amendment in any form is prohibited. For STP values below 55 ppm Mehlich 1-P, manure can be applied based on crop N needs (Wolfe et al., 2005). Compared to the P based nutrient management plan, a P Index describes only a risk management tool without the option of reducing STP long term (Maguire et al., 2006).

CONCLUSION AND OBJECTIVES

An enormous amount of research has been conducted in the area of P runoff potential from agricultural and non-agricultural fields over the last two decades. These studies have been used to evaluate the risk of P losses from fields in different environments, types of soils, vegetation, and under different management practices. The results have been used to create regional P Indices. Many states, including

Virginia, have adopted their individual P Index to determine appropriate P application rates in the form of commercial fertilizers and/or manures, or to evaluate cropping or management alternatives to reduce the potential of P losses. Due to regional differences in soil types and climates among others, coefficients for each P Index have to be determined locally through practical experiments.

So far, runoff from pastures has received less attention than runoff from cropland, mainly due to the reduced runoff volume and consequent lower P losses overall. In addition, studies comparing and ranking manures from different sources, especially on pastures, to their P loss potential are rare. For example, the coefficients used in the P Index for Virginia for different types of manures applied to pasture or haylands have not been verified on Virginian soils, but were derived after review of available literature and by use of professional judgment (Wolfe et al., 2005). The coefficients stated in the current version (2.0) of Virginia's P Index are: 0.25 for inorganic fertilizer; 0.20 for dairy/beef manure, swine (under: other) manure, and untreated poultry litter. If Alum has been applied onto poultry litter, the coefficients decrease to 0.15, when the AL:P ratio is between 0.4 and 0.7, or to 0.10, when the ratio is between 0.7 and 1.0.

We hypothesized that a study on Virginia's soils would confirm the P source coefficients in their current form in Virginia's P Index. Therefore, the first conducted experiment aimed to determine the P loss potential for different types of manures applied to pasture on a benchmark soil in Virginia and to estimate an availability coefficient for P for manures amended to pasture. The objective of the second study was to qualify P losses from MIRG pasture. As a final objective, the results from both studies will be used to enhance the accuracy of the P Index currently used in Virginia.

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Chapter 2 : Phosphorus runoff potential of varying sources of manure applied to fescue pastures in Virginia

ABSTRACT

Version 2.0 of the P Index for Virginia uses coefficients describing the risk of P losses for different manure sources applied to pasture that have not been verified on Virginian soils. Four sources of manure (dairy slurry, piggery waste, beef solids, and poultry litter) and triple superphosphate (TSP) were applied iso-nitrogenously to pasture plots (1.5 m^2, 10% slope) with 31 ppm Mehlich 1-P soil test. The P treatments were amended in spring at a rate of 62.7 kg P_2O_5/ha and compared against a control treatment without P amendment. Soil type was a Frederick – Caneyville complex, a typical series for the Shenandoah Valley in north-western Virginia. Forage was cut and removed monthly (n=5). Five rainfall simulations (65-70 mm/h) were conducted on three occasions (June, August, and October); three simulations occurred on soil saturated 24 hours prior. Continuous runoff was collected for 30 min from each plot in accordance with the protocol of the National P Research Project. Data were statistically analyzed using Proc Mixed of SAS with rain event or cutting used as the repeated measure. Runoff concentrations of total P (TP) and dissolved reactive P (DRP) did not vary by treatment. The control showed less TP (0.126 mg/l) and DRP (0.068 mg/l) concentration than all other treatments (ranges 0.190 to 0.249 mg TP/l and 0.129 to 0.182 mg DRP/l) in runoff during the first rain simulation (40 d after treatment), whereas the control had the lowest (0.118 mg/l) and TSP the highest (0.248 mg/l) TP concentrations during the second simulation 24 h later. Samples taken at 5-min intervals during the second simulation showed a significant drop in TP and DRP concentrations over time for all plots but the control. Total Kjeldahl N (TKN) was highest during the first couple of simulations (2.8 mg/l) and dropped to 1.45 mg/l during the last three rainfalls. Treatments did not affect edge-of-the-field losses of TP, DRP, or TKN. Soil test P and water-extractable P measured after the fifth and final rainfall did not correlate to P concentrations in runoff. Forage yields and their respective N and P concentrations were not impacted. Concentration of P was elevated with averages for treatments across season ranging from 4.03 to 4.61 mg P/g and removal of P_2O_5 exceeded application rate for all treatments but beef solids. Results indicated a decreasing impact of manure spring-applied on pasture on runoff P concentrations throughout the season. Treatment TSP produced the highest runoff TP concentrations during the first pair of simulated rainfalls.

Keywords: Phosphorus Index, surface runoff, fescue pasture, manure application

INTRODUCTION

Excessive phosphorus (P) loss from agricultural grounds is one of the factors that has led to P enrichment of surface fresh waters and to their consequent impairment due to increased eutrophication (Carpenter et al., 1998; Lanyon, 1998). This phenomenon has given rise to the introduction of assessment or risk management tools, also known as P Indices (Lemunyon and Gilbert, 1993). Today, fine-tuned P Indices are used in states that abut the severely impaired Chesapeake Bay (SERA-IEG 17, 2001), including the Commonwealth of Virginia. The P Indices take into account source factors, such as soil test P (STP), fertilizer rates, method, timing, and P availability in applied P fertilizer, and transport factors like soil erosion, runoff potential, subsurface drainage, and distance to surface waters (USDA-ARS, 2003).

The Shenandoah Valley in Northwestern Virginia is the leading livestock producing area in the state. A significant portion of the Valley is in pasture, especially on shallower soils above bedrock with increasing distance to the Shenandoah River (Gaidos, 1997). Due to the import of – partially – indigestible P within grains, P has been accumulating in livestock wastes and, consequently, on manure-amended fields in the area (Brosius et al., 2000). Especially poultry producers find themselves in a quandary, since poultry rations contain large amounts of grain and do not require large land bases locally (Collins, 1996).

The goal of the Virginia P Index is to estimate the area-specific relative risk of P losses to water bodies at a field level (Wolfe et al., 2005), but the P source coefficients used have not been evaluated specifically on Virginia's pastures. We hypothesized that a study on Virginia's soils would confirm the P source coefficients (0.25 for inorganic P, 0.20 for dairy, beef, and swine (under: other) manure and untreated poultry litter; Wolfe et al., 2005) in their current form in Virginia's P index. Consequently, the objectives of this study were twofold. First, we wanted to determine the P loss potential for different types of manures applied to pasture on a typical soil series in the Valley. Our second objective was to estimate availability coefficients for manures amended to pasture. As an ultimate goal, the obtained data will increase the accuracy of Virginia's P Index.

MATERIALS AND METHODS

The runoff experiment was conducted on outdoor plots (2.0 x 0.75 m^2) within a permanent pasture at Virginia Tech's Shenandoah Valley Agricultural Research and Extension Station in the southern region of the Valley at Steeles Tavern in 2005. The sward consisted of mainly tall fescue (*Festuca arundinacea* Schreb.), portions of orchard grass (*Dactylis glomerata* L.), and sporadically of other grass species and weeds. The soil in the paddock was classified as a Frederick – Caneyville complex. Frederick (fine, mixed, semiactive, mesic Typic Paleudult) and Caneyville soils (fine, mixed, active, mesic Typic Hapludalfs) were chosen as a typical soil series for pastures and haygrounds in the Valley. Soil samples taken from the experimental paddock rated 'High' in soil test P (STP; 55 ppm Mehlich 1-P in top 25 mm of soil).

Beef cattle heifers had grazed the area once or twice each summer for the previous six years; additional growth was mowed and not removed. No other fertilizers had been applied during that period.

Soil samples obtained from the specific experimental site within the paddock just prior to the first rain simulation revealed a Mehlich 1-P concentration of 31 ppm in the top 25 mm (Table 2.1), which still ranks 'High' on the Virginia STP chart. Speculatively, cattle might have spent more time and, consequently, defecated more P on the flatter parts of the paddock, leading to a lower STP on the slope.

Manure sources

Four types of manure were used in the study: Dairy slurry, solid cattle manure, piggery waste, and poultry litter. The dairy slurry was collected with a column sampler from an anaerobic lagoon. The slurry had been accumulated over winter and originated from Holstein dairy cows (*Bos taurus*), which were kept confined and fed a total mixed ration. The solid cattle manure was collected from a feedlot where Black Angus cattle were fattened on a corn- (*Zea maize* L.) heavy diet. The piggery (*Sus scrofa domesticus*) waste was derived from a pit outside a finishing unit at the Agricultural Research and Extension Station in Tidewater, VA. The poultry (*Gallus gallus domesticus*) litter stemmed from broiler houses. The birds were fed corn with a high P availability or supplemented with exogenous phytase. The bedding material consisted of wood shavings. The litter was sprayed with alum in the winter months, and the houses were cleaned every third flock. The AL:P ratio of the litter was < 0.4 (0.07) as analyzed by the Agricultural Service Laboratory of the Clemson Extension. Therefore, Virginia's P Index stipulates P source coefficients of 0.20 for all four manure types and 0.25 for an inorganic P fertilizer (Wolfe et al., 2005). The manures were analyzed for total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_4-N), and total P (TP; AOAC, 1990). Organic N (N_{org}) was calculated as the difference of TKN and NH_4-N (Table 2.2).

Field study

Six treatments were used in the experiment consisting of the four manures, triple superphosphate (TSP), and a control that did not receive any P applications. Application rates of fertilizers were based on the crop removal of 62.7 kg P_2O_5/ha, assuming a forage yield of 7.84 t/ha consisting of 8 mg/g P_2O_5 (3.49 mg/g P). The crop yield was based on yields measured for the area (Allen et al., 1992; Smith et al., 2005) and adjusted to site specific limitations. All treatments received ammonium nitrate to supply a total of 112 kg/ha available N. Rates followed recommendations from the Virginia nutrient management standards and criteria (Department of Conservation and Recreation, 1995) and are shown in Table 2.3.

The six treatments were replicated thrice and arranged in a randomized complete block design. Each block represented a replication and contained each treatment. The treatments within a block were located horizontally on a 10% (±1%) slope, with the consecutive block placed approximately 4 m down slope. The plots within a block were visually selected so that slope, ground cover, and vegetation between plots matched as closely as possible. Single plots were 2 m long (down slope) and 0.75 m wide, two plots fitting within one split metal frame. The borders of the frames were installed 5 cm below and above ground to isolate surface flow within the borders, following the protocol of the National P Research Project (SERA-IEG 17, 2001).

On April, 24th 2005, just prior to installation of the frames, the grass was mowed to a height of 5 cm and all clippings, debris, and part of the excessive thatch were removed. Once the frames were set to isolate the surface runoff of each plot, treatments were applied on their respective plots at the same day. Forages were cut five times to a height of 10 cm during the season in roughly 30 d intervals (Fig. 2.1). Due to scheduling challenges, the first cutting was late (40 d) and the grass had already headed. Regrowth at the final cutting was minute due to drought (Fig. 2.1). All clippings were collected and weighed. A 200 – 300 g subsample (or all trimmings, if less than 200 g) from each plot was oven-dried at 60^{o} C to calculate dry matter (DM) and ground to pass a 1 mm screen, using a Wiley mill (Arthur H. Thomas, Philadelphia, PA). The samples were analyzed in duplicate for TKN and P (AOAC, 1990).

Soil samples to depths of 2.5 and 10 cm were taken from the area immediately adjacent to the plots prior to the first rainfall simulation and directly from each plot after the last simulation. Samples were analyzed for pH, Mehlich1-P, -K, -Ca, -Mg, and organic matter (OM). The method published by Pierzynski (2000) was used to analyze for water-extractable P (WEP). Soil samples just outside the metal border to a depth of 15 cm were taken for each frame immediately before each simulation, mixed, and subsampled. These samples were weighed, dried at 60^{o} C, and soil moisture content was determined.

After the last rainfall simulation, two digital images were taken for each plot, one from the front and one from the back. Soil cover was obtained by laying an 11 x

11 grid over each image and counting squares including productive ('green') cover and thatch versus bare soil. Rotz (2006) provides a more detailed description of the protocol.

Rainfall simulations

Rainfall was simulated on five occasions, following the established protocol by SERA-IEG 17 (2001) and its adaptations to Virginia's conditions (Mullins, 2003). The rainfall simulator was designed according to Miller (1987) and had been used for several previous studies by our laboratory (e.g. Mullins, 2003; Penn et al., 2004; Warren et al., 2006). Two simulations on each plot were conducted within 24 h after the first (June 6-9) and the third (August 9-12) cutting. The first simulation of each period was used to acquire field capacity and to equalize soil water concentration in the plots for the successive rain simulation 24 h later. Heavy rains just prior to the simulations in October eliminated this step (Fig. 2.1), so that only one rainfall per plot was simulated in October. Results from the second simulation of each event and the October simulation were therefore more comparable inter alia. Parameters of the well water used as artificial rain are given in Table 2.4.

Rainfall intensity was set at 65-70 mm/h, which our laboratory had used in similar studies for the area and, therefore, assured comparability between studies. The intensity resembled a 30 min storm with a 10-yr return rate for the region. Rainfall was simulated until runoff had occurred for 30 min. Time until initiation of runoff and weights of runoff at 5 min intervals were recorded. Throughout this paper, runoff will be reported as volume with a 1:1 conversion from its weight. A 1 L subsample of the mixed total runoff was taken and stored on ice. For the second event (June wet), samples were also collected from each 5 min increment. Since the runoff was collected in 19 L canisters and mechanically pumped into larger drums at the 5 min intervals, a small residue of runoff remained in the canisters. The source water was also sampled during each day of simulation (Table 2.4).

Portions of the runoff samples were filtered through a 0.45 µm filter within 24 h of collection, acidified with HCl to a pH below 2, and frozen. The filtrates were later used to determine DRP concentrations (Molybdate blue; Murphy and Riley, 1962).

Unacidified samples were stored at 4^{o} C and used to analyze for total and total suspended solids (TS, TSS; pooled samples only) and TP. Total solids were determined by drying 25 ml subsamples in triplicate (events 1 and 2) or 100 ml in duplicate (events 3-5) at 105^{o} C for 24 h. Total suspended solids were calculated from the residue remaining on a glass fiber filter (934-AH, Whatman) after filtration of 50 ml (events 1 and 2) or 100 ml (events 3-5) subsamples and drying at 105^{o} C (APHA, 1998). Total P concentrations in the water were determined by digestion of 10 ml samples in triplicate with nitric acid followed by perchloric acid and final analysis by the Molybdate blue method (Murphy and Riley, 1962). An additional subsample of the original pooled samples were acidified with sulfuric acid to a pH below 2, stored at 4^{o}C, and analyzed for TKN using a Foss Tecator (2400 Kjeltech Analyzer Unit).

Statistical analysis

The data were statistically analyzed utilizing Proc Mixed of SAS version 9.1 (SAS, 2002) with event as a repeated measure. For the hydrograms from event 2, the specific interval was the repeated measure. Results for runoff volume and composition, as well as forage yield and ingredients were tested for variation amongst treatments by using the least square means from

$$Y_{ijk} = \mu + T_i + P_{(i)j} + R_k + (TR)_{ik} + \varepsilon_{(ijk)} \qquad [1]$$

where:

Y_{ijk} = specific measure for an individual plot and event

μ = parameter mean

T_i = effect of treatment i (i = 1, …, 6)

$P_{(i)j}$ = effect of an individual plot j (j = 1, 2, 3) within treatment

R_k = effect of rain event (k = 1, …, 5)

$(TR)_{ik}$ = effect of the treatment by event interaction

$\varepsilon_{(ijk)}$ = residual

Plot within treatment was declared as the subject. We then hypothesized that the heterogeneous compound symmetry (type = CSH) would describe the error variance of the data best, since events, but not necessarily adjacent ones (events 1 and 3 vs. 2, 4, and 5), are correlated. This hypothesis will be verified with comparing type = CSH to types CS (compound symmetry), AR(1) (autoregressive variance), and UN (unstructured variance). In case of the hydrograms taken during the second rain simulation, event will be replaced with interval (k = 1, …, 6).

For the analysis of ground cover measures and soil test parameters taken upon completion of the experiment, event will be dismissed from the model [1], leaving the simplified model [2]

$$Z_{ij} = \mu + T_i + B_j + \varepsilon_{(ij)} \qquad [2]$$

where:

Z_{ij} = ground cover or soil test reading for an individual plot
μ = the mean of that reading
T_i = effect of treatment i (i = 1, …, 6)
B_j = effect of block j (j = 1, 2, 3)
$\varepsilon_{(ij)}$ = residual [random error and $TB_{(ij)}$ interaction]

Significance was declared at $P < 0.05$, a trend at $P < 0.10$. The slice option in SAS was utilized to identify significance of treatments within events and vice versa, since we expected the negative control (no P applications) to be significantly lower than all treatments. That could skew overall averages containing the control. Orthogonal contrasts were used to evaluate the treatments and rain simulations. Contrasts involve the rain simulations at field capacity (events 2 vs. 4 and 5: Proximity to amendment of treatments; and events 4 vs. 5) and the events on soils drier than field capacity (events 1 vs. 3). Contrasts in types of treatment (no P vs. all P applications; liquid vs. solid manure applications; commercial P fertilizer vs. manure applications) will evaluate forage, runoff, soil test and ground cover parameters.

Total P and DRP data were analyzed using different types of correlation structures among times. The CSH and UN exhibited the best fit (Table 2.5) and resulted in the lowest standard errors for the contrasts. The CS and UN showed the most significance for differences within treatment over events, whereas AR(1) showed the lowest *p*-value for deviations among events. Overall, CSH showed the modest fluctuation and the lowest Bayesian information criterion (BIC, Fig. 3), and was consequently used as type for the repeated measures. Only edge-of-the-field losses of TS and TSS were analyzed using the CS type, since CSH did not converge in a solution.

RESULTS AND DISCUSSION

Effect of rain simulation/season

Runoff

The simulated rainfall events affected surface runoff volume, which correlated weakly to the initial soil moisture (Fig. 2.2, 2.3; $r^2 = 0.30$). Consequently, rain simulations on previously wetted soil (June wet, August wet, and October wet), where rainfall had been either simulated (June and August) or had occurred naturally (October) 24 h prior, increased surface runoff per plot compared to all dry events. The rain event during the drought (August dry, no previous wetting of soil) produced the least runoff per plot. Even the successive rainfall event 24 h later led to significantly less captured overland flow than the other two events on pre-wetted soil. The effect of soil moisture on runoff volume has been well documented in the literature (e.g. Pote et al., 1999). Dryer initial soil also correlated negatively to the time from the onset of the rain simulation to the occurrence of continuous surface runoff (Fig. 2.4; $r^2 = 0.61$).

A typical hydrograph of all runoff events is presented in Fig. 2.5. The patterns of the curves are typical for the five rain simulations, where event 3 (August dry) during the drought produced the least surface runoff volume (8.0 L/plot). Event 1 (June dry) created more runoff (14.3 L/plot) than event 3 (August dry), but less than the simulations on pre-wetted soil. Of these, event 4 (August wet, but during the drought) produced the lowest runoff weight.

Runoff phosphorus

Concentrations of TP and DRP in the collected surface runoff differed across events using pre-planned, orthogonal contrasts (Fig. 2.6). Specifically, event 2 (June wet) produced higher TP (0.175 mg/l) and DRP (0.112 mg/l) concentrations than the other two rain simulations on pre-wetted soils (August wet and October wet), which did not differ among each other. Concentrations of nutrients are generally higher in the first runoff event after manure amendment and decrease with increasing time between the amendment and the runoff event (Edwards and Daniel, 1993; Kleinman and Sharpley, 2003; Penn et al., 2004). In addition, TP and DRP concentrations were higher in event 1 (June dry) versus event 3 (August dry). Some researchers (Pote et al., 1999) found evidence that DRP concentrations are higher in runoff from dry soil. Possible explanations may be the lysing of microorganisms under drought conditions and the contribution of leachate from water stressed plants (Sharpley, 1981). In this study however, the spring applications of P sources had an overriding effect, as runoff from all P amended plots contained less DRP in successive rain events. The DRP concentration in runoff from the control plots spiked during the rain events after dry conditions (August dry and October wet) but the increase was not statistically significant.

Edge-of-the-field losses of TP and DRP are presented in Fig. 2.7. Throughout this paper, edge-of-the-field losses will be presented in g/ha, since this is the general method of reporting edge-of-the-field losses. We want to emphasize, however, that overall P losses from the plots can not be extrapolated to present losses on a per ha basis. The losses of TP during the fourth simulation (August wet, 17.9 g/ha) were less than losses during the fifth event (October wet, 27.2 g/ha), and both events averaged less TP losses than the second event (June wet, 32.5 g/ha). Losses of TP occurring from event 1 (June dry) were greater than event three (August dry) losses. Calculations of edge-of-the-field losses of DRP displayed similar variations by rain event. Pote et al. (1999) also found a high dependence of DRP losses on runoff volume. These findings support the avoidance of applying manure and fertilizer on wet soils.

Runoff of solids and nitrogen

Total solids concentrations differed among rain simulations (Fig. 2.8). Overall, a low percentage of TS were suspended, the majority consisted of dissolved solids. There were significantly higher TS concentrations in the runoff collected during event 3 (August dry) compared to all other events. Since TSS concentration was not increased during event 3, dissolved solids contributed to the higher TS concentrations. The dissolved particles may have accumulated from dust and atmospheric depositions during the drought and leachates from water-stressed plants. Concentrations of TSS were numerically lower during the rain simulation on wet soils, except for the last event (October wet), which was proceeded by a natural rain storm (Fig. 2.1). It remains unknown, how much runoff, if any, this natural event produced. Event 5 (October wet) resulted in significantly higher TSS per L than event 4 (August wet).

The rain events also impacted edge-of-the-field losses (Fig. 2.9). Event 1 (June dry) resulted in more overall erosive losses compared to event 3 (August dry), due to the low runoff weights during the third event. Overall, erosive losses from event 4 (August wet) were reduced versus event 5 (October wet) for the same reason. The highest amount of suspended solids were lost during the last rain simulation (October wet), but overall loss of eroded sediments was negligible. Since suspended solids in runoff pose a significant source of P (McDowell and Sharpley, 2002), the lack of TSS in runoff in the current experiment may have led to lower TP concentration than reported in other studies using bare soils (Kleinman and Sharpley, 2003) or row-crops (Warren et al., 2006).

Total Kjeldahl N concentrations were highest during the first couple of rain simulations (Fig. 2.10). Event 5 (October wet) had significant higher concentrations of TKN in the runoff than event 4 (August wet). Generally, the standard errors for each event were small. Clearly, organic N from applied manure and from organic residue was nitrified to nitrites and nitrates, or was volatilized during between June and August. Total Kjeldahl N only describes organic and ammonia N, so an increase in nitrites and nitrates would not have been detected in our study. Because of the drought conditions, additional organic matter may have accumulated as dead plant material on the soil surface, leading to the slight, but significant increase in runoff

TKN (Fig. 2.10). Other research showed no differences in runoff TKN from plots having received swine slurry when the first runoff event was varied from 4 to 14 d (Edwards and Daniel, 1993).

Effect of treatment and treatment by season interaction

Runoff

The application of manures and/or commercial fertilizer affected neither average volume of surface runoff nor the volume at any given rain simulation. The high variability of runoff volume within treatment and event from pasture plots was previously observed by Daniel et al. (1993).

Runoff phosphorus

Total P and DRP concentrations in the collected surface runoff over all five rain simulations were not affected by treatment (Fig. 2.11). But pre-planned contrasts showed significantly lower concentrations of TP and DRP in runoff from the control compared to all other treatments. No differences were found in TP or DRP concentrations between liquid (dairy and swine) and solid manures (beef and poultry) and between TSP and all manure treatments.

Differences were observed with treatment when evaluated within specific runoff events. Total P (Fig. 2.12) and DRP (Fig. 2.13) concentrations in runoff during the first simulation (June dry) tended to be influenced by treatment. The control treatment was lower in TP and DRP concentrations when contrasted against all other treatments. Total P, but not DRP, was affected by treatment during the second simulation (June wet). Again, the control treatment produced lower concentrations than all other treatments, but TP concentration in runoff from the TSP treated plots was significantly higher than TP concentrations in all manure treatments. Treatment did not influence TP and DRP concentrations in succeeding rain events. Previous research had pointed out that amendment with commercial P fertilizer produced higher TP concentration in runoff from pasture compared to poultry litter (Nichols et al., 1994) and to liquid dairy slurry and farmyard manure (Heathwaite et al., 1998). Both studies used higher application rates of P_2O_5 (199 kg/ha and 229 kg/ha, respectively) than the current study. The low application rate of P, which were designed to mirror current management practices in the Valley, may have hindered a clearer differentiation among P sources, as high application rates amplified differences between manure types (Kleinman and Sharpley, 2003).

Total P and DRP concentrations in runoff from the control treatment were similar across events (Fig. 2.12 and 2.13), whereas event impacted the TP concentration in runoff from the TSP, dairy slurry, piggery waste, beef solids, and poultry litter treatments ($P < 0.001$, 0.01, 0.06, 0.10, and 0.08, respectively), as well as the DRP concentration ($P < 0.001$, 0.001, 0.09, 0.08, 0.10, respectively). Initially, runoff from plots amended with TSP and dairy slurry had the numerically highest concentrations of TP and DRP, which dropped to the same level (background concentration) as the no P control. Therefore, succeeding rainfall events had a stronger impact on the TSP and dairy slurry treatments as compared to other treatments.

To the contrary, Kleinman and Sharpley (2003) reported that TP and DRP concentrations of dairy slurry were initially lower than those of swine slurry and poultry litter when applied at the same P rate on bare ground. But runoff P concentrations for swine slurry and poultry litter regressed more over successive events and ultimately equaled the concentrations of runoff P from dairy slurry. In that study, successive rainfalls were simulated indoors at 3 d, 10 d, and 24 d post amendment. The time-lag between treatment application and first rain simulation may have impacted results in the current study, as solid manure and litter produced numerically less runoff P than the two liquid manure sources and commercial P fertilizer. Speculatively, two or three natural rain events may have produced surface runoff prior to the first rain simulation (Fig. 2.1), but the intensities of those rainfalls are not known. As a result, more P could have been washed from the two solid manure treatments, since solid manure has less contact area with the soil (Harmel et al., 2004). This would explain the spike in runoff P from litter, but not from swine slurry in Kleinman and Sharpley (2003).

Examining the DRP portion of TP in runoff water represents the immediately reactive allotment of TP. Ratio of DRP to TP concentration in the collected runoff disclosed the lowest ratio from the control plots (57% DRP). No other differences were detected in the ratios (Fig. 2.14). Other researchers had reported previously that manure application would increase the dissolved reactive portion within the TP in surface runoff (Preedy et al., 2001; Kleinman et al., 2002)

A strong ($r^2 = 0.80$) linear relationship was observed between TP and DRP with a slope of 0.77 (Fig. 2.15). In consideration of the low y-intercept (-0.016 mg DRP/l), DRP represented about three quarters of TP. Dissolved RP constituted practically all of runoff TP from pasture plots in Nichols et al. (1994). The lower rain intensity (50 mm/hr), proximity of rain simulation (7 d after amendment), and the different soil type (Captina silt loam, Typic Fragiudult) may contribute to the higher DRP:TP ratio revealed in that study. Poultry litter amendment did not change the ratio of DRP:TP compared to our study (67% vs. 66%). Heathwaite et al. (1998) reported 67% DRP in runoff from pasture after inorganic P application. The ratio in runoff from non-amended bare soils was 9% in the study reported by Kleinman et al. (2002), but the researchers also reported high TSS concentrations (1129 – 11299 mg/l). Runoff DRP is usually higher from pasture than cropland, due to the filtration effect of the vegetation on suspended particles high in particulate P, as demonstrated in the current study.

Overall, no effects of treatment or treatment by event interactions on edge-of-the-field losses of TP and DRP were observed (Fig. 2.16). Plot-specific and treatment-independent variations in the amount of collected overland flow seemed to have either an overriding effect on losses of P or led to larger deviations within treatments. Edge-of-the-field losses should not be used to evaluate the risk of P losses, since they are very site specific, unless an impact of P amendment on overland flow is evident. Furthermore, total losses from these small plots should not be extrapolated to a per ha basis, as different flow dynamics, including P adsorption during transport (Sharpley et al., 1993) are involved with increasing distance to the edge-of-the-field. Overall, losses of sediment and nutrients need to be monitored over longer time periods on a field or small watershed-scale (Harmel et al., 2004).

The P loss from each treatment above the background loss set by the no P control is indicated by the dotted top portions of the bars in Fig. 2.16. Application of TSP almost doubled TP losses to surface runoff (significance not tested to keep contrasts orthogonal). This portion represented only 13.3 g P per ha. Originally, 27.4 kg P per ha had been applied. Although there might have been losses in natural rain events, especially in the time between manure application and first simulation (Fig. 2.1), the detected losses were exponentially less than reported by Kleinman and Sharpley (2003). In their study, manures were applied on two types of bare soil. Over successive rain simulations using the same protocol on d 3, 10, and 24 after manure amendment at a 3% slope, plots lost 9 and 19%, 7 and 12%, and 5 and 3% of applied P (100 kg P_2O_5/ha) from poultry litter, swine manure, and dairy slurry, respectively. Previously, the same researchers reported the same rankings of manure sources, with dairy slurry showing the least concentrations of runoff P, and no differences between swine slurry and poultry litter (Kleinman et al., 2002). The current study numerically ranked TSP above both liquid manures followed by both solid manures during the course of a growing season.

Runoff hydrograms

The total volume of surface runoff collected during the second rain simulation (June wet) displayed an increase in volume for each individual 5 min increment (Fig. 2.17) for the first 15 min of runoff. There was no effect of treatment or of treatment within an interval on the volume of overland flow. Runoff flows therefore peaked and stabilized after 15 min of continuous runoff from pasture at the given hydrologic parameters and rain intensity.

Furthermore, TP and DRP in the runoff were not affected by treatment, but effects of interval and interval by treatment interaction were shown. Concentration of TP dropped significantly from one increment to the next (Fig. 2.18). Extrapolation of the resulting trendline (r^2 = 0.99) indicated a TP concentration of 0.208 mg/l at initiation of the runoff and a decline of 0.012 mg/l per min of runoff occurrence. The reduction of TP concentration was significant for all intervals when compared to the previous interval. Edwards and Daniel (1993) did not find such a clear cut regression for runoff TP in their hydrograms following the application of swine slurry to tall fescue.

The concentration of TP in the control treatment (0.110 mg/l) tended to be lower than all other treatments (0.176 mg/l). Amended plots did not differ amongst each other overall and within interval (Fig. 2.19). To the contrary, fine clay particles, which eroded in high quantities at the initiation of runoff, contributed more P to runoff than coarser particles, which usually adsorb less P in Quinton et al. (2001). The change in TP concentrations in the runoff from the control in the current study did not support those findings, as its TP concentrations increased numerically until the 10-15 min interval. We did not evaluate particle sizes and their rate of P adsorption. All P treatments, unlike the control, disclosed a significant drop in TP concentration in runoff by increment.

Overall, DRP concentrations in surface runoff dropped over the duration of the simulation (Fig. 2.18). But the magnitude of the drop was less profound (0.004 mg/l DRP min^{-1}) and defined (r^2 = 0.85) than the drop in TP. This phenomenon is depicted in Fig. 2.20 in more detail for each treatment. The control treatment tended to produce lower DRP concentrations in the runoff, which changed slightly over the course of the simulation. Interval had a significant effect on all other treatments. Schreiber and McDowell (1985) noted that runoff DRP declined quickly over the course of a rain simulation on wheat straw. The authors attributed the early spike in runoff DRP to soluble P leached from plant material and accumulated dust. This peak may have occurred during the rainfall event 24 h prior to the event used for the hydrograph in the current study, as concentrations for the no P control increase over the initial 20 min of runoff (Fig. 2.20).

The concentrations of DRP analyzed for the hydrogram correlated more to TP concentrations (r^2 = 0.89; Fig. 2.21) than for all rain events (r^2 = 0.81; Fig. 2.15). The slope of the regression line was shallower (0.60 v. 0.77), since the sum of DRP lost in each interval was lower than the overall loss of DRP as measured by the pooled sample taken at the end of the simulation. This may have been an artifact of collection methods, as there may have been a higher concentration of DRP in the residual water that was left in the collection jars, when the runoff water was pumped from the jars into the barrels between intervals. Total P in the pooled samples varied from TP in the samples taken at the increments by less than 5% in 13 of the 18 plots, and by less than 10% in 17 plots.

The first five minutes of continuous runoff produced less edge-of-the-field losses of TP and DRP than sequential increments (Fig. 2.22). Other successive intervals, as well as treatments, did not differ from each other. Additionally, treatments showed no effect on each individual time increment, whereas TP and DRP losses were affected by interval within each treatment. After initiation of runoff, the increasing surface runoff equalized the decreasing P concentration. Again, runoff volume due to plot specific attributes overrode any possible differences among treatments.

Runoff of solids and nitrogen

Treatment and treatment by rain event interactions did not affect TS and TSS concentrations. Total solids concentrations in surface runoff were not correlated to initial soil moisture content. Edwards and Daniel (1994) reported higher TSS content in runoff from fescue plots having received poultry litter than from plots treated with an inorganic P fertilizer, when rainfall was simulated at d 7 after amendment. Again, the time lag between application and simulation in the current study may have impacted our results.

Concentrations of TKN in surface runoff water (Fig. 2.23) and edge-of-the-field losses of TKN were not impacted by treatment. We did not expect great differences, since only a portion of N was applied as organic matter on the manure amended treatments and additional N was applied as ammonium nitrate. This outcome is in concert with results from Harmel et al. (2004), where N, in forms of poultry litter and inorganic fertilizer, was applied on cropland and pasture. When amended at higher rates, inorganic N fertilizer created higher runoff N concentrations than an organic N source (Edwards and Daniel, 1994).

Soil phosphorus

Soil samples taken from each plot immediately after the last rain simulation did not differ in STP and WEP by treatment (Table 2.1). This was expected, as a one-time application of P on the basis of crop removal should have little impact on STP after the growing season.

Water-extractable P did not correlate to DRP concentration in surface runoff collected during the final rain simulation. Other studies have shown an interaction of STP or WEP and DRP concentrations in runoff from non-amended soils (e.g. Pote et al., 1999; Kleinman et al., 2002; Harmel et al., 2004), whereas Daniel et al. (1993) did not discover a significant relationship between WEP to runoff DRP from tall fescue plots. Application of P is more likely to increase runoff P if initial STP is high (Hart et al., 2004). Since no treatment increased runoff DRP significantly over the last three rainfall simulations, we hypothesized that the plots had returned close to the background configuration or to an equilibrium and expected some impact of either STP or WEP on runoff DRP concentrations.

Forage

Forage dry matter yields differed by cutting, but not by source of P amendment (Fig. 2.24 and 2.25). Forage yields averaged 7.33 t/ha, 0.5 t/ha on average less than originally expected, ranging from 6.63 to 7.97 t/ha. The north-west location of the slope and/or the dry conditions in late summer may have impacted the forage yields negatively.

Average N concentrations in forage from the various treatments ranged from 26.4 to 30.4 mg N/g, equivalent to 16.5 to 19.0% crude protein on pure grass stands. Treatments did not affect either the N concentration or N removal by the harvested forage (Fig. 2.26). The resulting N removal by forage was higher than the applied 112 kg/ha of available N because of a high crude protein concentration of the forage.

Phosphorus concentration of the forage analyzed higher than expected, with averages ranging from 3.86 mg P/g at the second cutting to 5.35 mg P/g at the fourth cutting (Fig. 2.27). The averages weighted by yield for the whole season were 4.03 mg P/g (control), 4.37 mg/g (TSP), 4.61 mg/g (dairy slurry), 4.41 mg/g (piggery waste), 4.10 mg/g (beef solids), and 4.42 mg/g (poultry litter). A count of 4003 grass samples analyzed at Cumberland Valley Analytical Services, Inc., Hagerstown, MD, revealed a mean P concentration of 2.67 mg/g. The 90th quantile of the samples had a P concentration of less than 3.90 mg/g, and 99.5 % had less than 5.74 mg/g (Ralph Ward, personal communication, 2006). A second laboratory technician confirmed the P content of some randomly selected forage samples in the present study, but no samples were analyzed externally. Luxury consumption of P seems unlikely from the perspective that STP did not analyze excessively high.

Overall, treatments did not affect forage P concentration, but forage from the control treatment was lower in P than forage from all other treatments. Additionally, a trend for a treatment by cutting interaction was observed, as treatment tended to impact forage P concentration in the first, second, and fourth cutting. Specifically, P concentration in forages from the first cutting was higher for liquid slurries (dairy and piggery) than for solid manures (beef and poultry). Forages grown on plots without P amendment tended to be lower in P overall and were significantly lower in P from the second and fourth cutting, respectively, as compared to forages from amended plots (Fig. 2.28).

Phosphorus removal by forage did not vary among treatments due to an overriding effect of yield variation, but varied by cutting. Only forage from the treatment receiving beef solids removed P on the basis of the previously calculated removal rate of 62.7 kg P_2O_5/ha, forages from the remaining treatments removed more P_2O_5/ha than applied (Fig. 2.26). We cannot recommend applying P at a higher rate due to the unusually elevated P concentration of the forage. Forage P did not correlate to STP or WEP or to TP or DRP in surface runoff (all $r^2 < 0.13$).

Soil Cover

There was a significant effect of block on soil cover, as the second block had on average 25.5% bare soil versus 18.7% and 18.3% for the remaining two blocks. The application rates used, which were based on forage P removal, did not affect the portion of bare soil of the whole plot. Productive (green) cover was 50, 45, and 54% for the three blocks, respectively, and thatch accumulated to 31, 30 and 28%. Productive cover and thatch are expected to have similar effects on runoff, e.g. reducing impact of rain drops, decreasing velocity of runoff, increasing infiltration rate etc. The front and the back halves of each plot were analyzed separately, but again, no differences were detected.

The percentage of bare soil did not correlate to forage yield or to runoff parameters including runoff weight, TP, DRP, or TS concentrations. The bare soil portion of a plot also did not affect the time lag from start of the rain simulation to the point of continuous runoff. The differences in portions of bare soil may not have been great enough in the current study, as Elliott et al. (2002) detected increased volume of runoff and sediment losses with decreasing soil cover.

CONCLUSIONS

A ranking of the manure sources included in this study in comparison to TSP is difficult due to the low application rate of P_2O_5 and the time lag between manure amendment and the first rainfall simulation. The application rate was chosen to simulate current management practices from the Valley in the study, although a higher application rate may have described possible differences between manure sources better. Due to the high variations in runoff volume, possibly as a result of hydrological differences within plots, a larger plot size (2.0 x 1.5 m^2) may have increased distinction of P loss on a mass balance.

The current P Index for Virginia uses coefficients of 0.25 for inorganic P fertilizer, 0.2 for cattle and swine manure, and between 0.1 and 0.2 for poultry litter, depending on whether it was treated with Alum and at which rate (Wolfe et al., 2005). Our results showed clearly a seasonal effect of P applications on P losses. Based on the results of the second rain simulation (June wet), TSP produced 0.13 mg more TP/l compared to the control. Treatment with dairy slurry and piggery waste increased TP 0.07 mg/l and beef solids and poultry litter 0.04 mg/l in comparison to the control, whose ‘background’ contribution of TP was 0.118 mg/l during event 2 (June wet). Treatments did not impact P concentrations in surface runoff at successive rain simulations in Aug. and Oct. Hydrograms compiled during the second rain event (June wet) displayed decreasing TP and DRP concentrations, along with an increasing DRP:TP ratio for each treatment over the course of a 30 min runoff event. Short runoff events will produce less runoff volume with higher concentrations of P, based on the results of the interval samples taken during the second event (June wet).

ACKNOWLEDGEMENTS

The authors want to thank the Virginia Ag Council for sponsoring this experiment. Fellowship for Marcus Hollmann was provided by the John Lee Pratt Fellowship for Animal Nutrition. We also like to thank Mr. David Fiske from the Shenandoah Valley Agricultural Research and Extension Station for use of the paddock and logistic support. Additionally, we are grateful to all the help provided by undergraduate and graduate students at Virginia Tech, especially Tzu-Hsuan Yang and Zunyang Zhao.

Table 2.1. Results of soil samples taken at two soil depths in spring and autumn from pasture plots amended with different sources of P in spring.

		Mehlich 1, Extractable											
Treatment	**pH**	**P**	**K**	**Ca**	**Mg**	**Zn**	**Mn**	**Cu**	**Fe**	**B**	**WEP[†]**	**OM[‡]**	**CEC[§]**
		---ppm in soil---										%	meq/100g
2.5 cm soil depth													
Initial[¶]	6.30	31	165	1290	228	4.6	8.4	0.5	6.9	0.6	2.039	10.0	n/a
No P control	6.68	35.00	92.67	1308.67	193.00	4.60	8.30	0.57	8.40	0.50	2.311	10.03	8.37
TSP[††]	6.73	34.67	82.00	1314.67	197.00	4.27	7.37	0.60	7.40	0.57	2.721	9.17	8.40
Dairy slurry	6.67	33.33	84.33	1236.00	195.33	4.43	8.57	0.57	9.90	0.53	2.476	9.43	8.03
Piggery waste	6.67	36.00	91.67	1302.67	192.00	4.87	7.83	0.63	8.83	0.57	3.037	9.17	8.33
Beef solids	6.73	29.33	105.00	1383.00	212.67	3.83	9.97	0.40	7.20	0.57	1.694	9.50	8.93
Poultry litter	6.63	26.67	83.67	1201.33	178.67	4.03	7.77	0.60	9.30	0.50	1.999	9.20	7.70
10 cm soil depth													
Initial[¶]	6.23	28	157	1095	179	3.4	7.0	0.9	7.7	0.5	1.060	6.2	n/a
No P control	6.72	29.00	112.00	1065.67	165.00	2.97	7.13	0.63	11.00	0.43	1.861	n/a	7.00
TSP[††]	6.77	24.67	87.33	1084.67	160.00	2.53	6.50	0.53	7.97	0.47	1.505	n/a	7.00
Dairy slurry	6.54	21.33	71.00	889.67	134.00	2.47	6.67	0.60	11.63	0.40	1.368	n/a	5.90
Piggery waste	6.63	25.33	76.33	1019.00	139.33	2.70	6.80	0.63	11.00	0.47	1.428	n/a	6.47
Beef solids	6.72	24.00	95.00	1115.00	169.00	2.50	6.63	0.47	7.77	0.47	1.526	n/a	7.23
Poultry litter	6.57	19.33	72.33	903.33	126.00	2.23	6.50	0.60	10.47	0.40	0.987	n/a	5.87

[†] Water-extractable P.

[‡] Organic matter.

[§] Cation exchange capacity.

[¶] Samples taken in June from non-treated soil within the experimental area.

[††] Triple superphosphate.

Table 2.2. Nutrient composition of the different manure sources.

	Manure Source			
	Dairy Slurry	**Piggery Waste**	**Beef Manure**	**Poultry Litter**
Nutrient	- - - - - - - - - mg/ml	- - - - - - - - -	- - - - - - - - mg/g	- - - - - - - -
TKN[†]	2.73	3.38	5.11	36.54
NH_4-N[‡]	0.684	0.915	0.28	6.81
Organic-N	2.046	2.465	4.83	29.73
P_2O_5[§]	1.47	2.54	4.97	30.50
Availability[¶]	- - - - - - - - - -	- - - - - - - - - %	- - - - - - - - - -	- - - - - - - - - -
NH_4-N[‡]	45	45	25	50
Organic-N	35	50	35	60

[†] Total Kjeldahl nitrogen.

[‡] Ammonia nitrogen.

[§] P_2O_5 equals elemental P multiplied by a factor of 2.29.

[¶] Available in the first season after application, according to Virginia's Nutrient Management Standards and Criteria (Department of Conservation and Recreation, 1995).

Table 2.3. Application rates of manures and inorganic N and P to tall fescue pasture.

Treatment	Rate	available TKN[†]	P_2O_5[‡]	Added NH_4-N[§]	Total available N[¶]
	m^3/ha	kg/ha			
Dairy Slurry	43.0	43.9	62.7	200	112
Swine Slurry	24.7	40.5	62.7	211	112
	kg/ha				
Beef Manure	14,128	22.2	62.7	264	112
Poultry Litter	2,302	43.7	62.7	200	112
TSP[††]	152	0.0	62.7	329	112
Control	0	0.0	0.0	329	112

[†] In accordance to availability coefficients from Table 2.2.

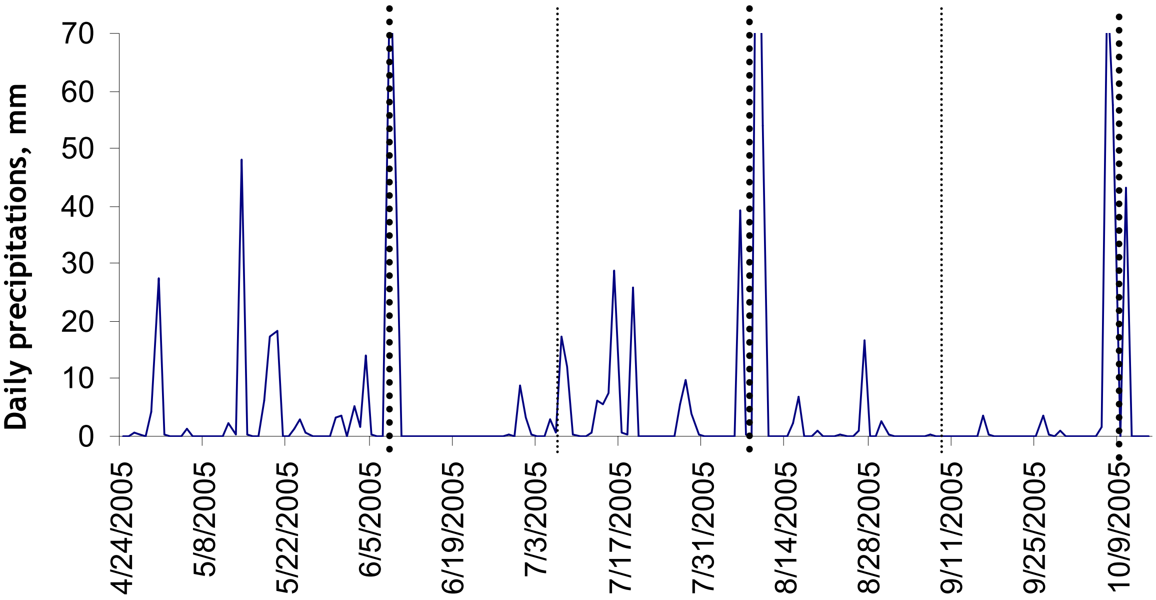
[‡] P_2O_5 equals elemental P multiplied by a factor of 2.29.

[§] The needed balance (112 kg/ha minus available TKN supplied by manure) applied as ammonium nitrate, available N = 0.34.

[¶] Sum of available TKN and NH_4-N.

[††] Triple superphosphate.

Fig. 2.1. Daily precipitations at the experiment site in Steeles Tavern, VA, from April to October 2005[†].



[†] Dotted lines indicate cutting date. Larger dotted lines express dates of rain simulation. After the 1st and 3rd cutting, rainfall was simulated on plots twice in a 24 h interval and runoff was collected for 30 min. After the 5th cutting, rainfall was simulated only once.

Table 2.4. **Parameters of the well water used for artificial rain simulations[†].**

	TP	DRP	TKN	TS	TSS
Events 1 and2	---	---	mg/l	---	---
June, 06	0.025	0.018	0.77	409	6
June, 07	0.025	0.006	0.69	409	1
June, 08	0.024	0.010	0.69	407	-2
June, 09	0.028	0.016	0.60	384	-8
Events 3 and 4					
August, 09	0.017	0.010	0.03	361	3
August, 10	0.016	0.005	-0.14	379	4
August, 11	0.013	0.005	-0.14	315	4
August, 12	0.012	0.004	0.22	331	3
Event 5					
October, 11	0.017	0.006	0.58	362	2
October, 12	0.013	0.003	0.44	367	2

[†] TP: Total P; DRP: Dissolved reactive P; TKN: Total Kjeldahl N; TS: Total solids; TSS: Total suspended solids.

Table 2.5. Fit statistics for different types of correlation structures among times for total phosphorus (TP) and dissolved reactive phosphorus (DRP) in surface runoff [†].

Type of repeated measure	TP	DRP
CSH[‡]	-199	-240
CS[§]	-195	-224
AR(1) [¶]	-188	-223
UN[††]	-202	-237

[†] Numbers represent Sawa's Bayesian information criterion (BIC). Smaller numbers indicate a better fit.

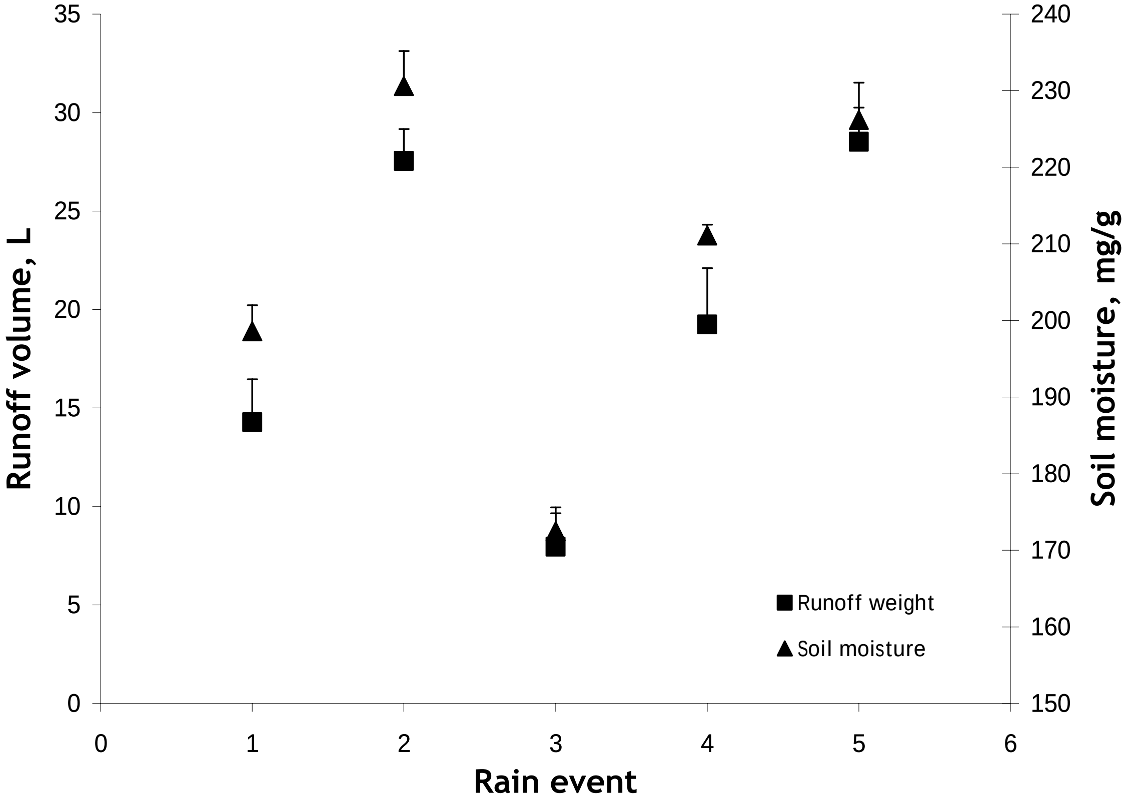
[‡] Heterogeneous compound symmetry.

[§] Compound symmetry.

[¶] Autoregressive variance (correlations larger for adjacent periods).

[††] Unstructured variance (no pattern for correlations).

Fig. 2.2. Weight of surface runoff and initial soil moisture following five rainfall simulations on fescue pasture.



[†] Error bars represent the standard error.

Fig. 2.3. Correlation of initial soil moisture and surface runoff volume.

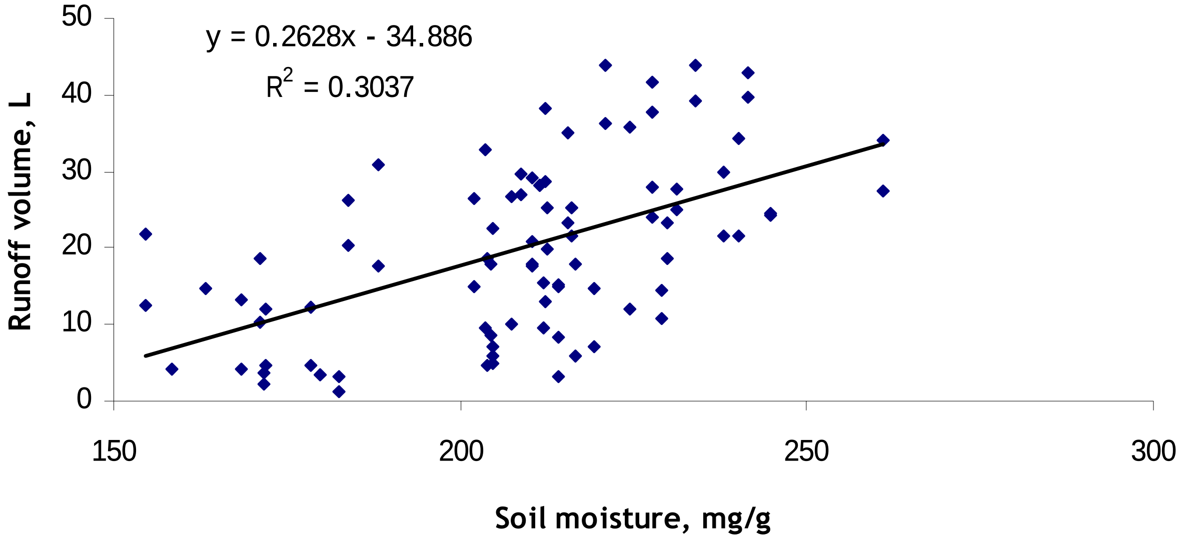


Fig. 2.4. Dependence of lag time from initiation of rain simulation to the occurrence of continuous surface runoff from pasture plots on the initial soil moisture concentration.

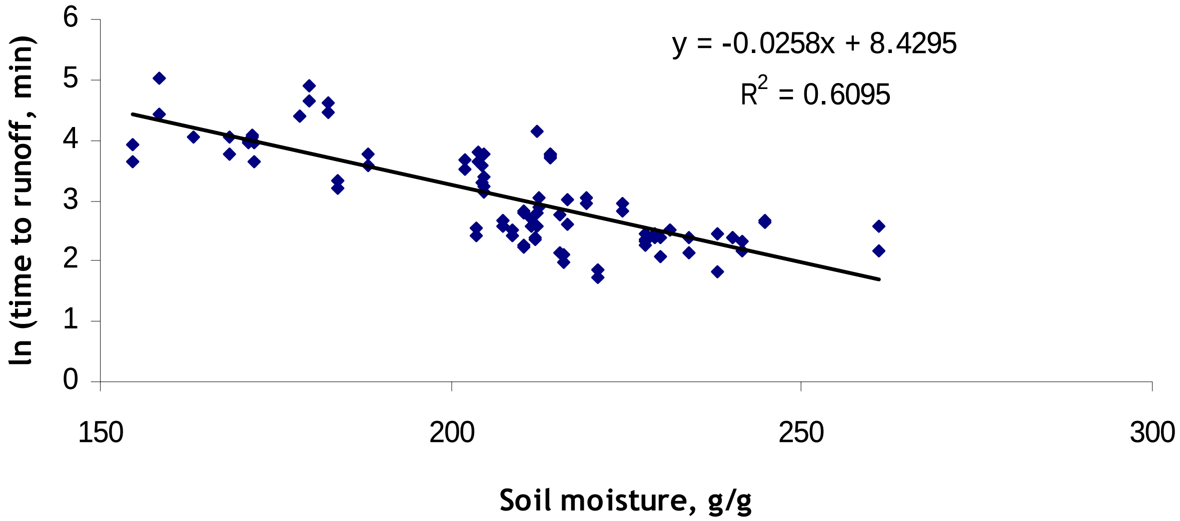
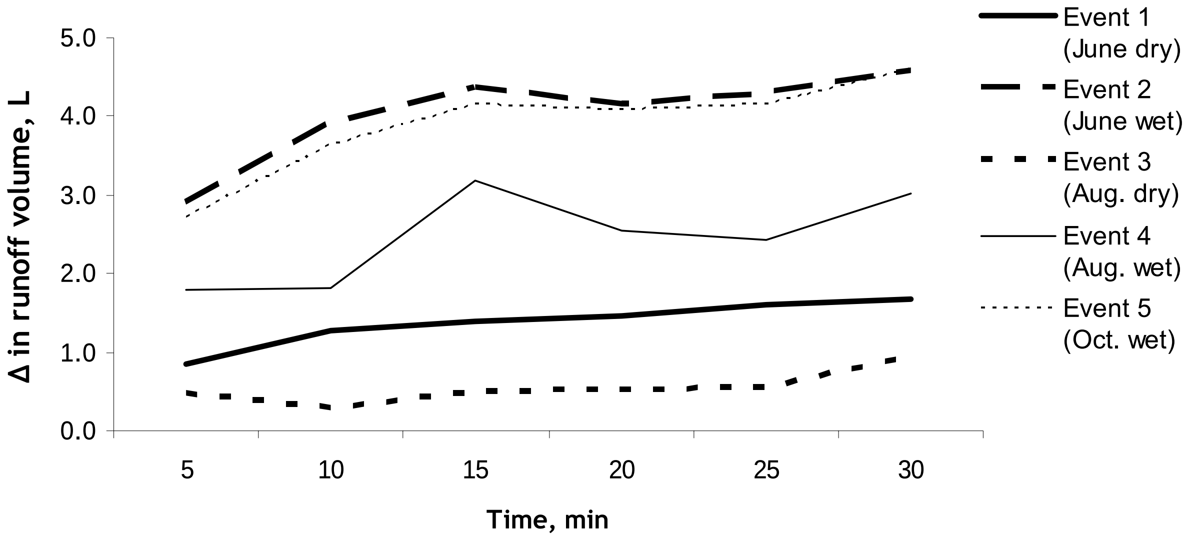
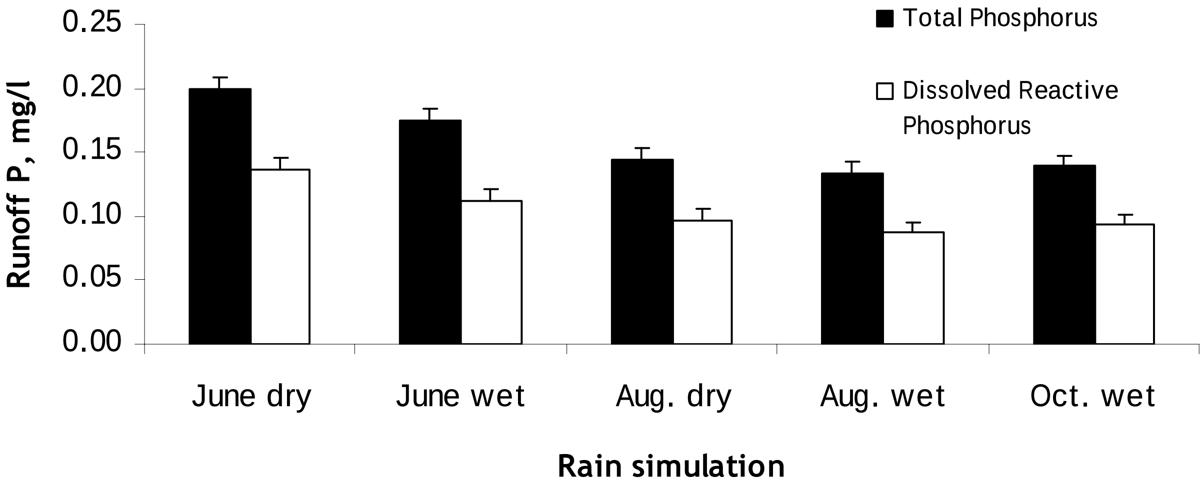


Fig. 2.5. This hydrograph of the plot amended with piggery waste in block one represents a typical graph of the amount of surface runoff collected from pasture plots during 5-min intervals during five separate rainfall simulations[†].



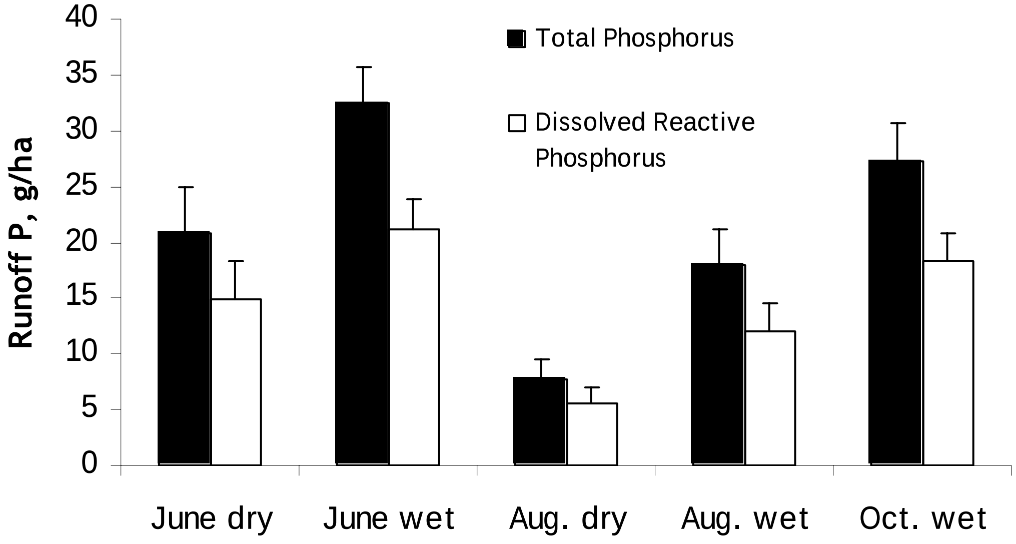
[†] Events 1 and 2 were simulated in June, 3 and 4 in August, and 5 in October.

Fig. 2.6. Total P and dissolved reactive P concentrations in surface runoff collected during five simulated runoff events from fescue pasture[†].



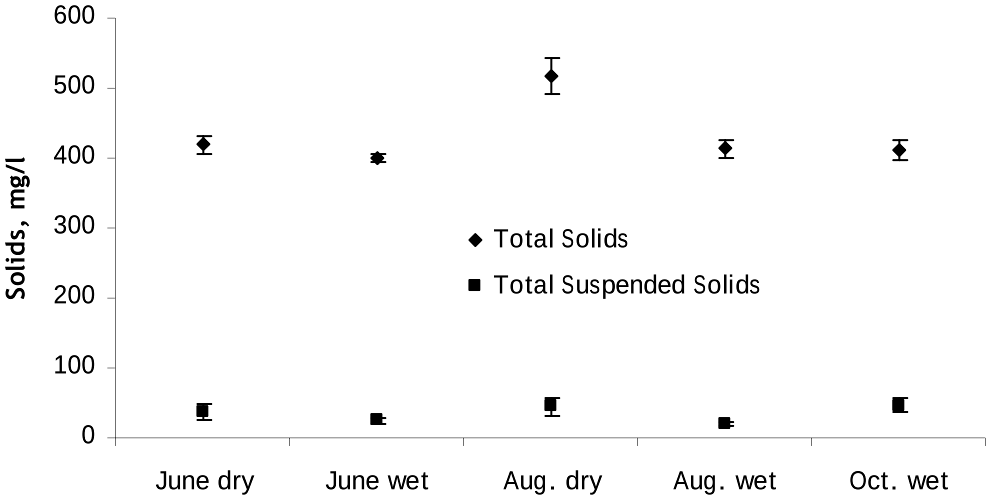
[†] Error bars represent the standard error.

Fig. 2.7. Edge-of-the-field P losses in surface runoff collected during five simulated runoff events from fescue pasture†.



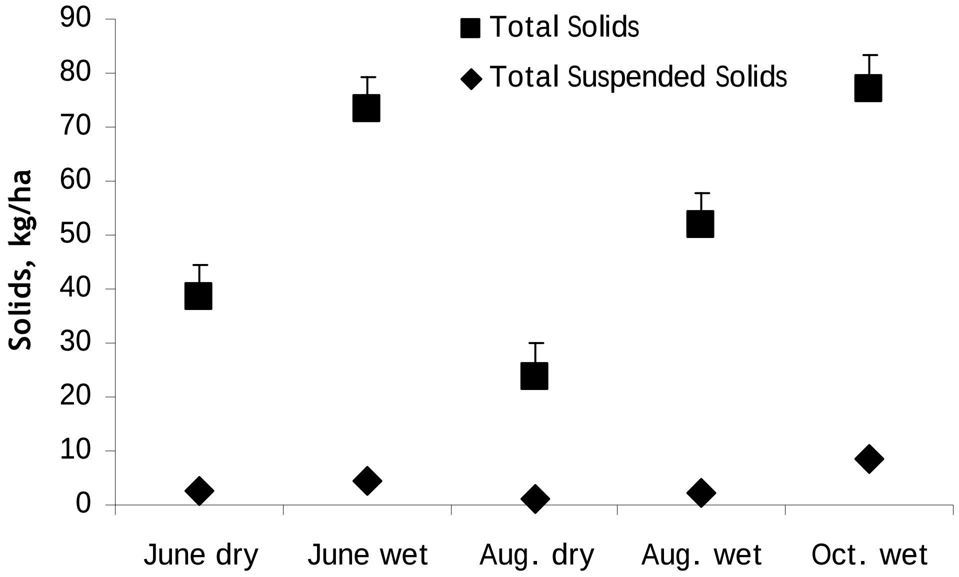
† Error bars represent the standard error.

Fig. 2.8. Concentrations of total solids and total suspended solids in surface runoff collected during five simulated runoff events from fescue pasture[†].



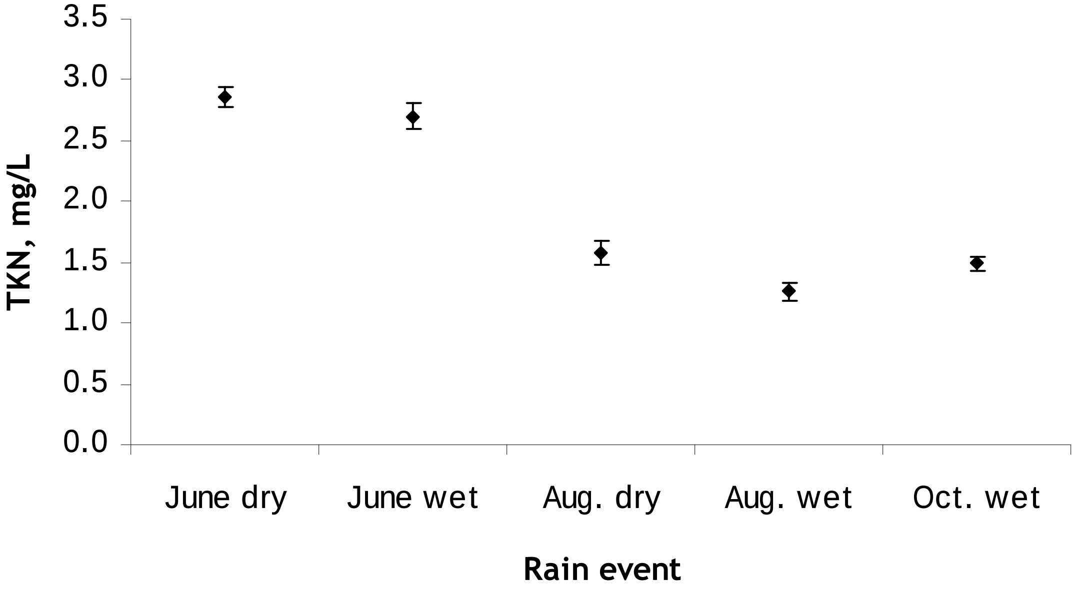
[†] Error bars represent the standard error.

Fig. 2.9. Total solids and total suspended solids in surface runoff collected during five simulated runoff events from fescue pasture[†].



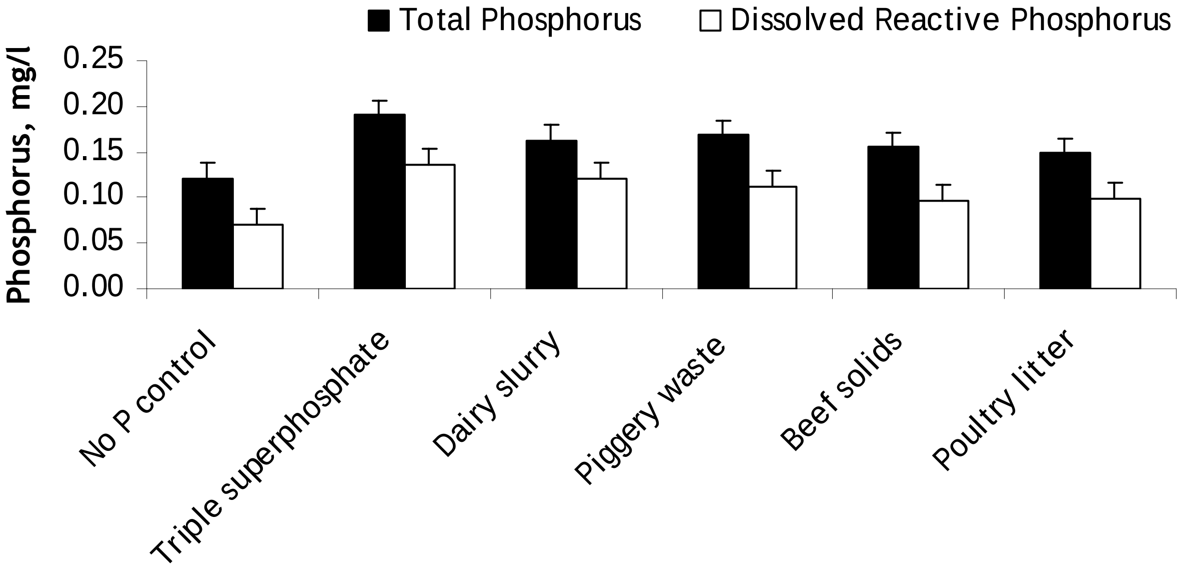
[†] Error bars represent the standard error.

Fig. 2.10. Concentrations of total Kjeldahl N in surface runoff collected during five simulated runoff events from fescue pasture[†].



[†] Error bars represent the standard error.

Fig. 2.11. Total P and dissolved reactive P concentrations in surface runoff collected during five simulated runoff events from fescue pasture[†,‡].



[†] Events 1 and 2 were simulated in June, 3 and 4 in August, and 5 in October 2005.
[‡] Error bars represent the standard error.

Fig. 2.12. Total P concentrations in surface runoff collected during five simulated runoff events from fescue pasture.

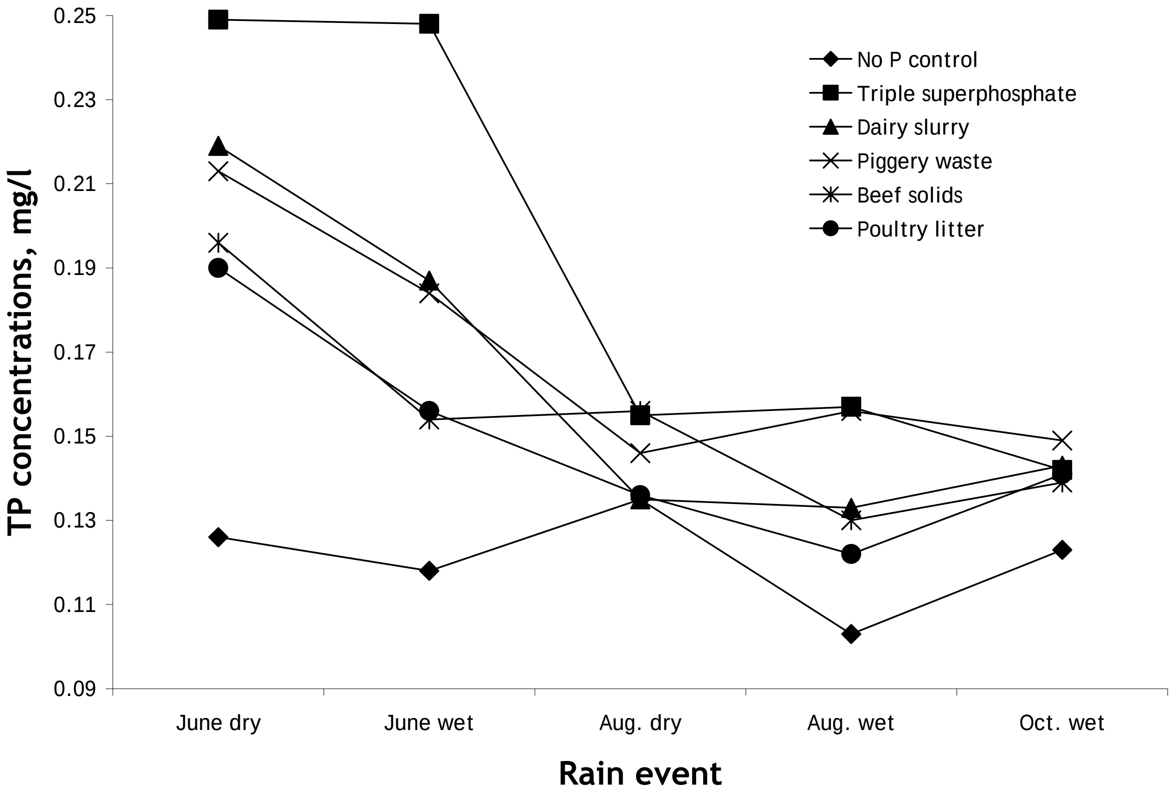


Fig. 2.13. Dissolved reactive P concentrations in surface runoff collected during five simulated runoff events from fescue pasture.

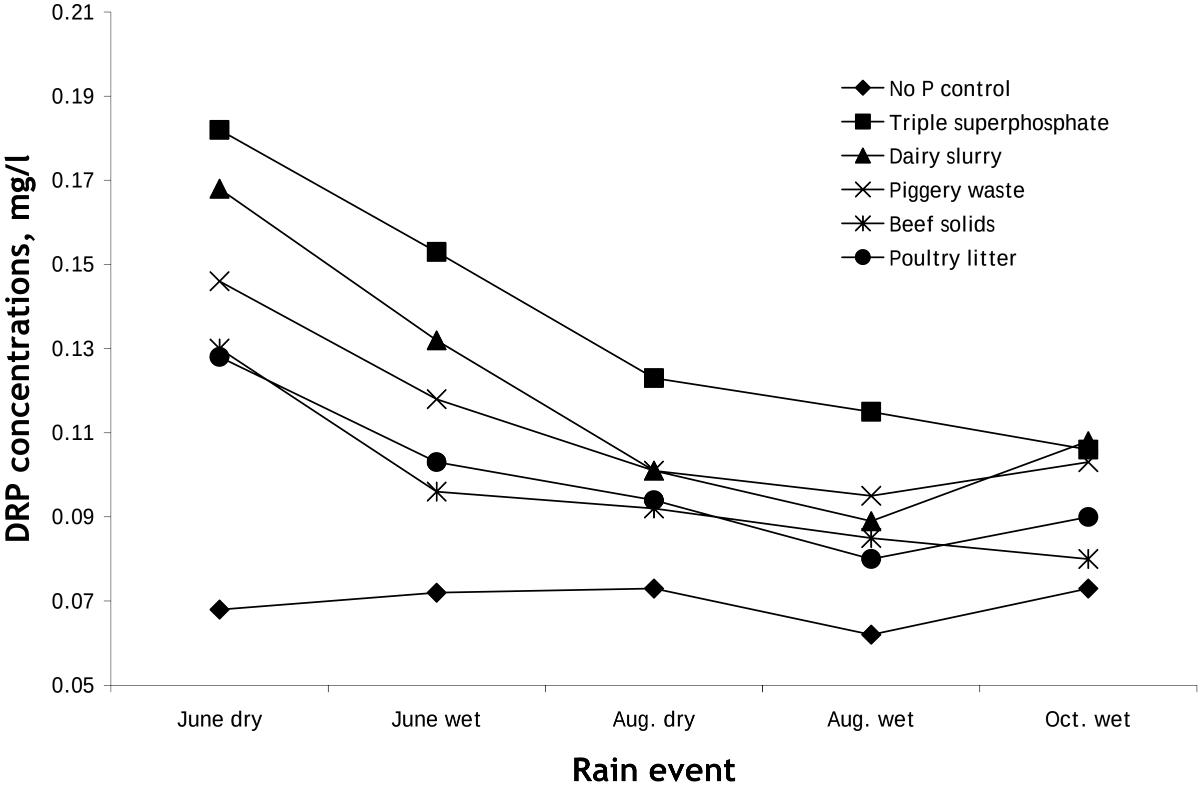


Fig. 2.14. Ratios of dissolved reactive P to total P concentration in surface runoff collected during five simulated runoff events from fescue pasture.

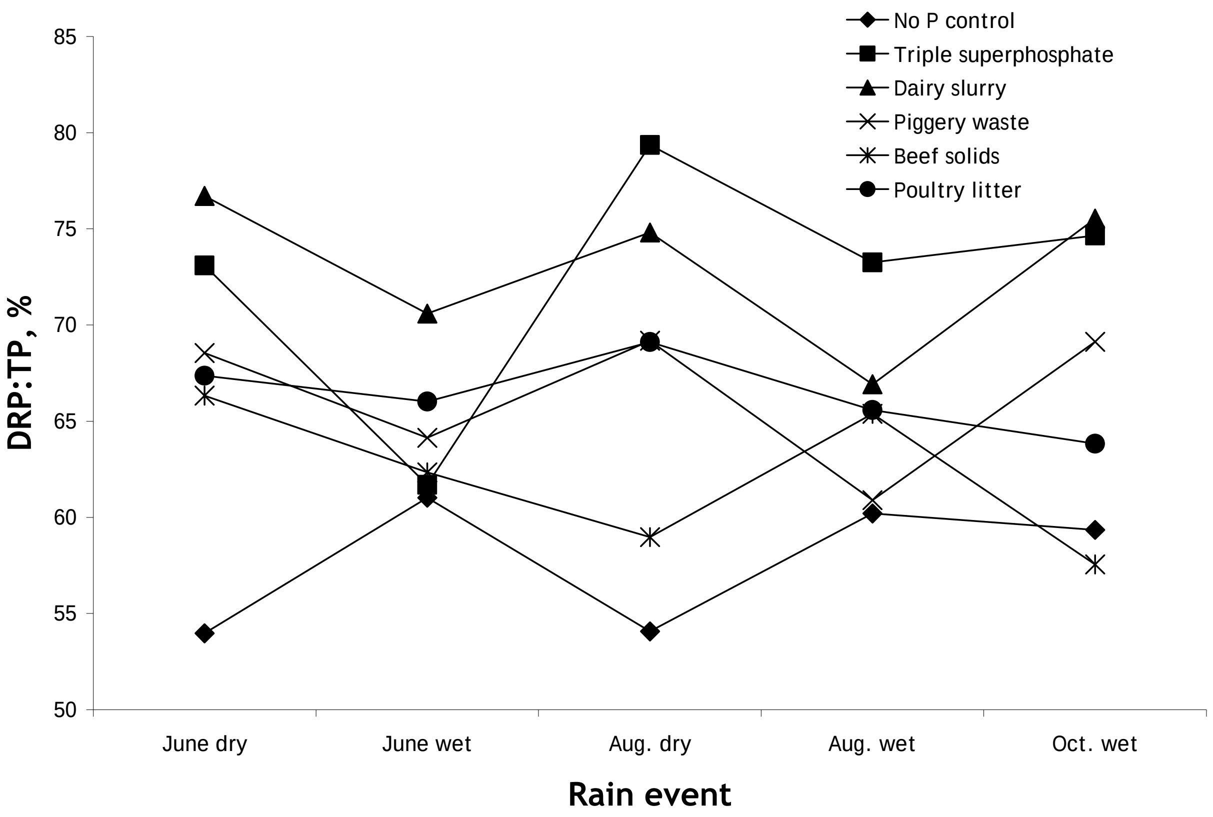


Fig. 2.15. Correlation of dissolved reactive P with total P in surface runoff collected during five simulated runoff events from fescue pasture.

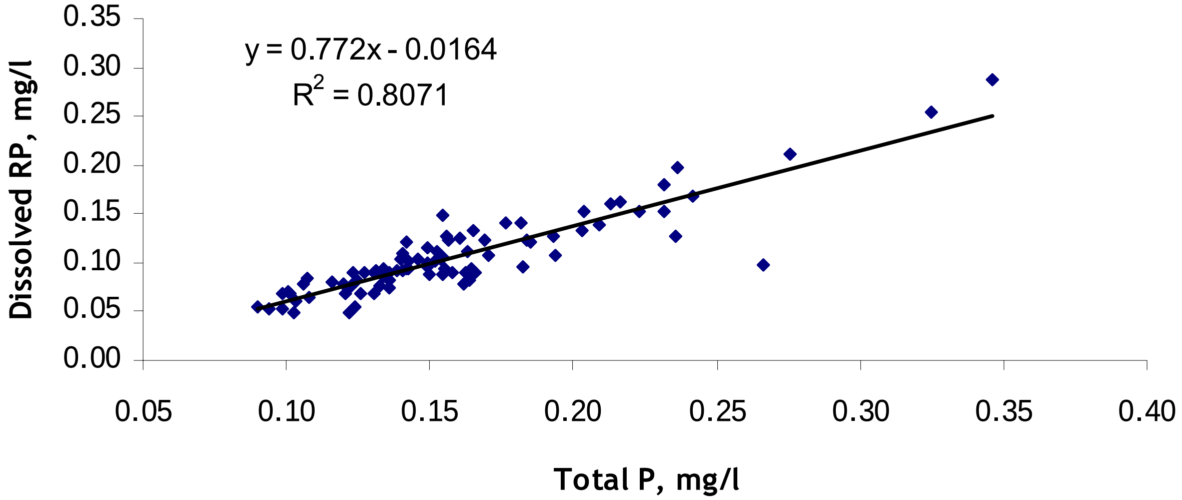
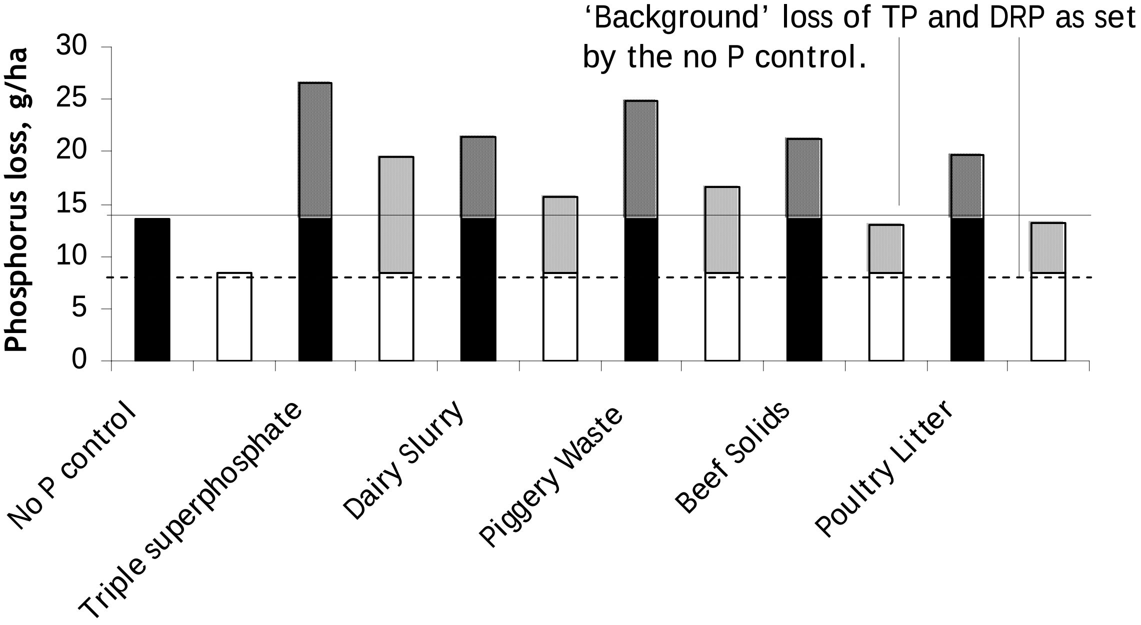


Fig. 2.16. Total P (TP) and dissolved reactive P (DRP) losses in surface runoff collected during five simulated runoff events from fescue pasture[†,‡].

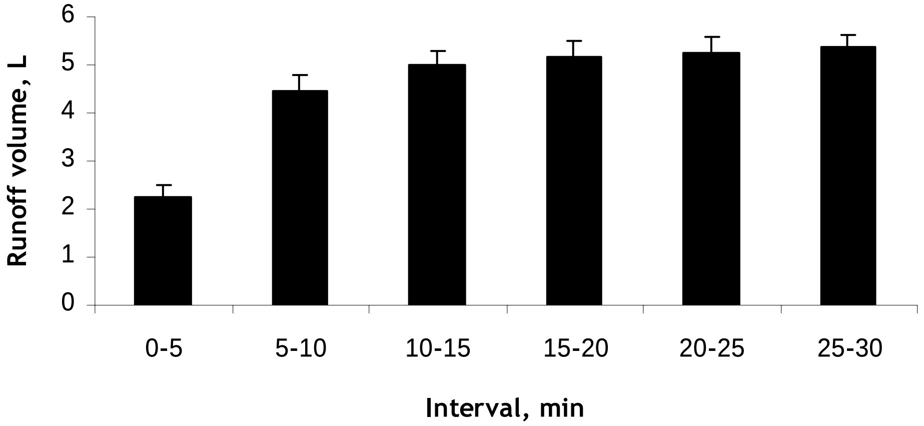


‘Background’ loss of TP and DRP as set by the no P control.

[†] Events 1 and 2 were simulated in June, 3 and 4 in August, and 5 in October.

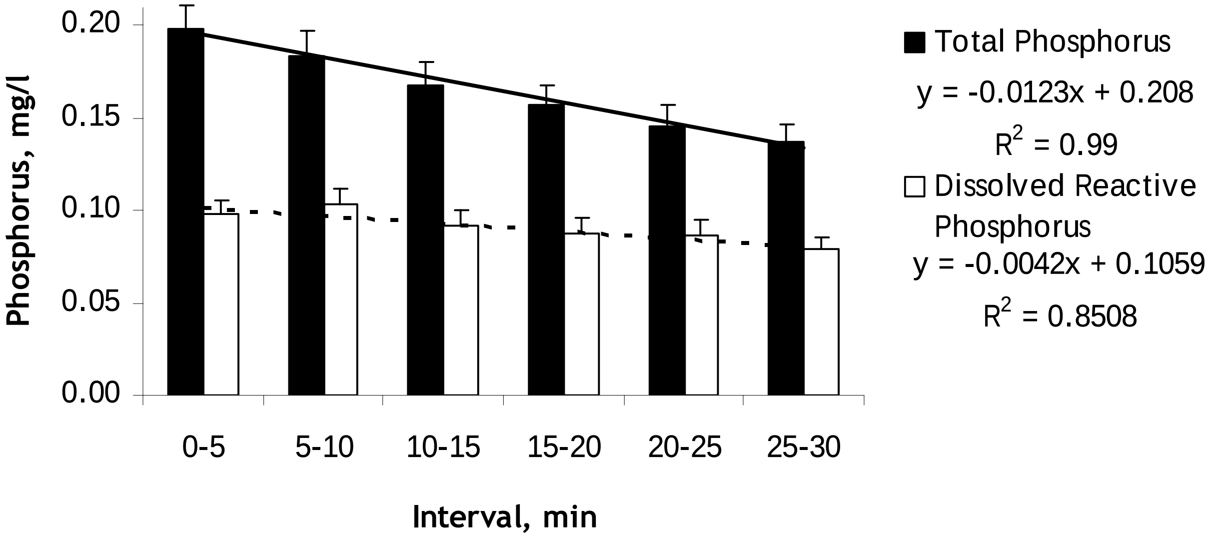
[‡] Black bars represent TP, white bars DRP. Top portions present the additional losses above background losses from the no P control. 27.4 kg P/ha were applied.

Fig. 2.17. Weight of surface runoff in 5-min increments collected over a 30-min period. Simulated rainfall at 65 mm/h induced the runoff from fescue pasture exposed to a 10-yr rainstorm 24-h prior[†].



[†] Error bars represent the standard error.

Fig. 2.18. Changes in total P and dissolved reactive P concentration in surface runoff in 5-min increments collected over a 30-min period. Simulated rainfall at 65 mm/h induced the runoff from fescue pasture exposed to a 10-yr rainstorm 24-h prior[†].



[†] Error bars represent the standard error.

Fig. 2.19. Total P concentration in surface runoff in 5-min increments collected over a 30-min period. Simulated rainfall at 65 mm/h induced the runoff from fescue pasture exposed to a 10-yr rainstorm 24-h prior.

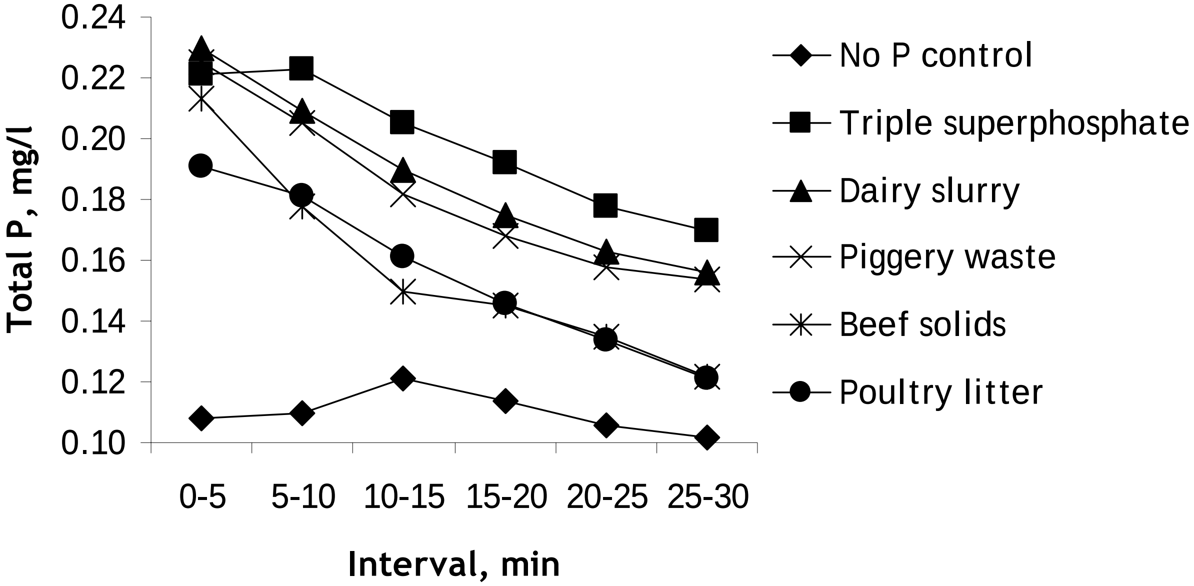


Fig. 2.20. Dissolved reactive P concentrations in surface runoff in 5-min increments collected over a 30-min period. Simulated rainfall at 65 mm/h induced the runoff from fescue pasture exposed to a 10-yr rainstorm 24-h prior.

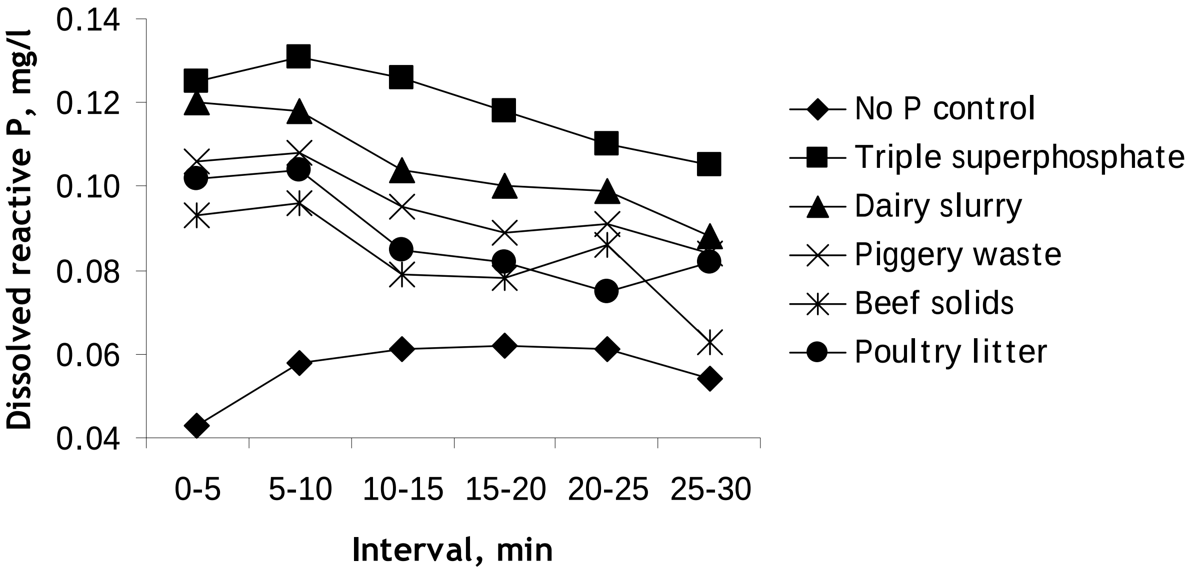


Fig. 2.21. Dependence of dissolved reactive P on total P in surface runoff in 5-min increments collected over a 30-min period. Simulated rainfall at 65 mm/h induced the runoff from fescue pasture exposed to a 10-yr rainstorm 24-h prior.

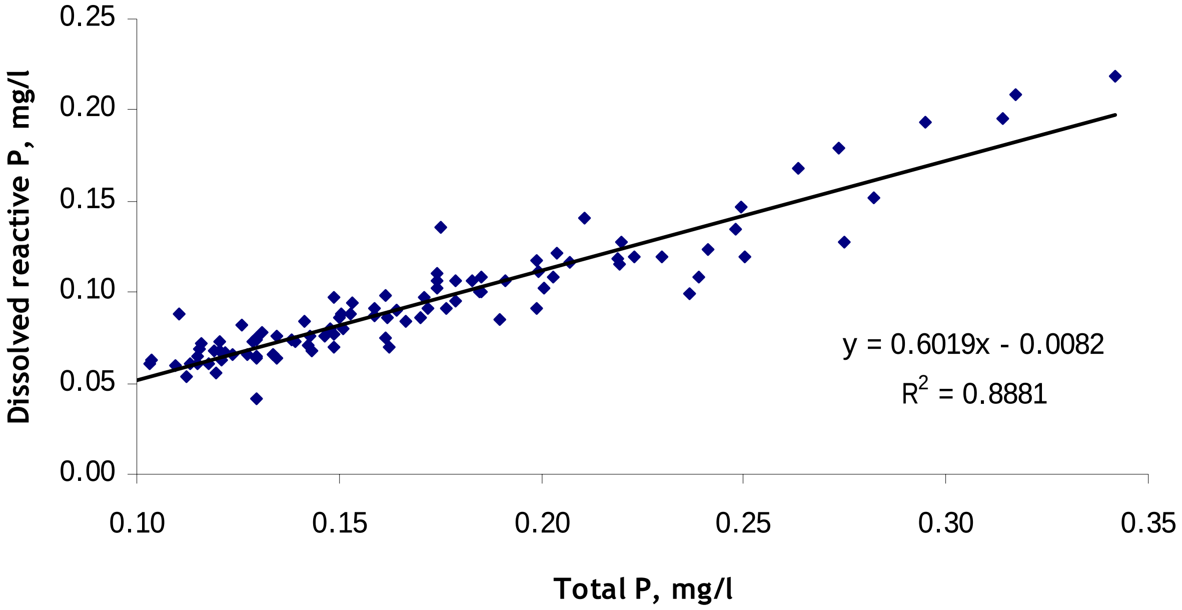
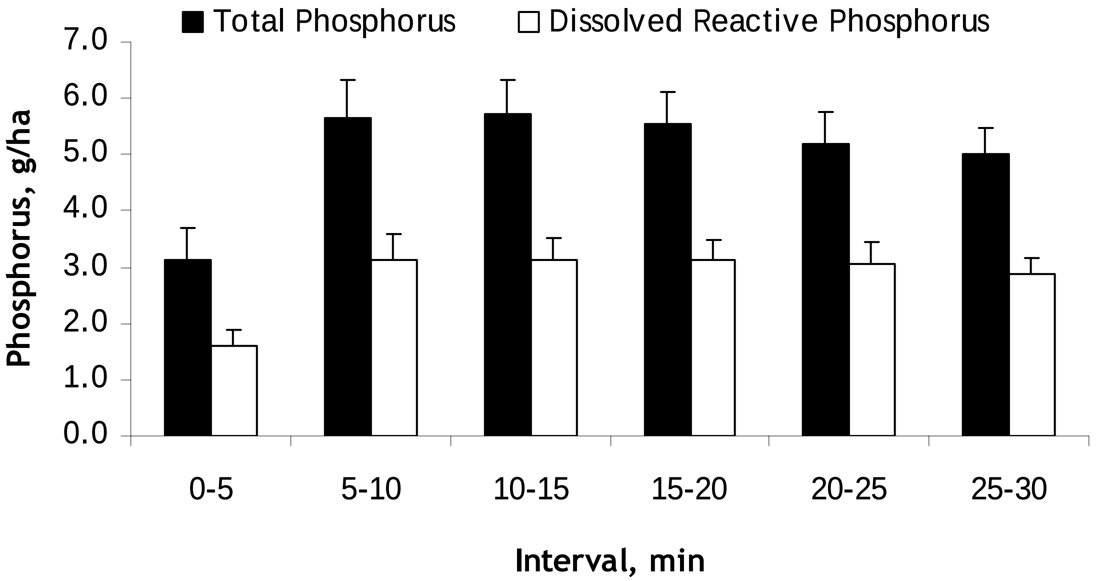
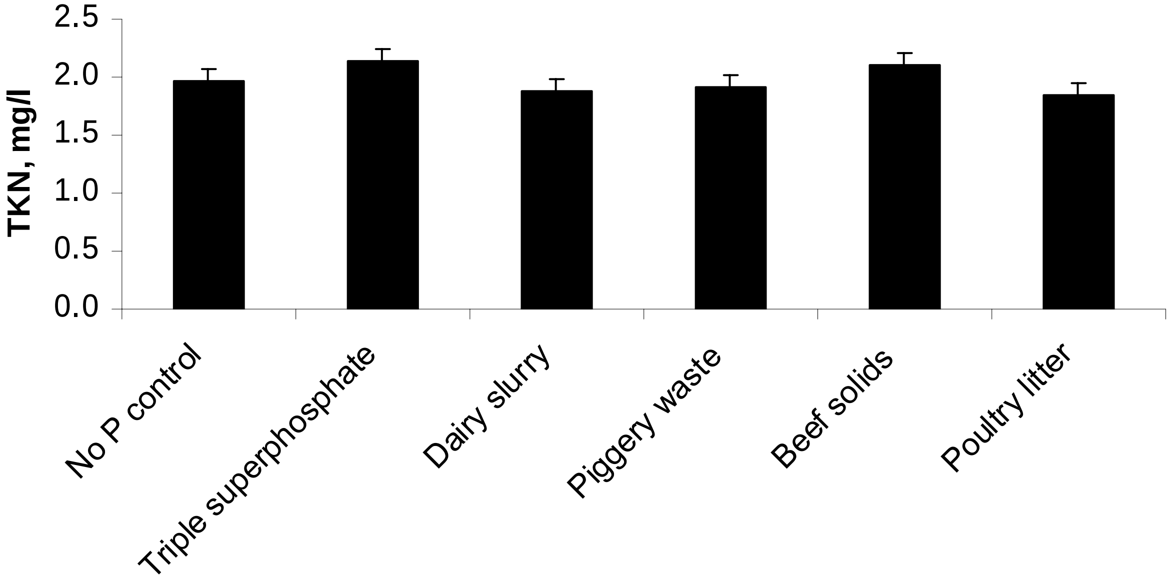


Fig. 2.22. Edge-of-the-field losses of total P and dissolved reactive P in surface runoff in 5-min increments collected over a 30-min period. Simulated rainfall at 65 mm/h induced the runoff from fescue pasture exposed to a 10-yr rainstorm 24-h prior[†].



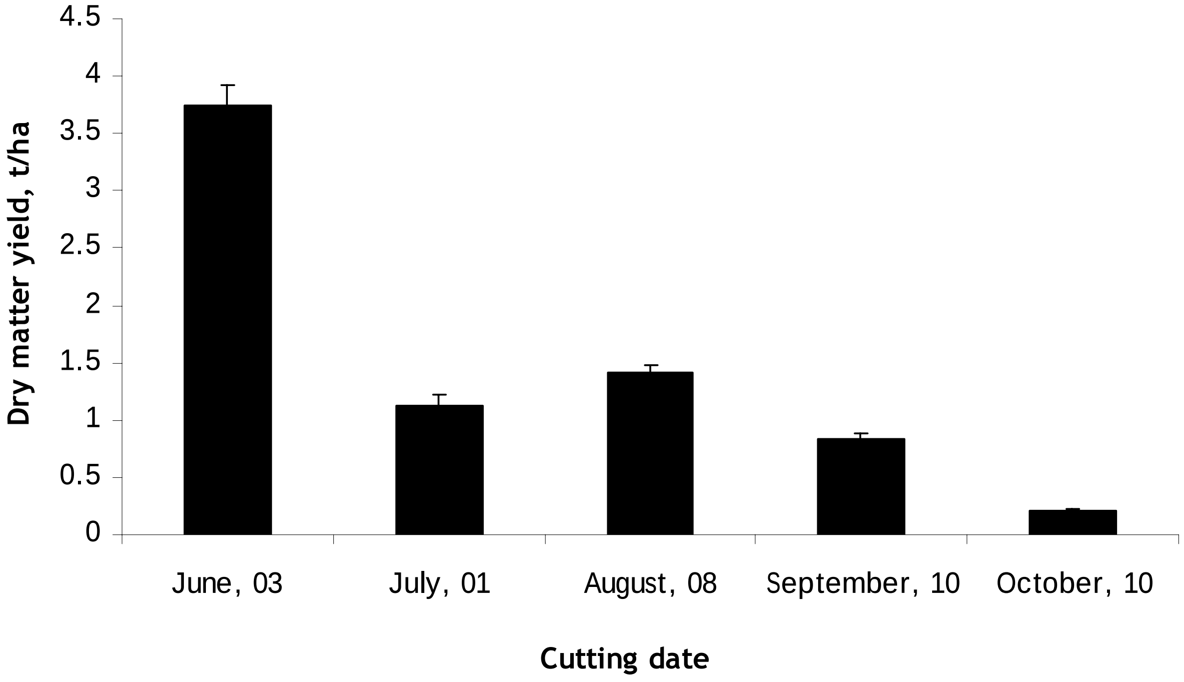
[†] Error bars represent the standard error.

Fig. 2.23. Total Kjeldahl N concentrations in surface runoff collected during five simulated runoff events from fescue pasture†,‡.



† Events 1 and 2 were simulated in June, 3 and 4 in August, and 5 in October.
‡ Error bars represent the standard error.

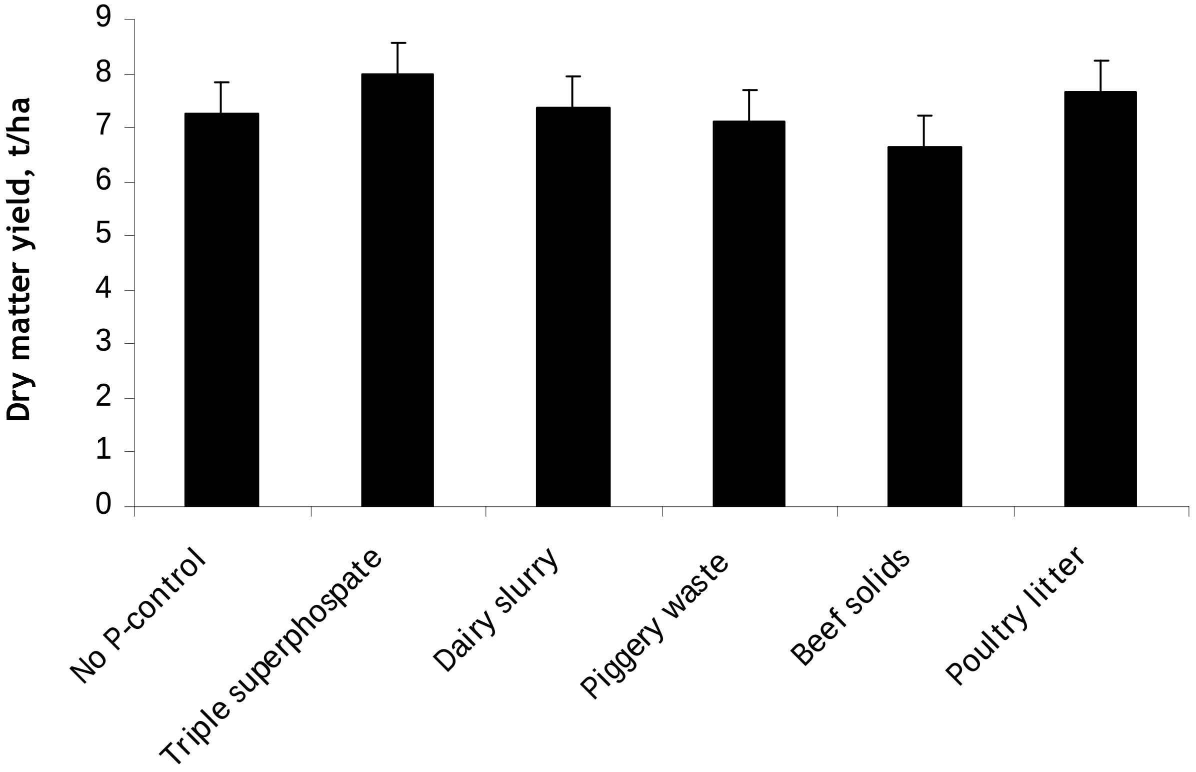
Fig. 2.24. Forage dry matter yields summed over five cuttings during 2005 from permanent fescue plots[†,‡].



[†] Plots were clipped to a height of 5 cm on April, 24. Trimmings and excessive thatch were removed and their weights were not recorded.

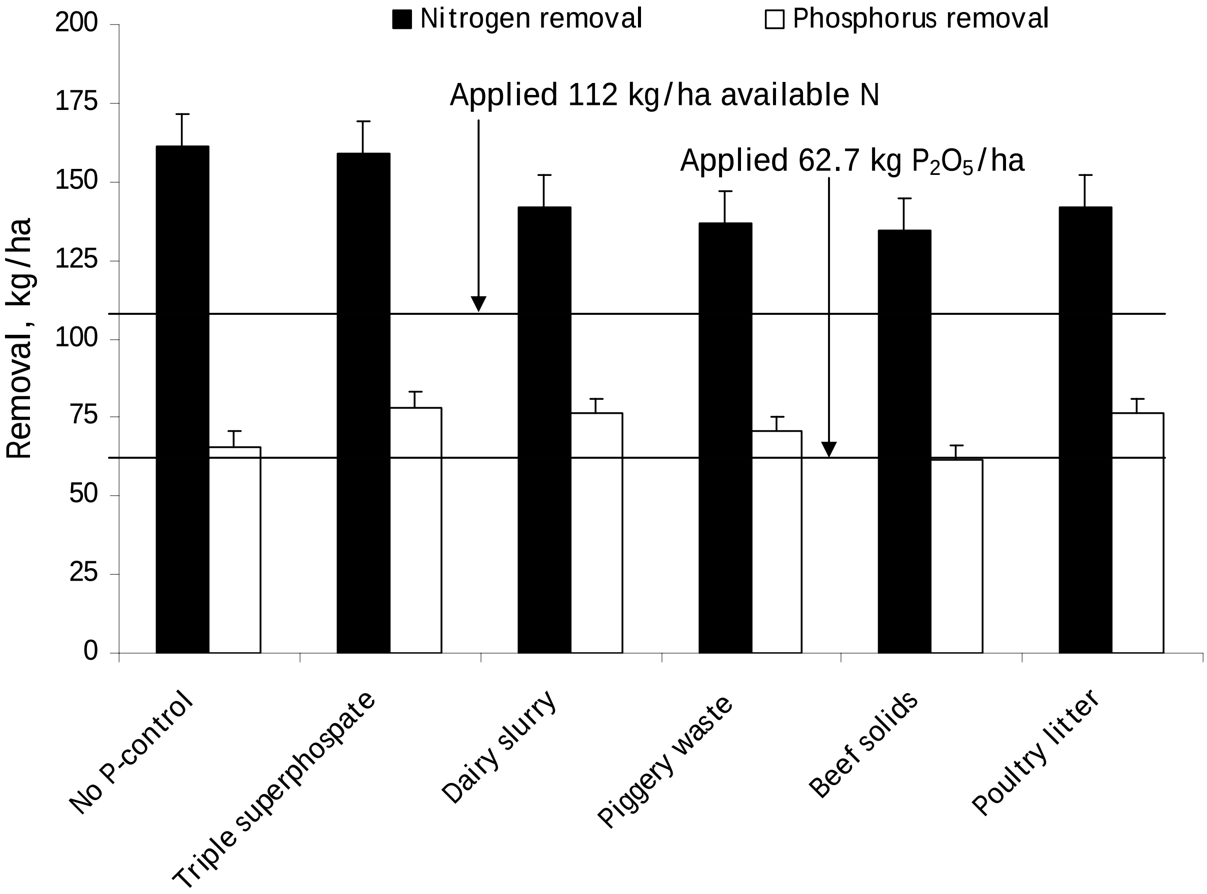
[‡] Error bars represent the standard error.

Fig. 2.25. Total forage dry matter yield from pasture plots amended with differing sources of N and P[†].



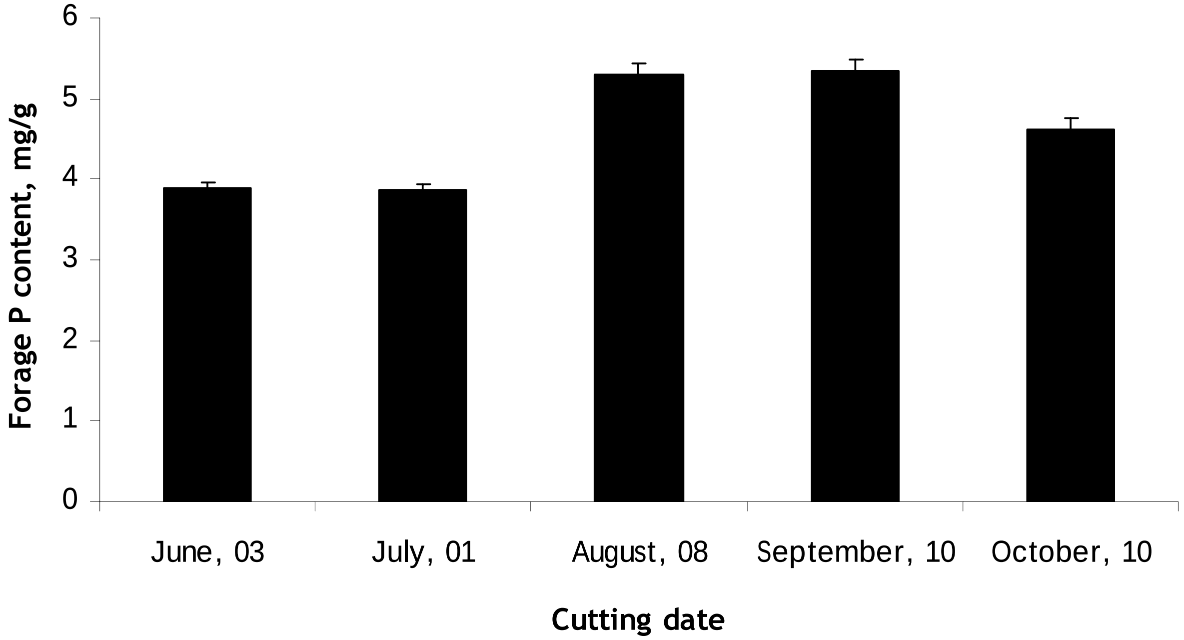
[†] Error bars represent the standard error.

Fig. 2.26. Harvested forage crop removal of N and P_2O_5 from permanent pasture plots over the growing season of 2005[†].



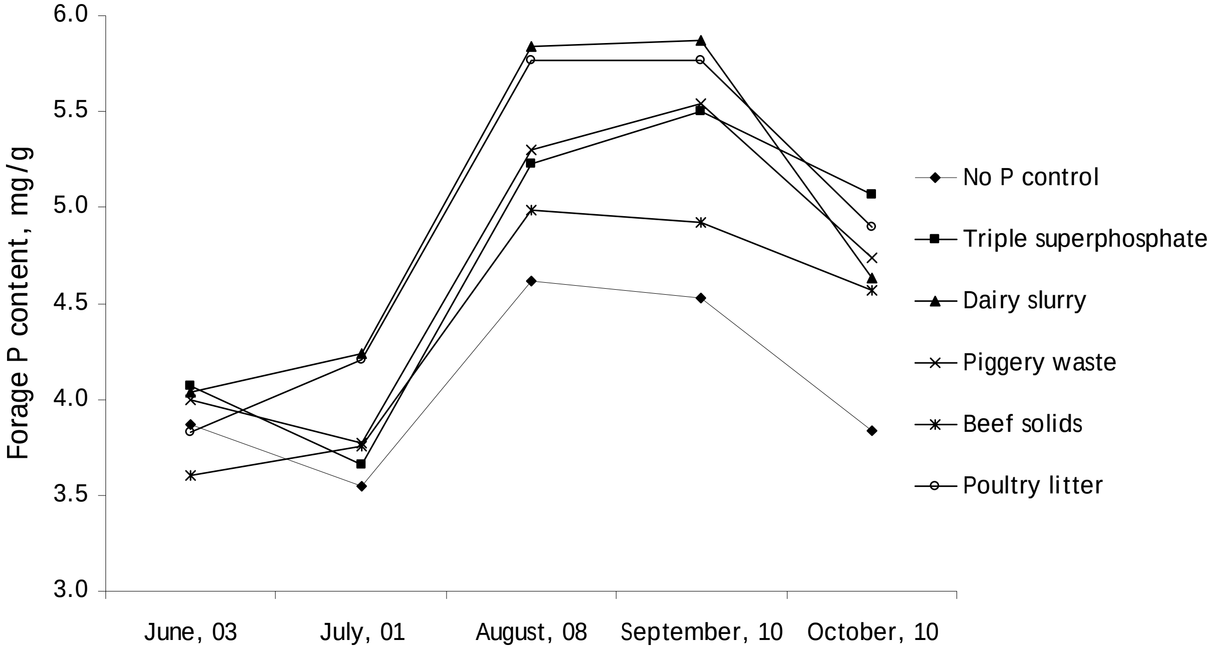
[†] Error bars represent the standard error.

Fig. 2.27. Phosphorus concentration in harvested forage from pasture plots amended with differing sourcing of N and P[†].



[†] Error bars represent the standard error.

Fig. 2.28. Forage P concentrations following five cutting dates in 2005. Forage was harvested from pasture plots amended with different N and P sources once in the spring.



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Chapter 3 : Nutrient runoff potential from fescue pastures using simulated rotationally grazing of lactating dairy cows

ABSTRACT

This study was designed to evaluate P losses from grazed pasture in order to further enhance the Virginia P Index. Sods of tall fescue (*Festuca arundinacea* Schreb.) were transplanted into 0.184 x 1 m^2 boxes designed according to the protocol by the National P Research Project. Ten boxes represented a paddock each in a 20 d, every-other-day grazing rotation; one box simulated a no P control and inorganic P fertilizer was applied at two rates (P1: Rotational requirements, and P2: Total seasonal requirements) to two boxes. All 13 treatments were iso-nitrogenous and done in triplicate. Inorganic fertilizers were applied at d 1 of the rotation. Forages of the control, P1, and P2 were cut at d 1 of the rotation; all other forages were removed at their particular day within the rotation. Dairy slurry obtained from a grazing dairy was applied daily on the respective boxes. Manure was amended on a P removal basis, split up into 8 rotations per year. Application rates were 62.7 kg P_2O_5/(ha*yr) and 112 kg available N/(ha*yr). Rainfall (65 mm/h) was simulated at the end of each of three rotations (d 21) using a 12% slope and continuous runoff was collected for 30 min. Runoff constituents of rain events 2 and 3 were analyzed using the Mixed procedure with rain event as a repeated measure. Total P (0.136 mg/l and 0.244 mg/l) and dissolved reactive P in the runoff (0.104 mg/l and 0.184 mg/l) was lower from the control treatment than from treatments amended with P, but no differences occurred between those treatments. Total Kjeldahl N was lowest from non-manured treatments. There was a linear increase of runoff TKN as manure application occurred closer to rainfall simulation. Overall, the small size of the boxes did not allow an accurate risk assessment of P losses from rotational grazed pasture.

INTRODUCTION

Excessive loads of phosphorus (P) inter alia from land in agricultural production have led to impairment of several surface waters, especially the Chesapeake Bay

(Carpenter et al., 1998; Lanyon, 1998). To reduce P release into waters, many states already have introduced or are in the process of introducing a P Index as a risk managing tool (Lemunyon and Gilbert, 1993; USDA-ARS, 2003). The P Index provides an on-site assessment of the relative risk of P losses. Parameters of the index are classified as source and transport factors and include soil test P (STP), rates, methods, timing, and availability of P from inorganic and organic P, as well as soil erosion, runoff potential, and distance to surface waters (USDA-ARS, 2003).

Management intensive rotationally grazed (MIRG) pastures have been advocated to maximize pasture production and for environmental stewardship. According to a survey by Groover (1998) 50% of all dairy farms in Virginia grazed their cows; 11% utilized fresh paddocks at least every fourth day. Two thirds of all dairies in Virginia responded to the survey. In 1999, 22% of dairy farms in Wisconsin utilized MIRG defined as rotating their milking cows to a new paddock at least once a week (Undersander et al., 2002). Haan et al. (2005) showed that a switch from the traditional continuous grazing to MIRG along with an increase in sward height after grazing from 5 to 10 cm reduced P loss in runoff by 65%. The P Index for Virginia currently lacks specific information about the potential P loss from MIRG (Wolfe et al., 2005). This study therefore aimed to rank P loss from MIRG pasture versus commercial P fertilizer and no P amendment and, consequently, to improve the P Index for Virginia.

MATERIALS AND METHODS

This study was designed to complement a concurrent experiment conducted outdoors on 1.5 m^2 pasture plots (Hollmann et al., submitted). Manures (dairy slurry, piggery waste, beef solids, and poultry litter) were applied in spring. The grass was cut approximately every 30 d and removed. After the first, third, and fifth and final cutting, rainfall was simulated and runoff was collected following the same protocol as described below. The manure amended treatments were compared to plots receiving triple superphosphate (TSP) or no P. Results from the current experiment will be likened to the findings of that study.

This experiment was conducted using indoor soil boxes as described by the National P Research Protocol (SERA-IEG 17, 2001), with adaptations in size (100 x 18.4

cm^2). The depth was increased to 10 cm to increase total water holding capacity and rooting depth, since grass was to be grown for several months. The bottom half of the boxes were filled with topsoil from the Virginia Tech Dairy Center and compacted to acquire a bulk density of about 1.3 g/cm^3. Sod for each runoff box was cut in early July from a permanent pasture at Virginia Tech's Shenandoah Valley Agricultural Research and Extension Station in Steeles Tavern, VA. The pasture mainly consisted of tall fescue (*Festuca arundinacea* Schreb.) and was described earlier (Hollmann et al., submitted). The sod was placed on top of the soil in the runoff boxes within 6 h of being cut, tamped down softly without compaction, and immediately moistened. The sod was fertilized with 17 kg N/ha as liquid urea as a starter two weeks later. The soils were kept moist without producing any runoff. Boxes were kept outside and moved inside if heavy rain was predicted.

Manure source

Manure was obtained in the form of scrapings from a holding pen at a local grazing dairy. The cows, a mix of breeds averaging an estimated bodyweight of 430 kg, had calved in spring. At the time of collection, cows were on average 100 days in milk, producing roughly 27 kg of milk per cow per day. They were fed a total of 5.5 kg of grain daily in addition to free choice pasture (MIGR). A sample of the manure was taken for analysis; the rest was frozen in 0.5 L aliquots. The manure was analyzed for TKN, NH_4-N, and TP (AOAC, 1990). The results are shown in Table 3.1.

According to soil samples collected from the top 2.5 cm taken from the general area of the sods in Nov of 2004, the soil ranked 'high' in soil test P (STP; 55 ppm Mehlich-1 P) for Virginia standards. The Virginia P Index recommends manure application on STP 'high' fields to offset crop P removal. Therefore, manure application rate was calculated two ways: A P-based rate using the same crop removal (62.7 kg P_2O_5/ha) as the accompanying study (Hollmann et al., submitted), and a stocking density rate mirroring the management practice on the farm. Calculated rates were similar and we chose to proceed with the P based manure amendment so our results would be valid for incorporation into the P Index for Virginia. Table 3.2 lists the application rates per rotation, with 8 rotations per year.

Treatment applications and forage testing

Thirty-nine boxes were randomly assigned to one of 13 treatments (3 replications). Treatment 1 served as a control without any P amendment, treatments 2 and 3 received TSP, and the remaining 10 treatments each simulated a paddock for a grazing dairy using an every-other-day rotation and an 18-d rest period between grazing. Treatment 4 was 'grazed' during the first two days of the rotation and then again at d 21 and 22, etc., treatment 5 at d 3, 4, 23, 24, etc. (Table 3.2). Nitrogen (N) fertilizer was applied as ammonium nitrate at 112 kg N/(ha*yr). This resulted in 11.9 kg N/ha per rotation (Table 3.2), or 35 kg/ha of ammonium nitrate, excluding the 17 kg N/ha starter fertilizer and using 8 rotations per year.

At d 1, all non-manure treatments (1-3) and treatment 4 (the first paddock of the rotation) were clipped to a height of 10 cm, and all clippings were discarded. Ammonium nitrate was applied to all treatments. Treatment 2 (P1) was amended with its share of P as TSP based on the yearly crop removal divided into 8 rotations. This procedure simulated the impractical application of a commercial fertilizer at each cutting. Treatment 3 (P2) received all its yearly N and P at this point and no further applications in the future, mirroring the practical once-a-year application of a commercial P-fertilizer. Each box of treatments 4-13 was clipped to the same height of 10 cm at the first day of its rotation and all clippings were removed.

Each day, manure was applied on the respective 3 boxes from a height of approximately 50 cm, since the natural drop from a height of approximately 130 cm was impractical due to the narrow width of the boxes. An aliquot of manure was thawed every other day. A more detailed timeline of treatments is presented in Table 3.2. Three boxes not used in the experiment were randomly placed among the 39 boxes in the study. Those 3 boxes were weighed every other day. Their average weight loss was used to determine the amount of water that was applied to all boxes by misting to maintain moisture, while preventing any runoff or soil surface sealing (Fig. 3.1).

After the completion of the first rotation, the first rainfall simulation was conducted at d 21 (see below). Immediately after this and the second rainfall simulation at d 42, all boxes received the same procedure as at d 1, with the exceptions that all clippings were sampled and dried at 60^{o} C to determine their dry matter (DM) yield and that treatment 3 (P2) received no additional fertilizer.

Forage growth halted after the first killing frost in mid October. The two forage samples from each box were combined and ground to pass a 1 mm screen (Wiley mill, Arthur H. Thomas, Philadelphia, PA). Samples were analyzed for total Kjeldahl N (TKN) and P concentration (AOAC, 1990).

Rainfall simulations

Rainfall simulations were conducted at d 21, 42, and 63 (Fig. 3.1), following the protocol of the National P Research Project (SERA-IEG 17, 2001). Miller (1987) first described the simulator. Penn et al. (2004) used the same simulator and set up as the current study. The rear of the runoff boxes was raised to result in a 12% slope. Rain was simulated at an intensity of 65-70 mm/h. A 30 min storm of this intensity has an approximately 10-yr return rate for the Shenandoah Valley in NW Virginia. Our approach was to mimic the effects of a heavy rainfall on runoff from different paddocks in a MIRG system.

The simulations were continued until 30 min of runoff had occurred. Several boxes did not produce any runoff during the first event. At d 22, some holes along the edges of the sods were stuffed with the original sod and some drainage holes on the bottom of the boxes were caulked closed. Runoff occurred from almost all boxes during the second and third event. Time to runoff and runoff volume (as weight with a 1:1 conversion) were recorded. Portions of the collected runoff from each box were acidified with sulfuric acid to a pH below 2 for TKN analysis and stored at 4^{o} C, or passed through a 0.45 µm filter, acidified with HCl, and frozen for dissolved reactive P (DRP) determination. The final portion of the collected runoff was cooled and used for identification of total suspended solids (TSS) and total P (TP) concentrations. Total Kjeldahl N was analyzed using a Foss Tecator 2400 (Foss, Silver Spring, MD). Total P and DRP concentrations were determined via the Molybdate blue method (Murphy and Riley, 1962). One hundred milliliter, if available, in triplicate were filtered (Whatman AH-934 filter) to quantify TSS concentration of the runoff (APHA, 1998) after drying the remainder at 105^{o} C.

Runoff of less than 400 ml per plot and event was not included in any analysis. These portions often mirrored the water used for the simulation or were lower in nutrient concentrations than other samples from the same treatment. These runoff samples might have originated from leaves hanging into the covered collection trench, creating some dripping of rain water.

Statistical Analysis

The runoff data were analyzed with event as a repeated measure using Proc Mixed in SAS version 9.1 (2002). Runoff volume and its TKN, TP, DRP, and TSS concentration were tested for variation amongst treatments by using the least square means from

$$Y_{ijk} = \mu + T_i + B_{(i)j} + R_k + (TR)_{ik} + \varepsilon_{(ijk)} \qquad [1]$$

where:

Y_{ijk} = specific measure for an individual plot and event
μ = parameter mean
T_i = effect of treatment i (i = 1, …, 13)
$B(i)j$ = effect of box j (j = 1, 2, 3) within treatment i
R_k = effect of rain event (k = 2, 3)
$(TR)_{ik}$ = effect of the treatment by event interaction
$\varepsilon_{(ijk)}$ = residual error

Box within treatment was declared the subject. Compound symmetry was used as type of repeated rain events. Results from the first rain simulation were omitted in the analysis of runoff due to the reduced number of boxes that initiated overland flow during said event.

Nitrogen and P concentration of the forages were analyzed statistically utilizing the GLM procedure of SAS (2002):

$$C_{ij} = \mu + T_i + \varepsilon_{(ij)} \qquad [2]$$

where:

C_{ij} = concentration of forage-N or P for an individual box
μ = mean of that reading
T_i = effect of treatment i (i = 1, …, 13)
$\varepsilon_{(ij)}$ = residual error

Results were considered to have differed significantly at $P < 0.05$ and tended to differ at $P < 0.10$. Investigation of an interaction of treatment and event was accomplished via the slice option in SAS. The expected lower concentrations of N and P in runoff from the control would influence interaction. The following orthogonal contrasts were used to evaluate the treatments and rain simulations: Control versus all other treatments; P1 versus P2; and P1 and P2 versus all manure-amended treatments. The latter were checked linearly and quadratically for an effect of time between defecation of manure and rain event.

RESULTS AND DISCUSSION

Runoff

Treatment did not affect runoff volume of the collected surface runoff (Fig. 3.2). We concluded that the manure applications did not decrease the infiltration rate of the rainwater. This outcome confirmed results of the companion study. Only heavy slurry applications followed by a rain event within 1 to 3 d seemed to seal the soil surface, producing more surface runoff in Edwards and Daniel (1993a) and Kleinman et al. (2002). The current study simulated crop removal and manure deposition, but ignored hoof-impacts and shearing actions. Treading increased not only runoff volume, but also the portion of bare soil and erosive losses in the field (Elliott et al., 2002). Haan et al. (2005) reported greater runoff volumes from shorter grazed paddocks, but all boxes were cut to a constant height in the present study.

Runoff sediments

Erosive losses showed outlying results for d 13/14 (486 mg TSS/l) and d 15/16 (226 mg TSS/l) of the 20 d rotation during the second rain event. Each of these values was based solely on one box each, since the other boxes produced less than 400 ml of runoff. Consequently, the two outliers where replaced using the replace option of the Standard procedure of SAS (2002). No variations of sediment loss were observed (Fig. 3.3). Overall, sediment concentrations in the runoff were almost twice as high (66 mg/l vs. 35 mg/l) as in the outdoor study (Hollmann et al., submitted).

The disturbance during sod transplantation may have increased amounts of loose particles on the soil surface, but in that case successive rains should have produced lower TSS. No difference was observed. In addition, suspended solids from applied manure should have led to a difference between manured and non-manured plots, but the increase was not significant. However, erosive losses observed here were only a small fraction compared to losses from bare soils, which ranged from 200 mg/l to 3500 mg/l (Kleinman et al., 2002). It is the belief of the authors that the area of the boxes was too small to accurately evaluate the effect of treatment because runoff concentrations were too low and variable.

Runoff phosphorus

Boxes that produced extremely high sediment losses for single boxes on d 13/14 and 15/16 during the second event also exhibited elevated TP, but not DRP concentrations (data not shown). Therefore, sediment-bound or particulate P (PP) increased the TP concentration. Increased PP concentrations correlate generally to higher TP, but not necessarily DRP concentrations in runoff, when soil but not manure particles are involved (Hansen et al., 2002; Kleinman et al., 2002). As with the sediment outliers, experimental averages replaced the TP results in question.

Total P, but not DRP varied by treatment ($P < 0.06$ and $P < 0.15$, respectively). Runoff from the control treatment contained less TP (0.136 mg/l and 0.244 mg/l) and DRP (0.104 mg/l and 0.184 mg/l) than from all other treatments (Fig. 3.4). No further distinctions were found for DRP concentrations (Fig. 3.5). These results are in concert with the data from the companion paper, although there, DRP tended to differ among treatments during rain events closest to fertilizer amendment (Hollmann et al., submitted).

There was a higher TP concentration for P1 (TSP applied at rotational requirements only) than for P2 (TSP applied at total season requirements) during event 3 ($P < 0.05$), but overall P1 and P2 did not differ ($P < 0.24$; Fig. 3.6). A possible explanation is the application of P fertilizer at each start of a rotation to P1, while P2 only received P once, at the start of the experiment. The rain simulation and the distance in time to application may have eradicated expected higher P losses from P2. Total P and DRP concentrations in runoff from TSP treatment were highest in the first couple of rain simulations (occurred within 24-h of each other 40 d after amendment of treatment), but did not vary during successive rain events (Hollmann et al., submitted). Generally, inorganic P fertilizer creates higher runoff P concentrations than organic P (Nichols et al., 1994; Heathwaite et al., 1998), but those studies were conducted on larger plots.

Assessing DRP:TP ratios revealed a larger portion of DRP in the runoff from boxes having received an inorganic P fertilizer (Fig. 3.7) compared to all treatments receiving manure. Concentrations of DRP correlated to TP ($r^2 = 0.62$; Fig. 3.8). The slope of the regression line of DRP:TP was shallower than in the concomitant work (Hollmann et al., submitted), where DRP accounted for about three quarters of TP for the overall project. As aforementioned, higher TSS in the current study may have been accompanied by particulate P and consequently decreased DRP portions. Additionally, the relationship between TP and DRP was more pronounced in the other study ($r^2 = 0.81$), what emphasizes the loss of descriptive power of the smaller plot size.

Other studies have shown an increase in the DRP:TP ratio after application of P fertilizer (Preedy et al., 2001; Kleinman et al., 2002; Hollmann et al., submitted) or after successive (natural) rain events (Fleming and Cox, 2001). In the case of an increased ratio, DRP is solubilized from the applied manure or directly taken from the inorganic fertilizer, whereas the first of successive rainstorm dissolves the most ‘readily-available’ particles. Surprisingly, DRP:TP for the control did not differ statistically nor numerically in the current study.

No effect of edge-of-the-field losses of TP and DRP were observed (Fig. 3.9). Runoff volume, which did not vary by treatment, had an overriding effect on differences in P concentrations between the control and the treatments. Even work on larger plots did not result in differences of edge-of-the-field losses of DRP and TP (Hollmann et al., submitted). The DRP losses in this study (Fig. 3.10), as well as TP losses (Fig. 3.11) correlated to runoff weight (r^2 = 0.91 and 0.87, respectively), but their respective concentrations did not ($r^2 < 0.08$). This phenomenon implied that edge-of-the-field losses, but not the risk of P loss depended highly on soil hydrology parameters such as infiltration rate, which seem to change significantly in a very small area. For example, almost invisible high and low spots or bunchgrasses may control the runoff volume significantly on the box-scale used. We stress the fact that manures should be ranked on the basis of runoff concentrations, since they are not impacted by the volume of the surface runoff.

Runoff nitrogen

Nitrogen concentrations did not differ by treatment or between the no P control and all P receiving treatments (Fig. 3.12). Runoff from P1 and P2 contained numerically as much TKN as the control (not tested), but less TKN than from all manure amended boxes ($P < 0.02$). Rotationally grazed boxes received 75% of the ammonium nitrate applied to the control, P1, and P2 treatments, to ensure all treatments were iso-nitrogenous.

As 50% of the commercial N fertilizer already existed as nitrate, which is non-detectable by the Kjeldahl analysis, less readily transformable organic N from the manure contributed to the increased TKN concentration in the runoff. Increasing amounts of organic N were broken down to non-Kjeldahl N and/or lost to volatilization or leaching as manure aged, leading to a trend for a linear increase in runoff TKN concentrations ($P < 0.07$) with day of rotation. Edwards and Daniel (1993b) reported an increase in nitrate concentration in surface runoff when rain simulation was delayed after manure amendment. The rise in nitrate may have been a result of mineralization of organic N, but was not measured. In our study, runoff volume, again, eliminated any differences in edge-of-the-field loss of TKN (data not shown).

Forage

Treatment had a significant impact on N concentration of the removed ('grazed') crop, as forage from P1 analyzed less N than P2 (Fig. 3.13). However, P1 and P2 contained significantly more N than all manured boxes, although P1 numerically equaled those. No other trends concerning forage N were observed.

Phosphorus concentration of the forage was overall high, but in concert with the concurrent study, which analyzed forage from the original pasture. Phosphorus concentration differed by treatment (Fig. 3.14), as the control treatment produced forage containing less P than all P amended treatments. Forage of the P2 treatment had numerically the lowest P, differing from P1. The reason behind the increased N and decreased P concentration in P2 is not known. Phosphorus concentrations in the runoff from P2 were not lower than P1, which may have indicated an earlier loss of P from the P2 boxes. Runoff P concentrations during event 1 did not support this theory either, as they were not elevated (0.340 mg TP/l and 0.253 mg TP/l from two P2 boxes producing runoff during event 1). As expected, no effects of the timing of manure application/ grazing relative to rain event were detected.

CONCLUSIONS

Although our results demonstrated an increase in TP and DRP in surface runoff from P amended pasture, they did not differentiate between manure and inorganic P fertilizer, as we had demonstrated previously (Hollmann et al., submitted), or showed an aging or drying effect of the applied manure. Results from this study should only be used very cautiously when updating the Virginia P Index to assess the risk of P losses to runoff from grazed pasture.

However, the data showed a decrease in runoff TKN as manure aged. Previous data suggested that this decrease may coincide with a rise in nitrate concentrations (Edwards and Daniel, 1993b). Overall, the size of the boxes limited our ability to simulate a true grazing scenario. Results varied within a treatment, due to inconsistencies of the sod. Future research on runoff from grazed plots should utilize larger plots.

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Table 3.1. Nutrient composition (on a wet basis) and availability of manure from intensively grazed dairy cows.

Composition	mg/g
TKN	2.87
NH_4-N	0.82
Organic-N	2.05
P_2O_5[†]	2.56
Availability[‡]	%
NH_4-N	25
Organic-N	35

[†] P_2O_5 equals elemental P multiplied by a factor of 2.29.

[‡] Available in the first season after application, according to Virginia's Nutrient Management Standards and Criteria (Department of Conservation and Recreation, 1995).

Fig. 3.1. Every-other-day water applications in mm on runoff boxes planted with fescue pasture. Dotted lines indicate dates of rain simulation to produce runoff.

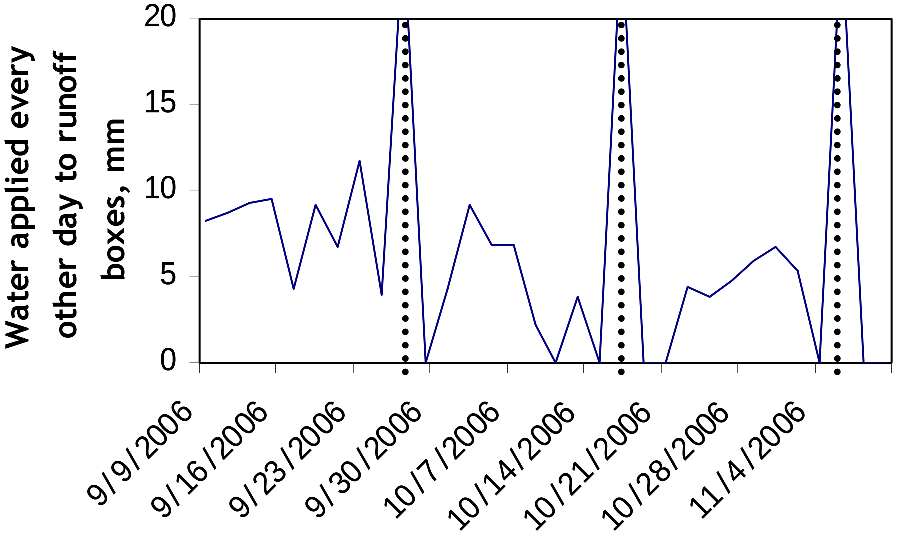


Table 3.2. Schedule of operations.

Day in Rotation	Treatment	Cut	Fertilizer/Manure application[†]	N rate[‡]	P_2O_5 rate[§]
				---------kg/ha---------	
1	no P control	x	NO_3-N	11.9	0.0
	P-1	x	NO_3-N; TSP	11.9	7.8
	P-2	x	NO_3-N; TSP	95.2	62.7
	all 'grazed' boxes		NO_3-N	9.1	0.0
	day 1/2	x	Manure	1.4	3.9
2	day 1/2		Manure	1.4	3.9
3	day 3/4	x	Manure	1.4	3.9
4	day 3/4		Manure	1.4	3.9
---------------------Repeated for remaining days of the rotation---------------------------					
19	day 19/20	x	Manure	1.4	3.9
20	day 19/20		Manure	1.4	3.9
21	all	----------------------**Rain simulation**---------------------			
	no P control	x	NO_3-N	11.9	0.0
	P-1	x	NO_3-N; TSP	11.9	7.8
	P-2	x	*NONE*	0.0	0.0
	all 'grazed' boxes		NO_3-N	9.1	0.0
	day 1/2	x	Manure	1.4	3.9
22	day 1/2		Manure	1.4	3.9
23	day 3/4	x	Manure	1.4	3.9
24	day 3/4		Manure	1.4	3.9
---------------------Repeated for remaining days of the rotation---------------------------					
39	day 19/20	x	Manure	1.4	3.9
40	day 19/20		Manure	1.4	3.9
41	all	----------------------**Rain simulation**---------------------			
	no P control	x	NO_3-N	11.9	0.0
	P-1	x	NO_3-N; TSP	11.9	7.8
	P-2	x	*NONE*	0.0	0.0
	all 'grazed' boxes		NO_3-N	9.1	0.0
	day 1/2	x	Manure	1.4	3.9
42	day 1/2		Manure	1.4	3.9
43	day 3/4	x	Manure	1.4	3.9
44	day 3/4		Manure	1.4	3.9
---------------------Repeated for remaining days of the rotation---------------------------					
59	day 19/20	x	Manure	1.4	3.9
60	day 19/20		Manure	1.4	3.9
61	all	----------------------**Rain simulation**---------------------			

[†] NO_3-N: Ammonium nitrate; TSP: Triple superphosphate.

[‡] N represents available N, which is 32.2% of total Kjeldahl N applied as manure.

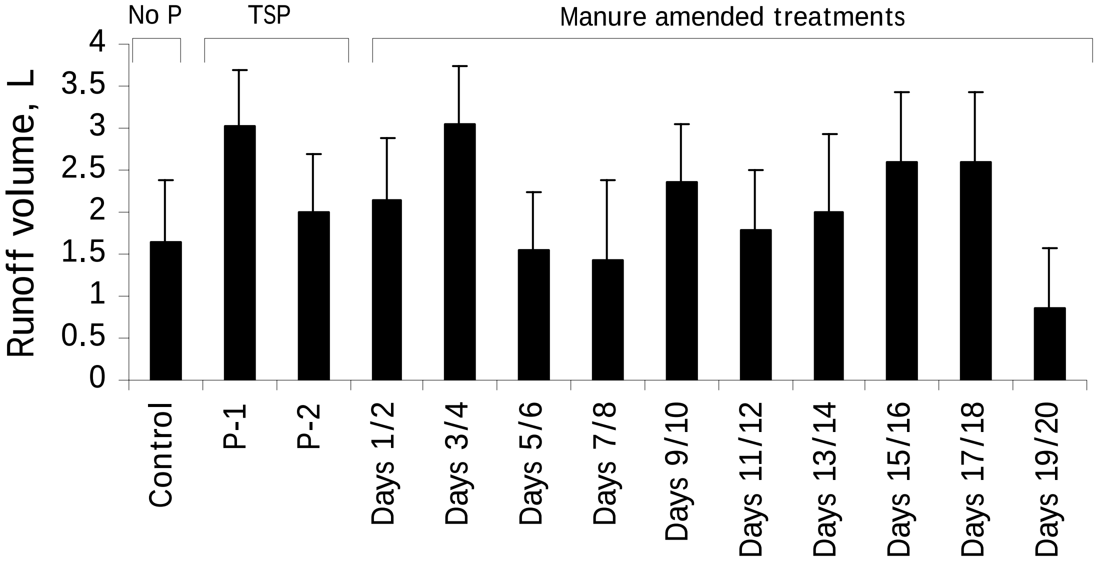
[§] Phosphorus is expressed as P_2O_5; P_2O_5 equals elemental P multiplied by a factor of 2.29.

Table 3.3. Parameters of the well water used for artificial rain simulations[†].

Event, date	TP	DRP	TKN	TSS
	------------------------------mg/kg---------------------------			
Event 1, Sep., 27th	0.045	0.040	0.93	2
Event 2, Oct., 17th	0.061	0.057	0.71	-2
Event 3, Nov., 6th	0.044	0.053	n/a	2

[†] TP: Total P; DRP: Dissolved reactive P; TKN: Total Kjeldahl N; TS: Total solids; TSS: Total suspended solids.

Fig. 3.2. Surface runoff weight from boxes containing fescue pasture sods simulating rotational grazing following two rainfall simulations[†,‡,§].

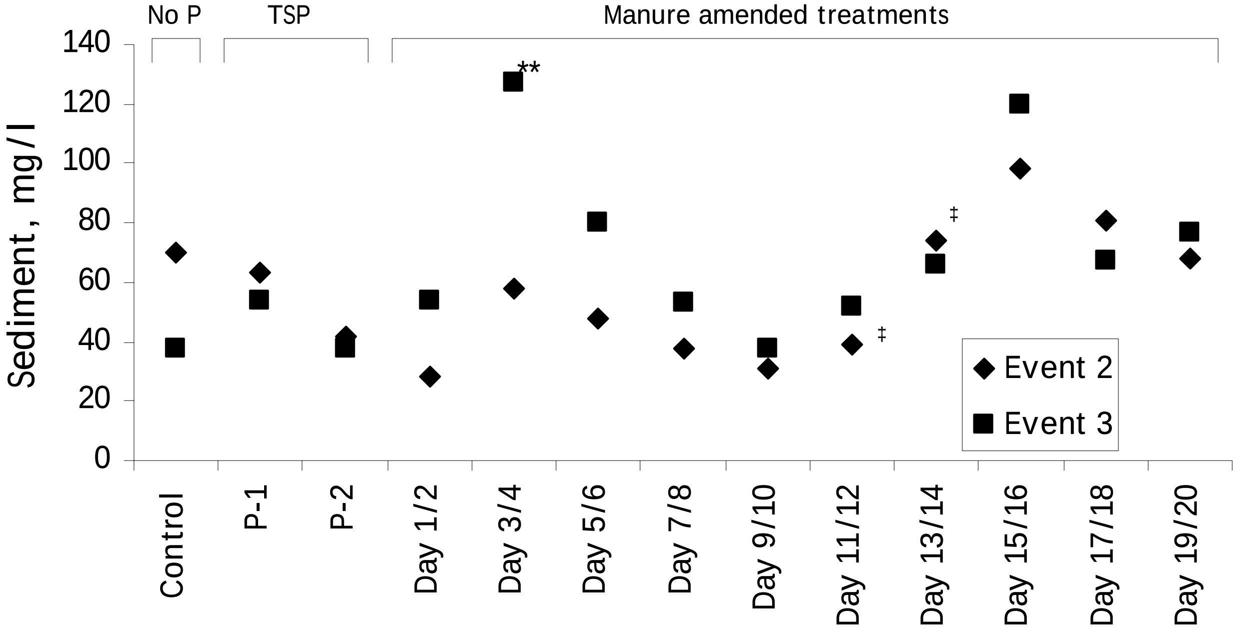


[†] Weights of less than 400 g were omitted.

[‡] Error bars represent the standard error.

[§] Control: No P control; P-1: P needs of rotation applied each rotation; P-2: Seasonal P requirements applied once; Days x/y: Day of rotation. Rain was simulated at day 21 of each rotation.

Fig. 3.3. Sediment concentrations in surface runoff from boxes containing fescue pasture sods simulating rotational grazing following two rainfall simulations[†].

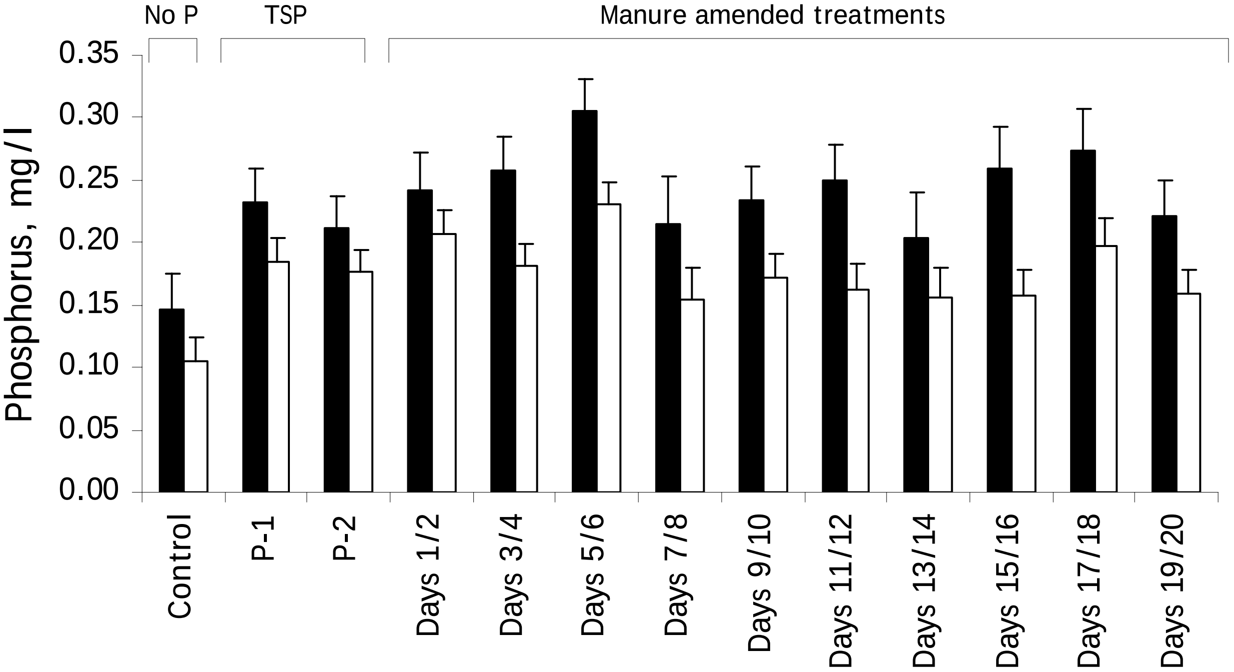


*, **, *** Concentrations between events varied (*P* < 0.10, *P* < 0.05, *P* < 0.01).

[†] Control: No P control; P-1: P needs of rotation applied each rotation; P-2: Seasonal P requirements applied once; Days x/y: Day of rotation. Rain was simulated at day 21 of each rotation.

[‡] Experimental averages replaced the outliers for this result.

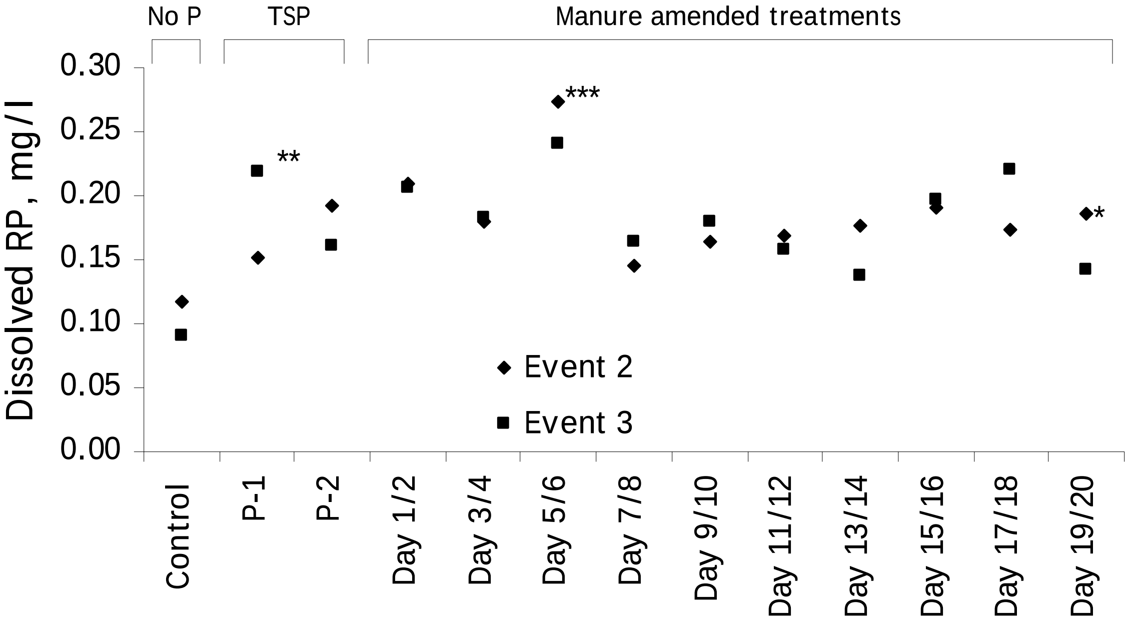
Fig. 3.4. Least squares means of total P (■) and dissolved reactive P (□) concentrations in surface runoff from boxes containing fescue pasture sods simulating rotational grazing following two rainfall simulations[†,‡].



[†] Control: No P control; P-1: P needs of rotation applied each rotation; P-2: Seasonal P requirements applied once; Days x/y: Day of rotation. Rain was simulated at day 21 of each rotation.

[‡] Error bars represent the standard error.

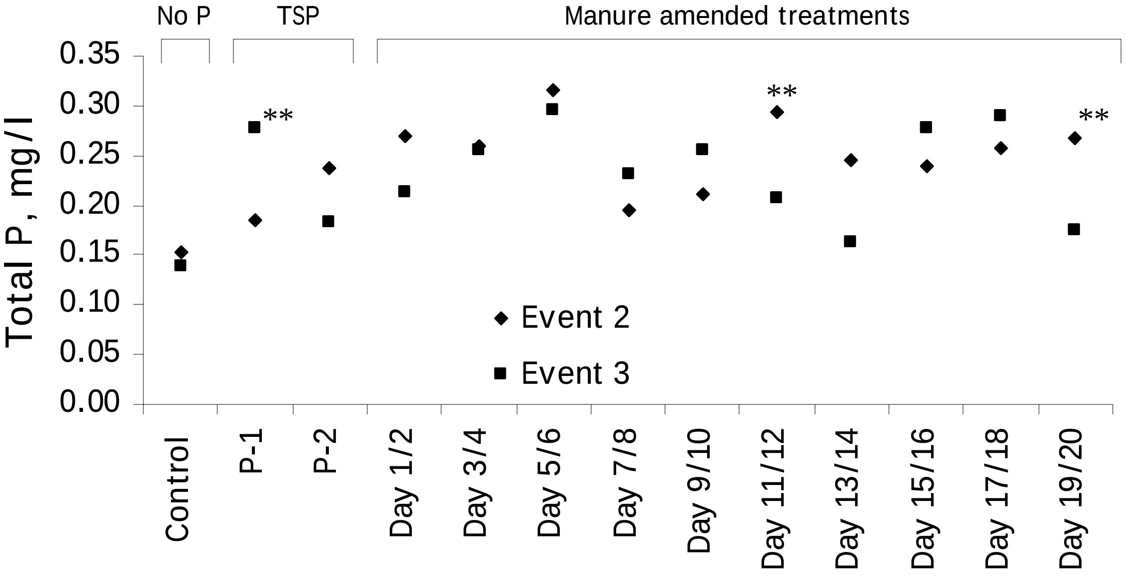
Fig. 3.5. Dissolved reactive P concentrations in surface runoff following two rainfall simulations on boxes containing fescue pasture sods simulating rotational grazing[†].



*, **, *** Concentrations between events varied ($P < 0.10$, $P < 0.05$, $P < 0.01$).

[†] Control: No P control; P-1: P needs of rotation applied each rotation; P-2: Seasonal P requirements applied once; Days x/y: Day of rotation. Rain was simulated at day 21 of each rotation.

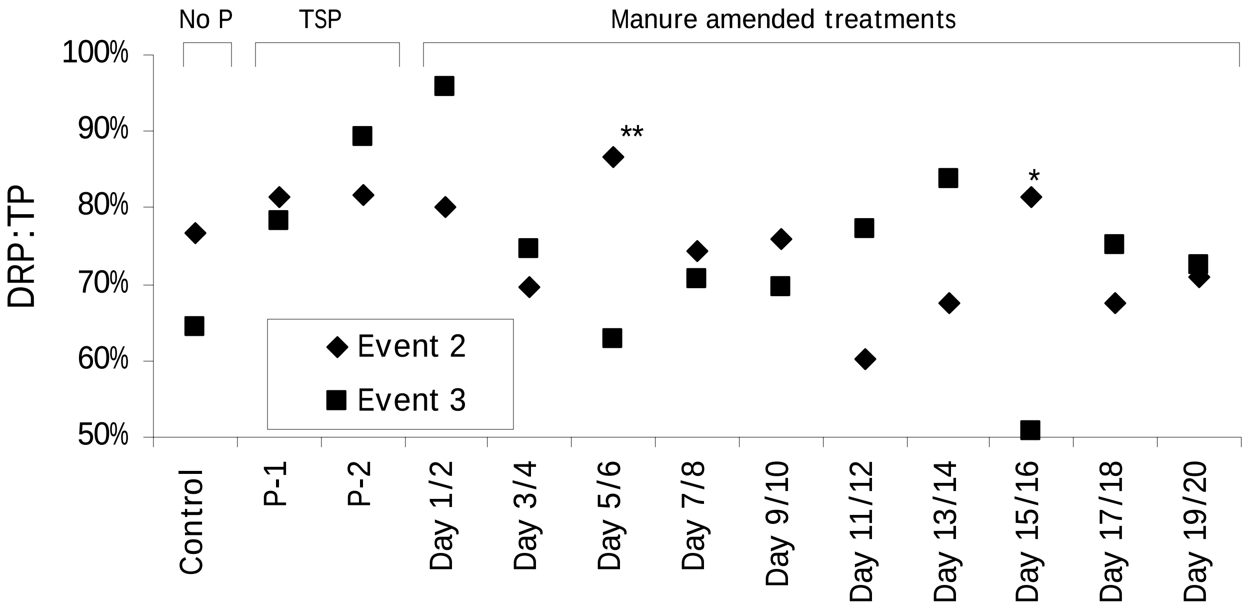
Fig. 3.6. Least squares means of total P concentrations in surface runoff following two rainfall simulations on boxes containing fescue pasture sods simulating rotational grazing[†].



*, **, *** Concentrations between events varied ($P < 0.10$, $P < 0.05$, $P < 0.01$).

[†] Control: No P control; P-1: P needs of rotation applied each rotation; P-2: Seasonal P requirements applied once; Days x/y: Day of rotation. Rain was simulated at day 21 of each rotation.

Fig. 3.7. Dissolved reactive P as portion of total P in surface runoff from boxes containing fescue pasture sods simulating rotational grazing following two rainfall simulations†.



*, **, *** Concentrations between events varied ($P < 0.10$, $P < 0.05$, $P < 0.01$).

† Control: No P control; P-1: P needs of rotation applied each rotation; P-2: Seasonal P requirements applied once; Days x/y: Day of rotation. Rain was simulated at day 21 of each rotation.

Fig. 3.8. Dependence of dissolved reactive P on total P concentrations in surface runoff from boxes containing fescue pasture sods simulating rotational grazing following two rainfall simulations.

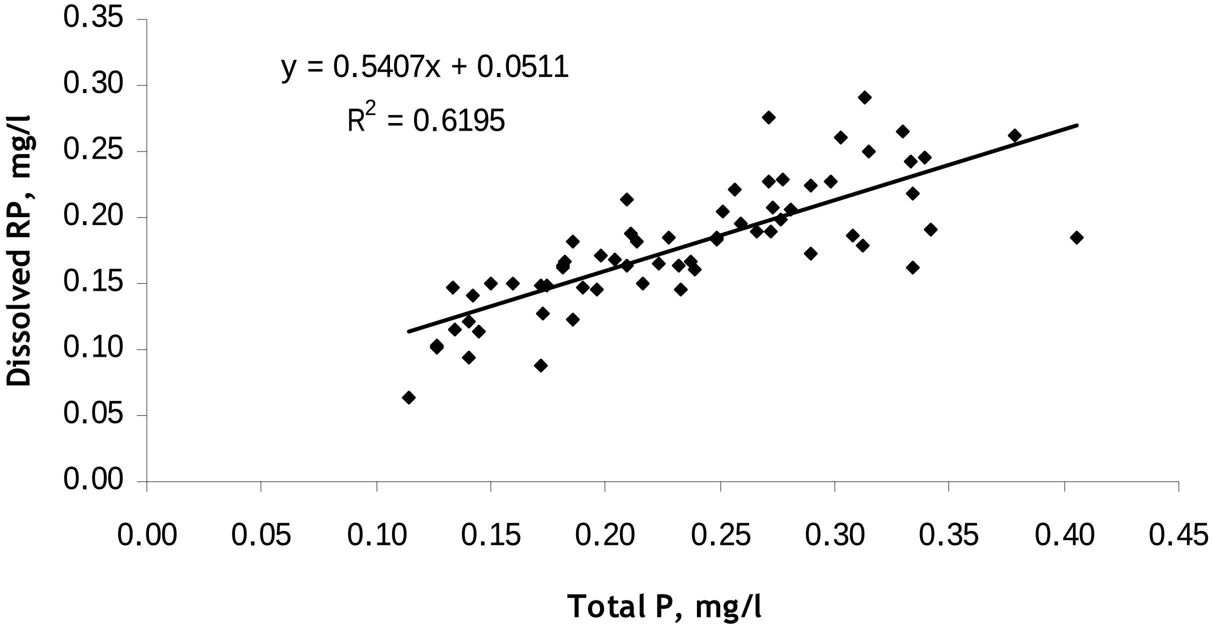
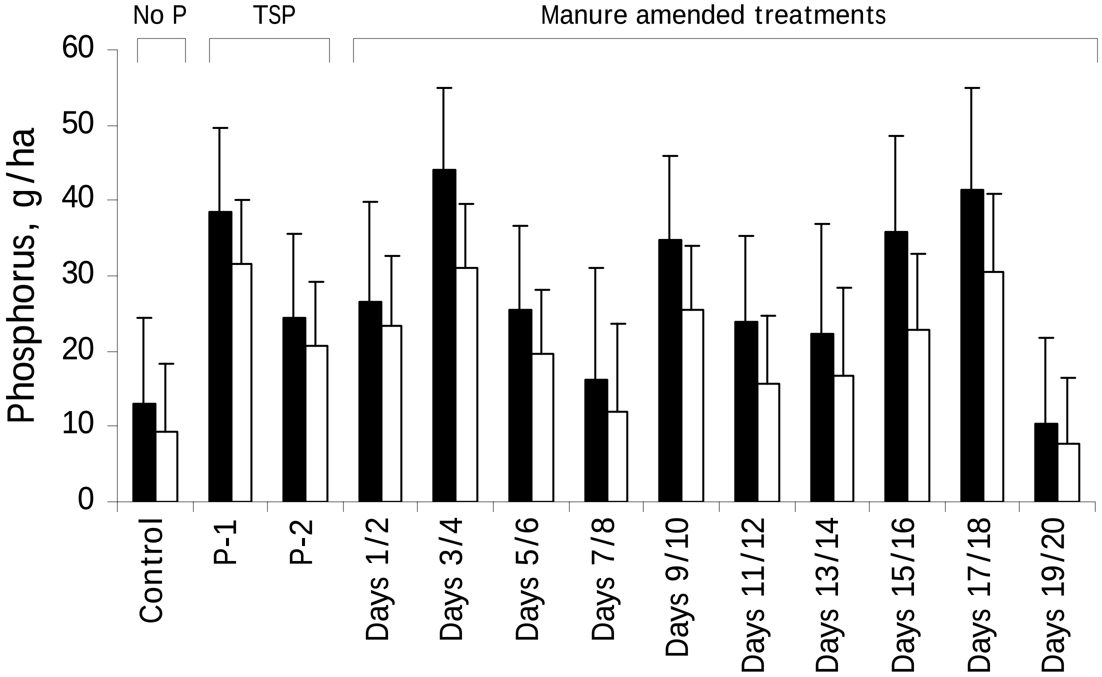


Fig. 3.9. Edge-of-the-field losses of total and dissolved reactive P in surface runoff from boxes containing fescue pasture sods simulating rotational grazing following two rainfall simulations[†,‡].



[†] Control: No P control; P-1: P needs of rotation applied each rotation; P-2: Seasonal P requirements applied once; Days x/y: Day of rotation. Rain was simulated at day 21 of each rotation.

[‡] Error bars represent the standard error.

Fig. 3.10. Dependence of dissolved reactive P losses on total surface runoff weight in surface runoff from boxes containing fescue pasture sods simulating rotational grazing following two rainfall simulations.

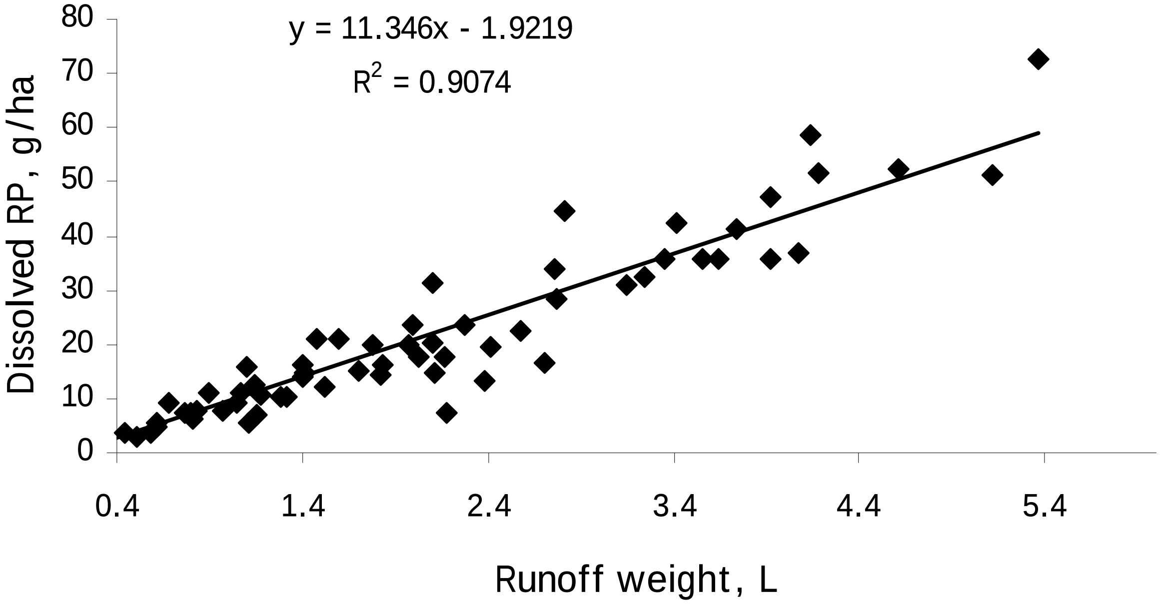


Fig. 3.11. Dependence of total P losses on total surface runoff weight in surface runoff from boxes containing fescue pasture sods simulating rotational grazing following two rainfall simulations.

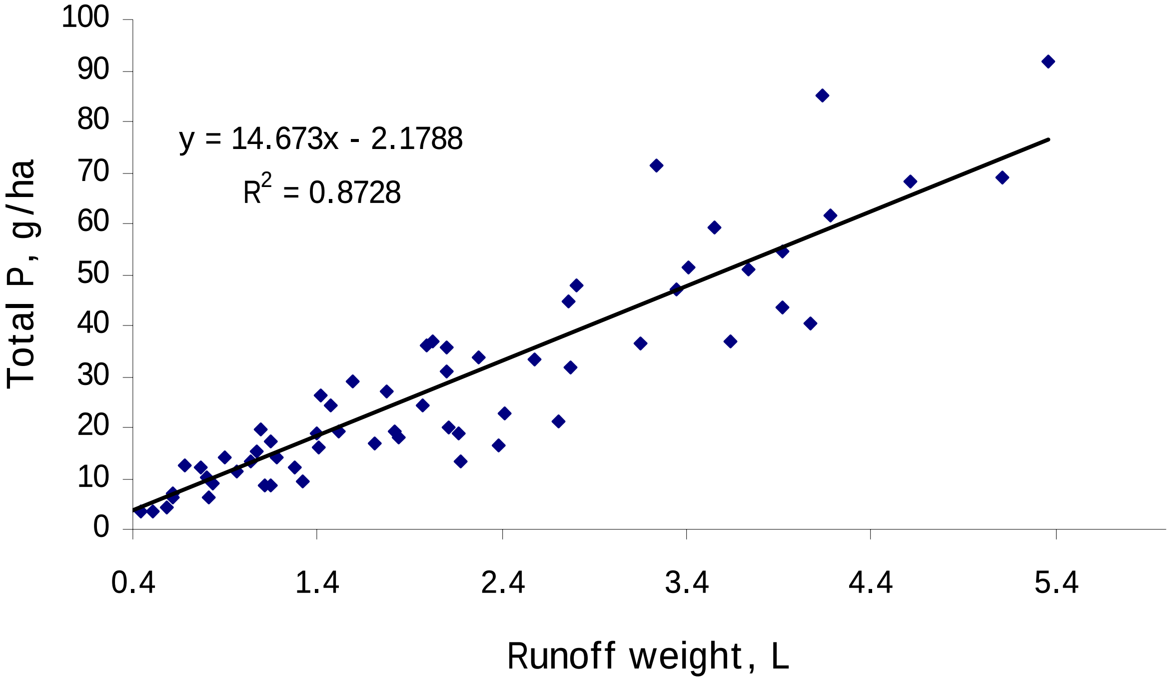
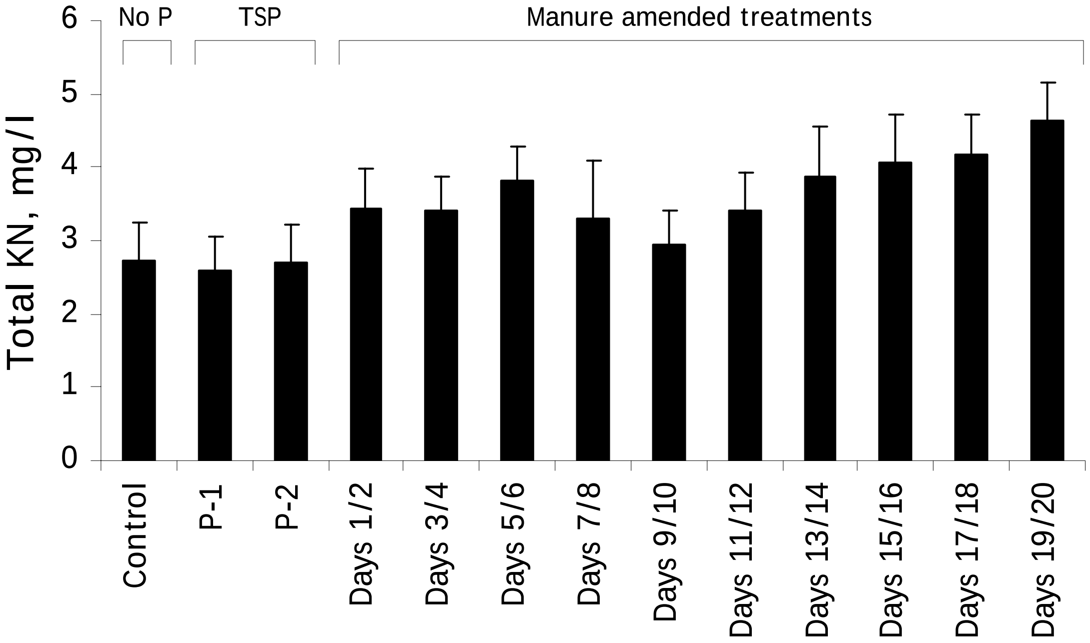


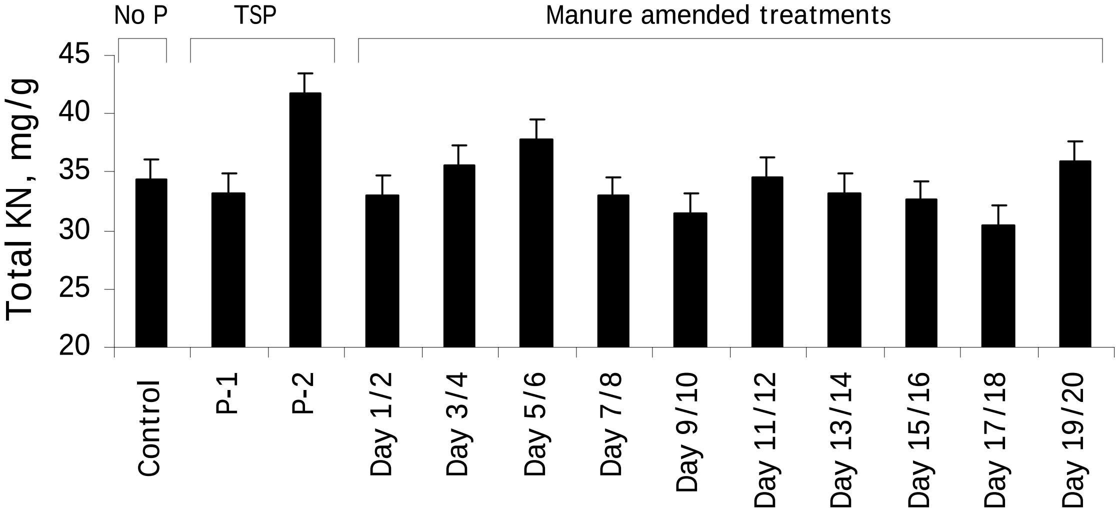
Fig. 3.12. Total Kjeldahl N concentrations in surface runoff from boxes containing fescue pasture sods simulating rotational grazing following two rainfall simulations[†,‡].



[†] Control: No P control; P-1: P needs of rotation applied each rotation; P-2: Seasonal P requirements applied once; Days x/y: Day of rotation. Rain was simulated at day 21 of each rotation.

[‡] Error bars represent the standard error.

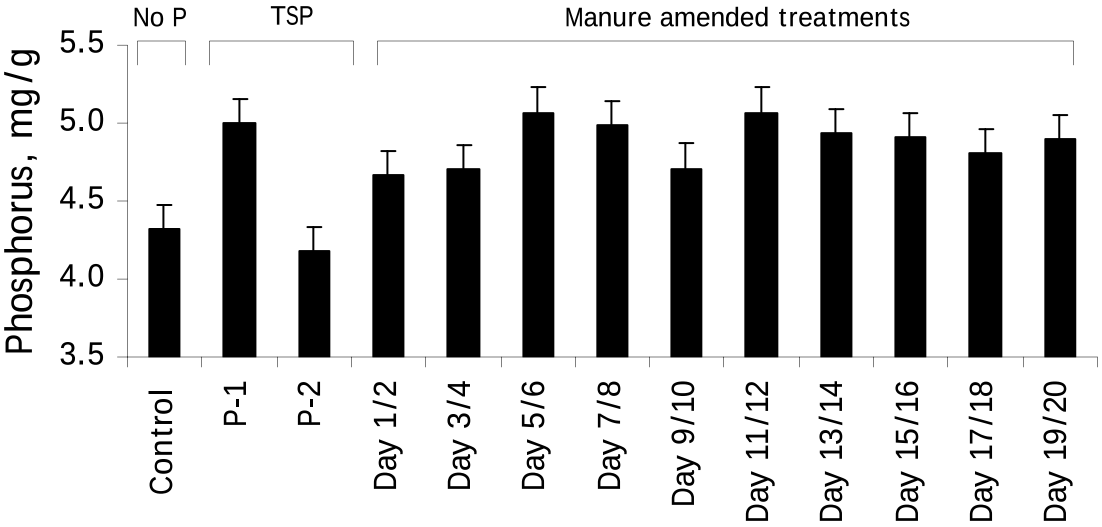
Fig. 3.13. Nitrogen concentration in harvested forage from pasture under simulated management intensive rotational grazing[†,‡].



[†] Control: No P control; P-1: P needs of rotation applied each rotation; P-2: Seasonal P requirements applied once; Days x/y: Day of rotation. Rain was simulated at day 21 of each rotation.

[‡] Error bars represent the standard error.

Fig. 3.14. Phosphorus concentration in harvested forage from pasture under simulated management intensive rotational grazing[†,‡].



[†] Control: No P control; P-1: P needs of rotation applied each rotation; P-2: Seasonal P requirements applied once; Days x/y: Day of rotation. Rain was simulated at day 21 of each rotation.

[‡] Error bars represent the standard error.

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Chapter 4 : Conclusion and Summary

Pasture is a major land use in Virginia and in the Shenandoah Valley. Most pastures are located on sloped, shallow grounds that do not suit row crops. The high density of livestock in some areas accumulates imported nutrients (N and P) in manures, which in turn are applied to local fields, leading to an accruing of P in top soils of manure amended fields. Due to the environmental hazard of P leaving the soil and entering streams either through soil erosion or in runoff in a dissolved form, regulations have been established to limit P applications in the form of manure and other (inorganic) fertilizers on fields. This has led to a need of applying manure on any possible agricultural ground, including pasture, since exporting manure is either not feasible due to its volume, or reducing volume by concentrating nutrients requires expensive technologies.

Many states like Virginia have adopted a P Index, which evaluates the potential risk of P losses based on area specific parameters. Thus far, there has not been any scientific work conducted on Virginia pastures to verify coefficients used in the P Index that describe the P loss potential of different manure sources applied to pasture or for (rotationally) grazed pasture. The two experiments therefore aimed to (i) rank potential P losses of common types of manure applied to pasture versus a commercial, inorganic P fertilizer and background P losses and to (ii) evaluate the risk of P losses from (rotationally) grazed pasture to (iii) enhance the P Index in Virginia.

In the first experiment, dairy slurry, piggery waste, beef solids, and poultry litter were spring-applied along with a TSP treatment to a sloped tall fescue pasture. Application rates were based on the estimated yearly P removal by the crop (62.7 kg P_2O_5/ha). All treatments received additional ammonium nitrate to equalize all plots at 112 kg N/ha. The plots were cut five times in monthly intervals and the forage was removed. Initiated runoff was collected at five occasions. Throughout the season, no differences in runoff P between treatments, including a control treatment were revealed.

Analysis of single rain events disclosed increased runoff TP and DRP from P amended plots compared to the control during the first two events, with TSP producing the highest runoff TP. No additional differences were observed during successive rainfall events. Samples taken at 5-min increments during the second rain event disclosed a drop of P concentrations over time, with the TP concentration dropping faster than DRP. Runoff P losses from the control treatment stayed steadily low, indicating that short intensive runoff events create higher P concentrations in the runoff from P receiving treatments.

Conclusively, spring applied P fertilizer to pastures rank in their potential of P runoff TSP > dairy slurry, piggery waste > beef solids, poultry litter, although the potential within 40 d of amendment is yet to be determined. Phosphorus, when spring-applied to pasture at a crop removal rate, did not significantly increase runoff P 100 d after application.

The plots showed a wide range of hydrology as runoff volume varied greatly. Therefore, we question the split-plot arrangement for pasture plots as stated in the experimental design in National P Research Project. Using whole plots ($3m^2$ instead of 1.5 m^2), although doubling the work-load, may reduce the variance between plots in their runoff volume. Alternatively, a set of rainfall simulations can be conducted prior to treatment application to establish background parameters for every plot.

The second trial was conducted to evaluate the risk of P losses from (rotationally) grazed pasture. Sod from the same paddock as experiment one was placed in indoor runoff boxes (0.18 m^2). A 20 d rotation was simulated, using a new paddock every-other-day as treatment and comparing it to a control and inorganic P fertilizer treatments. Manure from a grazing dairy was applied on an identical P-basis as in trial one every day to the specific treatment boxes. Rainfall was simulated at the end of each rotation and a 30-min runoff sample was collected.

There were no distinct effects of treatment on runoff P other than P concentrations being lower in runoff from the control than any P treatment. There was however a linear decrease in runoff TKN, as the manure aged. A follow-up study is needed to determine, whether total N in the runoff was reduced, or if nitrate concentration increased instead, either in surface runoff or in leachate. In conclusion, there are too many possible variations within a sod of this small size, so that successive work should utilize larger plot sizes.

An experiment set up to evaluate runoff parameters from an established sod should utilize the larger plot size in experiment 1 within a pasture. Transplanting sod into the indoor runoff boxes seemed to create too many variables affecting the runoff. Additionally, P concentration in pasture runoff is generally low, so that treatment differences may be easier to detect utilizing a larger treatment area.

IMPLICATIONS FOR VIRGINIA'S PHOSPHORUS INDEX

Currently the P Index uses the following P source coefficients for tilted cropland and for pasture: 0.25 for inorganic fertilizer and 0.20 for dairy and beef manure, poultry litter with an Al:P ratio of less than 0.4 as used in the present study, and 0.20 for 'other', including piggery manure. The values resulting from the formula for the P Index given in the introduction are ranked by their potential water impact (Wolfe et al., 2005):

- 0 – 30: Phosphorus applications according to N-based nutrient management are acceptable.
- 31 – 60: Phosphorus applications should not be greater than 1.5 times crop removal.
- 61 – 100: Phosphorus applications should not be greater than crop removal.
- > 100: No phosphorus should be applied.

The applied fertilizer DRP factor, the only management factor within the P Index, is the product of the rate of applied P, the P source coefficient, and the method of application factor. Since the applied fertilizer DRP factor is a summand of the P Index, varying the P source coefficient directly impacts the value of the P Index. Varying the P source coefficient by 0.10, while holding the rate of applied P (62.7 kg P_2O_5/ha = 24.5 lbs P/ac) and the method of application factor (0.20; surface applied, no incorporation) steady, the resulting P Index value consequently varies by 4.17. For example, dropping the coefficient for litter from 0.20 to 0.10 by raising the AL:P ratio above 0.7 would drop the P Index value by 4 units.

In the present study, TSP amendment increased the average concentration of TP in the runoff 1.57 times over the whole season when compared to the control treatment. Dairy slurry, piggery waste, beef solids, and poultry litter increased TP versus the control by 1.35, 1.40, 1.28, and 1.23, respectively. Leaving the coefficient for the inorganic P source at 0.25 would result in coefficients of 0.21 (dairy), 0.22 (swine), 0.20 (beef), 0.20 (poultry). The rankings of the P sources as published in Virginia's P Index are therefore confirmed.

The coefficient for the inorganic fertilizer seems to be too high. Phosphorus losses from the TSP treatment in the current experiment were ~ 1‰ of the applied P for the entire season, produced by five rainfalls. Each rainfall intensity had a return rate of more than 10 yrs. This loss represents the product of the P source coefficient and the method of application factor. Since the later factor is 0.20, the coefficient for the inorganic fertilizer should be 0.005 for the product to equal 0.001. At the application rate used in the present study, the overall impact on the P Index value would be 0.2.

There can be two more implications drawn from the current study. The first is the possibility of a seasonal factor. The P source differed in their runoff P concentrations from the control treatment predominantly during the first set of rainfalls ~ 40 d after P amendment. A season factor could rank the time of P amendment with the possibility of runoff producing rain storms following the time of P application, e.g. timely distance to a rain season.

Secondly, there may be a differentiation by manure moisture, e.g. solid versus semi-solid versus slurry. The solid manure sources (beef and litter) in the current study rank consistently, although only numerically, lower than the two slurries (dairy and piggery). Significant differences may surface by increasing the application rate, but this study was designed to duplicate management practices currently utilized in the Valley.

One needs to remember the overall achievements of these additional factors or fine-tuning of existing coefficients. As mentioned before, a 0.20 versus a 0.10 P source factor would impact the P Index value by 4. The chances proposed above are much smaller, so their overall impact on the Index value seems to be almost neglectable. Lowering the coefficient for inorganic fertilizer and, consequently, all other sources applied to pasture would result in the greatest impact.

The second experiment revealed no differences in runoff P concentrations from different paddocks used for rotational grazing. The results have to be evaluated cautiously, since the size of the treatment area limited the outcome. A decrease in P losses from aged manure would have implied that cows should be grazed on paddocks less prone to runoff in sight of a rain storm.

Chapter 5 : Appendix

Table A 1. Runoff weights and concentrations of total phosphorus (TP), dissolved reactive phosphorus (DRP), total Kjeldahl nitrogen (TKN), and total suspended solids (TSS) during simulated rainfalls following amendment of P sources to pasture.

Treatment	Runoff weight	TP	DRP	TKN	TSS
	kg	-----------------------mg/l			--------------------------
1. Rainfall					
No P control	11.50	0.126	0.068	2.74	38
Triple superphosphate	14.80	0.249	0.182	3.21	55
Dairy slurry	13.41	0.219	0.168	2.76	75
Piggery waste	17.38	0.213	0.146	2.69	15
Beef solids	16.19	0.196	0.130	3.05	24
Poultry litter	12.40	0.190	0.128	2.67	26
2. Rainfall					
No P control	25.39	0.118	0.072	2.67	25
Triple superphosphate	24.03	0.248	0.153	2.78	38
Dairy slurry	30.51	0.187	0.132	2.74	21
Piggery waste	31.33	0.184	0.118	2.71	18
Beef solids	30.50	0.154	0.096	2.86	19
Poultry litter	23.51	0.156	0.103	2.46	22
3. Rainfall					
No P control	5.36	0.136	0.075	1.58	45
Triple superphosphate	8.34	0.155	0.123	2.06	59
Dairy slurry	5.75	0.135	0.102	1.31	75
Piggery waste	11.78	0.146	0.101	1.48	27
Beef solids	6.94	0.156	0.092	1.66	28
Poultry litter	9.61	0.136	0.094	1.36	26
4. Rainfall					
No P control	17.07	0.103	0.062	1.37	19
Triple superphosphate	15.89	0.157	0.115	1.15	18
Dairy slurry	19.54	0.133	0.089	1.21	16
Piggery waste	17.49	0.156	0.096	1.22	25
Beef solids	22.32	0.130	0.085	1.35	13
Poultry litter	23.11	0.122	0.080	1.29	12
5. Rainfall					
No P control	22.71	0.123	0.073	1.51	47
Triple superphosphate	33.42	0.142	0.106	1.51	78
Dairy slurry	25.34	0.143	0.108	1.39	31
Piggery waste	28.56	0.146	0.103	1.43	32
Beef solids	28.85	0.139	0.080	1.63	36
Poultry litter	32.24	0.141	0.090	1.48	58

Table A 2. Significance of pre-planned contrasts[†] on parameters from P sources amended to pasture.

Parameter	1	2	3	4	5	6
	------------------------		*P* <		----------------------	
Runoff quantities						
Time delay of runoff initiation	0.01	0.01	0.01	0.19	0.87	0.44
Weight, all events	0.01	0.01	0.01	0.51	0.93	0.86
Total P, all events	0.01	0.01	0.01	0.25	0.71	0.56
Dissolved RP, all events	0.01	0.01	0.01	0.28	0.60	0.47
Total KN, all events	0.01	0.01	0.01	0.54	0.99	0.97
Total solids, all events	0.07	0.01	0.02	0.49	0.75	0.76
Total SS, all events	0.34	0.01	0.33	0.85	0.26	0.97
Weight, hydrograms event 2	n/a	n/a	n/a	0.57	0.36	0.30
Total P, hydrograms event 2	n/a	n/a	n/a	0.17	0.22	0.95
Dissolved RP, hydrograms event 2	n/a	n/a	n/a	0.18	0.29	0.67
Runoff qualities						
Total P, all events	0.01	0.42	0.01	0.03	0.41	0.11
Total P, event 1 (June dry)	n/a	n/a	n/a	0.01	0.42	0.15
Total P, event 2 (June wet)	n/a	n/a	n/a	0.03	0.26	0.02
Dissolved RP, all events	0.01	0.24	0.01	0.05	0.32	0.17
Dissolved RP, event 1 (June dry)	n/a	n/a	n/a	0.01	0.32	0.21
DRP:TP	0.32	0.76	0.80	0.03	0.18	0.33
Total KN, all events	0.01	0.02	0.01	0.97	0.42	0.10
Total solids, all events	0.22	0.88	0.01	0.52	0.91	0.96
Total SS, all events	0.12	0.01	0.62	0.34	0.57	0.43
Total P, hydrograms event 2	n/a	n/a	n/a	0.06	0.34	0.40
Dissolved RP, hydrograms event 2	n/a	n/a	n/a	0.07	0.45	0.24
Soil measures						
Initial soil moisture (15 cm)	0.01	0.33	0.01	0.31	0.58	0.37
Water EP, post-event 5 (2.5 cm)	n/a	n/a	n/a	0.91	0.12	0.50
Water EP, post-event 5 (10 cm)	n/a	n/a	n/a	0.22	0.69	0.66
Forage quantities						
Nitrogen, all events	n/a	n/a	n/a	0.13	0.93	0.10
Phosphorus, all events	n/a	n/a	n/a	0.24	0.37	0.21

[†] 1: rain simulation 2 vs. simulations 4 and 5; 2: simulation 4 vs. simulation 5; 3: simulation 1 vs. simulation 3; 4: no P control vs. all other treatments; 5: liquid manures (dairy and swine) vs. solid manures (beef solids and poultry litter); 6: inorganic P (TSP) vs. organic P (all manures).

Table A 3. Runoff weights and concentrations of total phosphorus (TP), dissolved reactive phosphorus (DRP), total Kjeldahl nitrogen (TKN), and total suspended solids (TSS) during simulated rainfalls following amendment of P sources on simulated rotationally grazed pasture boxes.

Treatment	Rep	Rain Event	Total Runoff g/plot	Total Phosphorus ppm	Dissolved Reactive P ppm	Total Kjeldahl N mg/l	Suspended Solids mg/l
Control	1	1	59	.	0.113	.	.
Control	2	1	.	.	.	.	.
Control	3	1	.	.	.	.	.
Control	1	2	2386	0.126	0.103	3.00	136
Control	2	2	1320	0.133	0.146	2.31	4
Control	3	2	508	0.127	0.102	2.47	.
Control	1	3	2173	0.115	0.064	2.58	61
Control	2	3	2109	0.173	0.128	3.16	15
Control	3	3	73	0.082	0.073	.	.
P1	1	1	218	0.110	0.049	.	.
P1	2	1	2508	0.153	0.108	2.56	44
P1	3	1	1987	0.178	0.129	4.28	20
P1	1	2	581	0.141	0.121	2.09	75
P1	2	2	4069	0.183	0.166	2.45	66
P1	3	2	3924	0.204	0.168	2.89	49
P1	1	3	2758	0.298	0.228	2.80	90
P1	2	3	3348	0.259	0.196	2.64	42
P1	3	3	3411	0.278	0.229	2.69	29
P2	1	1	163	0.117	0.093	.	.
P2	2	1	1338	0.340	0.219	1.73	10
P2	3	1	2722	0.253	0.207	2.50	12
P2	1	2	1279	0.175	0.149	2.70	22
P2	2	2	1778	0.281	0.206	2.81	92
P2	3	2	3919	0.256	0.221	2.53	14
P2	1	3	966	0.216	0.151	3.35	83
P2	2	3	445	0.150	0.150	.	13
P2	3	3	3638	0.186	0.181	2.15	16
Day 1/2	1	1	50	0.219	0.046	.	.
Day 1/2	2	1	2835	0.182	0.136	3.54	12
Day 1/2	3	1	1406	0.215	0.166	2.67	21
Day 1/2	1	2	59	0.201	0.141	.	.
Day 1/2	2	2	3733	0.251	0.204	3.41	6
Day 1/2	3	2	898	0.290	0.225	3.35	38

Treatment	Rep	Rain Event	Total Runoff g/plot	Total Phosphorus ppm	Dissolved Reactive P ppm	Total Kjeldahl N mg/l	Suspended Solids mg/l
Day 1/2	1	3	2771	0.211	0.188	3.60	77
Day 1/2	2	3	1406	0.209	0.214	3.35	26
Day 1/2	3	3	64	0.083	0.089	.	.
Day 3/4	1	1	100	0.160	0.115	.	.
Day 3/4	2	1	.	.	.	.	.
Day 3/4	3	1	1352	0.166	0.125	3.00	19
Day 3/4	1	2	5117	0.249	0.185	2.92	114
Day 3/4	2	2	1179	0.223	0.165	3.02	48
Day 3/4	3	2	3552	0.308	0.186	3.22	12
Day 3/4	1	3	2105	0.312	0.178	3.98	275
Day 3/4	2	3	1706	0.181	0.164	3.22	64
Day 3/4	3	3	4613	0.273	0.208	4.15	42
Day 5/6	1	1	.	.	.	.	.
Day 5/6	2	1	2599	0.291	0.232	43.80	44
Day 5/6	3	1	45	0.176	0.076	.	.
Day 5/6	1	2	1474	0.302	0.261	3.08	23
Day 5/6	2	2	2808	0.313	0.292	3.71	.
Day 5/6	3	2	1098	0.329	0.265	3.71	109
Day 5/6	1	3	680	0.339	0.245	3.31	101
Day 5/6	2	3	2100	0.271	0.275	3.51	13
Day 5/6	3	3	1148	0.277	0.198	5.52	126
Day 7/8	1	1	91	0.157	0.123	.	.
Day 7/8	2	1	290	0.187	0.161	.	.
Day 7/8	3	1	553	0.195	0.168	.	.
Day 7/8	1	2	64	0.201	0.126	.	.
Day 7/8	2	2	1823	0.196	0.146	3.16	38
Day 7/8	3	2	172	0.513	0.312	.	.
Day 7/8	1	3	1043	0.232	0.164	3.46	53
Day 7/8	2	3	64	.	0.103	.	.
Day 7/8	3	3	59	.	0.125	.	.
Day 9/10	1	1	68	0.225	0.104	.	.
Day 9/10	2	1	3007	0.159	0.147	.	25
Day 9/10	3	1	154	0.138	0.068	.	.
Day 9/10	1	2	1152	0.135	0.115	2.06	1
Day 9/10	2	2	4178	0.271	0.227	2.94	12
Day 9/10	3	2	2168	0.160	0.150	2.83	81
Day 9/10	1	3	1116	0.141	0.093	2.75	11
Day 9/10	2	3	4132	0.379	0.262	3.95	55
Day 9/10	3	3	1402	0.249	0.183	3.16	46

Treatment	Rep	Rain Event	Total Runoff g/plot	Total Phosphorus ppm	Dissolved Reactive P ppm	Total Kjeldahl N mg/l	Suspended Solids mg/l
Day 11/12	1	1	213	0.162	0.135	.	.
Day 11/12	2	1	.	.	.	.	.
Day 11/12	3	1	.	.	.	.	.
Day 11/12	1	2	1415	0.342	0.191	2.17	26
Day 11/12	2	2	245	0.159	0.124	2.79	.
Day 11/12	3	2	1515	0.233	0.146	3.02	55
Day 11/12	1	3	612	0.209	0.163	2.61	30
Day 11/12	2	3	2572	0.239	0.160	6.65	49
Day 11/12	3	3	2418	0.172	0.149	3.22	78
Day 13/14	1	1	.	.	.	.	.
Day 13/14	2	1	.	.	.	.	.
Day 13/14	3	1	45	0.143	0.095	.	.
Day 13/14	1	2	113	0.352	0.259	.	.
Day 13/14	2	2	2023	0.334	0.162	4.81	486
Day 13/14	3	2	327	0.185	0.123	3.08	.
Day 13/14	1	3	1837	0.182	0.162	3.49	90
Day 13/14	2	3	2708	0.145	0.113	2.37	43
Day 13/14	3	3	304	0.172	0.088	.	180
Day 15/16	1	1	.	.	.	.	.
Day 15/16	2	1	1116	0.143	0.112	4.09	21
Day 15/16	3	1	1901	0.204	0.088	12.88	37
Day 15/16	1	2	104	0.107	0.072	.	.
Day 15/16	2	2	191	0.354	0.305	10.66	9
Day 15/16	3	2	3239	0.406	0.185	4.15	190
Day 15/16	1	3	1991	0.334	0.219	4.86	144
Day 15/16	2	3	1973	0.228	0.184	3.43	164
Day 15/16	3	3	2277	0.272	0.189	3.57	52
Day 17/18	1	1	1347	0.213	0.137	3.11	149
Day 17/18	2	1	54	0.094	0.056	.	.
Day 17/18	3	1	132	0.179	0.105	.	.
Day 17/18	1	2	3148	0.214	0.181	4.12	69
Day 17/18	2	2	803	0.237	0.167	2.97	94
Day 17/18	3	2	191	0.130	0.085	.	.
Day 17/18	1	3	5366	0.315	0.250	4.53	38
Day 17/18	2	3	1070	0.266	0.189	5.03	96
Day 17/18	3	3	91	0.096	0.070	.	.
Day 19/20	1	1	835	0.311	0.193	3.62	45
Day 19/20	2	1	2227	0.236	0.127	3.57	24
Day 19/20	3	1	222	0.235	0.197	.	.

Treatment	Rep	Rain Event	Total Runoff g/plot	Total Phosphorus ppm	Dissolved Reactive P ppm	Total Kjeldahl N mg/l	Suspended Solids mg/l
Day 19/20	1	2	807	0.142	0.142	2.15	8
Day 19/20	2	2	1592	0.333	0.243	4.17	123
Day 19/20	3	2	767	0.290	0.173	4.09	73
Day 19/20	1	3	95	0.116	0.094	.	.
Day 19/20	2	3	835	0.198	0.171	2.58	94
Day 19/20	3	3	612	0.190	0.148	9.09	92

Vita

Marcus Hollmann was born to Antje and Wilhelm Hollmann in Heide/Holstein, Germany. He completed his journeyman in agriculture in Schleswig-Holstein, Germany, while working at Elm Park Farms, Wisconsin, and for Werner Knaus, Wanderup, Germany. He received a Technical Diploma in Dairy Herd Management from Lakeshore Technical College in Cleveland, Wisconsin, while working at Summit Farms (Robert and Peggy Webb, owners and operators) in Plymouth, Wisconsin. Marcus then obtained a Bachelor's degree in Crop and Soil Science and in Dairy Science from the University of Wisconsin - River Falls.