Nutrient Dynamics in Cool-Season Pastures

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ABSTRACT

Understanding the nutrient dynamics of pastures is essential to their profitable and sustainable management. Tall fescue [*Schendonorus phoenix* (Scop.) Holub.] is the predominant forage species in Virginia pasturelands. Although tall fescue pasture is common, little research has attempted to document how soil and herbage nutrient concentrations change through time. This thesis summarizes two studies conducted within the context of a larger grazing systems project near Steele's Tavern, VA. The objectives were to: (1) examine temporal changes in plant available soil nutrient concentrations in four grazing systems, (2) determine how hay feeding and use of improved forages affected soil and herbage nutrient concentrations (3) examine the relationship between and variability within soil and herbage nutrient concentrations, (4) analyze the seasonal variation in herbage mineral concentration with regard to beef cattle requirements, and (5) create a statistical model to predict variation in herbage mineral concentration across the growing season. Analysis of plant and soil nutrients through 5 years of grazing produced several important findings. Soil pH, P, and Ca, Mg, and B declined through five years of grazing. Higher concentrations of herbage N and K and soil P, K, Fe, Zn, and Cu were measured in hay feeding paddocks. Herbage nutrient concentrations showed less variability in P and K than did soil test results. Fertility testing in pastures is important to monitor changing nutrient concentrations, and this study showed that herbage analysis may provide a more stable and accurate assessment of pasture fertility than soil testing. Pasture herbage, grown without fertilization, contained sufficient concentrations of macronutrients to meet the requirements of dry beef cows through the growing season and to meet the requirements of lactating beef cows in April. A model was developed using soil moisture and relative humidity that predicted ($R^2 = 0.75$) variation in herbage mineral concentration throughout the growing season. As described in this thesis, use of modeling to predict nutrient dynamics in pasture could allow for more efficient mineral supplementation strategies that lead to improved profitability, nutrient retention, and livestock health.

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Chapter 1. Introduction

An improved understanding of nutrient dynamics in cool-season pastures can help to maximize profitability, reduce nutrient losses to the environment, and improve livestock health. Two studies were conducted as part of the interdisciplinary systems research project: "Economic Pasture-Based Beef Systems in Appalachia." The overall objective of the research project was to produce a 12-month supply of pasture-based beef by expanding the harvest window with retention of acceptable meat quality. The two studies detailed here provide thorough analysis of soil and pasture herbage nutrient dynamics in the cow-calf portion of this systems research project.

This thesis is organized in 5 chapters. This introduction is followed by a review of literature on nutrient dynamics in cool-season pasture focused on inputs and loss pathways, the effects of grazing on nutrient cycles, and nutrient requirements of pasture plants and livestock. Chapter 3 assesses changes in soil and herbage nutrient concentration under 5 years of rotational stocking, differences between 3 paddock types and 4 grazing systems, and the relationships between and variability within soil and herbage nutrient concentrations. Chapter 4 examines the within season variation in herbage mineral concentration in the context of beef production and develops a predictive model to explain variation in herbage mineral concentration throughout the growing season. The final chapter presents overall conclusions of this research.

Chapter 2. Literature Review

INTRODUCTION

An understanding of nutrient dynamics is necessary for the efficient management of pasture. Studies of nutrient dynamics in cool-season pasture in the U.S. are few. The majority of work in the field has taken place in the U.K., Europe, and New Zealand, often in perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) pasture managed for dairy production. An attempt has been made here to cite examples from a variety of systems, and when possible, studies conducted with tall fescue-based cool-season pasture in the eastern U.S. are used.

The structure of this review is based around the dynamics of sets of related nutrients, with sections for: nitrogen, phosphorus, sulfur, macronutrient cations (K, Ca, and Mg), and micronutrients (Fe, Zn, Cu, Mn, and B). Discussion of complete nutrient cycles is beyond the scope of this review. Specific attention will be paid to: (1) inputs and loss pathways in pasture systems, (2) the influence of grazing animals on nutrient cycles, (3) the nutritional requirements of plants and livestock for beef production in cool-season pasture systems.

NITROGEN DYNAMICS

The supply of N from the soil is commonly a major limiting factor for the primary productivity of grass-dominated pastures (Floate, 1987). Nitrogen in plant tissue is a constituent of proteins, nucleic acids, and chlorophyll among other compounds (Hawkesford et al., 2012). Given its importance to increased yields and potential for excesses to cause environmental degradation, N is the most commonly studied nutrient in pasture systems (Kayser and Isselstein, 2005).

Inputs & Loss Pathways

Chemical fertilizer and biological N fixation (BNF) are the major inputs of N to pastures. A comparatively minor source of reactive N is atmospheric deposition; between 2007 and 2011 a site near Charlottesville, VA measured 4.17 kg N ha^{-1} yr^{-1} as wet atmospheric deposition (NADP, 2013). While it has been shown, in Virginia, that tall fescue yields can increase with applications of up to 897 kg N ha^{-1} yr^{-1} and frequent harvests (Hallock et al., 1965), low rates of nitrogen are commonly applied to tall fescue-based pasture. Wilkinson and Mays (1979) state low N rates are typically applied to tall fescue pastures because (1) producers consider pasture to be a low value crop and cannot justify heavy fertilization, (2) legumes in mixed swards can provide N, and (3) the increase to already high spring yields as a result of N fertilization requires management beyond the means of producers in order to achieve efficient utilization.

Legumes in pasture and hayland swards can provide significant N through BNF. Mixtures of either kura clover (*Trifolium ambiguum* M. Bieb.) or birdsfoot trefoil (*Lotus corniculatus* L.) and cool-season grasses achieved yields for which in order for pure grass stands to meet would have required 74 to 325 kg N ha^{-1} (Zemenchick et al., 2001). Tracy et al. (2013) found the yield of tall fescue and alfalfa mixtures to be equivalent to yields of pure tall fescue with 112 kg N ha^{-1}. The amount of N supplied to a pasture ecosystem through BNF by legumes is related to the proportion and yield of legumes in the stand, and swards not fertilized with P or K and which are lightly grazed may experience BNF of < 25 kg N ha^{-1} yr^{-1} (Whitehead 2000). Nitrogen input beyond plant uptake capacity, regardless of the source, can lead to losses of N from the ecosystem.

Losses of nitrogen occur as the result of leaching of NO_3^-, volatilization of NH_3 to the atmosphere, denitrification to N_2 and NO_x compounds, losses of NH_4^+ and organic N through soil erosion, and with the removal of crop or livestock biomass (Stevenson and Cole, 1999). Nitrogen removed as animal products constitutes 5-30% of N consumed, with animal tissue at the lower end of the range compared with dairy products (Rotz et al 2005). Losses of N vary depending on the soils, fertilization, grazing management, climate, and other factors. The effects of grazing on pasture N cycling and losses are significant and will be discussed in the following section.

Influence of Grazing on the N Cycle

Livestock play a significant role in the movement of nutrients through the soil-plant-animal system. The removal of herbage from pasture plants by livestock stimulates regrowth and uptake of soil nutrients (Williams and Haynes, 1990). Nutrients from plant material digested and excreted by livestock are more soluble than the organic forms found in undigested plant litter (Floate, 1970; Whitehead, 2000). Overall, grazing by livestock increases the rate of nutrient cycling in pasture ecosystems (Williams and Haynes, 1990; Rotz et al., 2005).

The deposition of concentrated nutrients as manure and urine have marked effects on plant production, herbage mineral composition, and nutrient losses from pasture. Beef cattle excrete 90 - 95% of dietary N as manure and urine (Whitehead, 2000). Manure contains approximately 8 g N kg^{-1} of feed consumed, with urine N concentration, ranging from 40 - 80% of total N excreted, being correlated to the concentration of feed N

(Haynes and Williams, 1993). Rates of N applied in a manure or urine patch can be equivalent to approximately 1000 kg N ha^{-1} (Ledgard, 2001). In a single application, these rates well exceed the uptake ability of pasture plants and losses can be significant. Losses of N from urine, as a proportion of N excreted, can be 4 – 5 times greater than losses from manure (Ledgard, 2001). Only 20 - 25% of N in manure is water-soluble, and it contains little free NH_3 (Rotz et al., 2005). In comparison, 50 - 80% of urine N is urea (Haynes and Williams, 1993). Urea hydrolysis raises soil pH (Havlin et al., 2005), and increased pH, in addition to high concentrations of NH_4^+/NH_3, can delay nitrification (Rotz et al., 2005) causing increased losses of urine N to volatilization (Lockyer and Whitehead, 1990). NH_3 volatilization can cause losses of 10-25% of urine patch N (Lockyer and Whitehead, 1990). Leaching of NO_3^- is correlated to increased N input, either from fertilizer or BNF (Ledgard, 2001). In pasture systems, NO_3^- leaching is most common in urine patches on sandy soils (Clough et al., 1996; Whitehead, 2000). Researchers in New Zealand found that 4.4% of manure N and 18.7% of urine N were taken up by pasture plants within one year of application (Sakadevon et al., 1993). In Florida, White-Leech et al. (2013) found that 12.4% of urine N was recovered from bahiagrass (*Paspalum notatum* Flügge) pasture, but manure N recovery was nearly zero. Manure and urine are concentrated sources of nutrients in pasture; the distribution of manure and urine patches is not random across pastures (Rotz et al., 2005) and that heterogeneity can dramatically impact nutrient dynamics.

Nutrients accumulate in areas where livestock congregate including feeding and watering areas and in shade (Haynes and Williams, 1993). Ledgard (2001) calculated that sheep camping sites could accumulate an N surplus 8-times greater than the farm average and concluded there would be significant N loss at these sites. In tall fescue pasture, West et al. (1989) found that total N was 4.2 g kg^{-1} soil in the area near the water source as opposed to 2.1 g kg^{-1} in the grazing area of the pasture. They also speculated that since the proportion of N as compared to P and K found around the water source was less than found in the general grazing area, that N was likely lost through leaching and volatilization in the areas of concentrated nutrients. The uneven distribution of excreta across pastures can result in areas with concentrated soil nutrients which can be major loss pathways for pasture systems.

Nitrogen Requirements of Pasture Plants and Ruminant Livestock

Plants require N as a constituent of proteins, nucleic acids, chlorophyll and other compounds (Whitehead, 2000). Jones et al. (2000) reported that the N sufficiency ranges for tall fescue, orchardgrass (*Dactylis glomerata* L.), and white clover were 3.40 - 3.80, 3.20 - 3.40, and 4.50 - 5.00, respectively, based on 4 - 6 week clipping intervals.

In livestock, N is required for proteins which make up muscle tissues and enzymes. Crude protein is related to total N in feeds by multiplying total N by 6.25 (Whitehead, 2000). A dry beef cow and a lactating beef cow require 1.12 - 1.28 and 1.60 - 1.76% N unit $^{-1}$ dry matter, respectively (NRC 2000). Pasture herbage frequently supplies sufficient protein to livestock. Pasture grass is, however, often N limited with herbage N concentrations less than the sufficiency ranges listed above. High concentration of NO_3^- in livestock feed can be toxic; the maximum safe NO_3^- concentration has been reported to be between 2,000 and 4,800 mg kg^{-1} (Bush et al., 1979). High rates N fertilizer have been shown to cause unsafe NO_3^- concentrations in tall fescue but concentrations decline with time after fertilization (Hojjati et al., 1972).

PHOSPHORUS DYNAMICS

Phosphorus is often considered the second most limiting nutrient in terrestrial ecosystems behind N. In comparison to other nutrients, P tends to occur in relatively immobile forms in soils. Degradation of water quality as a result of P pollution has made the study of P in agroecosystems an important topic.

Inputs & Loss Pathways

Phosphorus occurs in the parent material of many soils in the form of apatite (Whitehead, 2000). As P from primary minerals dissolves into solution it is precipitated into secondary minerals, including Fe and Al containing minerals such as variscite and strengite in acidic soils (Havlin et al., 2005). Plants uptake P as $H_2PO_4^-$ and HPO_4^{2-}. The availability of soil P to plants is determined by the quantity of inorganic P in soil solution, the solubility of Fe- and Al-P minerals and Al and Fe oxides in acidic soils, the amount and quality of soil organic matter and residues, and activity of soil microorganisms (Stevenson and Cole, 1999). Fertilization is an important P source in agronomic systems. Phosphorus in commercial fertilizer is soluble when applied to soil and is taken up by plants, immobilized by microorganisms, or fixed through precipitation or adsorption to soil particles (Havlin et al., 2005). Atmospheric input of P is negligible (Whitehead, 2000), leaving fertilization and imported feeds as the major inputs of P to pasture systems.

Given the low solubility of P in soils, surface runoff is a major loss pathway with little P lost through leaching (Whitehead, 2000). Heavy rainfall after application of P fertilizers or manure can results in P losses. In an intensive dairy system fertilized with

38 kg P ha^{-1} in New Zealand, Parfitt (1980) calculated that 4 kg P ha^{-1} yr^{-1} could be lost to runoff. In comparison, Timmons and Holt (1977) measured P loss to runoff of approximately 0.1 kg P ha^{-1} yr^{-1} from an ungrazed, unfertilized, native prairie in Minnesota. Phosphorus-fertilized and rotationally-stocked orchardgrass, bluegrass, and tall fescue pasture in Ohio, lost approximately 0.3 kg P ha^{-1} yr^{-1} to surface runoff and subsurface flow over the 15-year study (Owens et al., 2003). Poultry litter is a fertility source for some pastures in Virginia and losses to P to the environment are a concern. Losses of poultry litter P from pasture are related to application rate, method, and precipitation following application (Schroder et al., 2004; Maguire et al., 2011). Wilkinson and Lowrey (1973) hypothesized a tall fescue pasture ecosystem on a sandy clay loam in Georgia and estimated nutrient cycling under cow-calf grazing. They determined the total ecosystem P was 4161.7 kg ha^{-1} with 260.7 kg ha^{-1} of that being actively cycled. Losses from their system were 3.8 kg P ha^{-1} yr^{-1} with the majority of that removed as animal products, mainly calves. Approximately 10% of ingested P is retained by livestock as liveweight and greater quantities can be removed in intensive dairy systems (Whitehead, 2000). Without significant removal of biomass or animal products or major input of fertilizer, P losses from pasture systems are small.

Influence of Grazing on the P Cycle

Because P is relatively immobile in soil, the concentrated application of nutrients in excreta is less of a loss pathway for P than for N, S, or K. Almost all P is excreted by ruminants as manure. Manure tends to contain a set amount of organic P (approximately 0.6 g organic P 100 g^{-1} feed consumed) with the remainder in inorganic forms, such as dicalcium phosphate, and the total quantity of P excreted depends on P concentration in feed (Barrow and Lambourne, 1962; Haynes and Williams, 1993). During and Weeda (1973) found that manure applied to low-fertility pasture increased yield and P concentration of the herbage that grew in an area 5-times larger than the area affected by manure and the results persisted for two years following application. Given a stocking rate of 4 cattle per hectare and an average of 12 defecations per day, the authors calculated that nearly 40% of the pasture would be affected by manure deposition after one year. This, however, would assume a relatively even distribution of manure across the pasture.

Another impact of grazing animals on P cycling is the uneven distribution of manure deposition across pastures. Schnyder et al. (2010) found that the long-term grazing of livestock created nutrient accumulation and depletion zones in pastures. By comparing the manure distribution density, the pre- and post-graze biomass, and the herbage nutrient concentrations over two rotational grazing periods, the authors determined that grid areas in the lowest quartile for extractable soil P lost > 0.8 g m^{-2} P while grid areas in the highest quartile of extractable P gained > 0.1 g m^{-2} P. Livestock tended to move nutrients from hillsides to level areas where they slept. West et al. (1989) found a 10 - 20 m area around a water source to have extractable soil P concentrations 3 to 7-times greater than the general grazing area for a continuously grazed pasture after 5 years. The soil is often poorly covered or bare of vegetation around watering and feeding sites and in shade. These disturbed sites can be loss pathways in pastures as the lack of vegetative cover and plant roots allows for increased erosion and P loss (Haynes and Williams, 1993; Dougherty et al., 2004).

Phosphorus Requirements of Pasture Plants and Ruminant Livestock

Plants require P as a constituent of nucleic acids, cytoplasmic membranes, and the energy transport molecules: ADP and ATP (Whitehead, 2000). The usual range for P concentration in grass and legume herbage is 0.1 - 0.6% (Whitehead, 2000). Jones et al. (1991) reported that the P sufficiency ranges for tall fescue, orchardgrass, and white clover were 0.34 - 0.45%, 0.23 - 0.35%, and 0.36 - 0.45%, respectively, based on 4 - 6 week clipping intervals.

Given the insolubility of P in soils, the quantity of total P has little bearing on the availability of P for plant uptake (Havlin et al., 2005). A wide range of tests for plant available soil P exist. The methods and extractant used to determine plant available P depends on a variety of soil conditions including texture and pH (Stevenson and Cole, 1999).

The P requirement for livestock varies depending on the species, age, and growth rate. Between 80 - 85% of P in livestock is in the form of hydroxyapatite in the skeleton, but P also has a variety of important roles in ruminant physiology (Karn, 2001). The minimum dietary P requirement for a dry beef cow and lactating beef cow are 0.19 and 0.27%, respectively (NRC, 2000). In a review of phosphorus nutrition for grazing cattle, Karn (2001) expressed concern for the dearth of studies examining the P requirement of beef cattle on pasture since the 1940's. Wilkinson and Mays (1979) reported accounts of beef cattle grazing forage with less than 50% of the minimum P requirements and noted negligible adverse effects.

SULFUR DYNAMICS

Sulfur is an essential and often overlooked nutrient in grassland ecosystems. Like N, the majority of soil S is present in organic forms, and thus the availability of S for plant uptake is mediated by mineralization and immobilization, and like NO_3^-, SO_4^{2-} is susceptible to leaching losses (Nguyen and Goh, 1994). With improved industrial pollution standards and more concentrated fertilizers, S input to agroecosystems has been declining (Whitehead, 2000), and this could lead to deficiencies in soils where deficiencies have not been previously noted.

Inputs & Loss Pathways

Inputs of S to grassland systems consist of those from weathering of soil minerals, fertilizer applications, and from atmospheric deposition (Nguyen and Goh, 1994; Whitehead, 2000). The primary origin of S in soil is pyrite (FeS_2) in igneous rock, and one estimate of S input to agricultural soils states that 0 - 5 kg S ha^{-1} yr^{-1} are derived from the weathering of parent material (Whitehead, 2000). In the past, macronutrient fertilizers often contained S. The use of S-containing fertilizers such as superphosphate and ammonium sulfate has declined in favor of other sources (Havlin et al., 2005) and as a result have reduced S inputs to agricultural soils. Atmospheric inputs of S can vary depending on proximity to major industry. In areas of concentrated industrial activity, atmospheric S inputs have been reported as high as 200 kg ha^{-1} yr^{-1} (Whitehead, 2000). In recent decades, legislation aimed at reducing acid rain, has contributed to a reduction in atmospheric S deposition in the U.S. At a site in Shenandoah National Park, between 1989 and 1993, 12.75 kg S ha^{-1} yr^{-1} were deposited onto soils as combined wet and dry deposition as compared to 5.66 kg S ha^{-1} yr^{-1} between 2007 and 2011 (EPA, 2013; NADP, 2013). With reduced inputs of S from fertilizer and atmospheric deposition, agronomic crops should be monitored for S deficiency.

Leaching, volatilization, erosion, and removal in hay and animal products are loss pathways for S in grassland ecosystems (Nguyen and Goh, 1994). In intensively managed grassland systems, leaching losses of 11 - 43 kg S ha^{-1} yr^{-1} have been determined, with precipitation, soil characteristics, fertilization, and vegetative cover, all affecting leaching losses (Nguyen and Goh, 1994). In saturated soils, there may be volatile loss of S, but the quantities tend to be of little significance in regard to the total quantity of S cycled in grassland systems (Whitehead, 2000). Sulfur losses through erosion and surface runoff also tend to be small in unfertilized systems. Smith et al. (1983) found that surface runoff losses of S in unfertilized pastures was 0.9 kg ha^{-1} yr^{-1}, while in pastures receiving 43 kg S ha^{-1} yr^{-1} as superphosphate lost 5.5 kg S ha^{-1} yr^{-1}. For their hypothetical pasture, Wilkinson and Lowrey (1973) determined that the total ecosystem contained 1832.6 kg S ha^{-1} and of that 221.6 kg S ha^{-1} were actively cycling. Sulfur losses were estimated as 40.6 kg ha^{-1} yr^{-1} with 97% of that as leaching. Grassland systems managed for grazing tend to lose little S in livestock and products removed. Between 87 and 90% of sulfur ingested by livestock is returned to soils as manure and urine (Nguyen and Goh, 1994). While little S is exported in livestock, grazing has major effects on the cycling of S in pastures.

Influence of Grazing on the S Cycle

As with N, livestock have a major impact on S cycling in pastures. The majority of ingested S is returned to the pasture and recycled or transported to feeding and watering areas or into shade where S can be lost through leaching (Nguyen and Goh, 1994). The proportion of S in manure versus urine is highly dependent on the feed S concentration (Haynes and Williams, 1993). Like with N, a fixed quantity of S tends to be excreted as manure with the remainder excreted as urine. On average, the proportion of urine S to manure S is 1:1 (Nguyen and Goh, 1994). The majority of fecal S is in organic forms, while the majority of urinary S is inorganic SO_4^{2-} and is thus more easily plant available (Nguyen and Goh, 1994). Sakadevon et al. (1993) found that 1.6% of S applied in sheep manure was taken up by ryegrass pasture in the year following application, while 29% of urine S was taken up over the same period. The authors also concluded that the remaining S was likely immobilized into organic forms or was adsorbed onto soil surfaces and exchange sites with < 3 kg S ha^{-1} lost to leaching.

As with N and other nutrients, S is transferred by livestock from grazing areas to less productive areas near feeding and watering sources. Nguyen and Goh (1992) compared sheep camp areas to general grazing areas and found that camp area soils contained more S than did general grazing areas and increased quantities of S were mineralized from camp sites. The higher concentrations were attributed to increase excreta deposition and that transport of nutrients could deplete available S in general grazing areas. Little work has been done studying sulfur dynamics in pastures in the U.S. This may be related to the relatively high atmospheric S inputs to grassland systems in the past. As this atmospheric deposition is reduced, understanding sulfur dynamics in pasture systems will become more important.

Sulfur Requirements of Pasture Plants and Ruminant Livestock

Sulfur in plant tissue occurs primarily in the form of proteins. Approximately 90% of organic sulfur in plant tissue occurs as the amino acids: cysteine, cystine, and methionine (Stevenson and Cole, 1999). Mayland and Wilkinson (1996) stated that the range of adequate S concentrations in whole-plant tissue samples for cool-season grasses was 0.2-0.4%. Jones et al. (1991) reported the S sufficiency range for orchardgrass and white clover as 0.20-0.25 and 0.25-0.50%, respectively. Sulfur occurs with N in fixed proportions in amino acids. The N:S ratio is valuable in determining S deficiency; values greater than 14:1 are consider deficient (Jones et al., 1991).

The minimum dietary S requirement for all classes of beef cattle is 0.15% (NRC, 2000). Sulfur is essential for the synthesis of rumen microbial biomass, and is, therefore, important to digestion (Whitehead, 2000). As compared with beef cattle, sheep and dairy cows have a greater S requirement because of their higher rate of S removal in animal products (Nguyen and Goh, 1994).

MACRONUTRIENT CATION DYNAMICS

Potassium, Ca, and Mg are essential nutrients in pasture systems. They are grouped together here because of their similar dynamics in soils and plant tissue. As compared to N and P in grassland systems, there has been much less research focused on the dynamics and cycling of macronutrient cations (Kayser and Isselstein, 2005). This is possibly because there is little concern about the effects of cations lost from agriculture systems on the environment.

Inputs & Loss Pathways

Inputs of K, Ca, and Mg to pasture systems are primarily the weathering of parent material, fertilization, and inputs in supplementary feed. Potassium occurs in micas and feldspars in soil parent material (Whitehead, 2000). Calcium and Mg occur in a range of minerals, and in Virginia, the weathering of dolomitic limestone is an important source of both divalent cations. Rate of K input through weathering has been reported to range from 3 to 80 kg ha^{-1} yr^{-1} with much of the variability related to the age, texture, and mineralogy of the soils in question (Kayser and Isselstein, 2005). Of the three nutrients, K is most commonly applied to pasture systems as fertilizer, while Ca and sometimes Mg are added through the liming process (Whitehead, 2000). Atmospheric deposition is a minor input of macronutrient cations; at a site near Charlottesville, VA, average annual wet-deposition of K, Ca, and Mg were 0.88, 0.23, and 0.19 kg ha^{-1}, respectively, between 2007 and 2011 (NADP, 2013). Regardless of the quantity of input of cations to a pasture system, losses of these nutrients are likely to occur.

Leaching is a major loss pathway for macronutrient cations. Leaching losses are influenced by the quantities of exchangeable cations in the soil, its clay content, and texture (Kayser and Isselstein, 2005). Inputs of K can displace Ca and Mg from exchange sites leading to leaching of the latter two nutrients (Whitehead, 2000; Havlin et al 2005). Wilkinson and Lowrey (1973) estimated that 2.7, 15.8, and 4.4% of the total ecosystem pools of K, Ca, and Mg were actively cycled, respectively, and losses, mostly through leaching, from the hypothetical ecosystem were 143.7, 179.5, and 76.7 kg ha^{-1} yr^{-1} for K, Ca and Mg, respectively. Export of cations by livestock is small; as little as 10, 8, and 20% of K, Mg and Ca ingested are retained in livestock tissues or are exported as milk (Kayser and Isselstein, 2005). No volatile losses of macronutrient cations occur (Whitehead, 2000). Runoff losses of cations, though small in comparison to leaching, have been reported from fertilized tall fescue pasture (Wilkinson and Lowrey, 1973; Owens et al., 2003) and from native prairie (Timmons and Holt, 1977). While several loss pathways for macronutrient cations exist, leaching losses are the most important in pasture systems, and livestock can play a major role in cation losses.

Influence of Grazing on the K, Ca, and Mg Cycles

Livestock influence macronutrient cycles by stimulating uptake through the removal of vegetation, the excreting high concentrations of nutrients over small areas, and through the spatially heterogeneous nature of that excretion. Potassium is the only nutrient primarily excreted in urine; 10-30% of K is excreted as manure, while the majority of Ca and Mg are excreted in that form (Haynes and Williams, 1993). Potassium in urine is in ionic form, available for plant uptake, while Ca and Mg are primarily excreted in insoluble forms (Whitehead, 2000). Sakadevan et al (1993) found that 31% of K in a urine patch was recovered in herbage within 1 year and that leaching losses of 2.0, 8.0, and 2.9 kg ha^{-1} of K, Ca, and Mg, respectively, were recorded under urine patches. With large applications of K and N in urine, herbage from urine patches accumulates high concentrations of K as compared to Ca and Mg, and the increased ratio of K/(Ca + Mg) can pose health risks to livestock (Kayser and Isslestein, 2005). A urine patch can contain up to the equivalent of 1000 kg K ha^{-1}, and such rates are well beyond the uptake ability of pasture plants resulting in high concentrations of K moving downward through the soil profile displacing Ca and Mg from exchange surfaces often leading to leaching loss of Ca and Mg and relatively small losses of K (Kayser and

Isselstein, 2005). Carran and Theobald (2000) documented this process when they found concentrations of Ca and Mg under the fence line of a long-term pasture to be higher than the concentrations in the general grazing area; concentrations of K were higher in the general grazing area than under the fence line.

As with other nutrients, the uneven return of K, Ca, and Mg caused by the uneven deposition of manure and urine across a pasture can influence the dynamics of those nutrients. Soil K concentrations have been shown to be 3 - 4 times greater near a pasture water source than in general grazing areas (West et al., 1989). Hay feeding areas have also been shown to accumulate soil K (Owens et al., 2003; Flores and Tracy, 2012). Owens et al (2003) reported that pastures used for winter hay feeding lost 47 kg K ha^{-1} yr^{-1}; 60% of the loss was as surface runoff, 26% lost to leaching, and 14% lost as sediment. The same pasture lost 112 kg Ca ha^{-1} yr^{-1} and 71 kg Mg ha^{-1} yr^{-1} with more than 80% of those losses as leaching. In comparison, pastures used for summer grazing lost 14, 58, and 30 kg ha^{-1} yr^{-1} of K, Ca, and Mg, respectively, over the same period. As with other nutrients, feeding and watering areas and shade can be important loss pathways for K, Ca, and Mg in pasture systems.

Potassium, Ca, and Mg Requirements of Pasture Plants and Ruminant Livestock

Potassium, Ca, and Mg ions contribute to the balance of osmotic potential within the plant cell membrane (Whitehead, 2000). Calcium contributes to the structural integrity of cell walls as calcium pectate, and Mg is a constituent of chlorophyll (Whitehead, 2000). Jones et al. (1991) reported that the K sufficiency ranges for tall fescue, orchardgrass, and white clover were 3.00 - 4.00%, 2.60 - 3.50%, and 2.00 - 2.50%, respectively, based on 4 - 6 week clipping intervals.

The National Research Council (2000) lists the dietary cation requirements of dry beef cows as 0.60, 0.19, 0.12% for K, Ca, and Mg, respectively, and the requirements for lactating beef cows as 0.70, 0.27, and 0.20% for K, Ca, and Mg, respectively. All three nutrients occur in the body tissue, blood serum and milk of cattle (Whitehead, 2000). Potassium is involved with maintaining the osmotic pressure and pH of cells, the vast majority of Ca is in the form of hydroxyapatite in bone, and Mg is also a constituent of the skeleton and is involved in neuromuscular function (Spears, 1994; Whitehead, 2000). Imbalances of these nutrients can cause major health issues in cattle.

Hypomagnesemia, commonly known as grass tetany, may be the most important mineral-related health problem in beef production on pasture (Spears, 1994; Shewmaker et al., 2004). It can reduced animal gains and lead to death (Whitehead, 2000). It has been estimated that grass tetany causes $400 million of losses in the U.S. and 40% of those losses occur on tall fescue pasture (Shewmaker et al., 2004). High concentration of N and K in herbage can depress Mg concentrations increasing the occurrence of grass tetany (Fontenot et al., 1989). A ratio of K/(Ca+Mg) in herbage is sometimes used to determine grass tetany risk; a value > 2.2 based on milliequivalents is considered high risk (Shewmaker et al., 2004). The high concentrations of K and N and low concentrations of Ca and Mg in urine can increase the grass tetany risk of herbage from urine patches (Kayser and Isselstein, 2005). Limiting spring application of N and K and supplementation of Mg have been recommended to reduce incidence of grass tetany (Robinson et al., 1989). An understanding of cation nutrient dynamics in pasture systems is important in preventing grass tetany.

MICRONUTRIENT DYNAMICS

Given their low concentrations in soils and plant tissue and their relative adequacy for plant production in many areas, study of the cycles of micronutrients have been limited. Further, few studies have examined micronutrients in pasture ecosystems. Though they are required in small quantities, deficiencies can have major impacts on plant and livestock production. Discussion will be limited here to nutrients commonly tested for in soil and plant tissue analysis programs: Fe, Zn, Cu, Mn, and B.

Inputs & Loss Pathways

A major input of micronutrients to agroecosystems is through weathering of soil parent material (Whitehead, 2000). Soil properties and environmental factors are often more important in affecting micronutrient availability than their actual content in soils (Gupta et al, 2001). Availability of Mn, Zn, Fe and B for plant uptake decreases as pH is increased through liming (Stevenson and Cole, 1999; Whitehead, 2000; Gupta et al, 2001). Micronutrient fertilizers are commonly applied as seed treatments or foliar sprays as opposed to soil applications (Gupta et al., 2001; Havlin et al., 2005). More B is applied to alfalfa than to any other agronomic crop (Stevenson and Cole, 1999). Macronutrient fertilizers and sewage sludge are sometimes sources of micronutrients, but atmospheric deposition is generally negligible (Whitehead, 2000). Losses of micronutrients from soils are minimal in relation to the total soil content, though B, which commonly occurs as $H_2BO_3^-$, BO_3^{2-}, and H_3BO_3 in soil solution, is susceptible to leaching losses (Stevenson and Cole, 1999).

Influence of Grazing on Micronutrient Cycles

As with other nutrients, livestock concentrate micronutrients and distribute them unevenly across pastures. Livestock excrete micronutrients, except B, as primarily manure; B excretion occurs in both urine and manure (Haynes and Williams, 1993; Whitehead, 2000). Joblin and Keogh (1979) reported that herbage from urine patches contained lower concentrations of Fe and Mn but similar Zn and Cu concentrations compared to non-urine patch herbage. This reduction may have been caused by the temporary increase in soil pH from the urine application. Whitehead (2000) calculated that 80 g B ha^{-1} yr^{-1} could be lost to leaching from a grass/clover pasture stocked for beef production and that no leaching losses of Fe, Mn, Cu, or Zn would likely occur. Information regarding the redistribution of micronutrients across pastures could not be found.

Micronutrient Requirements of Pasture Plants and Ruminant Livestock

Iron, Zn, Mn and Cu are required for a variety of functions in plants including enzyme activity, and B is important is cell wall structure (Stevenson and Cole, 1999; Havlin et al., 2005). Jones et al. (1991) reported sufficiency concentrations for orchardgrass as 50 - 200, 50 - 150, 20 - 50, 3 - 5, and 8 - 12 mg kg^{-1} for Fe, Mn, Zn, Cu and B, respectively, and ranges for white clover as 50 - 100, 25 - 100, 15 - 25, 5 - 8, and 25 - 50 for Fe, Mn, Zn, Cu and B, respectively.

Iron is important in livestock as a constituent of hemoglobin and is seldom deficient in grazing animals (Whitehead, 2000). Copper, Zn and Mn are all constituents and activators of a variety of enzymes essential to livestock (Spears, 1994). Boron, though present in all animal tissues at small concentration, is considered a non-essential nutrient for livestock (Whitehead, 2000). Both dry and lactating beef cows require 50, 10, 30, 40 mg kg^{-1} of Fe, Cu, Zn, and Mn, respectively (NRC, 2000). Copper deficiency occurs on a range of soils worldwide, while Mn and Zn deficiencies in grazing animals are rare (Reid and Horvath, 1980; Spears, 1994; Whitehead, 2000). While required in much smaller quantities in both plants and livestock than macronutrients, micronutrient deficiencies and imbalances can seriously limit the productivity of agricultural systems.

CONCLUSIONS

Continued study of nutrient dynamics of pasture system is required for their efficient management. Many studies in the U.S. have examined the yield and quality responses of forages to nutrient inputs though mostly in the context of hay production, while Europe and New Zealand provide much of the research on nutrient cycling in pastures. Pastures are commonly thought to efficiently recycle nutrients, and while this is often the case, significant nutrient loss potential exists. With an increased need to limit P losses to the environment and with declining atmospheric S inputs, continued study of the nutrient cycles and dynamics of pasture systems is required to meet the management objectives of producers, regulations of legislators, and demands of consumers.

REFERENCES

Barrow, N.J. and L.J. Lambourne. 1962. Partition of excreted nitrogen, sulphur, and phosphorus between the faeces and urine of sheep being fed pasture. Aust. J. Agric. Res. 13:461-471.

Bush, L., J. Boling, and S. Yates. 1979. Animal Disorders. In: Tall Fescue. R.C. Buckner and L.P. Bush, Editors. ASA-CSSA-SSSA, Madison, WI. pp: 247-292.

Carran, R.A. and P.W. Theobald. 2000. Effects of excreta return on properties of a grazed pasture soil. Nutr. Cycl. Agroecosyst. 56:79-85.

Clough, T.J., R.R. Sherlock, K.C. Cameron, and S.F. Ledgard. 1996. Fate of urine nitrogen on mineral and peat soils in New Zealand. Plant Soil 178:141-152.

Dougherty, W.J., N.K. Fleming, J.W. Cox, and D.J. Chittleborough. Phosphorus transfer in surface runoff from intensive pasture systems at various scales: A review. J. Environ Qual. 33:1973-1988.

Environmental Protection Agency (EPA). 2013. Clean Air Status and Trends Network. Site: SHN418.

Floate, M.J.S. 1970. Mineralization of nitrogen and phosphorus from organic materials of plant and animal origin and its significance in the nutrient cycle of grazed upland and hill soils. J. Br. Grassl. Soc. 25:295-302.

Fontenot, J.P., V.G. Allen, G.E. Bunce, and J.P. Goff. 1989. Factors influencing magnesium absorption and metabolism in ruminants. J. Anim. Sci. 67:3445-3455.

Gupta, U.C., F.A. Monteiro, and J.C. Werner. 2001. Micronutrients in grassland production. Proceedings of the XIX International Grassland Congress. Sao Paulo, Brazil.

Hallock, D.L., R.H. Brown and R.E. Blaser. 1965. Relative yield and composition of Ky. 31 fescue and coastal bermudagrass at four nitrogen levels. Agron. J. 57: 539-542.

Haynes, R.J., and P.H. Williams. 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Adv. Agron. 49:119-199.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2005. Soil Fertility and Fertilizers. 7th ed. Pearson, Upper Saddle River, NJ.

Hojjati, S.M., T.H. Taylor, and W.C. Templeton, Jr. 1972. Nitrate accumulation in rye, tall fescue, and bermudagrass as affected by nitrogen fertilization. Agron. J. 64:624-627.

Jarvis, S.C. 2000. Soil-Plant-Animal Interactions and Impacts on Nitrogen and Phosphorus Cycling and Recycling in Grazed Pastures. In: Grassland Ecophysiology and Grazing Ecology. CABI International. pp: 317-337.

Joblin, K.N. and Keogh, R.G. 1979. The element composition of herbage at urine patch sites in a ryegrass pasture. J. Agr. Sci. 92:571-574.

Karn, J.F. 2001. Phosphorus nutrition of grazing cattle: A review. Anim. Feed Sci. Technol. 89:133-153.

Kayser, M and J. Isselstein. 2005. Potassium cycling and losses in grassland systems: a review. Grass Forage Sci. 60:213-224.

Ledgard, S.F. 2001. Nitrogen cycling in low input legume-based agriculture, with emphasis on legume/grass pastures. Plant Soil 228:43-59.

Lockyer, D.R. and D.C. Whitehead. 1990. Volatilization of ammonia from cattle urine applied to grassland. Soil Biol. Biochem. 22:1137-1142.

Maguire, R.O., P.J.A. Kleinman, C. Dell, D.B. Beegle, R.C. Brandt, Q.M Ketterings, and J.M. McGrath. 2011. Manure management in reduced tillage and grassland systems: A review. J. Envron. Qual. 40:292–301.

Mayland, H.F. and S.R. Wilkinson. 1996. Mineral Nutrition. In: Cool-Season Forage Grasses. L.E. Moser, D.R. Buxton, and M.D. Casler, Editors. ASA-CSSA-SSSA. Madison, WI. pp: 165-191.

National Atmospheric Deposition Program (NADP). 2013. Annual Summary: Sites VA 27 and VA 00.

National Research Council (NRC). 2000. Nutrient requirements of beef cattle. 7th Rev. ed. Natl. Acad. Press, Washington, D.C.

Nguyen, M.L. and K.M. Goh. 1992. Sulphur mineralization and release of soluble organic sulphur from camp and non-camp soils of grazed pastures receiving long-term superphosphate applications. Biol. Fert. Soils 14:272-279.

Nguyen, M.L. and K.M. Goh. 1994. Sulphur cycling and its implications on sulphur fertilizer requirements of grazed grassland ecosystems. Agric. Ecosyst. Environ. 49:173-206.

Owens, L.B., R.W. Van Keuren, and W.M. Edwards. 2003. Non-nitrogen nutrient inputs and outputs for fertilized pastures in silt loam soils in four small Ohio watersheds. Agric. Ecosyst. Environ. 97:117-130.

Parfitt, R.L. 1980. A note on the losses from a phosphate cycling under grazed pasture. New Zeal. J. Exp. Agr. 8:215-217.

Reid, R.L. and D.J. Horvath. 1980. Soil chemistry and mineral problems in farm livestock. A review. Anim. Feed Sci. Technol. 5:95-167.

Robinson, D.L., L.C. Kappel, and J.A. Boling. 1989. Management practices to overcome the incidence of grass tetany. J. Anim. Sci. 67:3470-3484.

Rotz, C.A., F. Taube, M.P. Russelle, J. Oenema, M.A. Sanderson, and M. Wachendorf. 2005. Whole-farm perspectives of nutrient flows in grassland agriculture. Crop Sci. 45:2139-2159.

Sakadevon, A.D. Mackay, and M.J. Hedley. 1995. Influence of sheep excreta on pasture uptake and leaching of sulfur, nitrogen and potassium from grazed pastures. Aust. J. Soil Res. 31:151-162.

Schnyder, H., F. Locher, and K. Auerswald. 2010. Nutrient redistribution by grazing cattle drives patterns of topsoil N and P stocks in a low-input pasture ecosystem. Nutr. Cycl. Agroecosyst. 88:183-195.

Schroeder, P.D., D.E. Radcliffe, and M.L. Cabrera. 2004. Rainfall timing and poultry litter application rates effects on phosphorus loss in surface runoff. J. Environ. Qual. 33:2201-2209.

Shewmaker, G.E., D.A. Johnson, H.F. Mayland, S.A. Martin, and S.B. Hansen. 2004. Elemental uptake in relation to root characteristics of tall fescue. Commun. Soil Sci. Plant Anal. 35:1339-1355.

Stevenson, F.J. and M.A. Cole. 1999. Cycles of Soil. 2nd ed. Wiley, New York, NY.

Smith, C.M., P.E.H. Gregg, and R.W. Tillman. 1983. Drainage losses of sulphur from yellow-grey earth soil. New Zeal. J. Agr. Res. 26:363-371.

Spears, J.W. 1994. Minerals in Forages. In: Forage Quality, Evaluation, and Utilization. G.C. Fahey, Editor. ASA, CSSA, SSSA. pp. 281-317.

Timmons, D.R. and R.F. Holt. 1977. Nutrient losses in surface runoff from a native prairie. J. Envron. Qual. 6:369-373.

Tracy B., K. Albrecht, J. Flores, M. Hall, A. Islam, G. Jones, W. Lamp, J. MacAdam, H. Skinner, and C. Teutsch. 2013. Forage yield, weed suppression and fertilizer nitrogen replacement value (FNRV) of alfalfa-tall fescue mixtures. Grassland Science in Europe. 18:xx-xx.

West, C.P., A.P. Mallarino, W.F. Wedin, and D.B. Marx. 1989. Spatial variability of soil chemical properties in grazed pastures. Soil Sci. Soc. Am. J. 53: 784-789.

White-Leech, R., K. Liu, L.E. Sollenberger, K.R. Woodard, and S.M. Interrante. 2013. Excreta deposition on grassland patches. I. Forage harvested, nutritive value, and nitrogen recover. Crop Sci. 53:688-695.

Whitehead, D.C. 2000. Nutrient Elements in Grassland: Soil-Plant-Animal Relationships. CABI, New York, NY.

Wilkinson, S.R. and R.W. Lowrey. 1973. Cycling of Mineral Nutrients in Pasture Ecosystems. In: Chemistry and Biochemistry of Herbage. Volume 2. G.W. Butler and R.W. Bailey, Editors. Academic Press, New York. pp. 248-315.

Wilkinson, S.R. and D.A. Mays. 1979. Mineral Nutrition. In: Tall Fescue. R.C. Buckner and L.P. Bush, Editors. ASA-CSSA-SSSA, Madison, WI.

Williams, P.H., and R.J. Hayes. 1990. Influence of improved pastures and grazing animals on the nutrient cycling within New Zealand soils. New Zeal. J. Ecol. 14:49-57.

Zemechik, R.A., K.A. Albrecht, and M.K. Schultz. 2001. Nitrogen replacement values of kura clover and birdsfoot trefoil in mixtures with cool-season grasses. Agron. J. 93:451-458.

Chapter 3. Pasture Soil and Herbage Nutrient Dynamics through Five Years of Rotational Stocking

ABSTRACT

Plant and soil nutrient concentrations should change minimally in pastures because most nutrients are efficiently recycled within the system. This process, however, has not been well documented in rotationally stocked tall fescue- [*Schendonorus phoenix* (Scop.) Holub] based pastures. The objectives of this study were to: (1) examine temporal changes in plant available soil nutrient concentrations in two creep grazing systems grazed by cows that differed in size, (2) determine how winter hay feeding and use of improved forages for creep grazing affected soil and herbage nutrient concentrations, and (3) examine the relationship between and variability within soil and herbage nutrient concentrations. From 2008 to 2012, soil and herbage samples were collected from 102 paddocks in an experiment that compared two creep grazing systems (dedicated and forward) stocked with two frame scores of cow (large and small). Nutrient concentrations in hay feeding paddocks (HFP) and dedicated creep grazing paddocks (DCP), planted with improved forages, were compared to those used for rotational stocking (RSP). Significant differences in soil nutrient concentration between creep grazing systems were observed prior to the initiation of grazing ($p < 0.05$) and were consistent through time. Soil pH and soil P, K, Ca, Mg, and B concentrations declined significantly over the course of the experiment ($p < 0.05$). Increased concentrations of soil P, K, Fe and Cu were found in HFP as compared to RSP, likely caused by importation of nutrients in hay. Fertilization at establishment of the improved forage species mixture in DCP was likely the cause of increased concentrations of P, K, Ca, Zn,

and B compared to RSP. Soil P and K showed greater variation across samples than did herbage P and K. The correlations between soil nutrient concentrations and herbage concentrations collected from the same paddock were weak. Because of variability in soil nutrients within paddocks, herbage nutrient analysis may provide a better assessment of pasture fertility status. Though year-to-year changes in soil nutrient concentration were small, assessment of the nutrient status of pasture systems is essential to optimize forage yield and livestock health.

INTRODUCTION

Understanding nutrient dynamics in pastures is important for improving livestock production, reducing costs associated with fertilizer application, and limiting nutrient losses to the environment. Studies of measured changes in pasture fertility over time and between grazing systems are few (Sigua et al., 2006), especially from tall fescue-based cool-season pastures. Soil and plant nutrient concentrations should change minimally over time in pastures because most nutrients are recycled and few are retained and removed by livestock. Between 60-99% of nutrients ingested by livestock are returned to pasture as urine and manure (Haynes and Williams, 1993). In continuous stocking systems, livestock have been shown to transport nutrients across pastures and concentrate them, as manure and urine, near feeding and watering areas and in shade (West et al., 1989; Franzluebbers et al., 2000; Sanderson et al., 2010). In rotational stocking systems, however, it has been suggested that this redistribution is limited by use of pasture subdivision with fencing to better distribute livestock and thus manure across the pasture (Williams and Haynes, 1990; Sigua et al., 2010). Studying the effects of stocking management on bahiagrass (*Paspalum notatum* Flügge) planted on sandy soils, Sigua et al. (2006) observed no linear trend in pH, P, K, Ca or Mg concentration under 15 years of rotational stocking. The effects of rotational stocking on nutrient concentrations in tall fescue-based cool season pastures have not been well quantified, and this information is important for decision making around fertilizer and lime applications and to meet the nutrient requirements of livestock.

Achieving high weaning weights in cow-calf production systems requires providing adequate nutrition to both calf and dam (Allen and Collins, 2003). Creep grazing, the practice of providing calves access to paddocks from which the cows are excluded, has been shown to increase calf weight gains by 80% as compared to calves fed milk alone (Blaser et al., 1986). Two forms of this type of management are defined: creep grazing or dedicated creep grazing, where calves have consistent access to a paddock often planted to a high quality forage, and forward creep grazing, where calves have access to the next paddock forward in a rotational stocking system (Allen et al., 2011). Endophyte infected tall fescue is a predominant forage species used for cow-calf production in the Appalachian region (Paterson et al., 1995). The negative effects of the alkaloids produced by infected tall fescue on livestock production are well known (Paterson et al., 1995). Dedicated creep grazing, wherein a paddock has been planted with species other than endophyte infected tall fescue, could improve calf performance by reducing the amount of alkaloid consumed (Harvey and Burns, 1998). The effects of the type of creep grazing system on nutrient dynamics have not been well documented. Dedicated creep grazing requires certain paddocks to be grazed by calves and not cows. The limited dry matter requirements of calves compared with cows could suggest that dedicated creep paddocks may have less herbage utilization and slower nutrient cycling than paddocks to which cows also have access (Floate, 1970). The nutrient composition of herbage depends on the genus, species, and variety of the plants in the sward (Fleming, 1973). If alternative forage species or varieties are planted in creep grazing paddocks, calves could carry nutrients from those paddocks into rotational stocking paddocks through manure and urine. This could potentially alter nutrient dynamics in dedicated creep grazing compared with forward creep grazing.

As forage dry matter accumulation slows during winter, feed supplementation is often required to meet livestock needs. The feeding of dry hay is a common practice in pasture-based livestock systems, and hay feeding can affect the nutrient dynamics of pastures. Nutrients are imported with hay and concentrations have been shown to increase in feeding areas (West et al., 1989; Franzluebbers et al., 2000; Flores and Tracy, 2012). With animal feeding in concentrated areas significant quantities of manure and urine are deposited. These areas of concentrated nutrients can also become loss pathways as nutrients are leached or lost on soil particles by erosion (Haynes and Williams, 1993). It is expected that soil nutrient concentrations in pasture would increase with repeated hay feeding.

Analysis of plant tissue and soils are two methods for evaluating the nutrient status of an agroecosystem. The relationships between crop yields and soil test nutrient concentrations have been well established (Havlin et al., 2005). The nutrient composition of pasture herbage, however, depends on several factors in addition to soil fertility and fertilization including the genus, species, and cultivar in question, their stage of maturity, and the season and temperature (Fleming, 1973). Baker and Reid (1977) studied the nutrient concentrations of grasses and legumes grown on a variety of soils in West

Virginia. They noted weak correlations between soil nutrient concentrations and plant tissue nutrient concentrations. The lack of correlation between plant and soil nutrients may be related to several factors. Because of topography and the deposition of manure and urine, soil nutrient concentrations are heterogeneous across pastures. The root systems of pasture plants also have access to a greater volume of soil than may be collected in a routine soil sample. For these reasons, herbage analysis could provide a less variable and thus more accurate assessment of the fertility status of cool-season pastures.

Evaluation of temporal nutrient dynamics in tall fescue-based pasture under different management strategies can provide information about the movement of nutrients among grazed and feeding paddocks and changes in nutrient availability through time. This study was part of a multi-institution, interdisciplinary research project, "Economic Pasture-Based Beef Systems in Appalachia." The cow-calf research for the project provides the context for this study. The study objectives were to: (1) examine temporal changes of plant available soil nutrient concentrations in two creep grazing systems grazed by cows that differed in size, (2) determine how hay feeding and use of improved forages for dedicated creep grazing might affect soil nutrient concentrations and pasture herbage nutrient concentrations across time, and (3) examine the relationship between soil and herbage nutrient concentrations and determine the variability associated with both nutrient measurement methods.

METHODS AND MATERIALS

Research Site

This study was conducted at the Virginia Tech Shenandoah Valley Agricultural Research and Extension Center in Steele's Tavern, Virginia (Lat: 37°55'49", Long: -79°12'50", Elev: 540 m). The soil at the site is a Frederick and Christian silt loam complex (fine, mixed, semiactive, mesic Typic Paleudults and fine, mixed, semiactive, mesic Typic Hapludults, respectively). Average precipitation is 882 mm annually. Average monthly temperatures range from 1°C in January to 22°C in July (SCAN, 2013) (Figure 3.1).

Experimental Design

Ninety Angus and Angus-cross cows were split into twelve groups and rotationally stocked in 12 pastures divided into 8 or 9 paddocks (mean paddock area = 0.8 ha). The experiment had four treatments replicated three times. The first treatment compared brood cows with a frame score of (3.0 - 5.0) (SM) with brood cows with a frame score of (5.1 - 7.0) (LG). Cows in the LG treatment were approximately 10 cm taller at mature hip height compared to SM treatment cows. LG cows were heavier; to maintain equal stocking rates between frame score treatments, the SM treatment included one more cow-calf pair than did the LG. The second treatment compared forward creep grazing (FWD) with dedicated creep grazing (DED). In the FWD treatment, calves had access, through creep gates, to the next paddock in the rotation, and in the DED treatments calves had consistent access to a dedicated creep paddock (DCP) planted with improved forages (Figure 3.2). The experimental unit was one set of 8 or 9 paddocks grazed by a group of cow-calf pairs (N = 12). The 4 treatment combinations were applied in a randomized complete block design (n = 3).

During April through September of 2008 through 2012, cow-calf pairs were rotationally stocked through the 3 replicates of the 4 grazing system treatments. During late summer several paddocks were excluded from the stocking rotation in each system and forage was allowed to accumulate for grazing from November through January. Hay, grown offsite, was fed from open-topped hay rings in a specified paddock of each grazing system, HFP, usually from January through mid-April. The same HFP were used each year, while forage was stockpiled in different paddocks during different years.

Pasture

Rotational stocking paddocks consisted of previously established tall fescue, orchardgrass (*Dactylis glomerata* L.), Kentucky bluegrass (*Poa pratensis* L.), and white clover (*Trifolium repens* L.). In September 2006, novel endophyte tall fescue (MaxQ) and alfalfa (*Medicago sativa* L.) were planted in DCP to attempt to improve forage intake and digestibility as compared to the RSP. Novel endophyte tall fescue seed has been infected with an endophyte that does not produce the toxic alkaloids responsible for poor livestock performance on wild-type tall fescue. Following establishment, DCP were amended to correct soil pH, P, and B to promote alfalfa growth. In winter 2007 and 2009, 4.5 kg ha^{-1} of both, white and red (*Trifolium pratense* L.) clover seed were broadcast over all pastures.

Soil Sampling & Analysis

Soil samples were collected each November from 2007 through 2012. Six soil cores were collected at a 0 – 15 cm depth from each paddock (102 total paddocks). Cores were aggregated by paddock for analysis. Watering and loafing areas and obvious manure patches were avoided. Soil pH, available P, K, Ca, Mg, Fe, Zn, Cu, Mn, and B concentrations were determined at the Virginia Tech Soil Testing Laboratory. The 1:1 (vol/vol) water pH was determined, and P, K, Ca, Mg, Fe, Zn, Cu, Mn, and B were extracted using a Mehlich 1, 0.05N HCl in 0.025N H_2SO_4, extracting solution before analysis by inductively coupled plasma atomic emission spectrometry (ICP-AES). The estimated cation exchange saturation percentages were calculated for K, Ca, and Mg from the respective charge, atomic weight, and available quantity of each element. Higher base cation saturation percentages indicate greater cation availability.

Herbage Sampling & Analysis

Pasture herbage samples were harvested from each paddock on approximately the 15th of the month from April through October (2008 to 2012). Herbage was harvested at 8 cm stubble height from a randomly selected 0.75 m by 3.5 m swath of the paddock using a Swift Forage Harvester (Swift Current SK, Canada). Samples were dried at 60°C for at least 48 h. A stratified subset of 20 paddocks were selected for nutrient analysis of their herbage. Herbage N concentration was determined by combustion at the Ruminant Nutrition Laboratory at Virginia Tech. Herbage P, K, S, Ca, Mg, Fe, Zn, Cu, Al, Mn, and B concentrations were determined using microwave-assisted acid extraction and ICP-AES at A & L Eastern Labs, Richmond, VA.

Statistical Analysis

Soil Nutrient Concentrations between Grazing Systems through Time

Multivariate analysis of covariance (MANCOVA) was used to examine differences in soil nutrient concentrations between the four treatments across the 5-year study.

Nutrient concentrations of soil samples from each paddock were summarized by grazing system using the median to reduce the impact of outlying values. The HFP and DCP paddocks were excluded from this analysis. Time was included in the model as a linear term, and an interaction term was added to test if the effect of time differed between grazing treatments. Each grazing system was considered a block; this related changes in nutrient concentration through time to the specific grazing system in question and not to the average nutrient concentration for the entire experiment. Model residuals were assessed for multivariate normality using Malahanobis distances. MANCOVA contrasts were selected for pairwise comparison between the 4 grazing systems; Bonferroni correction was used to protect against inflated Type 1 error (Bonferroni adjusted p = 0.0083).

ANCOVA was performed on each nutrient separately to determine significant model terms. Use of MANCOVA prior to ANCOVA provides protection from increased Type 1 error rates due to multiple comparisons. The initial ANCOVA model was:

$$Y_{ih} = \mu + \tau_i + \phi_h + \theta_{ih} + \beta_{1i}x_{ih} + E_{ih}$$

where Y = nutrient concentration; τ = treatment effect (i = 1, 2, 3, 4); ϕ = block effect (h = 1, 2, 3); θ = experimental unit block effect; β_1 = time effect by treatment; E = experimental error. A subset model was created for each nutrient including both blocking factors and only the significant ($p < 0.05$) model terms. The subset models were used to determine the coefficient of the time effect and to calculate the coefficient of determination (R^2) for each nutrient model. Treatments were checked for homogeneity of variance and model residuals were assessed for normality. Tukey's Honest Significant Difference was used to determine mean separation ($\alpha = 0.05$).

Soil nutrient concentrations were also compared between treatments in 2007 and 2012 using ANOVA. Assumptions were checked, and Tukey's HSD was used to determine mean separation ($\alpha = 0.05$).

Soil and Herbage Nutrient Concentrations among RSP, HFP, and DCP Paddocks

Soil and herbage nutrient concentrations in RSP, HFP, and DCP were compared using MANCOVA; one analysis each for soil and herbage data. The experimental unit for this analysis was one paddock not an aggregate of all paddocks in one grazing system as in the previous analysis. Paddocks used in this analysis were a subset of those with both soil and herbage data. Herbage data were selected from the June harvest to maximize the number of paddocks sampled. To balance contrast variance and take into account block variation, paddocks were selected at random to create an incomplete block design (4 paddocks, 3 treatments, 4 years, 5 blocks; $n = 16$). MANCOVA contrasts were selected for pairwise comparison among the three paddock types. Bonferroni correction was used to protect against inflated Type 1 error (Bonferroni adjusted $p = 0.017$).

Analysis of covariance was used to determine differences for each nutrient. The model included the paddock type effect, year effect, blocking, and paddock type by year interaction. Treatments were checked for homogeneity of variance, and model residuals were assessed for normality. Three outliers, defined as having a value greater than the group mean plus four times the group standard deviation exclusive of the value in question were replaced with the median group value. Herbage K, Ca, Cu, and B and soil

Ca, Mg, and Mn were transformed by $\log_{10}$, and analyses were rerun. Herbage Al and Fe were excluded from this and subsequent analysis due to soil contamination and, therefore, highly skewed distributions. Tukey's Honest Significant Difference was used to determine mean separation ($\alpha = 0.05$).

Relationships between Soil and Herbage Concentrations

The Pearson correlation coefficient was calculated for each nutrient to assess the relationship between soil and herbage concentrations. Soil sampled in November of each year was correlated to herbage harvested in April, July, and October of that year in addition to April of the following year. The DCPs were excluded because of the improved species mixture and fertilization of those paddocks. All soil nutrients and all herbage nutrients except N were transformed $\log_{10}$. Soil K, Ca, and Mg saturation percentages were also compared with herbage K, Ca, and Mg concentrations, respectively. Correlations were significant with a p-value < 0.05 ($n = 66$ or 80).

Soil nutrient concentrations and herbage nutrient concentrations from April, July, and October of 2008 - 2011 were used to calculate the coefficient of variation (CV) for each nutrient. Data from DCP were excluded, and no nutrients were transformed. The standard error for each CV was calculated with nonparametric bootstrapping. The bootstrapping technique used here entailed dropping a random observation, recalculating the CV, and then replacing the dropped observation and iterating that process 999 times to form a distribution of CVs from which the standard error could be determined.

RESULTS

Soil Nutrient Concentrations between Grazing Systems through Time

Multivariate analysis of covariance indicated significant differences among the soil nutrient concentrations of the four grazing system treatments ($p < 0.001$) with time as a significant covariate ($p < 0.001$). There was, however, insignificant grazing system by year interaction ($p = 0.896$) (Table 3.1). Contrasts indicated significant differences between all pairwise combinations of grazing systems except FWD LG and FWD SM.

Analysis of covariance of each soil nutrient (Table 3.2) showed that all but K, Zn, and Mn differed among grazing systems (Figure 3.3). The effect of time was significantly related to pH, P, Ca, Mg, Fe, Cu, and B. Soil pH was significantly lower in DED SM at 6.3 as compared with FWD LG, FWD SM, and DED LG (Figure 3.3 A). The two DED treatments did not differ significantly in terms of soil P, with average concentrations of 21.8 and 19.3 mg kg^{-1} for LG and SM, respectively. Soil P was, however, lower in FWD treatments as compared to DED LG (Figure 3.3 B). Soil Ca, Mg, and B were highest in DED LG followed by FWD SM, with lowest concentrations in FWD LG and DED SM (Figures 3.3 D, E, & J). Soil Fe and Cu concentrations were higher in DED LG with an Fe concentration of 11.5 mg kg^{-1} in DED LG versus an average Fe concentration of 7.1 mg kg^{-1} in the other three treatments. Herbage Cu concentration in DED LG was 0.7 mg kg^{-1} compared to an average of 0.5 mg kg^{-1} in the other three treatments (Figure 3.3 G & H). Coefficients of the effect of time indicated Fe and Cu increased by 0.33 and 0.002 mg kg^{-1} yr^{-1}, respectively (Table 3.2). Soil pH decreased by 0.05 units yr^{-1}, and P, Ca, Mg, and B decreased by 1.27, 28.44, 4.75 and 0.02 mg kg^{-1} yr^{-1}, respectively (Table 3.2; Figure 3.4 & 3.5). The R^2 values for subset nutrient models ranged from 0.78 for P to 0.63 for B (Table 3.2; Figure 3.4 & 3.5).

To assess whether differences existed among treatments before grazing began, soil nutrients were compared between 2007 (pre grazing) and 2012 (Table 3.3). Soil pH, P, Ca, Mg, and B concentrations were greater in 2007 than in 2012. Soil Mn concentration was 2.1 mg kg^{-1} greater in 2012 than in 2007. Differences between grazing system treatments were similar to those shown in Figure 3.2. There was no year by grazing system interaction for any nutrient.

Soil and Herbage Nutrient Concentrations among RSP, HFP, and DCP Paddocks

Results of MANCOVA of soil nutrient concentrations indicated significant differences between paddock types ($p < 0.001$) with a significant effect of time ($p < 0.001$) and no paddock type by time interaction ($p = 0.560$) (Table 3.4). Pairwise MANCOVA contrasts indicate that all paddock types differed significantly.

Analysis of covariance by each soil nutrient (Table 3.5) indicated that pH, P, K, Ca, Fe, Zn, Cu, and B differed among paddock types and that time was a significant covariate explaining variation in pH, Ca, Mg, Fe, Zn, and B. Soil pH was higher in DCP, 7.0, compared with HFP and RSP, 6.7 and 6.5 respectively (Figure 3.6 A). Soil P and K concentrations were lowest in the RSP paddocks compared with DCP and HFP (Figure 3.6 B & C). Calcium concentrations in DCP were significantly greater than in HFP and RSP (Figure 3.6 D). Iron and Cu concentrations were higher in HFP compared to RSP (Figure 3.6 G & H). Boron concentration was 33% higher in DCP compared with RSP (Figure 3.6 J) and showed significant paddock type by time interaction (Figure 3.7).

Results of MANCOVA analyzing herbage nutrient concentrations indicated significant differences between paddock types ($p < 0.001$) (Table 3.6). Time was a significant covariate ($p < 0.001$), and no paddock type by time interaction was found. Pairwise MANCOVA contrasts indicated that all paddock types were significantly different.

Analysis of covariance of each herbage nutrient (Table 3.7) showed that N and K varied significantly between paddock types (Figure 3.8). Herbage N concentrations were higher in DCP, HFP, compared with RSP (Figure 3.8 A). Average K concentrations were greater in HFP herbage compared with DCP and RSP (Figure 3.8 D). Herbage K in HFP also increased with time, while K concentrations remained stable in DCP and RSP (Figure 3.9). Copper concentrations increased significantly through time (Table 3.7).

Relationships between Soil and Herbage Concentrations

Coefficients of variation for soil nutrients ranged from 0.25 for B and Ca to 0.75 for P (Table 3.8). For April-harvested herbage, CVs ranged from 0.18 for P to 1.35 for Fe. July harvests ranged from 0.18 for Mg to 0.62 for Fe, and October harvest ranged from 0.16 for S to 0.94 for Fe. For P and K, soil CVs were nearly twice as large as for any of the herbage harvests. Herbage Fe has the highest CV for any nutrient, soil or herbage.

Correlations between soil nutrient concentrations and herbage harvested in April, July, or October or April of the following year were weak (Table 3.9). The strongest correlation was 0.41 between soil P and October herbage P. Correlations between soil P and herbage P were significant at all herbage harvest dates. Soil calcium and July-harvested herbage Ca were negatively correlated ($p < 0.05$). Herbage K was significantly correlated to both exchangeable soil K and K saturation percentage ($p < 0.05$).

DISCUSSION

Differences in the plant available soil nutrient concentrations between the grazing treatments were noted in 2007 prior to the initiation of grazing. The effect of time was consistent across the four treatments as indicated by non-significant treatment by time interaction for all nutrients. If the grazing treatments had major effects on nutrient dynamics and recycling, nutrient concentrations likely would have diverged through the five years of grazing. This divergence did not occur suggesting that the effect size of any change in nutrient recycling or redistribution was probably small between the grazing treatments.

Given the relatively small quantity of nutrients removed through livestock and the efficient recycling of nutrients in pasture systems, it was expected that pH and soil nutrient concentrations would remain relatively constant across the five-year study. A decline was, however, detected in soil pH and several other nutrients through the duration of the study. Decreasing soil pH over time was likely associated with acid rain, decomposition of organic matter, ion uptake by plants, and leaching losses of cations (Havlin et al., 2005). A loss of 0.05 pH units yr^{-1} or 0.8% of average concentrations per year was detected. The decline in pH was much less in these silt loam soils as compared to a pH decline of 1.53% per year shown under grazing and haying on sandy soils (Sigua et al., 2006). Extractable P decreased by 0.96 - 1.59 mg kg^{-1} yr^{-1} or 5 - 9% per year. While loss of P in grazing systems has been shown in other studies (Sigua et al., 2006), the magnitude of decline shown in this study was greater than expected. Part of the decline in P concentration over time might be explained by uneven deposition of manure across paddocks and heavy concentrations near watering and loafing areas (West et al., 1989; Mathews et al., 1999). It is unlikely, however, this would entirely account for the decline in extractable soil P shown here. Decreasing concentrations of Ca and Mg through time are supported by studies on effects of urine and manure on cation ratios in soil (Weeda, 1977). Higher K concentrations caused by urine deposition can replace Ca and Mg on soil particle exchange surfaces leading to leaching of the two divalent cations (Kayser and Isselstein, 2005). Data from this study did not, however, show increasing K concentration over time probably because of excreta deposition primarily near water sources and shade as opposed to general grazing areas (West et al., 1989; Mathews et al., 1999).

Several paddocks in each grazing system were managed differently, and it was hypothesized that this management could have affected the nutrient content of herbage and soils. Paddocks used for hay feeding showed higher concentrations of extractable soil P and exchangeable K, and lower concentrations of soil Ca. Soil P and K were higher in hay feeding as opposed non-hay feeding areas in a previous study at the same site (Flores and Tracy, 2012). The importation of P and K in hay was likely responsible for the increased concentrations in HFP soils. Lime and P and B fertilizers applied to DCP at establishment significantly increased soil pH, P, Ca, and Mg as compared to the unfertilized RSP. Boron concentrations were also significantly higher in DCP due to fertilization for the alfalfa component and declined significantly with time (Figure 3.7). Boron can be lost from soil through leaching of H_3BO_3, $H_2BO_3^-$, and BO_3^{2--} (Stevenson and Cole, 1999), and this may explain the decline in concentration. Higher Zn availability in DCP is counterintuitive as DCP had higher pH which should reduce Zn availability (Moraghan and Mascagni, 1991; Halvin et al., 2005). Concentrations of Zn have been reported in P fertilizers (Whitehead, 2000); it is possible that the P fertilization of HFP was also a source of Zn. Copper and Fe concentrations in HFP soils were also higher compared to RSP. Iron increased through the duration of the study, but this appears to be related to outlying values in 2011. Little to no system loss of Fe and Cu should be expected at lower grazing management intensities (Whitehead, 2000). Increased P, K, Fe, Cu concentrations in HFP can probably be explained by the importation of nutrients through hay, and increased P, K, Ca, Mg, Zn, and B concentrations in DCP were most likely a result of fertilization at establishment.

While P, K, Ca, Mg, Zn, Fe, Cu, and B concentrations in soil differed significantly among paddock types, only N and K concentrations were significantly affected in herbage. Higher herbage N in DCP was likely caused by the higher protein content of the alfalfa present in those swards. Potassium and N imported into HFP as hay would have been present in excreta in forms easily taken up by plants. Repeated urine deposition increased N concentration in the herbage of bahiagrass patches for more than 84 days (White-Leech et al., 2013). Increased herbage K has been associated with manure pats. Weeda (1977) studied the effects of manure on perennial ryegrass (*Lolium perenne* L.) and white clover pasture. He found that 62% of manure K was recovered in herbage within six weeks and 93% K recovery 14 months after manure depositions (Weeda, 1977). This is in agreement with the result showing increasing levels of herbage K in HFP as opposed to RSP.

Meeting the fertility requirements through soil testing and fertilization will help to ensure maximal dry matter production (Havlin et al., 2005). The relationship between soil and herbage nutrient concentrations is important in understanding the value of soil testing in determining the nutrient status and mineral concentration of pasture herbage and thus livestock feed. Correlations between soil and herbage nutrient concentrations were lower than expected. High spatial heterogeneity in nutrient concentration is common in pasture soils and is mostly associated with concentrated nutrient patches caused by excreta deposition throughout paddocks (Kuriuki et al., 2009). Pasture herbage was sampled from a single random swath at several dates through the growing seasons, while soil was sampled at 6 randomly selected cores per paddock each November. Soils and herbage were not sampled from exactly the same location within paddocks or the same time of year. Sampling the rhizosphere soil of the plants harvested would likely have a higher correlation with herbage concentrations. Soil tests of a pasture do not necessarily provide an indication to the nutrient concentration of the herbage growing in that pasture. Herbage nutrient analysis is required to determine if the herbage could meet the nutrient requirements of livestock.

The CVs of soil and plant nutrients were assessed to compare their variability and utility for fertility evaluation. The CVs for herbage P and K were smaller than those for plant available soil P and K. Therefore, herbage nutrient concentrations may provide more stable values for assessing P and K fertility in pasture systems. Contamination from soil, however, is a major problem for assessing Fe and Al concentrations in plant tissue (Jones et al., 1991). Coefficients of variation for Fe in pasture herbage were large, and were probably caused by soil contamination of herbage samples. Herbage samples must be washed prior to analysis if assessments of Fe or Al are to be made (Jones et al., 1991).

CONCLUSIONS

This study yielded several important findings in regard to the nutrient dynamics of soil and plants in cool-season pastures. Concentration of several soil nutrients declined over the course of the study. Soil testing is important to monitor changing soil pH and P concentrations, though changes from one year to the next appeared to be small in these pasture soils. The rate of change in soil nutrient concentration with time did not differ between cow frame score and creep grazing treatments. Hay feeding sites accumulate nutrients, increasing concentrations in soil and herbage, and strategic placement of hay feeding sites can be used to increase fertility of selected areas. Long-term hay feeding in one location could lead to increased losses as soils become saturated with nutrients. Differences between creep grazing system and livestock frame score did not have significant impacts on soil nutrient concentrations. With large spatial heterogeneity in soil nutrient concentrations within paddocks, measurement of herbage nutrient concentrations could serve as a more accurate and stable integrator of the nutrient status of pasture systems as compared to soil testing.

References

Allen, V.G., C. Batello, E.J. Berretta, J. Hodgson, M. Kothmann, X. Li, J. McIvor, J. Milne, C. Morris, A. Peters and M. Sanderson. 2011. An international terminology for grazing lands and grazing animals. Grass Forage Sci. 66: 2–28.

Allen, V.G. and M. Collins. 2003. Grazing Management Systems. In: Forages: An Introduction to Grassland Agriculture, 6th ed. R.F. Barnes, C.J. Nelson, M. Collins, K.J. Moore, Editors. Blackwell, Ames, IA. pp. 473-501.

Baker, B.S. and R.L. Reid. 1977. Mineral concentration of forage species grown in central West Virginia on various soil series. West Virginia Agric. Exp. Stn. Bull. 657.

Blaser, R.E., R.C. Hammes, J.P. Fontenot, H.T. Bryant, C.E. Polan, D.D. Wolf, R.S. McClaugherty, R.G. Kline, and J.S. Moore. 1986. Forage-Animal Management Systems. Va. Agric. Exp. Stn. Bull. 86-87.

Fleming, G.A. 1973. Mineral Composition of Herbage. In: Chemistry and Biochemistry of Herbage. Volume 1. G.W. Butler and R.W. Bailey, Editors. Academic Press, New York. pp. 529-566.

Floate, M.J.S. 1970. Mineralization of nitrogen and phosphorus from organic materials of plant and animal origin and its significance in the nutrient cycle of grazed upland and hill soils. J. Br. Grassl. Soc. 25:295-302.

Flores, J.P., and B. Tracy. 2012. Impacts of winter hay feeding on pasture soils and plants. Agric. Ecosyst. Environ. 149:30-36.

Franzluebbers, A.J., J.A. Stuedemann and H.H. Schomberg. 2000. Spatial distribution of soil carbon and nitrogen pools under grazed tall fescue. Soil Sci. Am. J. 64: 635-639.

Harvey, R.W., and J.C. Burns. 1988. Creep grazing and early weaning effects on cow and calf productivity. J. Anim. Sci. 66:1109-1114.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2005. Soil Fertility and Fertilizers. 7th ed. Pearson, Upper Saddle River, NJ.

Haynes, R.J., and P.H. Williams. 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Adv. Agron. 49:119-199.

Jones, J.B., B. Wolf, and H.A. Mills. 1991. Plant Analysis Handbook. Micro-Marco Publishing, Athens, GA.

Kariuki, S.K, H. Zhang, J.L. Schroder, T. Hanks, M.E. Payton, and T. Morris. 2009. Spatial variability and soil sampling in a grazed pasture. Commun. Soil Sci. Plant Anal. 40:1674-1687.

Kayser, M and J. Isselstein. 2005. Potassium cycling and losses in grassland systems: a review. Grass Forage Sci. 60:213-224.

Mathews, B.W., J.P. Tritschler II, J.R. Carpenter, and L.E. Sollenberger. 1999. Soil macronutrient distribution in rotationally stocked kikuyugrass paddocks with short and long grazing periods. Commun. Soil. Sci. Plant Anal. 30:557-571.

Moraghan, J.T. and H.J. Mascagni. 1991. Environmental and soil factors affecting micronutrient deficiencies and toxicities. In: Micronutrients in Agriculture. ASA-CSSA-SSSA, Madison, WI. pp. 371–425.

Paterson, J., C. Forcherio, B. Larson, M. Samford, and M. Kerley. 1995. The effects of fescue toxicosis on beef cattle productivity. J Anim. Sci. 73: 889-898.

Sanderson, M.A., C. Feldman, J. Schmidt, A. Herrman and F. Taube. 2010. Spatial distribution of livestock concentration areas and soil nutrients in pastures. J. Soil Water Conserv. 65:180-189.

Saunders, W.M.H. 1984. Mineral composition of soil and pasture from areas of grazed paddocks, affected and unaffected by dung and urine. New Zeal. J. Agr. Res. 27:405-412.

Soil Climate Analysis Network (SCAN). 2013. Site: 2088, Shenandoah. Natural Resources Conservation Service.

Sigua, G.C. M.J. Williams, S.W. Coleman. 2006. Long-term effects of grazing and haying on soil nutrient dynamics in forage-based beef cattle operations. J. Sustainable Agric. 29:115-134.

Sigua, G.C., R.K. Hubbard, and S.W. Coleman. 2010. Quantifying phosphorus levels in soils, plants, surface water, and shallow groundwater associated with bahiagrass-based pastures. Environ. Sci. Pollut. Res. 17:210-219.

Stevenson, F.J. and M.A. Cole. 1999. Cycles of Soil. 2nd ed. Wiley, New York, NY.

West, C.P., A.P. Mallarino, W.F. Wedin, and D.B. Marx. 1989. Spatial variability of soil chemical properties in grazed pastures. Soil Sci. Soc. Am. J. 53: 784-789.

Weeda, W.C. 1977. Effects of cattle dung patches on soil tests and botanical and chemical composition of herbage. New Zeal. J. Agr. Res. 20:471-478.

White-Leech, R., K.L., L.E. Sollenberger, K.R. Woodard, and S.M. Interrante. 2013. Excreta deposition on grassland. II. Spatial pattern and duration of forage response. Crop Sci. 53:696-703.

Whitehead, D.C. 2000. Nutrient Elements in Grassland: Soil-Plant-Animal Relationships. CABI, New York NY.

Williams, P.H., and R.J. Hayes. 1990. Influence of improved pastures and grazing animals on the nutrient cycling within New Zealand soils. New Zeal. J. Ecol. 14:49-57.

Table 3.1: Skeleton MANCOVA table comparing soil nutrient concentrations by grazing system

Source	df	Wilks λ	Approx. F	P-Value
Grazing System	3	0.029	11.04	< 0.001
Block	2	0.024	25.48	< 0.001
Exp. Unit	6	0.013	5.37	< 0.001
Time	1	0.409	6.78	< 0.001
System x Time	3	0.674	0.67	0.896
Error	56			

Table 3.2: F statistics for model terms in ANCOVA of plant available soil nutrient concentrations by grazing system: FWD LG, FWG SM, DED LG and DED SM. Coefficients of determination (R^2) for each nutrient model using only significant model terms are listed. Coefficients for the effect of time in the subset models are measured in mg kg^{-1} yr^{-1}, excluding pH, plus one standard error.

Term	pH	P	K	Ca	Mg	Fe	Zn	Cu	Mn	B
Grazing Sys.	14.05***	7.73***	1.03	16.77***	10.61***	16.01***	1.05	15.90***	1.53	11.70***
Time	21.03***	16.27***	1.23	8.74**	5.14*	4.23*	1.22	4.43*	1.27	10.20**
Sys. × Time	0.55	0.60	0.27	1.14	1.76	0.23	0.32	0.06	0.26	0.51
Subset R^2	0.65	0.78	-	0.65	0.66	0.64	-	0.73	-	0.63
Time Coef. (S.E.)	-0.05 (0.01)	-1.27 (0.31)	-	-28.44 (9.65)	-4.75 (2.14)	0.33 (0.16)	-	0.02 (0.01)	-	-0.02 (0.01)

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 3.3: Analysis of variance of soil nutrient concentrations between grazing treatments in 2007 and 2012. Within a nutrient and year, differing letters indicated significant differences based on Tukey's HSD ($p < 0.05$). (FWD, forward creep system; DED, dedicated creep system; LG, 7 cows of frame score 5.1-7.0; SM, 8 cows of frame score of 3.0-5.0).

		pH	P	K	Ca	Mg	Fe	Zn	Cu	Mn	B
Treatment	*Year*		(mg kg^{-1})								
FWD LG	2007	6.66 ab	24.83	137.17	1063.50 b	217.50 ab	7.70 ab	2.27	0.50 b	14.23	0.50 b
FWD SM		6.72 a	23.33	136.83	1177.17 ab	255.67 a	6.27 b	2.55	0.48 b	14.45	0.57 ab
DED LG		6.60 ab	28.00	114.00	1413.33 a	254.33 a	11.03 a	2.60	0.70 a	11.87	0.63 a
DED SM		6.35 b	24.33	120.67	1127.33 b	195.33 b	6.40 b	2.57	0.50 b	12.13	0.50 b
FWD LG	2012	6.47 ab	16.33	114.67	990.33 b	202.33 ab	6.57 ab	2.17	0.57 b	15.67	0.40 b
FWD SM		6.47 a	12.67	132.33	1124.33 ab	232.33 a	6.46 b	1.93	0.47 b	17.17	0.50 ab
DED LG		6.47 ab	18.00	106.00	1202.33 a	209.33 a	9.07 a	2.10	0.80 a	12.50	0.50 a
DED SM		6.23 b	17.33	113.67	1001.00 b	187.33 b	7.13 b	2.30	0.53 b	15.73	0.43 b
Year Effect		**	***	ns	*	*	ns	*	ns	*	**
Trt × Year Int.		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 3.4: Skeleton MANCOVA table comparing soil nutrient concentrations by paddock type: RSP, DCP, and HFP.

Source	df	Wilks λ	Approx. F	P-Value
Paddock Type	2	0.029	11.80	< 0.001
Block	4	0.005	6.85	< 0.001
Exp. Unit	5	0.009	4.02	< 0.001
Time	1	0.268	6.57	< 0.001
Type × Time	2	0.925	0.93	0.560
Error	33			

Table 3.5: F statistics for model terms in ANCOVA of plant available soil nutrient concentrations by paddock type: RSP, DCP, and HFP.

Term	pH	P	K	Ca	Mg	Fe	Zn	Cu	Mn	B
Paddock Type	17.10***	16.32***	4.77*	27.80***	2.16	6.65**	8.55**	8.64***	3.15	19.02***
Time	7.15*	0.003	0.42	7.52**	4.89*	15.12***	7.87**	1.30	1.70	18.04***
Type × Time	0.73	0.84	2.31	2.73	2.84	1.46	2.28	0.63	1.23	3.31*

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 3.6: Skeleton MANCOVA table comparing herbage nutrient concentrations by paddock type: RSP, DCP, and HFP.

Source	df	Wilks λ	Approx. F	P-Value
Paddock Type	2	0.093	5.454	< 0.0001
Block	1	0.110	1.838	0.0087
Exp. Unit	5	0.154	1.145	0.2758
Time	4	0.196	9.848	< 0.0001
Type × Time	2	0.528	0.903	0.5853
Error	33			

Table 3.7: F statistics for model terms in ANCOVA of herbage nutrient concentrations by paddock type: RSP, DCP, and HFP.

Term	N	P	K	S	Ca	Mg	Zn	Cu	Mn	B
Paddock Type	7.54**	1.18	8.90***	2.85	3.18	0.14	0.64	3.20	0.18	0.16
Time	1.32	0.42	2.77	1.32	1.83	0.87	2.59	13.11***	1.56	1.00
Type × Time	0.72	0.26	3.51*	0.65	0.16	0.43	0.06	0.19	1.70	0.27

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 3.8: Coefficients of variation of plant available soil nutrient concentrations and pasture herbage nutrient concentrations (+/- standard error).

	Soil	*Herbage*		
	November	April	July	October
N	-	0.19 (0.02)	0.25 (0.02)	0.25 (0.02)
S	-	0.20 (0.02)	0.20 (0.02)	0.16 (0.01)
P	0.75 (0.06)	0.18 (0.02)	0.27 (0.03)	0.27 (0.03)
K	0.54 (0.05)	0.22 (0.02)	0.29 (0.02)	0.30 (0.03)
Ca	0.25 (0.04)	0.26 (0.05)	0.30 (0.03)	0.23 (0.04)
Mg	0.26 (0.02)	0.20 (0.03)	0.18 (0.01)	0.26 (0.06)
Fe	0.46 (0.04)	1.35 (0.44)	0.62 (0.11)	0.94 (0.27)
Zn	0.54 (0.10)	0.35 (0.03)	0.30 (0.02)	0.79 (0.19)
Cu	0.71 (0.14)	0.38 (0.07)	0.27 (0.02)	0.84 (0.26)
Mn	0.31 (0.03)	0.45 (0.03)	0.55 (0.04)	0.48 (0.04)
B	0.25 (0.02)	0.47 (0.07)	0.29 (0.02)	0.43 (0.04)
n =	*80*	*66*	*80*	*80*

Table 3.9: Correlation coefficients (r) between soil nutrient concentrations, collected in November, and herbage nutrient concentrations from selected months of the growing season in which the soil was tested and the following season. Significant correlations (*p < 0.05*) are denoted with an asterisk.

	April	July	October	April
	---------------------	Current Season	--------------------	Following Season
P	0.35*	0.34*	0.41*	0.30*
K	0.08	0.23*	0.00	0.07
Ca	-0.10	-0.31*	0.13	0.08
Mg	0.07	-0.22	0.22	0.05
Fe	0.09	-0.08	0.13	-0.15
Zn	-0.15	-0.11	-0.17	0.38*
Cu	0.07	0.12	0.10	-0.03
Mn	-0.06	0.19	0.15	0.03
B	-0.07	-0.11	-0.12	0.14
K Saturation / K	0.19	0.22*	0.06	0.08
Ca Saturation / Ca	0.03	0.07	0.13	-0.02
Mg Saturation / Mg	0.08	0.07	0.19	0.12
n =	*66*	*80*	*80*	*64*

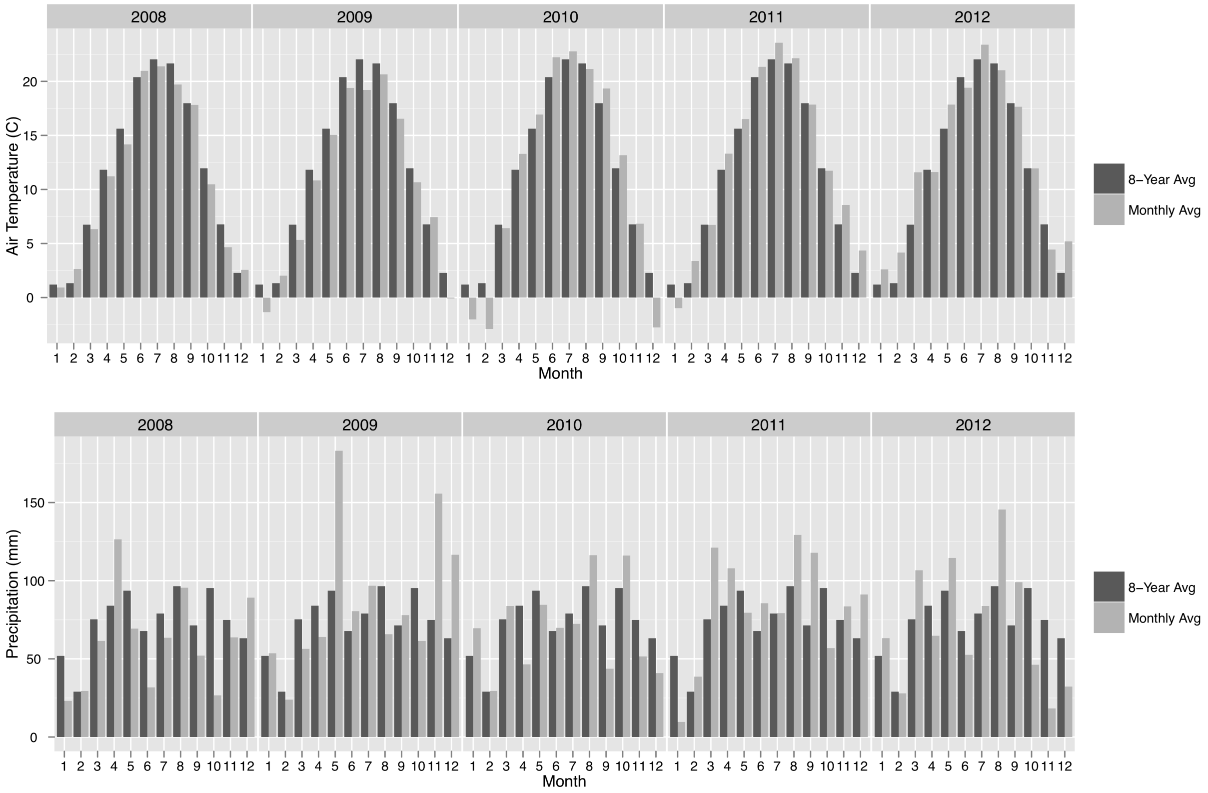


Figure 3.1: Average monthly air temperature and precipitation and 8-year averages for Steele's Tavern, VA (SCAN, 2013).

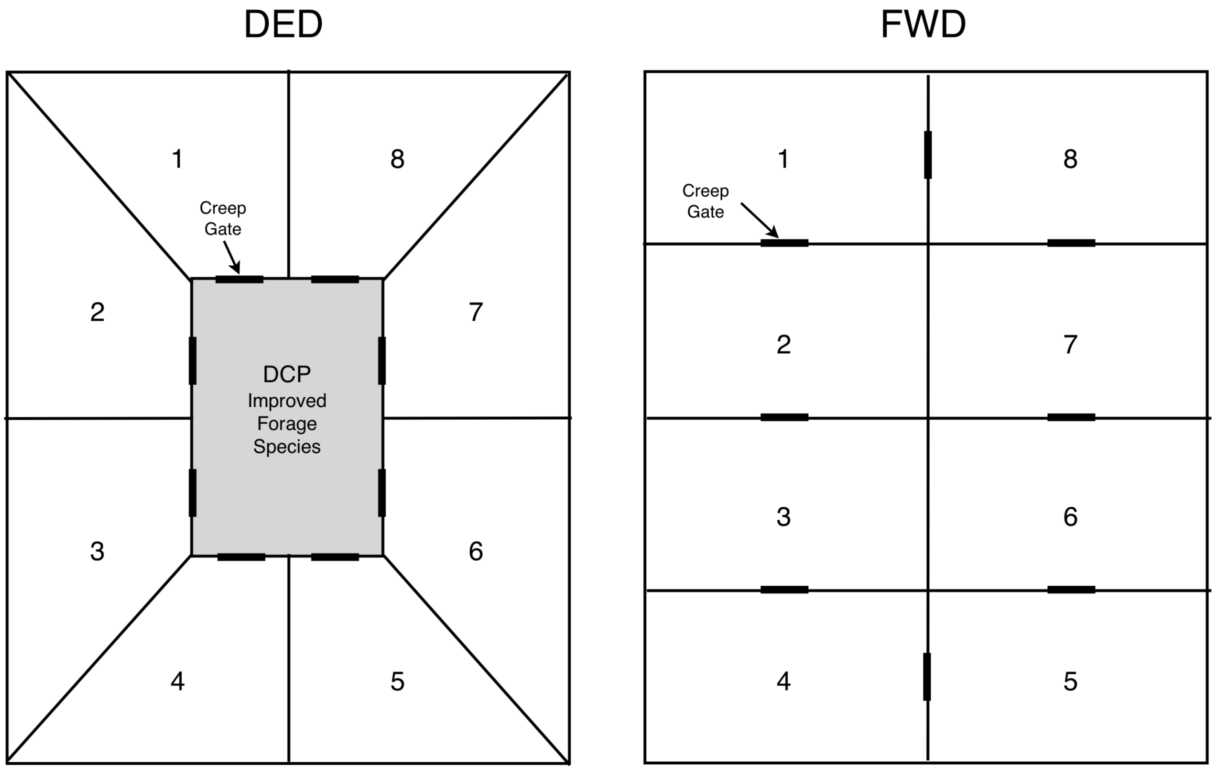


Figure 3.2: Schematic diagram of dedicated creep system (DED) and forward creep system (FWD). Creep gates allow calves to pass through, while excluding the cows. In DED, calves always had access to the dedicated creep paddock (DCP), which had been planted with alfalfa and novel endophyte tall fescue (MaxQ). In FWD, calves have access to the next paddock forward in the rotation (e.g. when cows are stocked in paddock #1, calves can access paddocks #1 and #2).

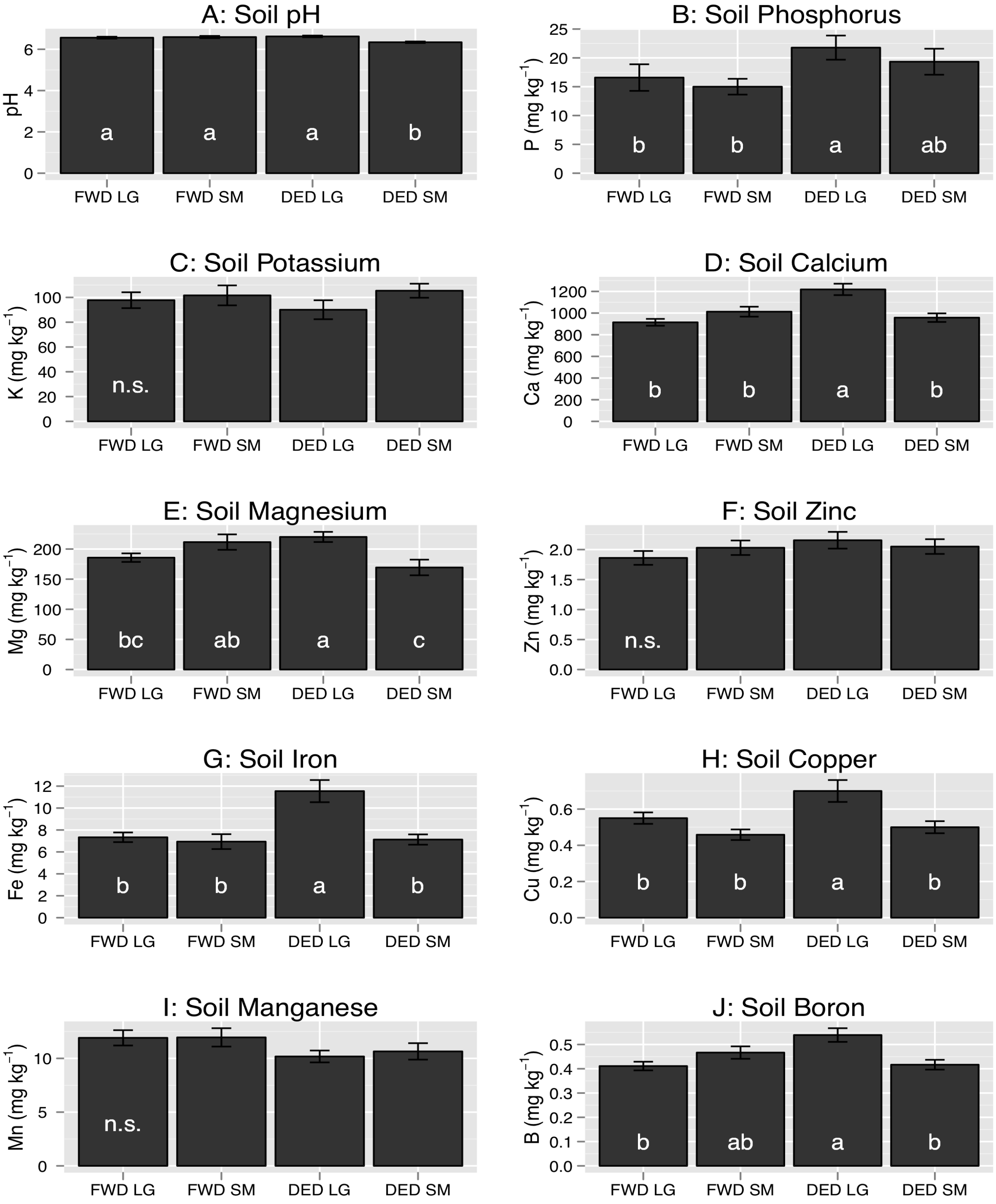
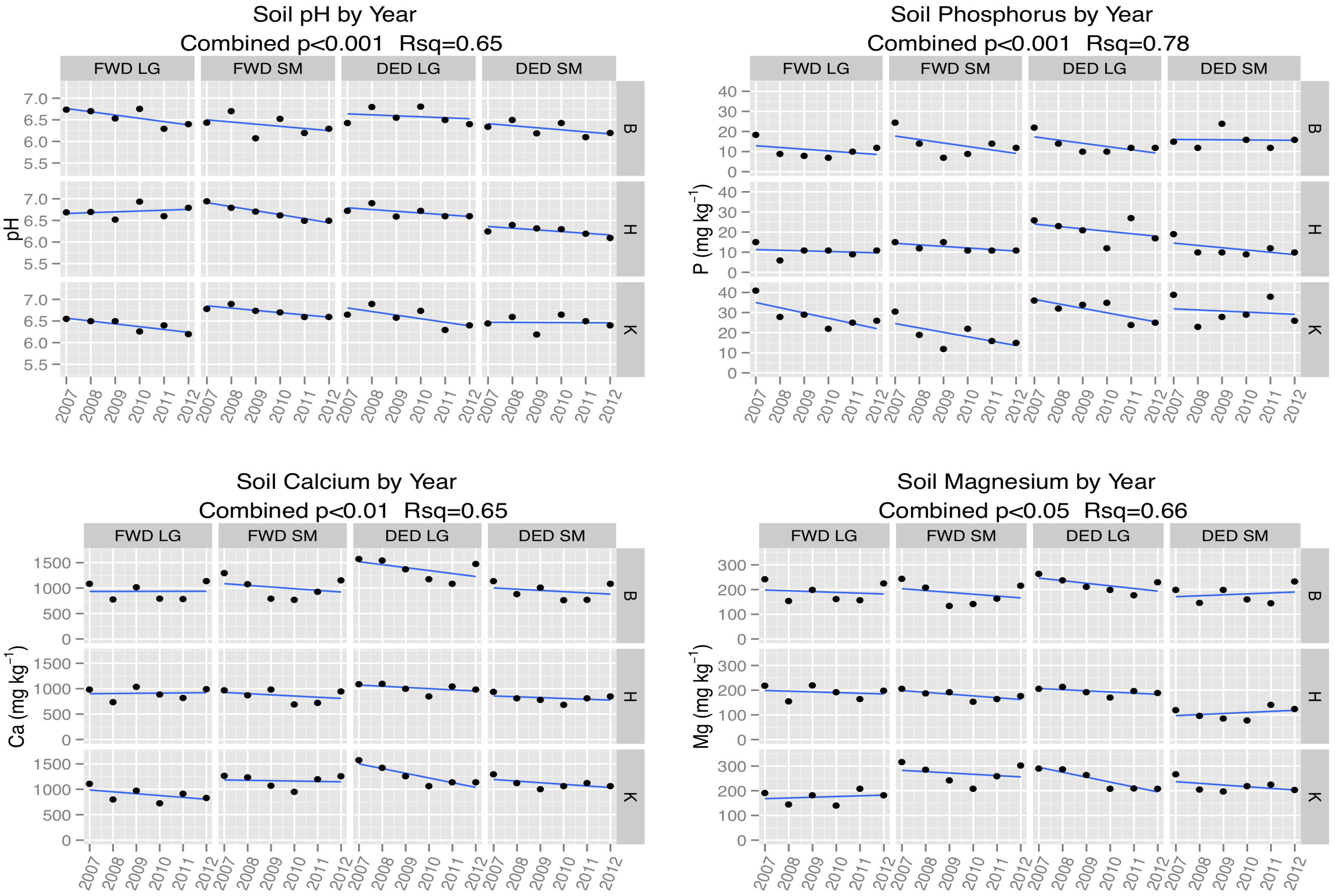


Figure 3.3: Soil nutrient concentration by grazing system (Six year average). Error bars are one standard error. Within a nutrient, differing letters indicated significant differences based on Tukey's HSD ($p < 0.05$). (FWD, forward creep system; DED, dedicated creep system; LG, 7 cows of frame score 5.1 - 7.0; SM, 8 cows of frame score of 3.0 - 5.0).


Soil pH by Year
Combined p<0.001 Rsq=0.65

Soil Phosphorus by Year
Combined p<0.001 Rsq=0.78

Soil Calcium by Year
Combined p<0.01 Rsq=0.65

Soil Magnesium by Year
Combined p<0.05 Rsq=0.66

Figure 3.4: Soil pH, P, Ca and Mg by year, grazing system (FWD, forward creep system; DED, dedicated creep system; LG, 7 cows of frame score 5.1 - 7.0; SM, 8 cows of frame score of 3.0 - 5.0) and block (B, H and K). The p-value for the combined effect of time across the 12 grazing systems and the R^2 of that model are listed.

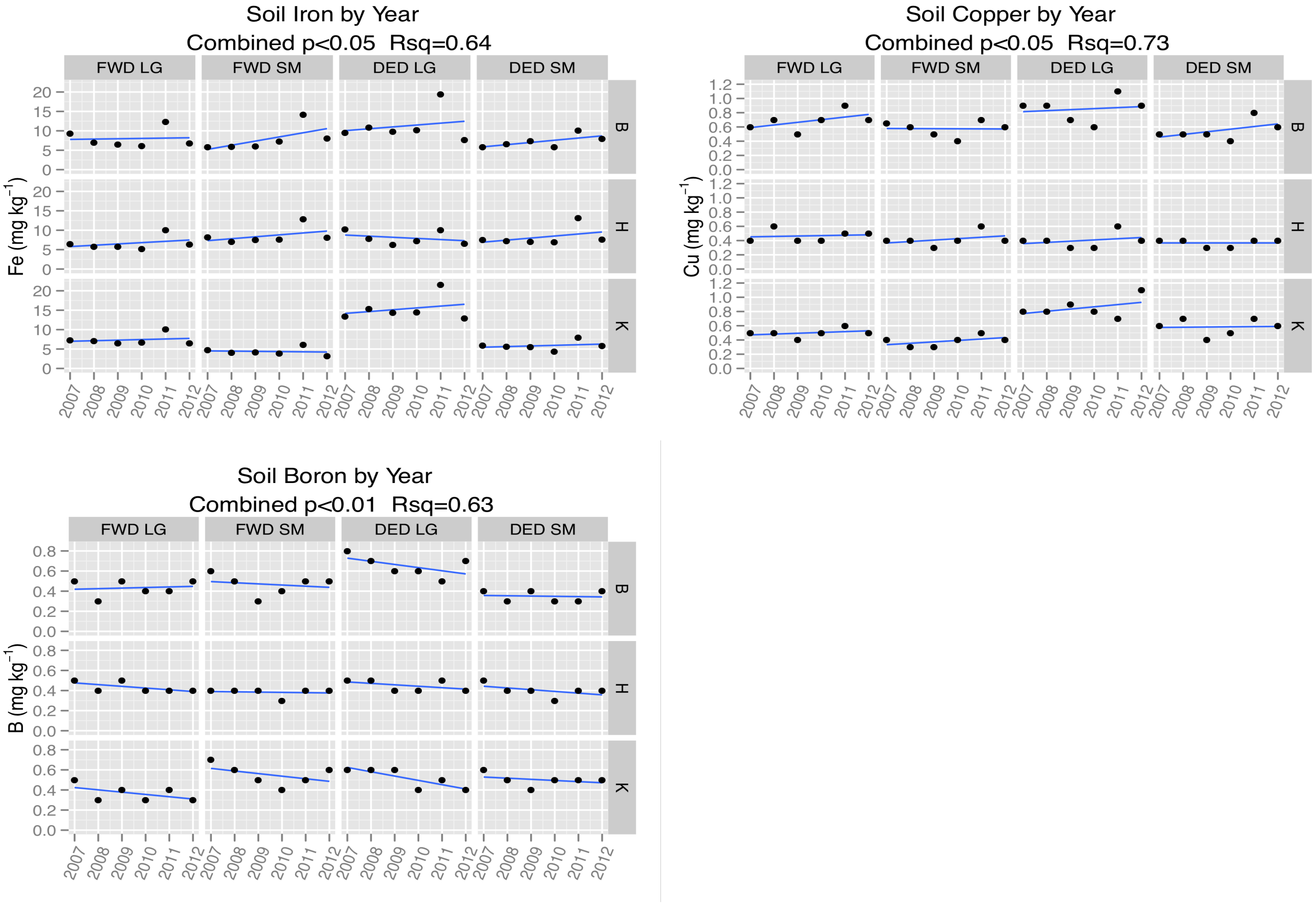


Figure 3.5: Soil Fe, Cu, and B by year, grazing system (FWD, forward creep system; DED, dedicated creep system; LG, 7 cows of frame score 5.1 - 7.0; SM, 8 cows of frame score of 3.0 - 5.0), and block (B, H and K). The p-value for the combined effect of time across 12 grazing systems and the R^2 of that model are listed.

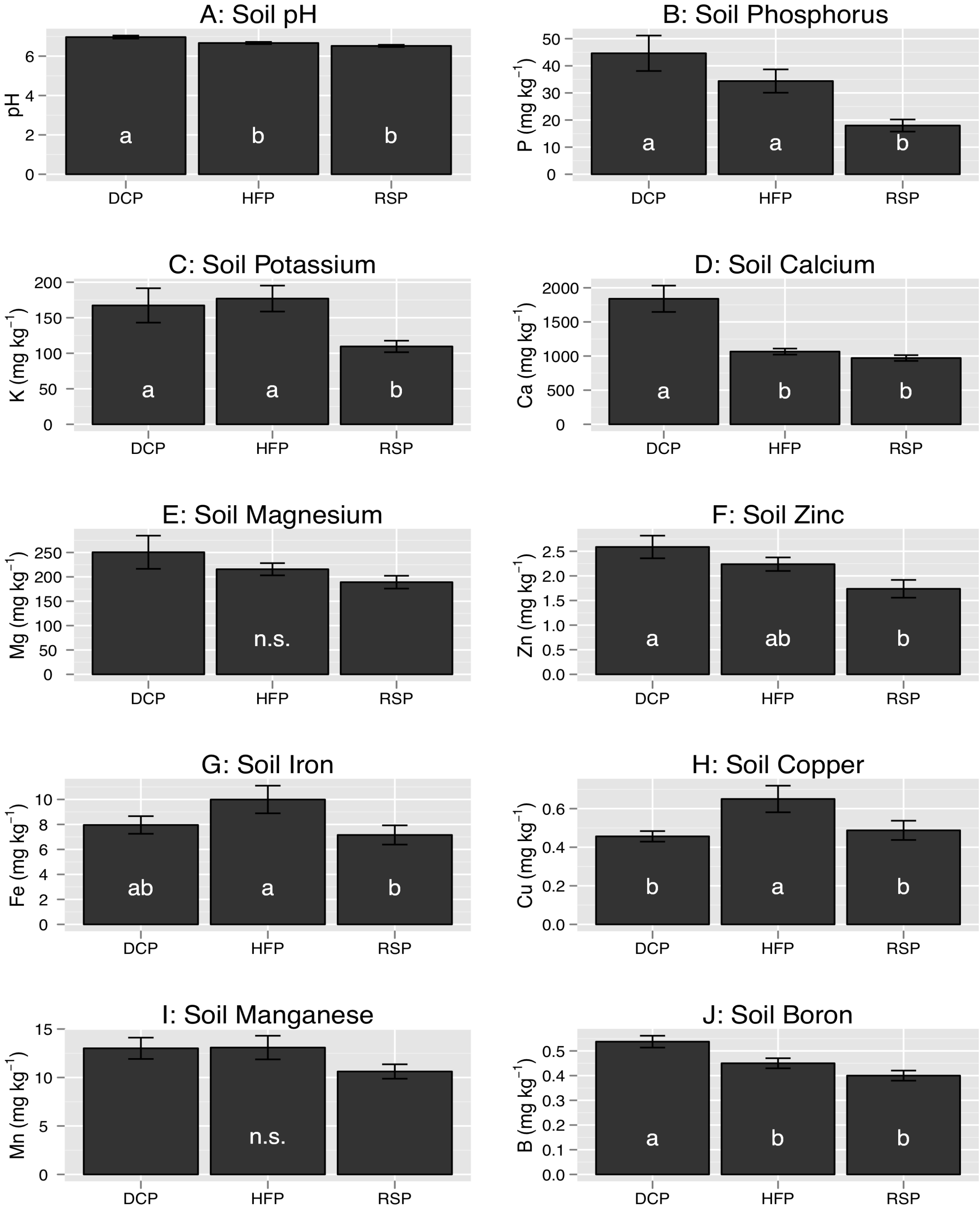


Figure 3.6: Soil nutrient concentration by paddock type (four year average). Error bars are one standard error. (DCP, dedicated creep paddock; HFP, hay feeding paddock; RSP, rotational stocking paddock). Within a nutrient, differing letters indicated significant differences based on Tukey's HSD ($p < 0.05$).

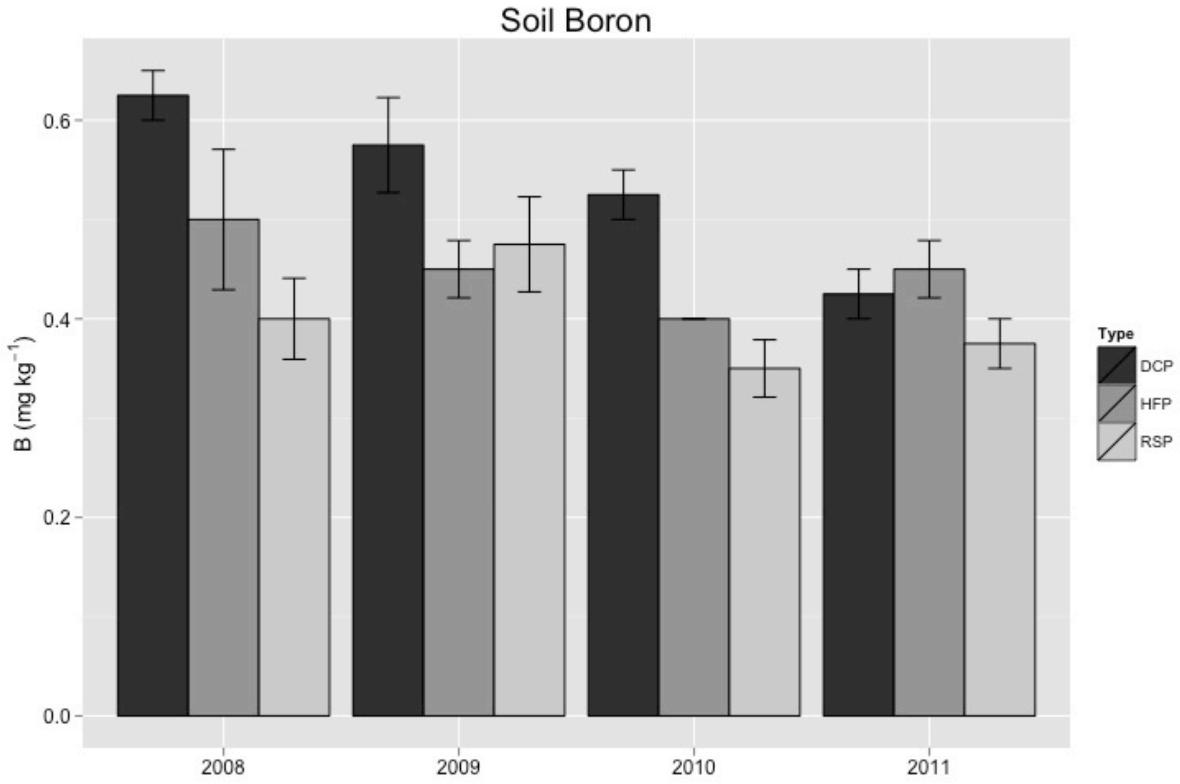


Figure 3.7: Soil B by paddock type and year. (DCP, dedicated creep paddock; HFP, hay feeding paddock; RSP, rotational stocking paddock). Error bars are one standard error.

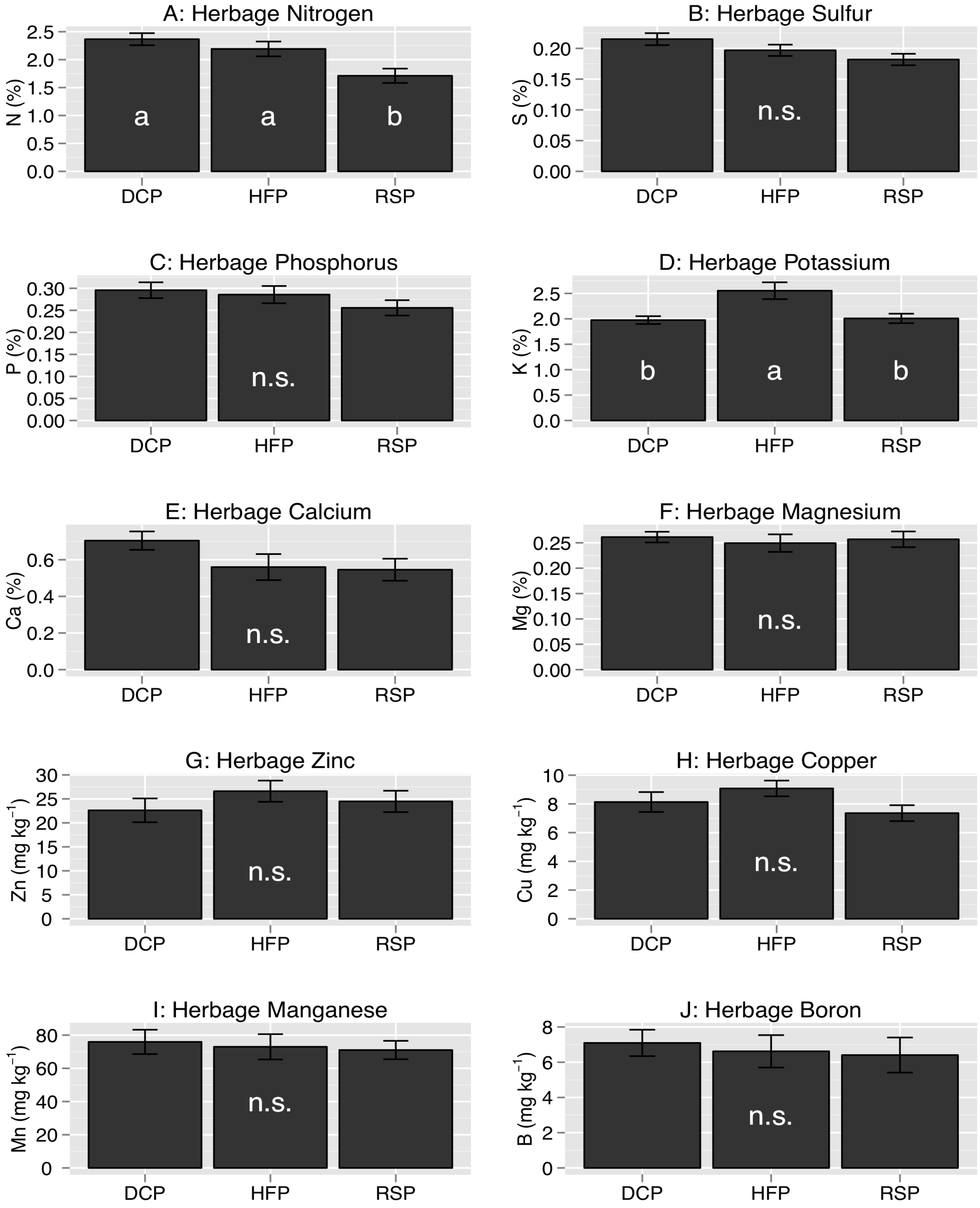


Figure 3.8: Herbage nutrient concentration by paddock type (four year average). Error bars are one standard error. (DCP, dedicated creep paddock; HFP, hay feeding paddock; RSP, rotational stocking paddock). Within a nutrient, differing letters indicated significant differences based on Tukey's HSD (*$p < 0.05$*).

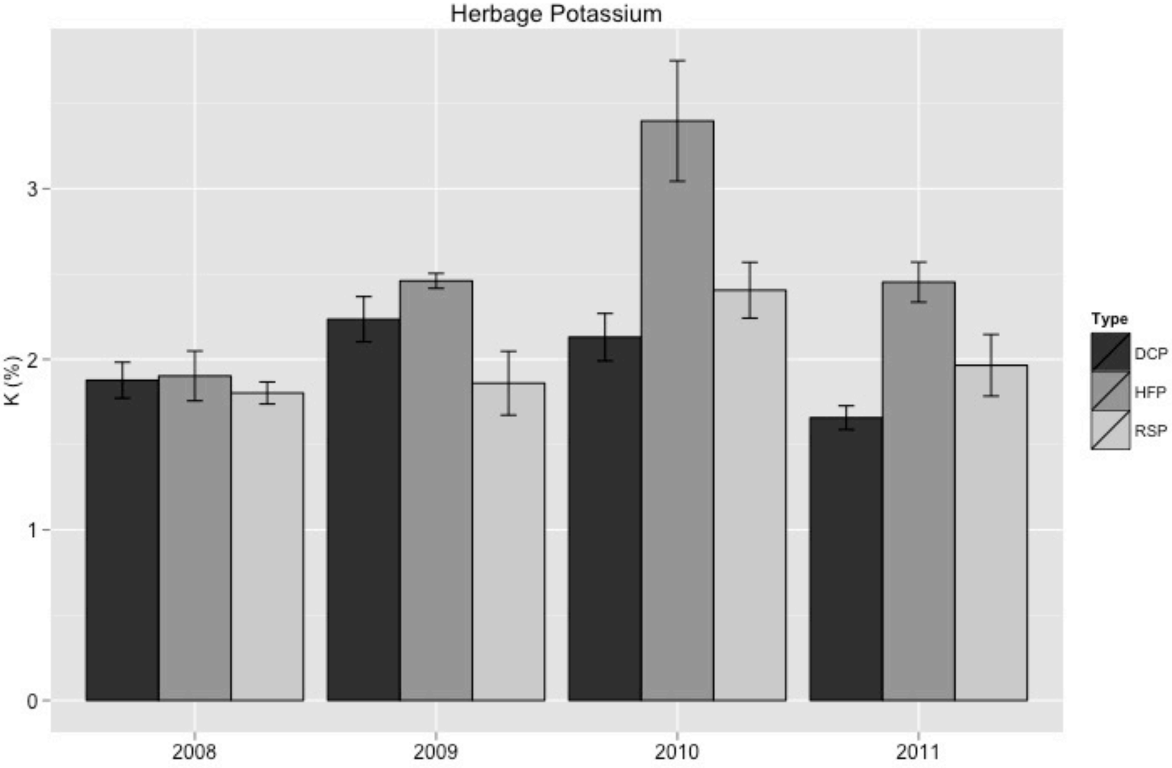


Figure 3.9: Herbage K concentration by paddock type and year. (DCP, dedicated creep paddock; HFP, hay feeding paddock; RSP, rotational stocking paddock). Error bars are one standard error.

Chapter 4. Evaluating Seasonal Variation in Mineral Concentration of Cool-Season Pasture Herbage

ABSTRACT

Pasture herbage can be a major source of minerals for livestock in pasture-based production systems. Plant maturity and climatic conditions influence herbage mineral concentrations. While mineral concentrations vary throughout the growing season, mineral supplementation to livestock is often constant. Times of excess supplementation could cause nutrient losses to the environment. The objectives of this study were to analyze the seasonal variation in herbage mineral concentrations in tall fescue- [*Schendonorus phoenix* (Scop.) Holub] based pasture with regard to beef cattle mineral requirements and to create a statistical model to predict variation in herbage mineral concentrations across the growing season. Pasture herbage was analyzed from 12 grazing systems in Steele's Tavern, VA to determine its mineral concentration from April through October of 2008 - 2012. The pasture herbage, grown without fertilization, contained adequate concentrations of macronutrients to meet the requirements of dry beef cows through the growing season and to meet the requirements of lactating beef cows in April. A model was developed using month of harvest, soil moisture, and relative humidity to explain variation ($R^2 = 0.75$) in an aggregated mineral factor comprised of N, P, K, S, and Cu concentrations. The cross-validated 90% prediction intervals of the model indicated that N, P, K, S, and Cu concentrations could be predicted to within 1.35, 0.08, 0.80, and 0.07% and 3.83 mg kg^{-1}, respectively. Prediction of herbage nutrient concentrations could help to improve livestock health, reduce costs to producers and limit nutrient losses to the environment.

INTRODUCTION

Ensuring an adequate supply of mineral nutrients to livestock is essential to maintaining their growth, reproduction and health. Pasture herbage is an important source of minerals in pasture-based livestock systems. In these systems, a consistent level of mineral supplementation is often provided throughout the growing season (McDowell, 1996). Soil factors, plant species, stage of maturity, seasonal and temperature effects, and fertilization and management can influence the mineral concentration of pasture herbage (Fleming, 1973). In perennial pasture, stage of maturity and soil moisture and temperature are major factors influencing variation in herbage mineral concentration within a growing season. Examining the nature of within season variation of mineral concentrations in pasture herbage could provide producers with information on when supplementation is necessary. Better management of mineral supplementation could improve livestock health, reduce production costs, and limit nutrient losses to the environment.

Managers of pasture-based livestock systems must match supplementation and herbage mineral concentrations with the mineral requirements of livestock. Mineral requirements vary depending on the species of livestock, age, and growth rate (Reid and Horvath, 1980; NRC, 2000). While severe mineral deficiencies occur, marginal deficiencies are probably more common, and marginal deficiencies can have substantial impacts on the growth, reproduction, and health of livestock (Spears, 1994). Grings et al. (2006) determined that rangeland species contained insufficient quantities of P, Na, K, Zn, and Cu to meet animal requirements. Studying bahiagrass (*Paspalum notatum* Flügge) pastures in Florida, Cuestra et al. (2001) found the pasture herbage did not contain sufficient quantities of P, Cu, Zn, Co, Na, and Se to meet livestock requirements and recommended mineral supplementation. While both studies examined variation in herbage mineral concentration at several dates per growing season and noted variation in mineral concentration between dates, neither paper recommended varying mineral supplementation to correspond with changing herbage mineral concentrations.

The variation in mineral concentration of pasture herbage within a growing season is related to the stage of maturity, soil temperature, and soil moisture effects. The effect of stage of maturity has been well studied (Blaser and Kimbrough, 1968; Reid et al., 1970; Baker and Reid, 1977; Ayres et al., 1998; Brink et al., 2006; Nordheim-Viken et al., 2009). Nitrogen, P and K concentrations decrease significantly with plant maturity while variation in calcium and magnesium concentrations tend to be less consistent. Several studies have used clipping or rotational stocking to maintain herbage in the vegetative stage; this allowed for the examination of seasonal effects on herbage mineral concentration without the influence of changing maturity (Fleming and Murphy, 1968; Saunders and Metson, 1971; Kappel et al., 1983). Herbage P and K concentrations declined from spring to summer in these studies, while seasonal effects on Ca, Mg, and micronutrient concentrations varied by species. The pattern of variation in mineral concentration, related to either stage of maturity or seasonal effects, differs among growing seasons (Reid et al., 1970; Greene et al., 1987; Grings et al., 1996). In temperate climates, the maturity of plants is related to the progression of the seasons; thus, it is difficult to separate seasonal effects from the effects of increasing maturity. In grazing systems, however, the actual mineral concentration of pasture herbage is the important factor for livestock production regardless of the source of variation.

Understanding variation in mineral concentration of pasture herbage throughout the growing season would allow producers to optimize mineral supplementation to livestock. Direct sampling of herbage and determination of its mineral concentration is a possibility, but mineral analysis is expensive and multiple samples are frequently required to gain an adequate assessment of current herbage mineral concentrations (Jones et al., 1991). Given the relationship between soil and environmental factors and the mineral concentration of herbage, this information could be used to inform producers of the mineral status of pasture herbage throughout the growing season. This could lead to times of excess supplementation causing nutrient losses to the environment. The objectives of this study were to analyze the seasonal variation in herbage mineral concentrations in tall fescue-based pasture with regard to beef cattle mineral requirements and to create a statistical model to predict variation in herbage mineral concentrations across the growing season.

METHODS AND MATERIALS

Research Site

This research was conducted as part of a wider grazing systems project at the Virginia Tech Shenandoah Valley Agricultural Research and Extension Center in Steele's Tavern, Virginia (Lat: 37°55'49", Long: -79°12'50", Elev: 540 m). The soil at the site is a Frederick and Christian silt loam complex (fine, mixed, semiactive, mesic Typic Paleudults and fine, mixed, semiactive, mesic Typic Hapludults, respectively). Average precipitation is 882 mm annually. Average monthly temperatures range from 1°C in January to 22°C in July (SCAN, 2013).

Ninety-six paddocks (0.8 ha each) were rotationally stocked by 12 groups of 7 or 8 Angus and Angus-cross cow-calf pairs. Each group of animals was stocked in a set of 8 paddocks; this comprised 1 grazing system. The 12 grazing systems were assigned to 4 animal size and creep grazing treatment combinations as described in Chapter 3 of this thesis. The paddocks were rotationally stocked from April through September of 2008 through 2012, and the cows were fed imported hay and stockpiled pasture during the winter dormant season.

Climate and soil data were collected from the Natural Resources Conservation Service Soil Climate Analysis Network station located at the site (SCAN, 2013). Soil moisture (10 cm depth), soil temperature (10 cm depth), air temperature, precipitation, and relative humidity were collected, and growing degree-days were calculated with base temperature 0°C (Frank and Hofmann, 1989).

Pasture Sampling & Analysis

The species composition of the pasture was predominately tall fescue with smaller proportions of orchardgrass (*Dactylis glomerata* L.), Kentucky bluegrass (*Poa pratensis* L.), and white clover (*Trifolium repens* L.). The sward was well established before initiation of the study. Soil fertility was adjusted to soil test recommendation levels prior the study and no additional fertilizer was added during the course of the experiment.

Pasture herbage samples were harvested from each paddock on approximately the 15th of the month from April through October (2008 to 2012). Herbage was harvested at 8 cm stubble height from a randomly selected 0.75 m by 3.5 m swath of the paddock using a Swift Forage Harvester (Swift Current SK, Canada). Samples were dried at 60°C for at least 48 h. A stratified subset of 20 paddocks were selected for mineral analysis of their herbage. Stratification ensured herbage from each of the 12 grazing systems was included in the sample. Herbage N concentration was determined by combustion at the Ruminant Nutrition Laboratory at Virginia Tech. Herbage P, K, S, Ca, Mg, Fe, Zn, Cu, Al, Mn, and B concentrations were determined using microwave-assisted acid extraction and inductively coupled plasma atomic emission spectrometry at A & L Eastern Labs, Richmond, VA.

Statistical Analysis

The statistical analysis for the study was conducted using R (R Development Core Team, 2011). The mineral concentrations were examined and positively skewed distributions of Fe and Al concentrations were noted. The outlying values of Fe and Al were likely caused by soil contamination (Jones et al., 1991), and these minerals were excluded from all subsequent analysis. Mineral concentrations were plotted by month and year of harvest. ANOVA was used to determine the effect of month, year, and month by year interaction on log-normal transformed herbage concentration of each nutrient. The model was:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + E_{ijk}$$

where Y is the log-normal herbage concentration of the nutrient in question; μ is the grand mean; α is the effect of month, $i = 1,2,\ldots7$; β is the effect of year, $j = 1,2,\ldots5$; γ is the blocking factor for the paddock sampled, $k = 1,2,\ldots20$; $\alpha\beta$ is the month by year interaction; and E is the experimental error. Tukey's HSD was used to determine mean separation ($\alpha = 0.05$). The 5-year average concentrations by month were compared to the dietary requirements of dry and lactating beef cows as specified by the National Research Council (NRC, 2000) (Table 4.1). A grass tetany risk index was calculated as the ratio of herbage K to the sum of Ca and Mg based on milliequivalents of charge and compared to the high-risk threshold of 2.2 (Shewmaker et al., 2004).

Pearson correlation coefficients (r) were calculated between all minerals using average herbage concentrations from each harvest (n = 35). Instead of creating a predictive model to determine concentrations of each mineral individually, the correlated nature of the mineral variables was used to create aggregated mineral scores. Factor analysis using varimax rotation was preformed, using the principle function in the 'psych' package in R, to reduce the dimensionality of the dataset (Revelle, 2012). Kaiser's Criterion was used to determine the number of factors to be retained—all factors with eigenvalues greater than 1 (Jackson, 1993). Neither Mn nor Zn were highly loaded onto the retained factors and were removed from the analysis. Boron was also removed because it is not an essential mineral for livestock nutrition. Given the relatively small sample size as compared to the number of nutrients analyzed, the data were randomly split into 2 parts and factor analysis was rerun on both to ensure that the factor loadings were consistent and were not skewed by outlying observations. The resultant scores from the factor analysis were used as the dependent variables in the prediction models.

Soil moisture, soil temperature, air temperature, precipitation, growing degree-days, and relative humidity were averaged over the 5, 15, and 30 days before each herbage harvest. The 3 intervals of climatic data were collected because the temporal relationships between climatic conditions and mineral concentrations were unknown. The 3 intervals of each of the 6 climate variables were used, in addition to the categorical variable of month, as the potential independent variables for the prediction models.

The all-possible regressions algorithm in the 'leaps' package in R was used to determine the best set of regressors to use in each predictive model (Lumley, 2009). Models were ranked in terms of adjusted R^2 and the number of terms in the model. Models with a large adjusted R^2 and a small number of terms were examined to determine if they met linear regression assumptions. Variance inflation factors (VIFs) were calculated and models were retained with VIFs less than 10 (Montgomery et al., 2012). The externally studentized residuals were calculated and assessed for normality, outliers, and leverage points. The studentized residuals were plotted against the fitted values and each regressor in the model. Plots of the studentized residuals by month and year of harvest were used to assess the potential for autocorrelation (Montgomery et al., 2012). The models were selected using these criteria and diagnostics to best explain the variation in the mineral factors.

The resulting models were validated using 10-fold cross validation performed in the 'DAAG' package in R (Maindonald and Braun, 2012). The average cross-validated mean squared error (MSE) was used to calculate prediction intervals for the model. A linear regression between the mineral factor scores and each mineral variable was created. The regression equations allowed for the conversion from the predicted mineral factor scores to predicted herbage mineral concentrations.

RESULTS

Herbage mineral concentrations differed significantly by month (Table 4.2). Greatest concentrations of N, P, K, S, Cu, and Zn occurred in April harvested herbage. Concentrations of those 6 minerals declined to minimum concentrations in July and

August. Calcium and Mn concentrations fluctuated throughout the growing season, while Mg concentrations tended to increase as the season progressed.

Average monthly herbage K, S, Ca, Mg, and Mn concentrations were sufficient to meet the requirement of dry and lactating beef cows throughout the growing season. Herbage N was sufficient to meet the protein requirement of a dry beef cow in all months and in all months except July for lactating beef cows. Phosphorus concentration was adequate for dry cows except for July of several years and tended to be adequate for lactating cows only in early spring. Copper concentration was deficient most months except April, and Zn concentrations varied between years. There was, however, significant month by year interaction for the concentrations each mineral ($p < 0.001$) (Figure 4.1). Herbage concentrations of N, P, K, S, Cu and Zn in 2009 tended to decline from spring to fall, while concentrations of these minerals were high in spring, low in summer, and high again in fall of the remaining years. The grass tetany ratio of herbage remained below the high-risk threshold throughout the year (Figure 4.1).

Herbage N, P, K, S, and Cu concentrations were all positively correlated to each other ($r \geq 0.53$) (Table 4.3). Calcium was correlated to Mg ($r = 0.68$) and B ($r = 0.69$). Zinc concentrations were moderately correlated to S ($r = 0.52$) and Cu ($r = 0.54$). Manganese concentrations appeared to be independent of the other minerals with a maximum correlation of 0.50 with Cu.

Factor analysis yielded two retained factors. The first factor contained 56% of the total variance in the data, and N, P, K, S, and Cu were highly correlated to this factor (Figure 4.2). The second factor contained 25% of the total variance, and Ca and Mg were highly correlated to this factor. When the data were split and factor analysis was run on both parts, the factor loadings were consistent with the loadings calculated for the entire dataset.

Model selection for Mineral Factor 1 (N, P, K, S, & Cu) resulted in a model including month as a categorical variable and soil moisture averaged over the 15 days before each harvest and relative humidity averaged over the 5 days before harvest. This model had an R^2 of 0.75 and all model terms were significant ($p < 0.05$) (Table 4.4). Model selection for Mineral Factor 2 (Ca, Mg) resulted in models with adjusted R^2 values of less than 0.37. A model explaining the majority of variability in Mineral Factor 2 could not be found using the regressors selected in this study. The remaining analysis and validation was performed on the model for Mineral Factor 1 only.

The initial prediction intervals were based on the model-generated MSE of 0.33. Ten-fold cross-validation yielded an average MSE of 0.42 (Figure 4.3). Prediction intervals based on the cross-validated MSE were converted from Mineral Factor 1 scores into concentrations of N, P, K, S, and Cu. The average width of 90% prediction intervals were 1.35%, 0.08%, 0.80%, 0.07%, and 3.83 mg kg^{-1} for N, P, K, S, and Cu, respectively.

DISCUSSION

The mineral concentration of tall fescue-based pasture herbage varied, as expected, throughout the growing season. A pattern of high mineral concentration in spring, low concentration in summer, and high concentration in fall was consistent with the expected pattern of sward maturation and vegetative regrowth through the growing season. Variation in the pattern between years appears to be related to climatic conditions. This is consistent with the concept that mineral concentration of herbage is determined by two sets of processes: those that control dry matter accumulation and thus the dilution effect, and those that control the uptake and transport of nutrients from the soil into plant tissue (Loneragan, 1973; Jarrell and Beverly, 1981). Differing climatic factors including soil temperature and moisture have impacts on both dry matter accumulation (Connor et al., 2011) and mineral uptake (Saunders and Metson, 1970; Fleming, 1973; Mirsa and Tyler, 1999), and are related to the variation in the pattern of mineral concentrations among the growing seasons.

Herbage met the macronutrient requirement for dry beef cows throughout the year, but was deficient in micronutrients during the summer and fall. Mineral requirements were met for lactating beef cows by April herbage but N, P, and micronutrients declined below their minimum requirements during the summer and fall. Cuestra et al. (1993) found many bahiagrass samples deficient in P and micronutrients compared to beef cow requirements. In the Great Plains, Grings et al. (1996) recommended supplementation of P, Na, K, Zn, Cu to livestock. Sodium and micronutrient supplementation is likely necessary with tall fescue pasture for dry beef cows, but P appears to be sufficient in herbage. Limiting unnecessary supplementation of P could reduce P losses to the environment. The herbage grass tetany ratio remained below the high-risk threshold throughout the year. Higher risk of grass tetany could be expected in the spring with N or K fertilization (Robinson et al., 1989)

Factor analysis yielded two nutrient factors, one explaining variability in N, P, K, S, and Cu, and the other the variability in Ca and Mg. The remobilization of certain nutrients as plants mature may be related to this grouping. Nitrogen, P, K, S, and Cu are mobile elements in plant tissue (White, 2012). The concentration of these nutrients followed a pattern through the growing season that could be explained by increasing maturity and vegetative regrowth, and thus, may be related to the mobility of minerals that comprise Mineral Factor 1. Calcium is immobile (White, 2012) and present in relatively high concentration in cell walls of grasses and legumes (Whitehead et al., 1985). It could be expected that concentrations of immobile minerals would behave differently throughout the growing season compared with mobile minerals. Magnesium is, however, a mobile mineral. Why Mg is correlated to Ca as opposed to other mobile nutrients is unknown. Previous studies of tall fescue have shown strong correlations between Ca and Mg concentrations in leaf tissue but do not offer explanations as to why this might occur (Shewmaker et al., 2004; Sleper et al., 1977). Using factor analysis to reduce the data to aggregated mineral factors has the benefit of reducing the number of predictive models that need to be developed and takes into account the correlated nature of the minerals.

The coefficients of the model developed here indicate increasing soil moisture and decreasing relative humidity positively affect N, P, K, S, and Cu concentrations. In fall of 2009, soil moisture was low and relative humidity was high as compared to the remaining years (data not shown). Lower than average October mineral concentrations occurred in 2009. Soil moisture and relative humidity are two of the factors that determine transpiration rate (Connor et al., 2011). Both soil moisture and transpiration rate are related to mineral uptake by plants and can explain the ability of the model to predict variation in herbage mineral concentration among growing seasons (White, 2012; Tanguilig et al., 1987). Evapotranspiration rate was not measured during this study, but these results indicate that evapotraspiration rate may be a good predictor of mineral concentration in pasture herbage.

The model developed could provide useful information to producers about the mineral concentration of their pasture herbage. A comparison of the 90% prediction intervals for N, P, K, S, and Cu with the actual ranges of concentration of those minerals through the duration of the study, shows that, on average, the prediction intervals were approximately 50% the size of the actual range of concentrations. A smaller percentage of the prediction interval to the total range would indicate better predictive ability. This model should detect major deviations from the normal pattern of variation in mineral concentration throughout the growing season. That information could inform producers as to when mineral supplementation is especially important and could limit the costs associated with unnecessary supplementation. A limitation of this model is it was developed from data that were collected from one site and soil type. Differences in initial nutrient concentrations, water-holding capacity, and species composition would vary from site to site, but it is expected that the general seasonal trends would hold true cool-season grass-based pasture throughout the Mid-Atlantic region.

CONCLUSIONS

This study showed that unfertilized, cool-season pasture herbage harvested in April could provide an adequate supply of N, P, K, S, Ca, Mg, Mn, Cu and Zn to meet the requirements of dry and lactating beef cows. Sulfur, K, Ca, Mg and Mn concentrations remained above lactating beef cow requirements through the growing season. All herbage nutrient concentrations, except Cu and Zn, remained above the requirements of a dry beef cow. Supplementation to dry beef cows can be limited to Na and micronutrients. This study found that herbage can meet the P requirements of dry beef cows and supplementation may lead to unnecessary P additions to the environment.

Prediction of herbage N, P, K, S, and Cu concentrations is possible using soil moisture and relative humidity. Using prediction of herbage mineral status could provide producers with useful information on when mineral supplementation is necessary for optimal livestock production.

REFERENCES

Ayres, J.F., K.S. Nandra, and A.D. Turner. 1998. A study of the nutritive value of white clover (*Trifolium repens* L.) in relation to different stages of phonological maturity in the primary growth phase in spring. Grass Forage Sci. 53:250-259.

Baker, B.S. and R.L. Reid. 1977. Mineral concentration of forage species grown in central West Virginia on various soil series. West Virginia Agric. Exp. Stn. Bull. 657.

Blaser, R.E. and E.L. Kimbrough. 1968. Potassium nutrition of forage crops with perennials. In: The Role of Potassium in Agriculture. V.J. Kilmer, S.E. Younts, and N.C. Brady, Editors. ASA, CSSA, SSSA. pp. 423-445.

Brink, G.E. K.R. Sistani, J.L. Oldham, and G.A. Pederson. 2006. Maturity effects on mineral concentration and uptake in annual ryegrass. J. Plant. Nutr. 29:1143-1155.

Connor, D.J., R.S. Loomis, and K.G. Cassman. 2011. Crop Ecology. 2nd Ed. Cambridge UP, New York. pp. 125-158.

Cuesta, P.A., L.R. McDowell, W.E. Kunkle, F. Bullock, A. Drew, N.S. Wilkinson, and F.G. Martin. 1993. Seasonal variation of soil and forage mineral concentrations in north Florida. Commun. Soil Sci. Plant Anal. 24:335-347.

Fleming, G.A. 1973. Mineral Composition of Herbage. In: Chemistry and Biochemistry of Herbage. Volume 1. G.W. Butler and R.W. Bailey, Editors. Academic Press, New York. pp. 529-566.

Fleming, G.A. and W.E. Murphy. 1968. The uptake of some major elements by grass as affected by season and stage of maturity. J. Br. Grassl. Soc. 23:174-184.

Frank, A.B. and L. Hofmann. 1989. Relationship among grazing management, growing degree-days, and morphological development for native grasses on the Northern Great Plains. J. Range Manage. 42:199-202.

Greene, L.W., W.E. Pinchak, and R.K. Heitschemidt. 1987. Seasonal dynamics of minerals in forages at the Texas Experimental Ranch. J. Range Manage. 40:502-506.

Grings, E.E., M.R. Haferkamp, R.K. Heitschmidt, and M.G. Karl. 1996. Mineral dynamics in forages of the Northern Great Plains. J. Range Manage. 49:234-240.

Jackson, D.A. 1993. Stopping rules in principal components analysis: A comparison of heuristical and statistical approaches. Ecology. 74:2204-2214.

Jarrell, W.M. and R.B. Beverly. 1981. The dilution effect in plant nutrition studies. Adv. Agron. 34:197-224.

Jones, J.B., B. Wolf, and H.A. Mills. 1991. Plant Analysis Handbook. Micro-Marco Publishing, Athens, GA.

Kappel, L.C., E.B. Morgan, L. Kilgore, R.H. Ingraham, and D.K. Babcock. 1983. Seasonal changes in mineral content of southern forages. J. Dairy Sci. 68:1822-1827.

Lumley, T. 2009. leaps: regression subset selection. R package version 2.9.

Loneragan, J.F. 1973. Mineral Absorption and its Relation to the Mineral Composition of Herbage. In: Chemistry and Biochemistry of Herbage. Volume 2. G.W. Butler and R.W. Bailey, Editors. Academic Press, New York. pp. 103-125.

Maindonald, J. and W.J. Braun. 2012. DAAG: Data Analysis And Graphics data and functions. R package version 1.12.

McDowell, L.R. 1996. Feeding mineral to cattle on pasture. Anim. Feed Sci. Technol. 60:247-271.

Misra, A. and G. Tyler. 1999. Influence of soil moisture on soil solution chemistry and concentrations of minerals in the calcicoles *Phleum phleoides* and *Veronica spicata* grown on a limestone soil. Ann. Bot. 84:401-410.

Montgomery, D.C., E.A. Peck, and G.G. Vining. 2012. Introduction to Linear Regression. Wiley, Hoboken, NJ.

Nordeim-Viken, H., H. Volden, M. Jørgensen. 2009. Effects of maturity stage, temperature, and photoperiod on growth and nutritive value of timothy (*Phleum pratense* L.). Anim. Feed Sci. Technol. 152:204-218.

NRC. 2000. Nutrient requirements of beef cattle. 7th Rev. ed. Natl. Acad. Press, Washington, D.C.

R Development Core Team. 2011. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Reid, R.L. and D.J. Horvath. 1980. Soil chemistry and mineral problems in farm livestock. A review. Anim. Feed Sci. Technol. 5:95-167.

Reid, R.L., A.J. Post, and G.A. Jung. 1970. Mineral composition of forages. West Virginia Agric. Exp. Stn. Bull. 589T.

Revelle, W. 2012. psych: Procedures for Personality and Psychological Research. Northwestern University, Evanston, IL. R package version 1.2.1.

Robinson, D.L., L.C. Kappel, and J.A. Boling. 1989. Management practices to overcome the incidence of grass tetany. J. Anim. Sci. 67:3470-3484.

Saunders, W.M.H. and A.J. Metson. 1970. Seasonal variation of phosphorus in soil and pasture. New Zeal. J. Agr. Res. 14:307-328.

Soil Climate Analysis Network (SCAN). 2013. Site: 2088, Shenandoah. Natural Resources Conservation Service.

Shewmaker, G.E., D.A. Johnson, H.F. Mayland, S.A. Martin, and S.B. Hansen. 2004. Elemental uptake in relation to root characteristics of tall fescue. Commun. Soil Sci. Plant Anal. 35:1339-1355.

Sleper, D.A., G.B. Garner, K.H. Asay, R. Boland, E.E. Pickett. 1977. Breeding for Mg, Ca, K, and P content in tall fescue. Crop Sci. 17:433-438.

Spears, J.W. 1994. Minerals in Forages. In: Forage Quality, Evaluation, and Utilization. G.C. Fahey, Editor. ASA, CSSA, SSSA. pp. 281-317.

Tanguilig, V.C., E.B. Yamboa, J.C. O'Toole, and S.K. De Datta. 1987. Water stress effects on leaf elongation, leaf water potential, transpiration, and nutrient uptake of rice, maize, and soybean. Plant Soil. 103:155-168.

White, P. J. 2012. Long-distance Transport in the Xylem and Phloem. In: Marschner's Mineral Nutrition of Higher Plants. 3rd Ed. P. Marschner, Editor. Academic Press, Waltham, MA. pp. 49-70.

Table 4.1 Minimum dietary requirements for a dry and lactating beef cows in units of percent or mg kg^{-1} of dry matter consumed (Adapted from NRC, 2000).

Mineral	Dry Cow Requirements	Lactating Cow Requirements
N (%)	1.12	1.70
P (%)	0.19	0.27
K (%)	0.60	0.70
S (%)	0.15	0.15
Ca (%)	0.19	0.27
Mg (%)	0.12	0.20
Mn (mg kg^{-1})	40	40
Cu (mg kg^{-1})	10	10
Zn (mg kg^{-1})	30	30

Table 4.2: Pasture herbage mineral concentrations by month (five-year averages). For a given row, letters indicate significant difference between months based on Tukey's HSD ($p < 0.05$). Analysis was performed with log-transformed data; results are not transformed.

Mineral	April	May	June	July	August	September	October
N (%)	3.08^{a}	2.50^{b}	2.00^{c}	1.68^{d}	1.85^{d}	2.46^{b}	2.43^{b}
P (%)	0.28^{a}	0.27^{a}	0.25^{b}	0.21^{c}	0.24^{bc}	0.25^{b}	0.24^{b}
K (%)	2.21^{a}	2.21^{a}	2.07^{ab}	1.59^{c}	1.57^{c}	1.96^{b}	1.97^{b}
S (%)	0.23^{a}	0.20^{b}	0.19^{cd}	0.16^{e}	0.19^{d}	0.21^{b}	0.20^{bc}
Ca (%)	0.54^{a}	0.45^{e}	0.51^{cd}	0.47^{de}	0.52^{abc}	0.53^{ab}	0.49^{bcd}
Mg (%)	0.23^{de}	0.22^{e}	0.25^{c}	0.24^{cd}	0.28^{b}	0.30^{a}	0.27^{b}
Mn (mg kg^{-1})	105.4^{a}	96.2^{abc}	79.5^{c}	85.8^{bc}	92.2^{ab}	87.1^{abc}	87.0^{bc}
Cu (mg kg^{-1})	11.0^{a}	8.9^{b}	7.9^{cd}	7.2^{d}	8.2^{bc}	8.7^{b}	9.0^{b}
Zn (mg kg^{-1})	34.2^{a}	30.2^{b}	25.8^{c}	23.3^{c}	24.9^{c}	25.7^{c}	26.8^{c}

Table 4.3: Correlation coefficients among herbage mineral concentrations averaged by harvest date (n = 35).

	N	P	K	S	Ca	Mg	Mn	Cu	Zn	B
N	1									
P	0.71	1								
K	0.70	0.78	1							
S	0.87	0.78	0.72	1						
Ca	0.12	0.24	0.27	0.30	1					
Mg	-0.00	-0.07	0.11	0.18	0.68	1				
Mn	0.37	0.36	0.08	0.29	0.40	-0.01	1			
Cu	0.82	0.60	0.53	0.74	0.20	0.03	0.50	1		
Zn	0.44	0.35	0.33	0.52	0.40	0.15	0.37	0.54	1	
B	0.35	0.44	0.57	0.43	0.69	0.25	0.29	0.49	0.49	1

Table 4.4: Regression model explaining variation in Mineral Factor 1. Coefficient for month is the starting value and is adjusted by the coefficient for soil moisture and humidity.

Term	Coefficient	P-value
Month	-	< 0.0001
April	3.2137	-
May	3.2804	-
June	2.7337	-
July	2.1345	-
August	2.5758	-
September	3.2578	-
October	2.5375	-
Soil Moisture (%)	0.0455	0.0062
Relative Humidity (%)	-0.0438	0.0474

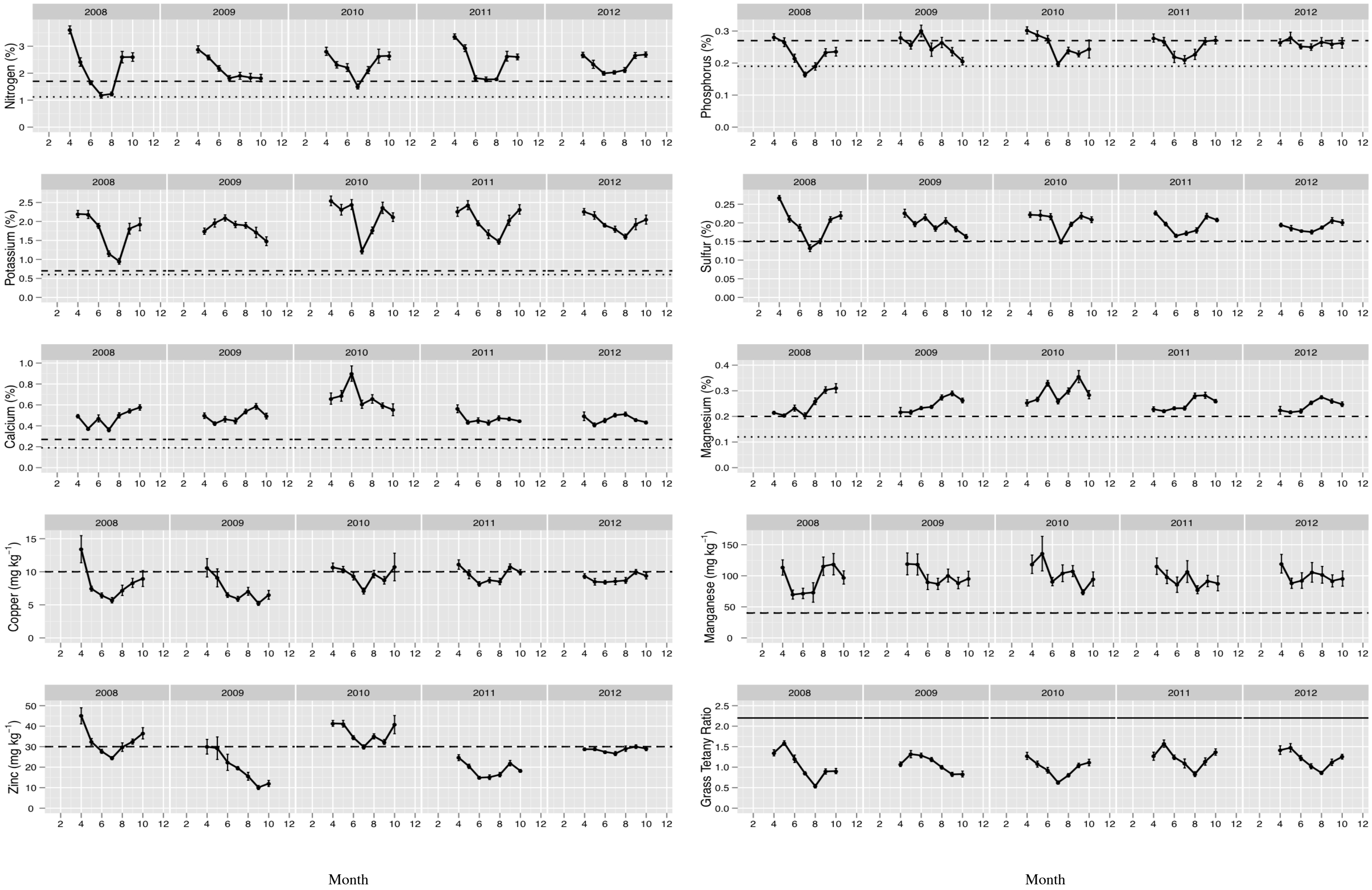


Figure 4.1: Herbage mineral concentrations by month and year. Average of approximately 20 samples per date +/- 1 standard error. Dashed and dotted lines are lactating and dry cow minimum requirements, respectively (NRC, 2000). Values above a solid line indicate high grass tetany risk.

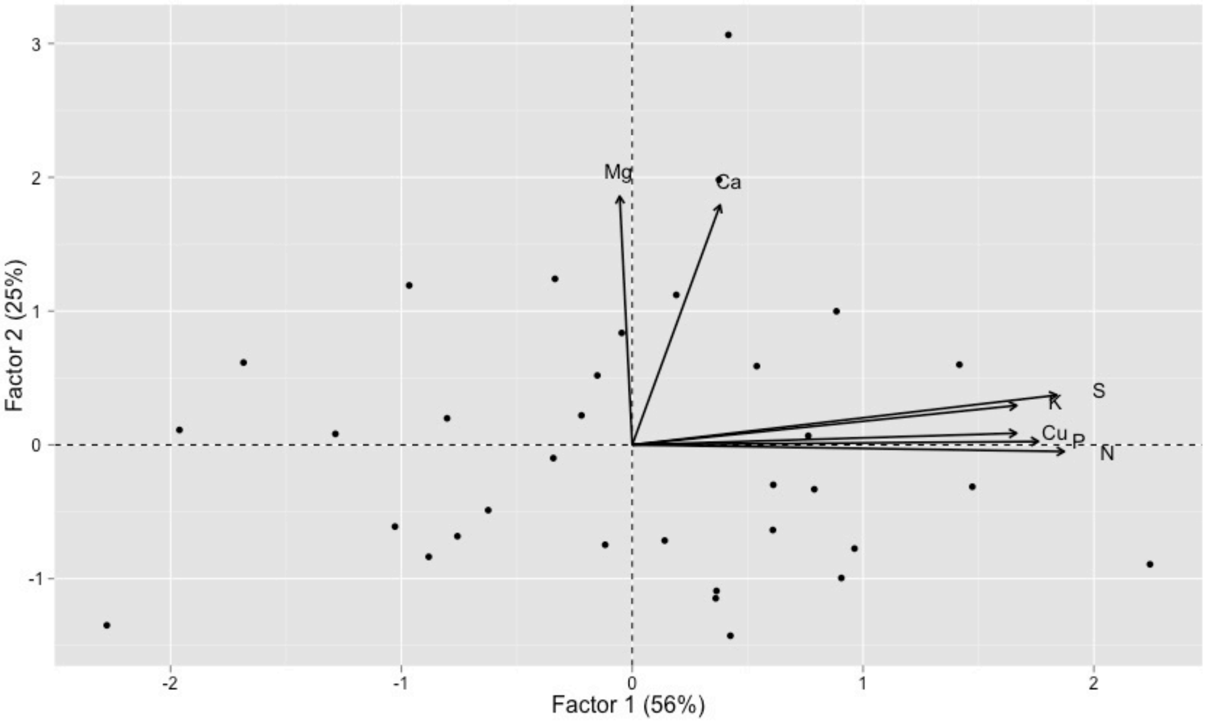


Figure 4.2: Biplot of factor analysis using varimax rotation on herbage mineral concentrations averaged by harvest date.

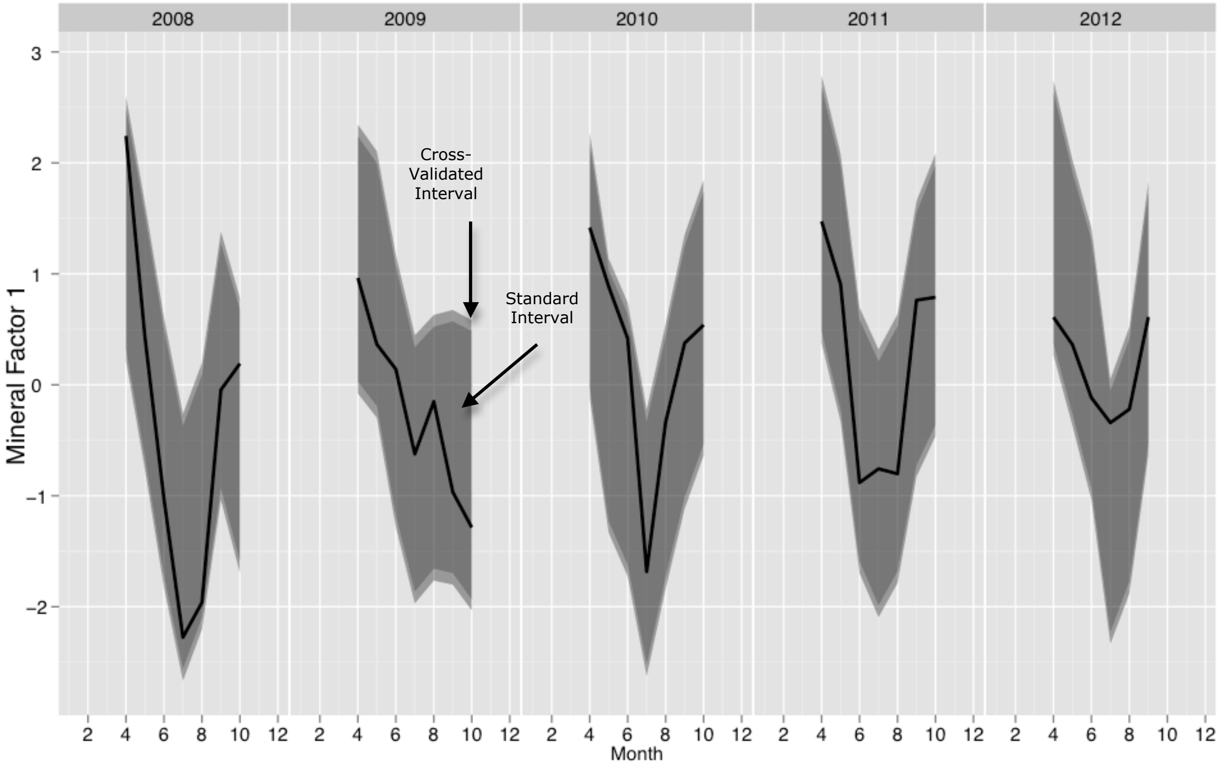


Figure 4.3: Standard (dark) and cross-validated (light) prediction intervals for Mineral Factor 1. The actual values for Mineral Factor 1 are shown by the black line.

Chapter 5. Conclusions

Changing fertilizer prices, increasing concerns about the environmental impact of agriculture, and growing global demands for food, fuel, and fiber require agriculture to be efficient and sustainable. Continued study of nutrient dynamics in cool-season pastures provides needed information to develop recommendations for optimal management. The studies associated with this thesis have yielded several important findings that improve our understanding of nutrient dynamics in pasture and can lead to improved management of these systems.

While nutrients tend to be efficiently recycled in pastures, decreasing soil P concentrations were measured during five years of rotational stocking. Nutrients were found to accumulate in the soils and herbage in hay feeding areas so strategic and varied placement of hay feeding areas is important to distribute nutrients across the farm and to limit losses associated with high nutrient concentrations in disturbed areas. Soil tests showed greater variability in the concentrations of several macronutrients than did herbage analysis indicating that use of herbage analysis may provide a more stable and thus accurate assessment of fertility in pastures as compared to soil tests.

Herbage nutrient concentrations varied throughout the growing season, and even without fertilization, herbage always met the macronutrient requirements of dry beef cows. Phosphorus supplementation to dry beef cows appears to be unnecessary in tall fescue-based pastures, and lowering P inputs by avoiding supplementation should reduce P losses to the environment. Lastly, research conducted within the context of this thesis showed that it is possible to use weather station data to predict variation in herbage mineral concentration. This information could one day help producers to better meet the supplementation needs of their livestock throughout the growing season and improve the efficiency of nutrient use in pasture systems.