Mob stocking effects on herbage nutritive value, herbage accumulation, and plant species composition

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Mob stocking affects herbage nutritive value, herbage accumulation, clover cover, and diet selected by beef cattle

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ABSTRACT

Mob stocking is a variation of rotational stocking known for restricting a large number of animals to a small area before being moved to new grass after a few hours. This method allows a long (90-day) recovery period but was hypothesized to diminish the nutritional value of herbage relative to continuous and rotational stocking with lesser stocking density at similar stocking rates. This thesis summarizes two studies conducted in Blacksburg and Raphine, and in Steeles Tavern, VA, respectively, at a single beef cattle stocking rate of 12 animal unit months per hectare live body weight. The objectives were to: (1) compare the yield and nutritional value of herbage in pastures managed with three stocking methods, termed "mob", "rotational", and "continuous" stocking; (2) compare the abundance of seeded clover species among the stocking methods; and (3) estimate the nutritional value of herbage that is consumed by beef cattle during 'mob' stocking using extrusa sampled from esophageally-cannulated animals. Analysis of standing herbage during two years produced several important findings. Although standing herbage mass was significantly greater in mob stocked pastures at Blacksburg and Raphine, aboveground net primary productivity in 2014 did not differ significantly among mob, rotational, and continuous stocking at any of the project locations. Herbage nutritive value did not differ significantly among stocking methods over two years at Blacksburg and Raphine; however, herbage from mob stocked pastures at Steeles Tavern contained significantly greater concentrations of crude protein in September and October relative to herbage from continuous- and rotationally-stocked pastures at those times. Differences in herbage mass likely contributed

to significant differences in establishment of seeded clovers: red clover [*Trifolium pratense* L. 'Cinnamon Plus'] establishment was similar among stocking methods but white clover [*Trifolium repens* L. 'Will'] establishment was greater in continuously stocked pastures than mob and rotationally stocked pastures. Hand-clipped samples collected at Blacksburg in September 2014 significantly underestimated the crude protein content of the herbage selected by the steers, although the concentrations of fiber constituents in herbage did not differ significantly between clipped samples and esophageal samples. Although the nutritive value of the herbage on offer did not generally differ among stocking methods at this stocking rate, diet selected was at times less nutritious during mob stocking than continuous and rotational stocking methods. At this stocking rate, stocking method had less influence on pastures than seasonal variation in weather and plant maturity.

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

ABBREVIATIONS

ANPP	aboveground net primary productivity
ADF	acid detergent fiber
ADG	average daily gain
AIC	Akaike Information Criterion
ANOVA	analysis of variance
AUM	animal unit month
BW	body weight
Ca	calcium
CP	crude protein
CV	coefficient of variation
DE	digestible energy
DM	dry matter
F	Fisher-Snedecor variance ratio
FA	forage allowance
GPS	global positioning system
HI	harvest index
HSD	Tukey's Honestly Significant Difference
IACUC	Institutional Animal Care and Use Committee
IS	index of selectivity
IVDMD	in vitro dry matter digestibility
K	potassium
LAI	leaf area index
LS	least squares
Mg	magnesium
N	nitrogen
NDF	neutral detergent fiber
NIRS	near infrared reflectance spectroscopy
NRC	National Research Council
OM	organic matter
P	phosphorus
P	probability
ρ	Pearson's correlation coefficient
PET	potential evapotranspiration
R^2	coefficient of determination
RFQ	relative forage quality
RPM	rising plate meter
SE	standard error
SDC	size density compensation
TDN	total digestible nutrients
VT	Virginia Tech
WSC	water-soluble carbohydrates
$\bar{x}$	population mean

Chapter 1. Introduction

1.1 Background and motivation

Significant research in the past two centuries has documented plant-animal relationships in grasslands. Grassland ecosystems occur on nearly one-third of the world's ice-free land surface, providing an enormous carrying capacity for domesticated livestock (FAO, 1996). Incongruence between forage supply and animal requirements has caused many of these extensively managed landscapes to become damaged by livestock (Savory, 1988). Herding is often used to manage the supply and demand for grass. Recent developments in herding involve high tensile wire, fence posts, and electric current to control livestock movement to improve forage utilization (Gerrish, 2004). Although abundant scientific literature exists on the topic of grassland management, adoption of intensive management of grazing livestock is not yet widespread (Winsten et al, 2011).

One barrier to adoption of intensive grazing management is the complex relationship of forage production and nutritive value with stocking management across time (Petrehn, 2011; Winsten et al, 2011). Ruminant nutrition from roughage diets is relatively well understood (Van Soest, 1994; Tilley and Terry, 1963); however, prediction of animal performance from heterogeneous grass swards is limited by the uncertainty associated with animal intake as sward nutritive value and mass change across time in response to grazing pressure (Brink et al, 2013; Carlassare and Karsten, 2002; Soder et al, 2007). Few studies have compared bovine diets among several levels of grazing pressure within a stocking system (Kothmann, 2009) and fewer have investigated more than two levels of stocking management (Dunn, 2013; Oates et al, 2011; Owensby and Auen, 2013; Russell et al, 2013).

Furthermore, a limited number of combinations of plant species and environments have been studied in the context of intensive management of grazing (McCartney and Bittman, 1994, for example). No studies have compared, for example, the establishment and persistence of red and white clover during intermittent dense stocking, rotational stocking, and continuous stocking in tall fescue pastures in humid subtropical climates, although two such studies were performed in the humid continental climate of Iowa (Dunn, 2013; Russell et al, 2013). While the ecological processes of competition for resources that affect plant growth are well understood, the interactions among plants, environmental resources, and animals that may occur because of human intervention with grazing management have yet to be documented extensively.

1.2 Research objectives and hypotheses

The goal of the proposed study was to evaluate how different stocking methods influence the growth and nutritional value of forage across time. The stocking methods were applied to adjacent perennial pastures located in south- and western-Virginia as cattle stocking demonstrations that span the grazing season. The cattle stocking treatments were termed Continuous, Rotational, and Mob. These stocking treatments are described in detail in Section 3. The forage dynamics of the Mob stocking demonstration is of particular interest because the method has not been studied in this region previously. The study had three main objectives and corresponding hypotheses:

- Objective 1: To compare the yield and nutritional value of herbage in pastures during three stocking methods across time.
- Hypothesis 1: The nutritive value of herbage in pastures during mob stocking will be less than in rotationally stocked pastures. Continuously stocked pastures will have the greatest herbage nutritive value. Herbage yield will be greatest with rotational stocking, intermediate with mob stocking, and least with continuous stocking.
- Objective 2: To compare the abundance of seeded clover species in pastures among the

three stocking methods.

- Hypothesis 2: Clover cover will be greatest during the continuous stocking method. Clover cover will be greater under rotational stocking than under mob stocking.
- Objective 3: To estimate the nutritional value of herbage that is consumed by beef cattle in the ‘mob’ stocking method with esophageally cannulated animals.
- Hypothesis 3: Forage collected by cannulated animals during mob stocking will be greater in nutritional value relative to hand-clipped samples.

Chapter 2. Literature Review

2.1 Stocking methods

2.1.1 Definition of grazing systems and stocking methods

Grazing systems are defined by all of the biotic and abiotic components that are specific to grassland-livestock interactions in each place (Allen et al, 2011). In much of the Eastern USA, for example, perennial grass pastures consist of tall fescue [*Schendonorus phoenix* (Scop.) Holub.], bluegrass (*Poa pratensis* L.), or orchardgrass (*Dactlyis glomerata* L.) combined with white clover (*Trifolium repens* L.) and red clover (*Trifolium pratense* L.; Allen et al, 1992). A typical grazing system might include mature beef cows (*Bos taurus* 'Angus') and their calves stocked continuously at 1.6 ha per cow-calf pair for nine months of the year with a single rest period during the winter dormant season (Hoveland, 1986). In the humid subtropical climate of Virginia, mean annual temperature is 13°C (range of monthly averages 7-19°C) with consistent precipitation year-round (1085 mm average total; Hayden and Michaels, 2000); however, a soil moisture deficit in late summer (August) sometimes follows greater temperatures in July-August. Greater temperatures slow the growth of cool-season grasses and cold winters induce a dormant period, which limit the productivity of these grazing systems (Peterson et al, 2006).

The stocking method is a component of every grazing system that refers specifically to human intervention in the "meeting of cow and grass" (Voisin, 1988, p. 1) to optimize the performance of grass and livestock or to meet specific management objectives. Stocking methods include altering the period of stay of animals on a particular paddock, altering the stocking rate of animals to alter grazing pressure in relation to the forage allowance, and altering the period of exclusion of animals ("rest period") from a particular paddock. A stocking cycle consists of a stocking period plus a rest period for a given area (Allen et al, 2011); the number of stocking cycles per season can vary from one (continuous stocking method) to nearly twelve (rotational stocking method). Given the range of possible combinations of stocking methods, some researchers and practitioners of stocking methods advocate for “management-intensive” stocking methods that apply knowledge about plants, animals, fencing, and other technologies to determine stocking methods in a grazing system at a point in time (Gerrish, 2004; Nation, 2004).

Terminology around stocking methods is an area of ongoing debate. For example, the phrase “mob grazing” (properly, mob stocking; grazing refers to the activity of eating, stocking refers to management of that activity; Allen et al, 2011) is presently used to refer to the following stocking methods: dense stocking (50,000-75,000 pounds animal live weight acre^{-1}) that is achieved with small paddocks, short durations of stocking (24 h or fewer), and long rest periods (60-90 d; USDA-NRCS, 2011). Some have attributed the concept to Savory (1988), which he termed “cell grazing”, although Holmes et al (1950) and Waite et al (1950) describe an identical system (quantified as 50-80 1000 lb cows acre^{-1}) termed “close folding” on ryegrass (*Lolium perenne* L.) and orchardgrass pastures in Ayrshire, UK. More recent terminology includes “short-duration grazing”, “flash grazing”, and “ultra high stocking density.” While several attempts have been made to standardize terminology (Allen et al, 2011; Hodgeson, 1979), the inherent variation in stocking methods and grazing systems limits comparisons between past studies of mob stocking.

While Savory (Savory and Parsons, 1980) recommended increasing stocking density to achieve rangeland management objectives, his main contribution was the concept of holistic management. Rather than advocating for the installation of extensive fencing systems, he simply applied a principle that many rangeland scientists knew at the time: varying the rest period in response to the rate of forage accumulation would necessitate periodic conglomerating of herds to de-stock certain parts of the landscape. Savory also hypothesized greater cattle density would provide disturbance of soil and plant litter that would rejuvenate rangeland plant growth if the rest periods were sufficient for plants to recover or establish. Savory hypothesized that rest period exerted more influence on the productivity of rangelands than the intensity of defoliation (stocking density). Sollenberger and Newman (2007), in their review of stocking management of tropical forages, reached different conclusions and reported that grazing intensity has a disproportionate impact on forage and animal response relative to defoliation frequency and stocking method. Studying humid pastures in Virginia, Blaser et al (1986, p.16) argued that the length of stocking and rest periods in rotational grazing systems should vary as a function of pasture growth rates during the season to avoid damage to pastures. The relative influence of grazing intensity versus frequency seems to depend on the context.

2.1.2 Relationships between stocking methods and grazing systems

Stocking methods cannot be considered independent from grazing systems. Productivities of grazing systems are typically constrained by one or more abiotic factors such as precipitation, temperature, (Parsch et al, 1997), light (Menzi et al, 1991), and soil fertility (Williams and Haynes, 1990): these factors put upper limits on stocking rates. In the continental United States (USA) grazing systems roughly follow an east-west division between rangeland (characterized by native plant species, low soil fertility, evaporation in excess of precipitation, and rapid changes in temperature typical of the western USA) and pastureland (fertile soil planted with introduced species that respond to a regime of abundant precipitation and stable temperature typical of the Eastern USA) at the 98° meridian (Barnes et al, 1995).

The evidence in support of an interaction between stocking method and climate is mixed; pasturelands are said to be less responsive than rangelands to rotational stocking. Briske et al (2008), for example, concluded that performance of cattle on different rangeland grazing systems largely depends on management (stocking methods such as the length of rest period) because performance is constrained by similar abiotic factors (precipitation, fertility, temperature). Kothmann (2009) synthesized many rangeland studies and concluded that grazing changes species composition but does not change primary production. Kothmann explained that the length of time required for succession in a plant community is a function of nutrient and water availability; plant growth and succession are much slower in low-rainfall areas so rangelands benefit most from long pasture rest relative to pasturelands. However, the management principles derived from rangeland and accompanying ecological models such as the state and transition model of disturbance described by Briske et al (2005) do not necessarily apply to humid grazing systems in which resources for plant regrowth are abundant. Changes in species composition in humid systems may be essentially linear in response to grazing pressure. Clark et al (2006), for example, provide evidence that plant communities in temperate pastures can change in response to moderate grazing pressure. Oates et al (2011) suggested that the interactions of plant species with stocking methods can be exploited to maximize grassland productivity.

Animal response to stocking methods on pasturelands can vary greatly: in a given grazing system, similar stocking rates may result in widely different animal performance as a result of differences in forage species, forage mass, or other sward canopy characteristics (Burns et al, 1989; Sollenberger et al, 2005). Subdividing a pasture does not change the stocking rate if all the paddocks are grazed for an equal interval; instead, rotational stocking resets the forage allowance for the herd with each new stocking period. Different responses to stocking rate depend on the context: increasing stocking rate when herbage is already limiting will not improve animal performance whereas increasing stocking rate when herbage exceeds animal demand could benefit animal performance. This is a limitation of past reviews that discuss stocking rate, such as Sollenberger et al (2012): the studies cited in that review varied the season-long stocking rate but none varied the stocking rate within the season in response to changes in herbage mass, as workers such as Edwards and Chapman (2011) have suggested for cool-season pastures that experience a summer slump. McKown et al (1991) is an example of a study in which adaptively changing the stocking rate during rotational stocking to match herbage mass improved herbage nutrient intake across time. The authors concluded that forage nutrient intake was periodically but not consistently diminished as a function of increasing stocking rate for rotationally stocked beef cattle on rangeland. Similarly, Hoveland et al (1997) working on endophyte-free ('AU Triumph') tall fescue pastures in Georgia that were stocked with beef cattle to maintain similar forage availability, found 38% greater stocking rate for rotational stocking of beef cows relative to continuous stocking.

Animals that are stocked continuously in one area tend to repeatedly graze less mature plants and avoid other plants that have reached reproductive maturity and declined in nutritive value, which creates "grazing patches" of mature intact plants (Adler et al, 2001; Baumont et al, 2005; Blaser et al, 1986). As a result of repeated grazing of individual plants, the true stocking rate at specific locations may differ significantly from the average for an entire paddock (Earl and Jones, 1996). Although Dunn (2013) found that differing lengths of stocking period resulted in minimal differences in animal performance when forage allowance was equal to and in excess of requirements, when forage allowance declines during the duration of stocking, animals may defoliate plants several times or graze plant regrowth, which reduces later forage yield (Baron et al, 2002). And while greater stocking density at a given stocking rate may contribute to uniform utilization of forages (Bailey et al, 1996), much of the increased uniformity previously observed in response to controlled stocking may be related to decreased distances to water (DeYoung et al, 1988; Hart et al, 1993). General conclusions regarding the effects of specific combinations of stocking methods on forage in temperate environments remain inconsistent because forage characteristics may vary more than the effects of stocking methods. For this reason the effect of stocking methods is best studied in the context of region-specific grazing systems.

2.1.3 Relationship between stocking methods and forage physiology

Stocking methods are often designed to manipulate the plant growth that occurs in the rest period after defoliation. Defoliation generally resets the progressive maturity (ontogeny) of plants to the vegetative stage to increase subsequent growth rate. Growth rate of grasses across progressive stages of maturity is nonlinear: leaf biomass accumulation is typically represented as a sigmoid (S-shaped) curve with maximum growth rate of leaves during the vegetative stages and slower growth rate during the reproductive stages when energy is supplied to the elongating stem and seed head (Moore et al, 1991; Morley, 1968). During vegetative growth of certain grasses (orchardgrass, tall fescue, and bluegrass) the growth of leaves (axillary meristems) is indeterminate because the growing point (apical meristem) is protected from decapitation (Murphy and Briske, 1992). Defoliation can occur during vegetative growth without removing the growing point of the plant.

After induction of the flower bud at the onset of reproductive development, growth of new tillers slows significantly. Induction in cool-season grass species depends on formation of the flower bud during the previous fall in response to short days and low temperature; therefore, these grasses have one reproductive cycle per year. If the apical meristem is removed after induction in the spring, resources will be available for the auxillary meristems, resulting in renewed leaf growth and tillering for the remainder of the year (Abaye et al, 2006). However, if the seedhead is not removed the plants will eventually regenerate from basal axillary buds;

grazing just advances the time when this regeneration would have occurred (Jewiss, 1993). Stocking to remove reproductive structures before seed development is critical to the productivity of cool-season grass pastures.

Defoliation must also optimize the height and density of the sward for plant regrowth in the context of plant energy reserves. Excluding animals from a pasture after plants are defoliated allows plants to regrow leaf area to optimum density for light interception (90% interception; Blaser et al, 1986), photosynthesis, and hence carbohydrate production (Davisdon and Millthorpe, 1965; Ward and Blaser, 1961). Brougham (1960) found that leaf area index at 95% interception was significantly correlated with maximum growth rate for red clover, white clover, and orchardgrass. After leaf area is sufficient to support growth, carbohydrates are diverted to storage (Blaser et al, 1986). Repeated grazing causes loss of leaf area, which depletes energy reserves to regrow, and grazing may even remove energy storage tissues at the base of stems (Barnes et al, 1995; Brink et al, 2010; Cullen et al 2006). Therefore, in grazing systems in the Eastern USA, stocking management recommendations are based on plant heights (pre-grazing and residual) as they relate to the location of the growing points and energy storage tissues in the stems and roots. Because upright grasses (orchardgrass) and legumes (red clover) store energy at the base of the stems, these species are more productive when grazed to taller residual heights than are sod-forming grasses (Kentucky bluegrass) and prostrate legumes (white clover) that store energy in rhizomes (modified stems) belowground (Blaser et al, 1986; Emmick and Fox, 1993; Hall, 1998). Stocking management must allow sufficient time for energy storage before defoliation to ensure that regrowth is vigorous.

Defoliation also changes the distribution and orientation of leaf area in a sward, thereby altering potential regrowth rate of individual species and competition between species (Abaye et al, 2006; Blaser et al, 1986). In an intact sward, tissue bulk density through the canopy profile often follows a sigmoid distribution (Hodgson, 1985). Removing a greater portion of the canopy results in dis-proportionally greater yield and utilization but reduces leaf area to a variable extent (Barnes et al, 1995, Gerrish, 2004). Consequently, the vertical distribution of leaf area characteristic of each grass species results in different rates of regrowth after defoliation (Belesky et al, 2006). Belsky (1986) added that in mixed-species swards, grazing releases short species from competition for light with tall species, subsequently increasing yield of the short species. Stocking management must consider differences in forage physiology that predict the tradeoff of utilization with regrowth after defoliation.

Defoliation can also modify the number, growth, and distribution of roots (Toughton, 1957). Defoliation can cause roots to senesce, which temporarily decreases plant access to water and soil nutrients and depletes plant carbohydrate stores to supply energy for growth of roots and leaves (Belesky et al, 2006; Blaser et al, 1986; Brown and Blaser, 1965). In fact, the survival of grass tillers may depend on the rate of root initiation (de Ropp, 1945). Crider (1955) quantified the relationship between defoliation and root senescence for tall fescue and orchardgrass; he found that removal of half or more of the foliage of tall fescue caused root growth to stop, although this pattern was not observed for orchardgrass after the first clipping, suggesting that root:shoot imbalance may confer orchardgrass intolerance of frequent grazing but superior performance with extended rest. Others have induced the "take half-leave half" principle of canopy height management to ensure optimum regrowth (Belesky and Fedders, 1994; Boland et al, 2007); however, Belesky and Fedders (1994) found that this practice actually reduced yield of orchardgrass and tall fescue x perennial ryegrass hybrid (*Festuca arundinacea* Schreb. x *Lolium perenne* L.) relative to 75% canopy removal and hay harvest treatments. The complexity of root growth in response to defoliation makes roots an impractical measure of plant fitness for stocking of animals.

2.1.4 Forage accumulation response to stocking methods

Growth rate of cool-season grasses is directly determined by temperature, water supply, and nitrogen supply (Gastal et al, 1992), and their interactions. For example, Lemaire (1988) found that appearance of new leaves on tall fescue tillers is constant in thermal time: a new leaf appears for every 217 degree-days relative to a 0˚C basis. However, leaf senescence is not responsive to temperature because leaf lifespan is relatively constant, implying that the amount of leaf senesced on a given date depends on the quantity of herbage that accumulated at an earlier date (Lemaire and Agnusdei, 2000). When water is not limiting, critical nitrogen concentration (N_c, % DM) for growth of C_3 plants including tall fescue is an allometric function of biomass (MS, tons ha^{-1}): $N_c = 4.8 \times (MS)^{-0.34}$ (Greenwood et al, 1990); this is logical because regrowth biomass tends to have greater N concentration than older material. However, in low-input grasslands where water is limiting at times, nitrogen nutrition is seen to interact strongly with water availability (Gastal and Durand, 2000): swards that experience water shortage may exhibit significant decreases in herbage N concentration despite a great supply of N (Onillion et al, 1995). Long-term water deficit reduces growth rate of tall fescue and the reduced rate of leaf elongation relative to pre-drought levels persists for up to two days after rewetting (Durand et al, 1995).

Continuing a morphogenic approach to describing plant growth (Lemaire and Agnusdei, 2000), grass yield can also be understood in the context of tiller demography (Matthew et al, 2000). When grazing pressure is released, accumulation of leaf biomass in the sward represents the balance between growth of new tillers and death of old tillers (Langer, 1963), as the lifespan of individual tillers averages 30-60 days, depending on resource availability (Ball et al, 2007, p. 113). Tillering continues until light interception by the canopy is almost complete; the tiller population will decrease when smaller tillers are shaded and die (Zarrough et al, 1983). Yield is the product of tiller density (number per unit area) and the average weight per tiller (Barnes et al, 1995). Average weight per tiller increases with extended rest, although tiller density stabilizes, a mechanism referred to as size-density compensation (SDC; Matthew et al, 2000). Therefore, optimum yield of a sward is typically less than maximum yield because light quality and quantity limit photosynthesis as the sward canopy closes. The high leaf area index of a sparsely-grazed pasture blocks light from penetrating into the sward; in an overgrazed pasture leaf area is insufficient to capture incoming solar radiation (Barnes et al, 1995). SDC is also an important mechanism in tall fescue swards. Tall fescue responds to the increased competition for light that accompanies increased plant height by decreasing the space between individual tillers but producing fewer total tillers, resulting in the formation of clumps of grass. Herbage yields are equal in the tall sparse sward and the short dispersed sward but density is different (Rayburn, 1977).

Seasonal changes in availability of light, ambient temperature, and soil moisture can interact with grazing pressure to limit yield of cool-season grasses (Brink et al, 2013). One factor in reduced yield is the reduction in tillering that occurs at greater temperatures when carbohydrate reserves are depleted by rapid growth (Matthew et al, 2000). If regrowth is removed by a large stocking rate in spring or summer, herbage yield in fall may be reduced if regrowth rate is limited by great temperature and low precipitation (Carlassare and Karsten, 2002). For example, Carlassare and Karsten (2002) found that the interaction of weather conditions and plant stage of development at initiation of stocking significantly influenced the quantity of bluegrass harvested at later grazing events. On the other hand, Abaye et al (2006) observed that in the Eastern USA optimum light interception occurs at shorter plant heights in the fall relative to the summer because the sun is at a lower angle in the sky. These outcomes reflect the balance of seasonal climate, residual leaf area, and energy reserves that drive rate of regrowth.

Extended rest will also waste some of the accumulated biomass when grass tillers senesce older leaves. Although productivity of cool-season grasses can increase by 50% with longer rest periods, accumulation of senescent plant material may also increase by 30 to 100% (Belesky and Fedders, 1994; Belesky et al, 2006; Bircham and Hodgson, 1983; Carlassare and Karsten, 2002). Senescent material generally decreases forage nutritive value and leads to grazing refusal (Belesky et al, 2006). Parsons et al (1983a), for example, found that herbage production was greater in perennial ryegrass pastures grazed by sheep to greater residual LAI (3.0), compared to lesser residual LAI (1.0), although animal intake was actually greater at lesser LAI because of less dead material in the sward. Carlassare and Karsten (2002), working in orchardgrass pastures in Pennsylvania found 40% more dead tissue in tall (6 in residual height, 12 in pre-grazing height) as in short pastures (2 in residual height, 8 in pre-grazing height), although green herbage mass was similar. In contrast, Skinner et al (2004), working in Pennsylvania with diverse seeded mixtures that included orchardgrass, bluegrass, and white clover found that stubble height had little effect on yield or forage nutritive value, although senescent material was not quantified. The effect of senescence on biomass and nutritive value likely depends on the balance of rates of growth and defoliation: pastures that are stocked at relatively constant rates may accumulate herbage in excess of intake, which would later senesce at the end of that herbage's lifespan before it can be harvested.

2.2 Forage nutritive value response to stocking methods

2.2.1 Definitions of forage nutritive value

The animal performance from a forage diet depends on assimilation of energy and essential nutrients via forage intake, digestibility, and utilization (Beever and Mould, 2000). Digestibility and utilization are complex processes that are difficult to measure *in situ*; therefore, the nutritional value of forages is often predicted from forage nutritive value and *in vitro* digestibility alone.

Forage nutritive value is measured in terms of several fractions of plant dry matter that are chemically separated via proximate analysis (Van Soest, 1994, p. 142). Although these fractionation procedures do not correspond exactly to digestive physiology, the derived fractions have been shown to account for much of the variation in the nutritional value of forages to ruminants (Tilley and Terry, 1963). Several common measures of forage nutritive value include neutral detergent fiber (NDF), acid detergent fiber (ADF), and crude protein (CP). CP is a function of the nitrogen concentration of forage, which is important for effective reproduction of rumen microbes and therefore effective fiber digestion. Neutral detergent fiber extract (NDF) describes structural carbohydrate or cell wall concentration (cellulose, hemicellulose, lignin, and pectin). NDF is inversely proportional to forage intake by ruminants (Waldo et al, 1972). NDF is known to regulate intake through the feed limitation mechanism of rumen fill (Mertens, 1994), although this effect may vary with different forages (Reid et al, 1988). Acid detergent fiber extract (ADF) describes the concentration of cell wall constituents (cellulose and lignin) without hemicelluloses. ADF predicts forage digestibility and corresponds to energy content. ADF is used to estimate total digestible nutrients (TDN), a measure of energy content that is used in ration formulation for forage diets. The carbohydrate fractions account for up to 60% of total adsorbed nutrients (Beever and Mould, 2000); therefore, ADF and NDF can be combined in a linear equation to develop an index of digestible energy, termed relative forage quality (RFQ), to rank cool-season grass and legume forages (Allen et al, 2011); however, the complexity of diet selection, digestion, and utilization limits prediction of nutrition directly from forage nutritive value parameters so RFQ is not widely used.

Digestibility of the ruminant diet predicts extent of utilization and also feeds back with level of intake. The chemical constituents that describe forage nutritive value are comprised of digestible and indigestible fractions that interact in the rumen (Beever and Mould, 2000). True digestibility of forage dry matter is often measured in vitro as dry matter disappearance (IVDMD) and is calibrated with measurements of in vivo digestion (Tilley and Terry, 1963). In terms of animal performance, Faverdin et al (1995) generalize that each 1 kg dry indigestible material decreases intake by 0.59 kg dry matter on average (r = 0.66), although models to predict dry matter intake have tended to under-predict intake of low-digestibility forages and over-predict intake of forages with greater digestibility (Hyer et al, 1991). However, laboratory measurements of individual feeds may not account for associative effects on nutritional value of mixing greater and lesser value feeds across time (Van Soest, 1994, p. 354), for example interactions between tannins and microbial protein synthesis (Van Soest, 1994, p. 202); nor do *in vitro* procedures necessarily account for compensatory effects of digestion such as nitrogen recycling in the rumen in response to low nitrogen diets which may improve extent of utilization (Sultan and Loerch, 1992). Existing estimates of *in situ* digestibility of heterogeneous forage diets have limited predictive value for animal performance; however, no cost-effective alternative is currently available.

2.2.2 Effect of plant physiology on nutritive value of grazed forage

Stage of maturity explains most of the variability in nutritional value of a given sward

(Blaser, 1962; Rayburn et al, 2006; Rayburn et al, 2008). As tillers of grass mature from vegetative to reproductive stages of maturity lignin replaces cellulose and hemicellulose in plant cell walls (Smith et al, 1972). Digestibility can decline when carbohydrates become cross-linked with lignin or phenolic compounds that are lignin precursors (Jung and Allen, 1995; Van Soest, 1994) although Fales (1986) found no relationship between lignin content and digestibility in tall fescue. Crude protein (CP) content also declines with maturity (Rayburn et al, 2006).

Variability in forage nutritive value through successive layers of the pasture canopy is a common reason for controlled stocking to favor selection of nutritious diets. Blaser et al (1960) compared top-, bottom-, and whole-plant grazing of alfalfa (*Medicago sativa* L.)-orchardgrass mixtures by Holstein cows in Virginia and found that top-plant grazers selected herbage greater in protein and digestibility and less rich in fiber than bottom-grazers. However, the observed nutritive value of forage in different canopy segments is inconsistent in the literature. Brink et al (2007) found increased NDF concentration between canopy segments in tall fescue, orchardgrass, and bluegrass from 25 to 10 cm sward height; however, Brink et al (2013) did not find this, which the authors suggest is perhaps due to increasing soluble carbohydrate concentration in the stem base (La Guardia Nave, 2012; Nelson, 1996).

Much work has focused on the distribution of the digestible water-soluble carbohydrates (WSC) in the grass canopy as a determinant of forage nutritive value. Parsons et al (1983b) found that nonstructural carbohydrates in perennial ryegrass swards contributed up to 200 g kg^{-1} DM and Nelson and Moser (1994) found that non-structural carbohydrates in some cool-season species can represent up to 30% of herbage DM. WSC accumulates in the top of orchardgrass swards during the day and is translocated to the stems in the evening. As a result, variation in WSC within a day is large in comparison with variation across the season. Evidence suggests that this predictable variation in WSC may be used to time the initiation of stocking in the context of management intensive grazing (Griggs et al, 2005). Carbohydrate storage also varies with plant temperature, with greater accumulation of nonstructural carbohydrates in legumes and cool-season grasses at low temperatures (Brown and Blaser, 1965; Nelson and Moser, 1994).

Growth conditions can account for some of the decline in forage nutritive value across the season in several ways. Asay et al (2002) observe that during water-limited conditions, tall fescue plants mature more slowly and have greater concentrations of crude protein and in vitro dry matter digestibility than plants growth with adequate water. Minson and McLeod (1970) observed that greater temperatures increase cell wall content and lessen digestibility in many studies of temperate grass species. Wilson (1982) quantified the negative effect of temperature on dry matter digestibility of grasses to be 6.4 g kg^{-1} for each 1°C increase in temperature on average. Fales (1986) also observed that the digestible fraction of NDF decreased with increasing growth temperature of tall fescue. Furthermore, in tall fescue pastures infected with the *Neotyphodium* endophyte fungus, warm weather, plant maturity, and slow growth correspond with increased concentration of ergovaline alkaloid toxin in plant tissue, subsequently depressing feed intake by livestock (Belesky et al, 1988; Boland et al, 2007; Boland et al, 2011; McClanahan et al, 2008; Stewart et al, 2008). Stocking management that extends the rest period of cool-season grasses during the summer may address potential negative effects of forage nutritive value on animal performance.

Accumulation of dead tissue in the sward also decreases forage nutritive value. Dubbs et al (2003) observed in tall fescue-clover pastures continuously stocked at a constant cattle stocking rate that peak NDF and ADF concentrations coincided with peak proportions of mature, senescent forage in the pastures in June, July, and August. Van Soest (1994, p. 84) suggests that any differences in nutritive value of a sward following grazing will result solely from differences in the nutritive value of the regrowth because the rejected material will not differ in nutritive value because of grazing. However, this concept may be at odds with the water-soluble carbohydrate mechanism that Brink et al (2013) proposed to explain consistent NDF content between canopy layers in the cool-season grass sward, in which translocation of soluble carbohydrates from leaves to stems was said to explain minimal differences in nutritive value between canopy layers.

2.2.3 Forage nutritive value response to stocking methods

Although many studies have examined the relationship between stocking methods and forage nutritive value, few studies have concluded that manipulation of the rest period or grazing intensity alone are significant sources of variation in the nutritive value of forage across time (Sollenberger et al, 2012). More often, observed differences between stocking methods are attributed to differences in stocking rate. For example, Walker et al (1989) attributed observed differences in herbage nutritive value between mob and continuous stocking on rangeland to differences in stocking rate. Bertelsen et al (1993) found no difference in herbage nutritive value between rotational and continuous stocking of an alfalfa-tall fescue-orchardgrass mix in Illinois.

Savory (1988) and others have suggested that implementation of dense stocking of cattle may increase the maximum sustainable stocking rate, although there are few peer-reviewed examples that clearly illustrate this response. Jung et al (1985), working with smooth bromegrass (*Bromus inermis* Leyss.) pastures in Texas stocked continuously or with a short duration rotation, found no difference ($P > 0.05$) in CP, IVDMD, cellulose, hemicellulose, or lignin between stocking methods or individual paddocks in the rotation in the first year, although nutritive value varied widely during the growing season. Jung et al suggest that both systems were under-stocked during the rapid growth phase in the spring, which allowed forage to mature and nutritive value to decline. When in the second year of the study the stocking rate of the short duration rotation was increased by 30% while the stocking rate was not changed in the continuous stocking system, herbage CP was greater ($P < 0.05$) in response to rotational stocking relative to continuous stocking and rotational paddocks stocked later in the year had lesser concentrations of CP and IVDMD and greater concentrations of cellulose and lignin. The authors write that available forage was similar ($P > 0.05$) in both systems in both years, suggesting that rotational stocking was more productive in the second year of the study. However, standing herbage in the rotational system in the first year was actually 36% greater in June and remained greater through August relative to continuously stocked paddocks, which could have carried-over leaf area and biomass to the second year of the study. The limitation of these findings is that the effects of stocking rate and stocking method were confounded; unfortunately, no studies are known that simultaneously compare stocking methods implemented at several stocking rates.

2.3 Legume establishment in cool-season pastures

2.3.1 Role of legumes in pastures

In low input perennial pastures, biological nitrogen fixation in association with legumes can represent the major source of nitrogen (N). In cool-season grass-clover pastures, 25-30% white clover content is considered optimal for contribution of fixed N (Hoover and Stokes, 1991), representing about 70 kg-N ha^{-1} (Ledgard, 1991), although Merry et al (2002) indicated that a 70:30 legume:grass mass ratio achieves an optimum level of microbial protein synthesis in an artificial rumen, which suggests a disconnect between common sward composition and animal requirements. Selective grazing behavior bridges this gap: livestock preferentially consume legumes relative to grass. As a result, nitrogen is concentrated and redistributed in the pasture

(Boland et al, 2012). The nitrogen transfer from legume to grass occurs primarily via dung and urine of livestock, although nitrogen is also provided by decomposition of plant material (Ledgard, 1991). Livestock excrete 75-90% of the nitrogen consumed in forage, returning it to the soil as ammonia, ammonium, and organic nitrogen (Frame et al, 1997, p. 67). Interestingly, application of urine, which contains 300-600 kg N ha^{-1}, to a mixed sward of grass in spring or summer has shown significant decline in white-clover stolon survival and rate of production of new branch stolons in patches, perhaps because of increased competition from grass (Marriott et al, 1987, 1991) or increased soil pH (Thomas et al, 1986). Although these relationships would seem to be entirely detrimental to legumes, in fact the cycling of nitrogen is central to the coexistence of grass and legumes in temperate humid grazing systems (Schwinning and Parsons, 1996).

2.3.2 Planting and persistence of red and white clovers

Preparation of the seed and seedbed can affect clover establishment and persistence. Soil phosphorus (P), potassium (K), and optimum soil pH in the range of 5.8 to 6.5 are critical (Ball et al, 2007, p. 83; Frame et al, 1997, p. 52). Rangeley and Newbould (1985) observed that P-deficient white clover plants had few leaves with small leaf area and reduced stolon formation. K-deficient white clover had more leaves with slightly larger leaf area but many of the older leaves were senescent. Inoculation of seed with an effective strain of *Rhizobium trifolii* bacteria also contributes to effective nodulation, nitrogen fixation, and legume persistence if soil fertility is adequate for plant growth (Ball et al, 2007, p. 108-111). Slope position also influences clover establishment: in cool-season pastures in Iowa counts of seeded clovers in swards cut to 5 cm were approximately three times greater on the summit than on the backslope, which the authors attribute to reduced competition from grass on backslopes (Guretzky et al, 2004).

Generally, white clover yields in the post-establishment year are less than in subsequent years (Dunn, 2013), as energy reserves are first stored in the taproot. White clover proceeds through two distinct morphological stages: first a taproot develops after establishment and then stolon growth proceeds in the following years (Brock et al, 2000). As Skinner and Moore (2007) describe, “Death of the taproot and primary stolon initiates the fragmentation of the initial plant into a number of independent clones that are rooted at nodes of the surviving stolons.” As vegetative propagation occurs, clover populations in a grass sward can fluctuate for 5-10 years before reaching equilibrium (Thornley et al, 1995). This shallow root system of white clover leads to early leaf wilting and senescence during drought, which can reduce white clover populations (Hart, 1987). Pearson and Ison (1997, p. 41) report that white and red clovers require 790 and 800 mm yr^{-1} minimum precipitation, respectively, although precipitation in excess of potential evapotranspiration (PET) in arid climates might logically exert greater influence on vegetation than precipitation alone.

Red clover, in contrast, regenerates from basal shoots, rather than fragmentation from stolons. Consequently, plant numbers tend to decline after germination. Stem extension is limited in the year of sowing; however, in long-day conditions in the second year the auxillary buds produce leafy stems and flowering occurs (Gill, 1980). Within two to four years after sowing, branching of individual plants compensates for the yield loss of individual plants (Jewiss, 1993). McBratney (1981, 1984, 1987) found that red clover maintained productivity in tall fescue swards for 4 to 6 years when no N was applied and contributed 36% of total biomass 8 yr after sowing. Gill (1980) notes that early and late varieties of red clover differ in their regrowth and persistence: because late red clover stems elongate at the same time, few shoots remain for further growth after flowering; however, late varieties tend to survive for two or more years.

However, Byers et al (2006) comment that crown and root diseases of red clover in the Eastern USA reduce persistence of this legume.

2.3.3 Legume establishment response to stocking methods

The relationship between stocking methods and legume establishment is inconsistent in the literature. As Belesky et al (2006) explain, heavy defoliation favors white clover because its prostrate growth habit protects a greater proportion of stolons from defoliation compared to red clover, which has an upright growth habit. Similarly, Schlueter and Tracy (2012) concluded that removing residual grass biomass before sowing was more important than seeding method (broadcast or no-till drilling) of white and red clover in cool-season grass pastures in Virginia. However, small white clover plants are sensitive to damage from frost heaving and cold in the winter in closely grazed swards (Belesky et al, 2006; Woledge et al, 1990), which suggests that sward biomass can have mixed effects on clover establishment. Increasing grazing intensity tends to increase white clover content (Pavlů et al, 2003), although Coffey et al (2005), working with red, white, and ladino clover in tall fescue pastures found no relationships between stocking density or stocking period and legume content. Dunn (2013) found that legume content did not differ between continuous, rotational, and mob stocking during two years, although differences in stocking density may have been too small to influence legume content.

Stocking methods can alter the growth habit of clover because clovers are known to exhibit phenotypic plasticity in response to stress (Frame et al, 1997, p. 17). White clover exhibits progressive dwarfing of leaves and petioles and reduction in stolon branching in response to greater grazing pressure (Frame et al, 1997, p. 17). Rest periods encourage development of larger laminae and petioles and vigorous expansion of stolons (King et al, 1978), although growing point density declines (Wilman and Asiegbu, 1982). In situations of partial defoliation, leaf appearance rate is not affected by defoliation interval, unless it is extremely short (< 3 d) or long (> 21 d; King et al, 1978). These patterns illustrate how phenotypic plasticity allows small-leaved cultivars of white clover to persist during less frequent defoliation, although with lesser yield, by trading off leaf size with leaf number and stolon production. Large-leaved cultivars of white clover are less able to adapt to infrequent defoliation (Brock and Hay, 1996). Interactions of clover cultivar by grazing method indicate that small-leaved cultivars of white clover perform best during frequent defoliation whereas large-leaved cultivars perform best during periodic defoliation (Evans and Williams, 1987; Swift et al, 1992; Wilman and Asiegbu, 1982). Selection of an appropriate cultivar for the intended stocking methods is relevant to clover establishment.

2.3.4 Effect of legume establishment on forage nutritive value

The effect of clover establishment on forage nutritive value is inconsistent in the literature. Legumes often have a greater proportion of N in relation to C than grass (Whitehead, 1995). As such, they are widely regarded as important sources of crude protein for grazing livestock. Rayburn (1991) quantifies the positive effects of legumes on forage nutritive value in rotationally stocked pastures in the Northeast: grass pastures with 16-50% legume content have greater CP and lesser NDF during the entire growing season than pastures with less than 16% legume. However, Dubbs et al (2003) found that interseeded red clover in continuously stocked tall fescue pastures in Kentucky did not affect ($P > 0.10$) crude protein, NDF, or ADF of the sward. Red clover stems actually have more ADF, lignin, and cellulose than red clover leaves; therefore, some have suggested that great grazing pressure in autumn can exploit the optimum leaf:stem ratio of younger red clover plants for nutritional value (Sheehan et al, 1985). Similarly, although white clover has greater cell contents and lesser cell-wall contents than grass herbage at the same degree of maturity, the flower-heads and stalks of white clover are less digestible than grass stems and leaves, which may explain why mixed grass/clover herbage may not be superior to pure grass in summer (Wilman and Altimimi, 1984; Søegaard, 1994). The benefit of clover for forage nutritive value may depend on management by season.

2.3 Diet selection in cool-season pastures

The goal of studying voluntary diets is to understand how animals respond to forage on offer. This response involves complex interaction between animals and herbage: as Cherney (2000) writes, "intake, digestibility, and efficiency of utilization are characteristics of forages that determine animal performance." When animal performance cannot be measured directly via weight gain, voluntary dry matter intake alone can account for 50-90% of the variation in average daily gain (Allen, 1996; Crampton, 1957; Crampton et al, 1960; Mertens, 1994). Achieving desired animal performance depends to a large extent on modifying the quality and quantity of the diet.

2.3.1 Definition of diet selection, preference, and opportunity

Diet selection is how animals moderate diet quality and quantity in heterogeneous environments. As defined by Allen et al (2011), "diet selection by grazing animals is a function of preference modified by opportunity." The relative importance of preference and opportunity are context-specific; preference often limits selection when opportunity is unlimited and vice versa. However, others believe specifically that when diet opportunities are limited by short time periods, large animal-to-forage ratio, and poor forage quality, as may occur during mob stocking, "in practice, stocking to overcome preference is rarely achieved" (Allen et al, 2011).

Preference, in the context of ruminant diets, is the choice made by an animal between alternative forages, measured by relative intake of two forages when access is unrestricted (Allen et al, 2011). Several hypotheses regarding animal preferences have been experimentally verified: partial preference for legumes (60:40 legume to grass; Boland et al, 2012; Rutter, 2006), diurnal pattern of preference for fibrous feeds (preference greater in the evening; Rutter, 2006; Dumont et al, 1995), preference for previous diets (Parsons et al, 1994; Voisin, 1998, p. 105), preference for variety (Newman et al, 1992), and preference for diets experienced in early life (Arnold and Dudzinski, 1978; Ganskopp and Cruz, 1999; Ramos and Tennessen, 1992). Several of these preferences explain observed patterns of selection in some situations.

A logical fallacy entails in the study of diet selection when mechanistic reasons are deduced to explain observed preferences (Hodgson, 1979; Parsons et al 1994). One example is the paradox that concerns whether animals eat certain plant species faster because they prefer them (sensory stimulus) or whether they prefer certain plant species because they can eat them faster (optimization of behavior; Illius et al 1999). Novelty, rarity, and sampling are other mechanisms induced to explain apparent patterns of preference for variety (Newman et al, 1992). Perhaps all of these mechanisms of preference influence the intake of certain plant species. Many studies of mixed diets address such paradoxes by simply measuring selection without alluding to preference (Parsons et al 1994).

The opportunity for grazing animals to consume plants in a given enclosure is commonly seen as a major limiting factor in diet selection. Herbage mass, height, and species are several components that define foraging opportunities for grazers. Forage intake is typically independent of the mass of forage on offer (ad libitum intake occurs) at certain levels of forage allowance (Stewart et al, 2008). However, dry matter intake will decline when forage mass declines below a threshold of forage allowance due to removal by grazing, senescence of mature tissue, or harvest losses by trampling and fowling. For orchardgrass-white clover swards, forage mass is positively correlated with intake below 1,350 kg dry matter ha^{-1}. Swards of tall fescue become limiting to intake at a greater forage mass because intrinsically greater tiller density reduces accessibility of the residual herbage (Brink and Soder, 2011). Whetsell et al (2006) generalized the intake-limiting threshold for cool-season grasses to 1,150 kg ha^{-1}; estimated intake below this level can be adjusted in proportion to herbage mass. In all cases, plant material shorter than 2 cm is inaccessible to bovines because this represents the distance between the lips and dental pad (Dunn, 2013; Voisin, 1988, p. 69). In essence, much of the variation in intake rate is a function of canopy density (Casey et al, 2004; McGilloway et al, 1999) and sward height (Brink and Soder, 2011; Laca et al, 1994; Penning et al, 1994; Tharmaraj et al, 2003) because these parameters decline rapidly after the initiation of stocking. Therefore, as Bailey et al (1996) write, "large herbivores may be forced to select lower quality diets to maintain intake when forage is limited."

2.3.2 Patterns of diet selection

Research has also revealed several patterns of selective behavior that may account for a significant amount of the variability in dry matter intake when herbage mass is not limiting. Animals tend to decrease selectivity in proportion to body size; therefore, young animals and females are more selective than older animals or males (Cazcarra and Petit, 1995; Peischel, 1980). Grazing animals of all sizes also tend to select mixed diets, exhibiting partial preference for clover relative to grass when both are offered as monocultures (Boland et al, 2012; Rutter, 2006), and tend to select novel foods to sample (Newman et al, 1992). However, selection is different in mixed swards than in monocultures: Clark and Harris (1985) observed that sheep grazing grass-clover swards selected less clover when the species are offered in an intimate mixture than in separate strips at the same proportions. On mixed plots they found no correlation between content of grass versus clover in the sward and selection of grass versus clover by esophageally fistulated sheep, which the authors conclude implies that the sheep grazed to optimize energy intake.

Researchers have observed several other nuances of diet selection. Hill et al (2009) found that sheep also selected a mixed diet when provided grass swards with large N and sparse N concentrations; however, Harvey et al (1996) did not find any effect of grass N concentration on clover selection by sheep, which complicates prediction of diet selection based on forage N concentration alone. Similarly, although bovines preferentially graze patches fertilized by urine, bovines also avoid forage in proximity to manure. However, Etter (1953) found that cows readily grazed clean grass that was cut away from manure pads and offered apart, reinforcing the context-specific nature of selection. Rook et al (2004) summarizes the complexity of applying this nuance, reminding readers that many patterns of selectivity do not describe choices in particular situations or specific spatial patterns of foraging.

2.3.3 Effect of stocking methods on diet selection

In simplest terms, grazing animals typically select a diet of greater nutritive value than the average of the forage on offer (Parsons et al, 1994; Rayburn, 1991; Sollenberger and Vanzant, 2011; Stewart et al, 2008). Grazers also select green leaves relative to dead leaves (Grant et al, 1985) and leaf relative to stem (Hodgson, 1990). To quantify the relationship between diet and herbage on offer, Dunn (2013) calculated selectivity indices as the ratio of the concentration of IVDMD or CP in rumen extrusa samples to concentrations in hand-clipped forage. Selectivity for CP tended to be lesser ($P = 0.09$) during mob stocking than during rotational and continuous stocking (1.01, 1.25, and 1.24, respectively), even though herbage chemical analysis and mean sward heights did not differ ($P > 0.10$) by stocking method.

One consistent result from studies of selection in different stocking methods is that given a heterogeneous sward livestock appear to select an adequate diet. Past studies with esophageally cannulated steers have shown limited differences in intake between stocking methods, with greater variation from month to month than treatment to treatment. For example, Walker et al (1989) found that diet nutritive value during rotational and continuous stocking on rangeland was correlated with the nutritive value and quantity of herbage on offer, which varied more among sequential sampling dates than between treatments; diet nutritive value also did not differ between the first and last days of grazing in the rotational grazing treatment, reinforcing a hypothesis that rotational stocking on rangeland would not affect animal performance relative to continuous stocking. However, evidence suggests that the nutritive value of the residual herbage is lesser post-grazing (Heitschmidt et al, 1982) so rotationally-stocked paddocks sampled on the same date would be expected to differ in nutritive value (Jung et al, 1985). Sollenberger et al (2012) describe how samples of clipped pasture and rumen extrusa can provide misleading results: Bertelsen et al (1993) compared continuous and rotational grazing of tall fescue alfalfa pastures in Illinois: although pre-graze pasture samples and extrusa samples from rotationally stocked pastures were lesser in ADF, NDF and greater in CP than continuously stocked pastures, total tract digestibility of those parameters did not differ by stocking treatment.

Other stocking methods, including paddock dimensions, stocking rate, and stocking density, are known to influence the spatial scales at which livestock select diets. Pastures are often heterogeneous at different spatial scales, with significant variation in sward characteristics and selective behavior from one scale to another. Soder et al (2007) hypothesizes in this respect, "when animals detect sward heterogeneity, their foraging walks are not random, but are structured to efficiently utilize the sward structure (Baumont et al, 2005; Parsons and Dumont, 2003)."

When animals select feeding sites at any given scale, selective behavior often follows consistent patterns, although the outcome is largely probabilistic (Parsons and Dumont, 2003). Bailey et al (1996) and Senft et al (1987) discuss six spatial scales of dietary selection, of which Roguet et al (1998) analyzed two available to livestock in enclosures: the bite and feeding station, which are both selected without moving the legs. Roguet et al (1998) considered enclosed livestock unable to choose among landscape scales, which are selected by moving the legs. However, Bailey (1995) observed patch selection, which is a spatial scale one order greater than feeding station, among a group of five steers: one or two consistently selected a patch to graze and the remainder followed the lead animal. Voisin (1988, p. 74) observed feeding site selection (a spatial scale one order greater than patch): “cows tend to graze together in accordance with certain rules: on a long, narrow pasture the group moves from one end to the other. On a square pasture they tend to travel in circles.” Bailey et al (1996) observed that animals tend to alternate between similar feeding sites, returning to the same patch until forage mass drops by five to 10 percent. Stocking methods often dictate that animals continue to graze in a given area until a predetermined reduction is forage height or mass is achieved or a certain amount of time passes.

Herders can influence diet selection through paddock design. Of the spatial scales discussed by Bailey et al (1996), “camp” and “home range” are analogous, respectively, to paddocks within a pasture and the stocked pastures on one farm. Herders might make selective decisions at these scales by intentionally or inadvertently establishing pastures that differ from each other, perhaps to manage around landscape features (Baumont et al, 2000). For example, it is generally thought that cattle tend to spend less time grazing on pasture slopes than summit or toeslope areas (Sollenberger et al, 2012, pp. 138). In other words, fences help people establish homogeneous areas that will foster predictable selective behavior by livestock (Belesky et al, 2006). Limiting foraging opportunities with fences may ensure that less nutritious material in the paddock is consumed when the average sward nutritive value declines with increasing duration of stocking. However, if a paddock consists of two extremes of forage nutritive value, livestock may graze the more nutritious material to the point of damaging the growing points of the plants before moving on to select the less valuable material. After a period of maximum intake of maximum nutritive value, both forage intake and nutritive value will decline and some material may be wasted altogether, limiting animal and plant productivity. To address these problems, stocking methods are selected to manipulate the tendencies of livestock to maximize the pasture resource; often, simply herding animals to a new paddock will stimulate intake. Context-specific knowledge of the dynamics of herbage nutritive value as pasture mass changes during grazing pressure can inform stocking methods to achieve specific forage and livestock production goals.

Conclusion

Fluctuations in forage nutritive value in response to maturity and weather strongly influence the diet of grazing livestock in comparison with stocking methods alone. However, stocking methods can impact forage nutritive value at subsequent stocking periods because of competitive release, the interaction of defoliation with climate, and phenotypic plasticity. Furthermore, establishment of legumes and the coexistence of grasses and legumes in mixed swards benefits forage productivity and forage nutritive value. While the effects of mob stocking methods in specific grazing systems are unexplored, it would be reasonable to predict that providing an increased rest period would increase forage maturity and height. Increased maturity would depress forage nutritive value through lignification and accumulation of senescent material. Increased height would increase canopy interception of light, which would reduce grass tiller density and decreased yield of white clover. However, in the context of low forage nutritive value and dense stocking, stocker cattle may be able to select a diet that is adequate for growth. Stocking density may also contribute to soil health if senesced residue is effectively trampled and stocking management facilitates uniform dispersion of excreta.

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Chapter 3. Materials and Methods

3.1 Study Sites

The grazing experiments were conducted at three locations in Virginia: Blacksburg, Raphine, and Steeles Tavern (Fig. 3.1). Samples from the Steeles Tavern location were analyzed separately from the Blacksburg and Raphine locations, which were analyzed together.

3.1.1 Blacksburg and Raphine, VA

Research in Blacksburg was conducted at the Prices Fork Research Center (Montgomery County, VA, 37˚12’48”N latitude and 80˚29’22”W longitude, elevation: 619 m, Fig. 3.2). The site consisted of a 7-ha pasture that was studied from 2013-2014. Soils were well-drained Groseclose and Poplimento loam soils (Fine, mixed, semiactive, mesic Typic Hapludults and Fine, mixed, semiactive, mesic Ultic Hapludults, respectively), with slopes ranging from flat to moderately steep, 2% to 25% slopes (Soil Survey Staff, 2010, 2014). For 20 years before 2012, the pasture was cut once or twice a year for cool-season grass hay and rarely fertilized (Teany, 2004). Beef cattle were stocked in 2012 with methods similar to this study (Williams, 2014). Tall fescue, orchardgrass, Kentucky bluegrass, and sweet vernal grass (*Anthoxanthum odoratum* L.) were the predominant vegetative cover in April 2012. Commercial fertilizer (10-10-10) was applied in 2006 and in April 2013 commercial fertilizer was applied according to soil test recommendations (Table 3.1 reports soil test results). Ladino clover (*Trifolium repens* L. ‘Will’) and medium-sized red clover (*Trifolium pratense* L. ‘Cinnamon Plus’) were broadcast in February 2013 at 1 and 2.5 kg ha^{-1} (3 and 6 lbs $acre^{-1}$), respectively, across all paddocks. Blacksburg has a humid continental climate with 1039 mm average annual precipitation. Average monthly temperatures range from -0.3˚C in January to 21.8˚C in July (Table 3.2; Menne et al, 2010). Total annual precipitation in 2013 exceeded the 30-year average but total annual precipitation in 2014 was less than average (Table 3.2 reports monthly precipitation; Menne et al, 2014). The spring of 2013 was cooler than average but fall 2013 was warmer than average.

Research near Raphine (Augusta County, VA, 37˚57’16”N latitude and 79˚13’26”W longitude, elevation: 540 m, Fig. 3.3) was conducted on private land. The site consisted a 16-ha pasture that was studied from 2013-2014. Soils were well-drained Frederick and Christian gravelly silt loams (Fine, mixed, semiactive, mesic Typic Paleudults, and Fine, mixed, semiactive, mesic Typic Hapludalts, respectively), with slopes ranging from flat to moderately steep, 2% to 25% slopes (Soil Survey Staff, 2010, 2014). Sweet vernal grass, tall fescue, white clover, and bluegrass were the predominant vegetative cover in April 2012. The pasture was rested in 2012 and had been managed for cool-season grass hay before then. Previous fertilization is unknown but commercial fertilizer was applied according to soil test recommendations in April 2013 (Table 3.1 reports soil test results); however, the “Continuous 1” paddock (Fig. 3.4) did not receive commercial fertilizer. Ladino clover and red clover were broadcast in February 2013 at 1 and 2.5 kg ha^{-1}, respectively, across all paddocks. Raphine has a humid subtropical climate with 993 mm average annual precipitation. Average monthly temperatures range from 0.3˚C in January to 23.1˚C in July (Menne et al, 2010). Total annual precipitation in 2013 exceeded the 30-year average but total annual precipitation in 2014 was less than average (Menne et al, 2014).

3.1.2 Steeles Tavern, VA

The third site was located at the Virginia Tech Shenandoah Valley Agricultural Research and Extension Center (SVAREC) near Steeles Tavern in Augusta County and Rockbridge County, VA (37˚55’45”N latitude and 79˚13’11”W longitude, elevation: 582 m, Fig. 3.4) and consisted of a 90-ha pasture studied in 2014. Soils on the site were well-drained silt loams from four series: Bookwood silt loam (Fine-loamy, mixed, semiactive, mesic Ultic Hapludalfs), Caneyville silt loam (Fine, mixed, active, mesic Typic Hapludalfs), Christian silt loam, and Frederick silt loam. The site contained limestone rock outcrops and slopes ranging from flat to moderately steep, 0% to 25% slopes (Soil Survey Staff, 2010, 2014). Vegetation at the site was dominated by endophyte-infected tall fescue, orchardgrass, and Kentucky bluegrass. In winter 2007 and 2009, 4.5 kg ha^{-1} of white clover and red clover seed were broadcast across all paddocks (Jones and Tracy, 2014; Emenheiser, 2014). Climate is similar to the Raphine location.

3.2 Experimental design

The Blacksburg and Raphine locations were complete blocks with one pasture at each location receiving one of three stocking treatments, termed 'mob', 'rotational', and 'continuous' stocking (stocking methods are described below; six total experimental units). Figures 3.2 and 3.4 diagram the pasture arrangements at each location. Within the pastures, paddocks were established with high-tensile wire or polywire to subdivide the pastures into units of approximately equal area to implement the stocking treatments. The number of paddocks within pastures differed between sites and among treatments but was generally consistent across years (Table 3.3). Beef cows (612±5 kg) and steers (314±3 kg) were stocked, respectively, at the Blacksburg and Raphine locations at 12 animal unit months per ha (AUM ha^{-1}; 1 AU = 454 kg live BW). Water and mineral were offered *ad libitum*.

The Steeles Tavern location was a randomized design with three replications of three stocking treatments, termed 'mob strip graze', 'rotational', and 'continuous' stocking (described below). Each treatment was applied to three areas (nine total experimental units; Figure 3.4). Within the treatment areas, pastures were subdivided into paddocks of approximately equal area with high-tensile wire and polywire to implement the stocking treatments. Mature beef cows

(623±7 kg) were stocked in all treatments at 12 AUM ha^{-1} and calves (35±2 kg) were retained with their dams post partum (Table 3.4).

The methods of stocking beef cattle employed in this study were termed 'mob', 'rotational', and 'continuous.' At the Raphine and Blacksburg sites, mob stocking consisted of two stocking periods each year of 12- to 16-h duration, stocking densities were 138,000-155,000 kg live BW ha^{-1} on 0.1- to 0.2-ha paddocks, and rest periods were 90- to 120-d during the growing season. Rotational stocking consisted of 6 to 7 stocking periods of 3- to 4-d duration on 0.3 to 0.7 ha paddocks with fixed 28-d rest periods. Continuous stocking consisted of one uninterrupted stocking period that spanned the duration of the growing season (110 to 196 d).

'Mob' stocking at the Steeles Tavern location consisted of three stocking periods each year, on 0.1 ha paddocks that were allocated to the cattle every 24 h. Paddocks were not back-fenced to allow access to water at a fixed location on one end of the pasture. Each pasture was rested for a fixed period of 64-d. Stocking density of approximately 43,000 kg live BW ha^{-1} was maintained on the paddocks.

3.3 Methods

3.3.1 Herbage mass

Standing herbage biomass at Blacksburg and Raphine was harvested in 2013 and 2014 at monthly intervals (Table 3.5) by clipping all vegetation within 0.25-m^2 square quadrats to the soil surface with sheep clippers or hand shears. Quadrats were treated as subsamples of the standing herbage in each pasture. Samples were taken at fixed intervals of 30-50 m apart; seven to 26 quadrats were harvested in each paddock each month. Figures 3.3 and 3.5 diagram the numbered sampling locations at Raphine and Blacksburg, respectively. Equal numbers of samples were harvested from each paddock each month. Sampling points were identified with a hand-held GPS (Juno 3B, Trimble Navigation Ltd., Huber Heights, Ohio). Harvested herbage biomass was dried in a forced-draft oven at 55˚C for 48 h and then weighed. In 2014, compressed herbage height was measured within each quadrat with an electronic rising plate meter (RPM; Farmworks F300, Manawatu-Wanganui, NZ) before herbage was harvested.

Standing herbage biomass at Steeles Tavern was harvested in 2014 at monthly intervals (Table 3.6) by cutting all vegetation in a 0.5-m^2 swath to 2 cm above the soil surface with a mechanical harvester (Swift Machine and Welding, Swift, SK). Samples were taken at a central location in each paddock of the mob and rotationally stocked pastures. Continuously stocked pastures were sampled at nine randomly selected locations in each pasture. The length of each swath and total wet weight were measured. Herbage subsamples (50 to 200 g) from each swath were collected, weighed before drying in a force-draft oven at 55˚C for 48 h, and then weighed after drying. Compressed herbage height was also measured with an electronic rising plate meter before and after stocking each month in one designated pasture within each treatment area. Compressed height was measured four times in the general area of 10 to 18 sampling points spaced at 20-m intervals in each pasture. Sampling points were identified with a hand-held GPS.

Herbage allowance (kg DM kg BW^{-1}) was calculated by dividing herbage DM by the cattle live BW in each paddock. Herbage DM was calculated by multiplying the mean herbage biomass within each paddock by the area of that paddock. Cattle live BW was calculated by multiplying the estimated mean cattle BW at the time of herbage sampling (± 5 d) by the number of cattle stocked. Cattle live BWs were measured 2 to 3 times each year at the Raphine location: before stocking, one month after initiation of stocking, and at the end of stocking. Cattle live BW was measured before stocking and at the end of stocking at Steeles Tavern. At the Blacksburg location, the herd manager at the VT Beef Center visually estimated the average BW of the cattle stocked in the study. The slope of a simple linear regression between BW endpoints was used to estimate average daily gain (ADG) for cattle assigned to each stocking treatment. BW at the time of herbage sampling was linearly interpolated using the mean ADG for cattle in each paddock.

Harvest index (*HI*) for the mob and rotational stocking treatments was calculated by the Carlassare and Karsten (2002) method using the following equation:

Equation 3.1: $HI = 1 - (\frac{DM_2}{DM_1})$

where DM_2 is herbage biomass immediately after stocking and DM_1 is herbage biomass immediately before stocking.

3.3.2 Herbage accumulation and disappearance

Changes in herbage mass over time were quantified in this project on annual, monthly, and daily scales. Growth of herbage is hereafter referred to in three ways: aboveground net primary productivity (ANPP; kg ha^{-1} yr^{-1}), herbage accumulation for a period of time (herbage A; kg ha^{-1}), and rate of herbage accumulation (kg ha^{-1} d^{-1}). The sum of intake of herbage and senescence of herbage are hereafter referred to as annual disappearance (kg ha^{-1} yr^{-1}) and herbage accumulation for a period of time (herbage D; kg ha^{-1}), respectively. Rates of herbage disappearance were not calculated.

Herbage A and D were measured in all pastures at all locations in 2014 with the difference method described by Lantinga et al (2001, p. 33). Calculations of herbage A and D varied by stocking method. Herbage A and D of continuously stocked pastures was measured with six 1-m^2 x 1.5-m tall wire mesh exclosures that were secured near the sampling points in one paddock of each of the continuously stocked pastures. Compressed forage height was measured four times each inside and in the general area outside of the cages with an electronic RPM each month before and after the cages were moved to new sampling points within the paddock. Measurements inside and outside of cages in each pasture were averaged to single values, respectively. Herbage A in the mob stocking pastures was measured monthly with the RPM; herbage D was calculated as the difference in compressed herbage height before and after a mob stocking period. Herbage A in the rotationally-stocked pastures was calculated as for the continuously stocked pastures: paddocks in the rotationally-grazed pastures that had not been stocked since the previous measurement were treated as exclosures; herbage D was calculated as the difference in compressed height of forage in paddocks that were currently stocked relative to the previous measurement, adjusting for accumulation. Unique RPM slope coefficients for each month were used to estimate herbage mass, as suggested by La Guardia Nave (2012). Rates of daily herbage accumulation were subsequently calculated by dividing the changes in mass during each period of accumulation by the number of days in the respective period.

At the Blacksburg and Raphine locations A and D were measured from May 5-November 11, 2014. Herbage A and D at Steeles Tavern were measured from July 22-November 22, 2014. The differences in herbage mass in each pasture between the beginning and end of these periods were taken to estimate accumulation that occurred before the initiation of stocking and account for residual biomass at the end of the stocking period. Accumulation each month was summed and added to the herbage mass baseline to estimate ANPP, according to the balance sheet approach of Lewis (1970). Monthly disappearance measurements were summed and added to the herbage mass at the end of the stocking period to calculate annual disappearance, assuming all residual herbage died at the end of the year. The calculations for ANPP and annual disappearance at Blacksburg and Raphine are summarized in Equations 3.2 and 3.3, respectively.

Equation 3.2: $ANPP = \left(Ys_{May\ 5} - \ Ye_{Nov.\ 11}\right) + \sum_{t=\text{May 5}}^{\text{Nov. 11}}(dYu)$

Equation 3.3: $Annual\ disappearance = (-Ye_{Nov.\ 11}) + \sum_{t=\text{May 5}}^{\text{Nov. 11}}(Ys - Ye - dYu)$

where *ANPP* is aboveground net primary productivity, *Ys* is herbage mass above the soil surface estimated with the rising plate meter at the start of a grazing period; *Ye* is herbage mass estimated with the rising plate meter at the end of a grazing period, and *dYu* is undisturbed herbage accumulation in the exclosure during a grazing period. ANPP and annual disappearance at Steeles Tavern were calculated with Equations 3.2 and 3.3 for July 22-Nov. 22, 2014.

3.3.3 Plant species composition

In 2013 and 2014, percent cover of herbage, dead material, and bare soil was measured in 0.5-m^2 rectangular quadrats in spring, summer, and fall at the Blacksburg and Raphine locations (Table 3.4). The sampling points were located according to the methods described in Section 3.3.1. Herbage cover measurement at Steeles Tavern was similar to the other locations but only occurred in 2014 (Table 3.5) and was made at eight to 18 sampling points spaced 20 m apart in pastures adjacent to the pastures that were measured with the electronic rising plate meter. Estimates of percent cover of individual species in each quadrat were recorded in the field and each estimate was later scaled so that the sum of all components was 100. Percent covers of clover, forage, and weed species were calculated by summing several components: clover was the sum of red and white clovers; forage was the sum of bluegrass, orchardgrass, and tall fescue; weed was the sum of all other live vegetation. Bare ground and dead material were also quantified.

After herbage cover was estimated at Blacksburg and Raphine, one half of each quadrat was harvested for standing herbage biomass, as described in Section 3.3.1.

3.3.4 Herbage nutritive value

The oven-dried samples of standing herbage biomass harvested from all locations (described in Section 3.3.1) were milled with Thomas-Wiley mills (2-mm screen; Philadelphia, PA) and cyclone mills (1 mm screen; Cyclotec, Hilleroed, Denmark) and then scanned with Near Infrared Reflectance Spectroscopy (NIRS; FOSS 6500, Hilleroed, Denmark). Herbage nutritive value and moisture content were predicted with a fresh forage equation. Accuracy of the fresh forage equation was assessed with the Global H (Mahalanobis distance) and Neighborhood H statistics (Shenk et al, 2007, p. 371). Crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) were predicted as percent by mass of the total sample and scaled to a dry matter basis. Energy content of each herbage sample was estimated in terms of the total digestible nutrient (TDN) content as a percent of DM, which was calculated with the following equation (Robinson, 1999):

Equation 3.4: $$TDN = 82.38 - \left(0.7515 \times \left(\frac{NDF\% - 3.41}{1.1298}\right)\right)$$

where 1 kg TDN = 4.4 Mcal digestible energy (DE; NRC, 2000). Conversion from DE to metabolizable energy (ME) is approximately 0.80.

3.3.5 Nutritive value of herbage selected by esophageally cannulated beef steers

This study was conducted Sept. 28 to Oct. 2, 2014 at the Blacksburg site with two esophageally-cannulated steers. The Virginia Tech Institutional Animal Care and Use Committee (IACUC) approved the protocol for handling and care of the steers used in this study (Amendment Application Number: 14-096). The steers were fasted overnight prior to initiation of the study and for up to 4-h when not in use. Masticated herbage was collected in duplicate from the esophageal cannula of the steers at 4-h intervals during three sequential 16-h stocking periods in the mob stocking pasture. Hand-plucked reference samples were harvested simultaneously with the masticate herbage samples by observing the plant species and portions of the herbage selected by the animals. Masticated herbage and hand-plucked samples were also harvested at 9:00 A.M. once each day for three days in the rotational and continuous stocking paddocks after sampling in a mob-stocking paddock. Masticated herbage and hand-plucked samples were immediately flash-frozen with liquid nitrogen and then stored at -20˚C before lyophilization (VirTis genesis 25EL, SP Scientific, Ridge Stone, NY). Lyophilized samples were milled and analyzed with NIRS to determine nutritive value as described in Section 3.3.4. An index of selectivity (IS; Dunn, 2013) was calculated by dividing the nutritive value of esophageal extrusa samples by the nutritive value of grab samples that represent the herbage on offer, where IS > 1 is selective and IS < 1 is non-selective.

3.4 Statistical analysis

Statistical analysis was performed in *R* Version 3.1.2 (*R*, Institute for Statistical Computing, 2008). Samples from the Steeles Tavern location were analyzed separately from the Blacksburg and Raphine locations, which were analyzed together. Samples collected within each treatment replicate each month were averaged together for the final analysis. Pearson's correlations and multiple linear regressions between herbage parameters were performed on complete pairs of observations from the samples collected within each treatment replicate.

For the Blacksburg and Raphine locations, multi-factor repeated measures analysis of variance (ANOVA) was performed to examine differences in herbage nutritive value, herbage cover, and herbage biomass among the 3 treatments and between 2 locations. Time (13 consecutive periods of the growing seasons 2013-2014) was included as a linear term to test if the effect of time differed among grazing treatments. Assumptions were checked and Tukey's Honestly Significant Difference (HSD) was used to determine mean separation ($\alpha = 0.05$).

The initial ANOVA model for Blacksburg and Raphine was:

Equation 3.5: $$Y_{ijk} = \mu + \alpha_i + \beta_j + \phi_k + \gamma_{ik} + \varepsilon_{ijk}$$

where Y = mean by treatment, location, and time; μ = overall mean; α = treatment effect (i = 1, 2, 3); β = location effect (j = 1, 2); ϕ = time effect (k = 1, 2, 3,…13), γ = time effect by treatment; and ε = experimental error. A subset model was created for each herbage parameter including the location and time factors and only the significant ($P < 0.05$) interaction terms. The subset models were used to determine the coefficients of the main effects and to calculate the coefficient of determination (R^2) for each model. Treatments were assessed for homogeneity of variance and model residuals were assessed for multivariate normality. Tukey's Honestly Significant Difference (HSD) was used to determine mean separation ($\alpha = 0.05$).

For the Steeles Tavern location, multi-factor repeated measures ANOVA was performed to examine differences in herbage nutritive value, herbage cover, and herbage biomass among the 3 treatments and 9 pastures. Time (8 consecutive months of the growing season in 2014) was included as a linear term to test if the effect of time differed among grazing treatments. Assumptions were checked and Tukey's Honestly Significant Difference (HSD) was used to determine mean separation ($\alpha = 0.05$).

The initial ANOVA model for Steeles Tavern was written as Equation 3.5, where Y = mean by treatment, location, and time; μ = overall mean; α = treatment effect (i = 1, 2, 3); β = pasture effect (j = 1, 2, 3,…9); ϕ = time effect (k = 1, 2, 3,…8), γ = time effect by treatment; and

ε = experimental error. A subset model was created for each herbage parameter including the location and time factors and only the significant ($p < 0.05$) interaction terms. The subset models were used to determine the coefficients of the main effects and to calculate the coefficient of determination (R^2) for each herbage parameter model. Treatments were assessed for homogeneity of variance and model residuals were assessed for normality. Tukey's Honestly Significant Difference (HSD) was used to determine mean separation ($\alpha = 0.05$).

One-way ANOVA was used to compare mean ANPP at Blacksburg and Raphine, mean partial-season ANPP at Steeles Tavern, and total days of hay feeding in Steeles Tavern in 2014. The one-way ANOVA model was:

Equation 3.6: $Y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij}$

where Y = mean by treatment and location; μ = overall mean; α = treatment effect (i = 1, 2, 3); β = location effect (j = 1, 2, 3,…9 at Steeles Tavern and j = 1, 2 at Blacksburg and Raphine); and ε = experimental error. Treatments were assessed for homogeneity of variance and model residuals were assessed for normality. Tukey's Honestly Significant Difference (HSD) was used to determine mean separation ($\alpha = 0.05$).

Means and post-hoc contrasts for all models were calculated with the lsmeans function in the lsmeans package in *R* (Lenth and Hervác, 2014).

Stepwise multiple linear regression was performed to assess diurnal variation in nutritive value of herbage samples harvested by cannulated steers at Blacksburg. Goodness of fit for models with linear and quadratic terms for time was assessed with the Akaike Information Criterion (AIC).

Monthly RPM slope coefficients were compared using the linearHypothesis function in the car package in *R* (Fox and Weisberg, 2011).

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Table 3.1: Mean soil pH, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and organic matter (OM) in April 2013 at Blacksburg, Raphine, and Steeles Tavern, VA.

Location	**pH**	**P†**	**K**	**Ca**	**Mg**	**OM**
		mg kg^{-1}				%
Blacksburg	6.1	7	27	467	105	3.0
Raphine	6.0	5	91	445	79	3.3
Steeles Tavern	6.5	22	130	1131	214	5.2

† Abbreviations are as follows: P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; OM: organic matter.

Table 3.2: Average monthly weather data between January 1 and December 31 for Blacksburg and Raphine, VA† (2013-2014), obtained from NOAA (2014)‡. The average daily temperature (˚C) is for the corresponding month. Precipitation (cm) is the average monthly accumulated rainfall. Values in parentheses are the deviations from the 20-yr averages (1980-2010)§.

	Temperature				**Precipitation**			
	Blacksburg		**Raphine**		**Blacksburg**		**Raphine**	
Time period	**2013**	**2014**	**2013**	**2014**	**2013**	**2014**	**2013**	**2014**
	˚C				cm			
January	1.4 (+1.7)	-4.0 (-3.7)	2.8 (+2.5)	-3.0 (-3.3)	19.7 (+11.9)	4.2 (-3.6)	8.9 (+2.1)	4.3 (-2.5)
February	-0.1 (-1.3)	0.9 (-0.3)	0.9 (-1.1)	1.4 (-0.6)	3.5 (-3.6)	10.1 (+3.0)	2.8 (-3.7)	9.5 (+3.0)
March	1.6 (-3.7)	3.3 (-2.0)	2.9 (-3.3)	2.8 (-3.4)	8.0 (-1.2)	6.2 (-3.0)	9.2 (+0.9)	10.1 (+1.8)
April	10.6 (+0.2)	10.9 (+0.5)	12.3 (+0.7)	11.7 (+0.1)	9.7 (+0.9)	10.0 (+1.2)	6.2 (-1.8)	10.8 (+2.8)
May	14.7 (-0.5)	17.0 (+1.8)	16.1 (-0.3)	17.7 (+1.3)	14.8 (+3.8)	7.2 (-3.8)	12.8 (+3.3)	12.5 (+3.0)
June	20.1 (+0.3)	21.1 (+1.3)	21.5 (+0.4)	22.1 (+1.0)	18.7 (+8.5)	7.2 (-3.0)	19.2 (+10.0)	10.1 (+0.9)
July	21.9 (+0.1)	21.2 (+0.6)	23.1 (+0.0)	22.0 (-1.1)	20.3 (+9.5)	5.5 (+5.3)	9.2 (-0.7)	5.3 (-4.6)
August	20.1 (-1.0)	20.0 (-1.1)	21.1 (-1.3)	20.9 (-1.5)	5.3 (-3.8)	15.1 (+6.0)	11.0 (+1.8)	6.0 (-3.2)
September	17.2 (-0.1)	18.4 (+1.1)	18.2 (-0.2)	19.2 (+0.8)	3.4 (-4.5)	9.7 (+1.8)	3.2 (-6.4)	2.2 (-7.4)
October	11.8 (+0.5)	12.2 (+0.9)	13.1 (+0.8)	13.6 (+1.3)	6.7 (-0.4)	10.3 (+3.2)	6.4 (-1.2)	10.5 (+2.9)
November	4.1 (-2.2)	-1.7 (-7.6)	5.5 (-1.8)	4.4 (-2.9)	7.7 (+0.4)	7.7 (+0.4)	5.1 (-2.7)	5.5 (-2.3)
December	2.8 (+1.8)	3.4 (+2.4)	3.8 (+1.7)	3.7 (+1.6)	13.4 (+5.9)	6.7 (-0.8)	15.0 (+8.0)	6.1 (-0.9)
Aver Temp¶	10.5 (+0.4)	10.8 (+0.1)	11.8 (-0.1)	12.1 (+0.2)	--	--	--	--
Total Precip	--	--	--	--	131.1 (+27.2)	99.9 (-4.0)	109.1 (+9.8)	92.9 (-6.4)

† Temperature and precipitation records were measured at the Blacksburg National Weather Service Office (USC00440766) and Staunton Wastewater Treatment (USC00448062) stations, which are 2 mi and 23 mi, respectively, from the project locations.

‡ Source: Menne, M.J., I. Durre, B. Korzeniewski, S. McNeal, K. Thomas, X. Yin, S. Anthony, R. Ray, R.S. Vose, B.E.Gleason, and T.G. Houston. (2014). Global Historical Climatology Network – Monthly (GHCN-Monthly). Version 3. NOAA National Climatic Data Center. http://www.ncdc.noaa.gov/ghcnm (accessed 20 Feb. 2014).

§ Source: Menne, M.J., I. Durre, B. Korzeniewski, S. McNeal, K. Thomas, X. Yin, et al. 2010. Global Historical Climatology Network – U.S. Monthly Climate Normals (1981-2010), Version 3. NOAA National Climatic Data Center. http://www.ncdc.noaa.gov/ghcnm (accessed 20 Dec. 2014).

¶ Abbreviations are as follows: Avg Temp: the average daily temperature from Jan 1 to Dec 31; Total Precip: the total accumulated rainfall from Jan 1 to Dec 31.

Table 3.3: Herd characteristics and stocking management for 11 April 2013-14 Nov. 2014 at the Blacksburg and Raphine, VA locations.

Location	Stocking method	Year	Stocking periods	Grazing days	Number of animals	Mean body weight†	Paddocks	Paddock area	Stocking cycles	Stocking density	Stocking rate
				—d —	$pasture^{-1}$	—kg —	$pasture^{-1}$	—ha —	$paddock^{-1}$	AU ha^{-1}‡	AUM ha^{-1}
Blacksburg	Mob	2013	06/05-06/08, 09/27-10/01	8	45	612	6	0.2	2	303	13.4
		2014	05/23-05/27, 09/29-10/03	8	45	646	6	0.2	2	320	14.2
	Rotational	2013	05/05-11/14	193	3	612	4	0.5	unknown	8	13.0
		2014	05/05-08/25, 08/27-11/14	187	3	669	8	0.3	6	15	11.1
	Continuous	2013	05/05-11/14	193	5	612	1	3.0	1	2	14.4
		2014	05/05-08/25, 08/27-11/14	187	5	628	1	3.0	1	2	14.1
Raphine	Mob	2013	05/20-05/31, 09/22-10/03	22	41	379	22	0.1	2	342	11.4
		2014	06/02-06/12, 08/27-09/07	21	41	342	21	0.1	2	309	10.4
	Rotational	2013	04/11-11/01	176	13	342	8	0.5	7	20	14.4
		2014	05/05-09/30	122	13	331	8	0.5	4-5	19	10.0
	Continuous	2013	04/11-11/01	176	28	354	3	3.2	1	2	13.3
		2014	05/05-09/30	122	28	362	3	3.2	1	2	9.4

† The herd manager at the Virginia Tech Beef Center visually estimated the mean body weight of the dry cows and heifers stocked at the Blacksburg location (Chad Joines, personal communication, 11 Dec. 2014). The herd manager at Steeles Tavern measured body weight of all steers at the Raphine location at the beginning, middle, and end of each grazing year.

‡ Abbreviations are as follows: AU: animal unit (454 kg = 1 AU); AUM: animal unit month (1 month = 30 days).

Table 3.4: Herd characteristics and stocking management 5 May—23 Dec. 2014 at the Steeles Tavern, VA location.

Stocking method	**Herd†**	**Stocking period**		**Grazing days**	**Hay days**	**Number of animals**	**Mean body weight‡**	**Paddocks**	**Paddock area**	**Stocking cycles**	**Stocking density**	**Stocking rate**
		Start	End	—d —	—d —	pasture^{-1}	—kg —	pasture^{-1}	—ha —	paddock^{-1}	AU ha^{-1}§	AUM ha^{-1}
Mob	H3¶	5/6/14	12/23/14	207	22	8	627	9	0.7	3-4	17-111	12.1
	H4	5/7/14	12/22/14	201	25	8	627	9	0.7	3-4	18-121	11.7
	K4	5/7/14	12/22/14	199	27	8	608	9	0.7	3-4	17-118	11.3
Rotational	H2	5/5/14	12/22/14	207	21	8	639	8	0.8	5-7	15	12.1
	K1	5/5/14	12/22/14	207	21	8	626	8	0.8	5-7	15	11.9
	K2	5/6/14	12/22/14	191	32	8	610	8	0.8	5-7	14	10.7
Continuous	B3	5/5/14	12/22/14	196	32	8	624	1	6.4	1	2	11.2
	B4	5/5/14	12/22/14	196	32	8	621	1	6.4	1	2	11.2
	K3	5/6/14	12/22/14	195	32	8	631	1	6.5	1	2	11.1

† Herds consisted of pregnant beef cows that calved Aug-Nov 2014. Calves were retained with their dams.

‡ The herd manager at Steeles Tavern measured body weights of all cows at the Steeles Tavern location at the beginning and end of each grazing year. Mean body weights do not include calf weights.

§ Abbreviations are as follows: AU: animal unit (454 kg = 1 AU); AUM: animal unit month (1 month = 30 days).

¶ Pasture locations are diagrammed in Fig. 3.6.

Table 3.5: Dates of herbage sampling at Blacksburg and Raphine, VA in 2013-2014.

Location	Sampling date	Herbage biomass	Compressed herbage height	Herbage cover	Herbage accumulation	Herbage nutritive value
Blacksburg	2013-04-11	✔				
	2013-04-30			✔		
	2013-05-02	✔				✔
	2013-05-31	✔				✔
	2013-06-28	✔				✔
	2013-08-05	✔		✔		✔
	2013-09-05	✔				✔
	2013-09-25†			✔		
	2013-10-18	✔		✔		✔
	2014-04-28	✔	✔	✔		✔
	2014-05-09		✔		✔	
	2014-05-22	✔	✔		✔	✔
	2014-05-27†	✔	✔			✔
	2014-06-17	✔	✔		✔	✔
	2014-07-18	✔	✔	✔	✔	✔
	2014-08-15	✔	✔		✔	✔
	2014-09-14	✔	✔		✔	✔
	2014-09-28		✔	✔	✔	
	2014-10-03†	✔	✔			✔
	2014-10-11	✔	✔		✔	✔
	2014-11-08	✔	✔		✔	
Raphine	2013-04-09	✔		✔		
	2013-05-15	✔		✔		✔
	2013-06-20	✔				✔
	2013-07-16	✔		✔		✔
	2013-08-20	✔				✔
	2013-09-17	✔				✔
	2013-10-24	✔		✔		✔
	2014-05-02	✔	✔	✔		✔
	2014-05-30	✔	✔		✔	✔
	2014-06-11†	✔	✔			
	2014-06-27	✔	✔		✔	✔
	2014-07-25	✔	✔	✔	✔	✔
	2014-08-26	✔	✔		✔	✔
	2014-09-06†	✔	✔		✔	✔
	2014-09-23	✔	✔		✔	✔
	2014-09-26			✔		
	2014-11-15	✔	✔			

✔Indicates that sampling occurred.
† Biomass or standing cover was measured only in the mob stocking paddock on these dates.

Table 3.6: Dates of herbage sampling in 2014 at the Steeles Tavern, VA location.

Location	Sampling date	Herbage biomass	Compressed herbage height	Herbage cover	Herbage accumulation	Herbage nutritive value
Steels Tavern	2014-05-19	✔				✔
	2014-05-27			✔		
	2014-06-25	✔				✔
	2014-07-16	✔				✔
	2014-07-21			✔		
	2014-07-22		✔		✔	
	2014-07-30		✔		✔	
	2014-08-13	✔				✔
	2014-08-23		✔		✔	
	2014-08-30		✔		✔	
	2014-09-15	✔				✔
	2014-09-23		✔		✔	
	2014-10-19		✔	✔	✔	
	2014-10-22	✔				✔
	2014-10-26		✔		✔	
	2014-11-16		✔		✔	
	2014-11-18	✔				✔
	2014-11-20		✔		✔	

✔Indicates that sampling occurred.

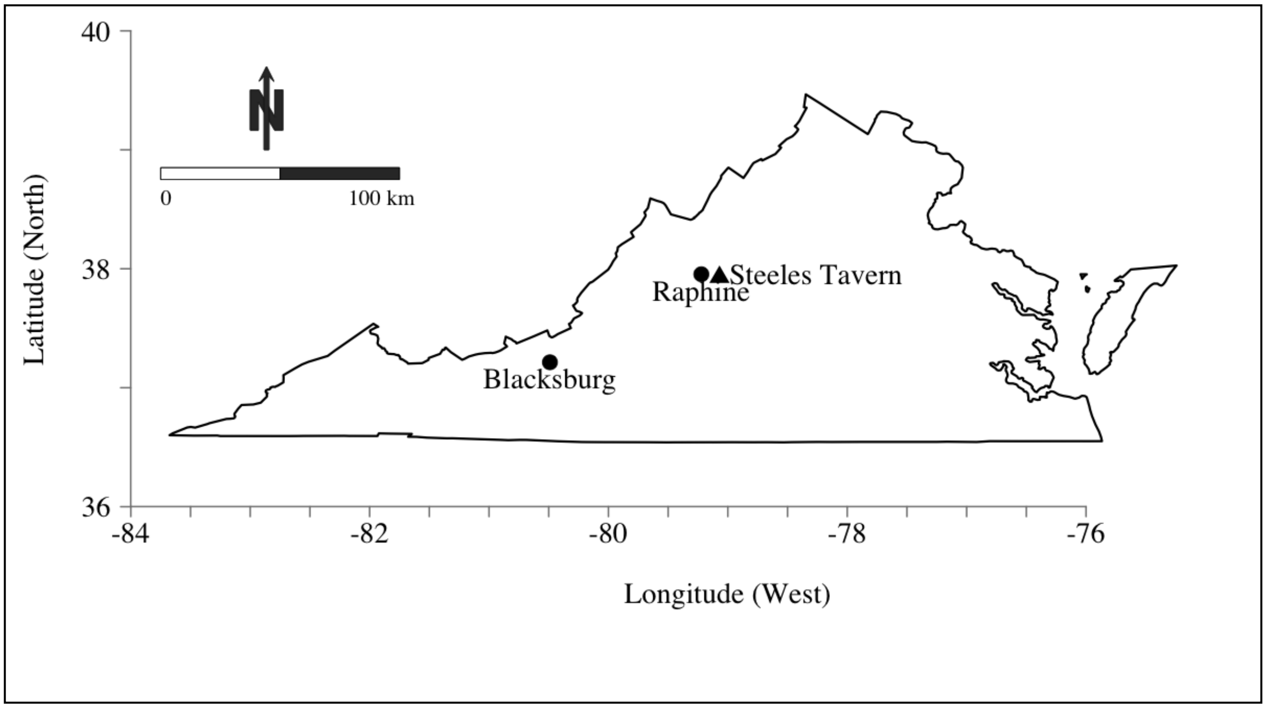

Figure 3.1: Locations of the study sites in Virginia.

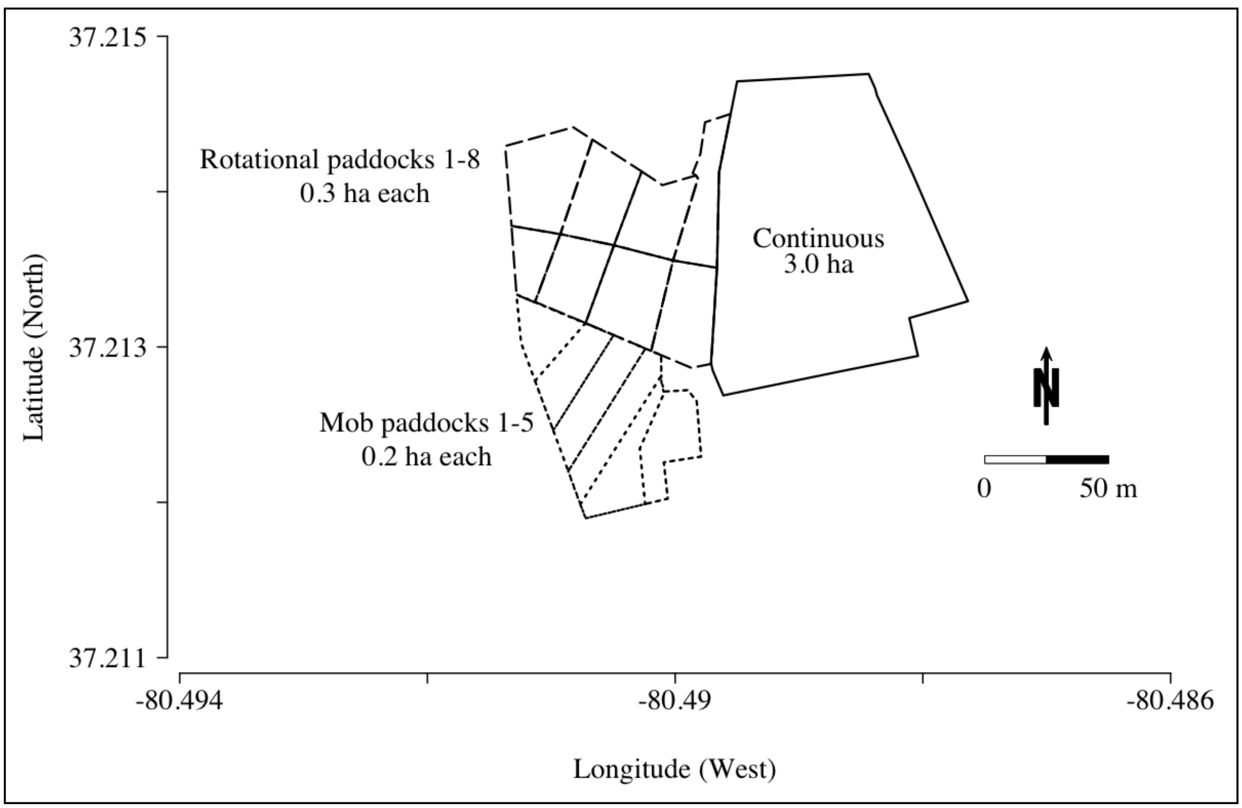

Figure 3.2: Paddock arrangements, dimensions, and sizes for the stocking methods study in Blacksburg, VA.

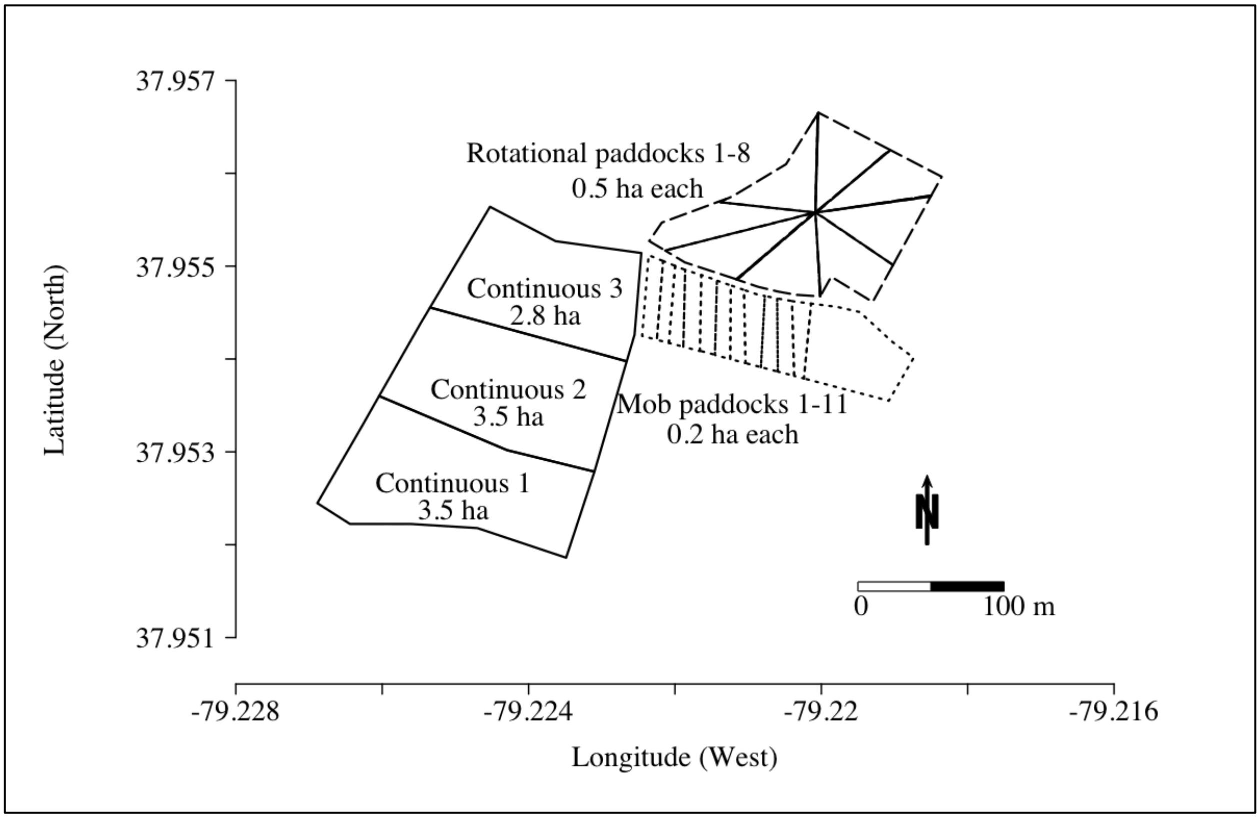

Figure 3.3: Paddock arrangements, dimensions, and sizes for the stocking methods study in Raphine, VA.

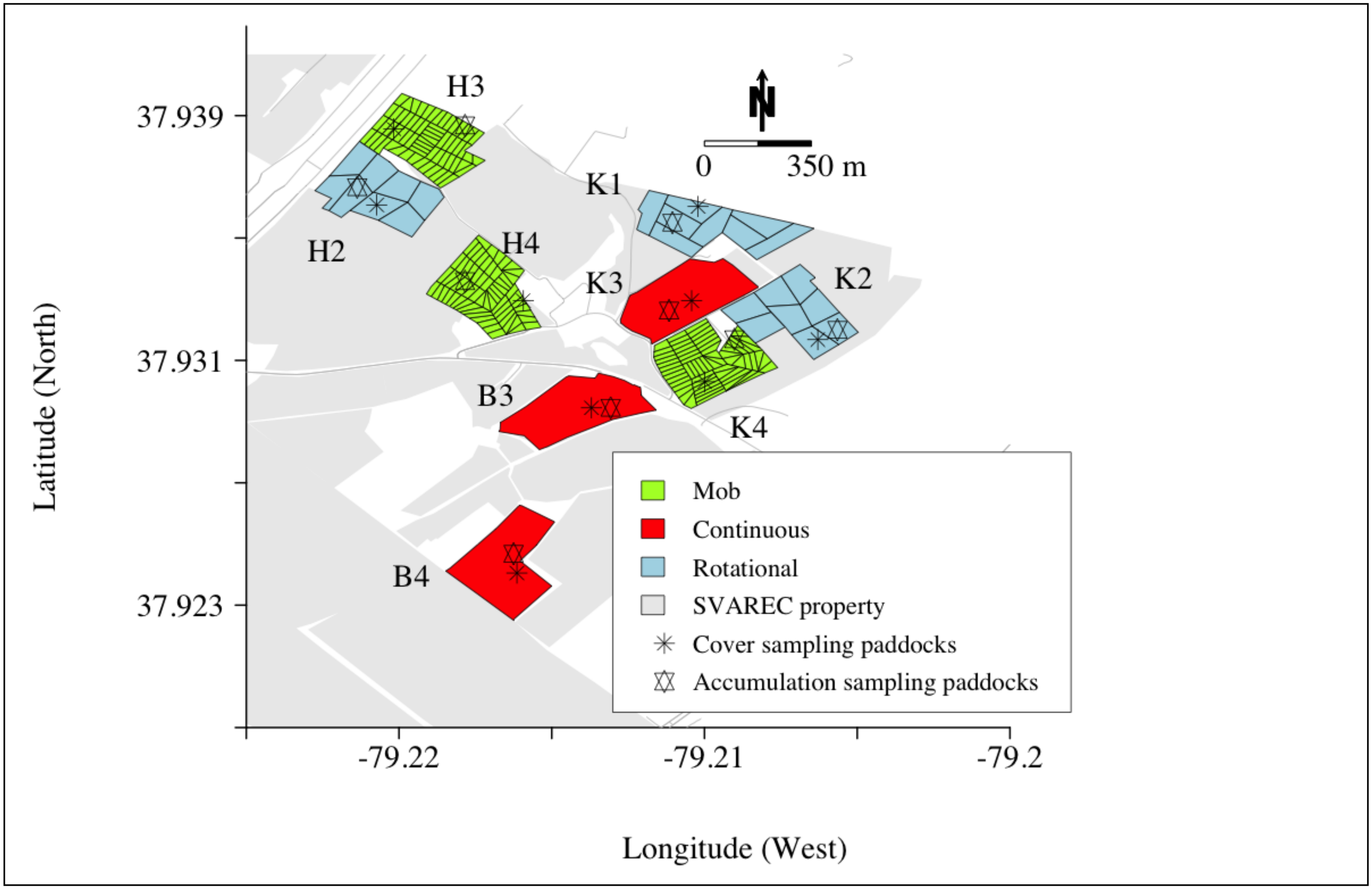

Figure 3.4: Arrangement of the stocked pastures in Steeles Tavern, VA.

† Abbreviations are as follows: SVAREC: Shenandoah Valley Agricultural Research and Extension Center.

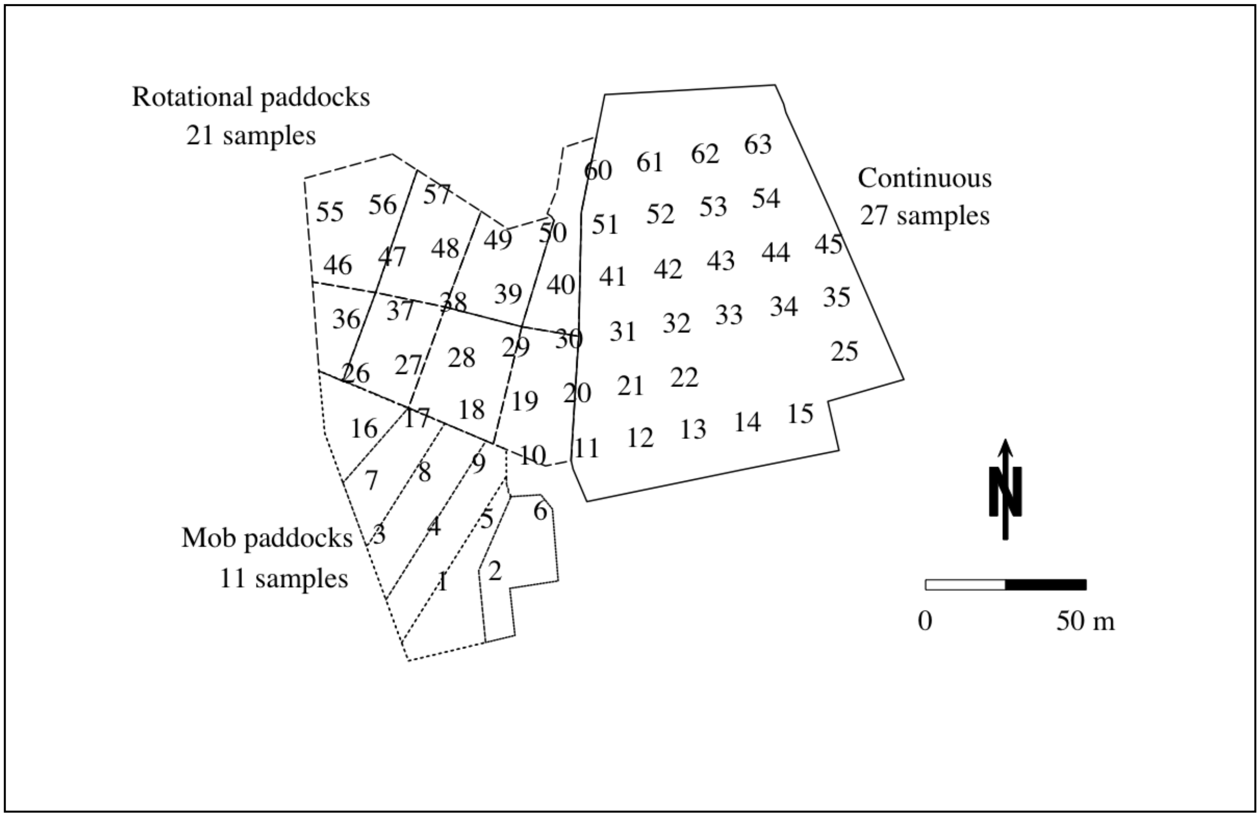

Figure 3.5: Herbage sampling points in Blacksburg, VA. Sampling points are 30 m apart. Points 23, 24, 58, and 59 were omitted from sampling.

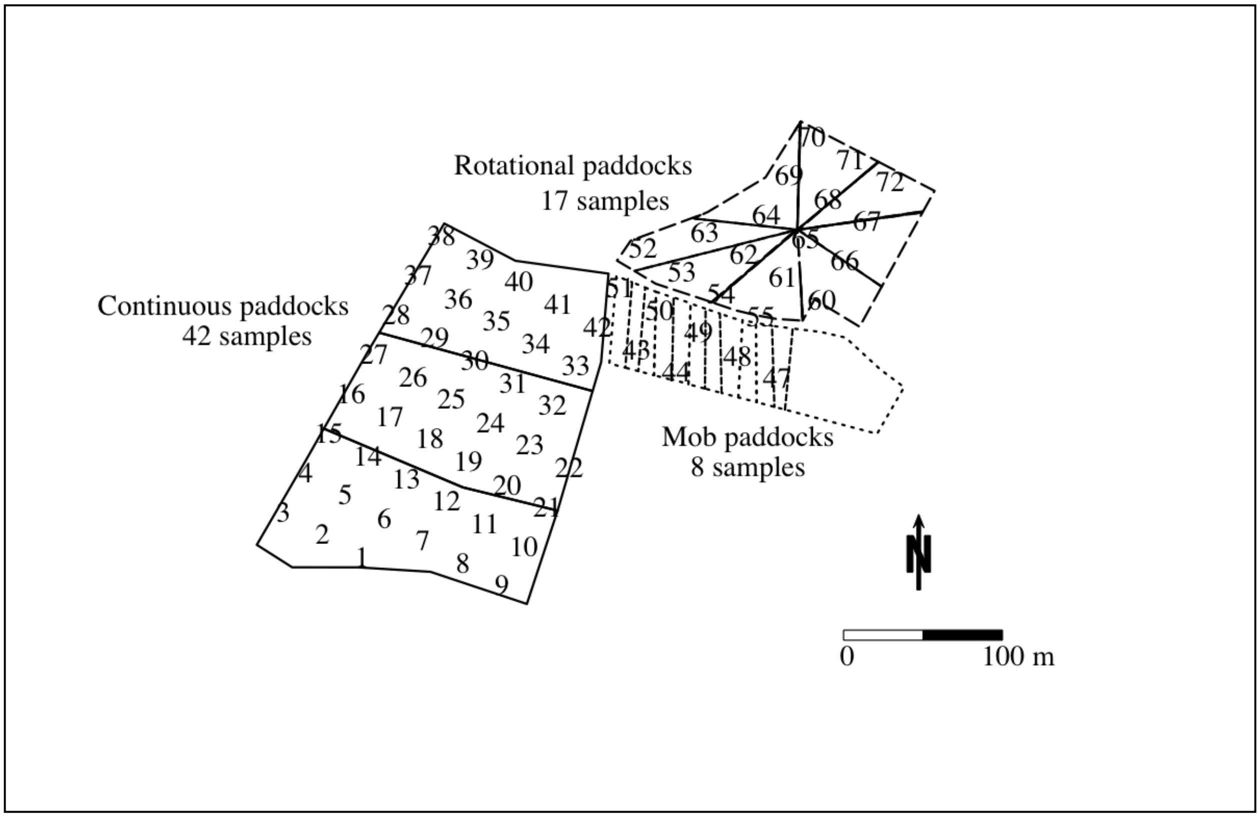

Figure 3.6: Herbage sampling points in Raphine, VA. Sampling points are 50 m apart. Points 45 and 46 were omitted from sampling.

Chapter 4. Results, Discussion, and Conclusions

4.1 Results

4.1.1 Herbage mass

4.1.1.1 Herbage mass at Blacksburg and Raphine.

At Blacksburg and Raphine in 2013-2014, the main effect of stocking treatment on standing herbage mass was significant ($P = 0.006$; Fig. 4.1). Mob stocked paddocks contained on average 595 kg ha^{-1} more herbage than rotationally stocked paddocks (3,176 vs. 2,638 kg ha^{-1}) and 543 kg ha^{-1} more herbage than continuously stocked paddocks, which contained 2,690 kg ha^{-1} on average. Herbage mass was 364 kg ha^{-1} greater at Blacksburg compared to Raphine ($P = 0.032$). Herbage mass in April 2013 (815 kg ha^{-1}) was less than in subsequent months (Fig. 4.2); however, average herbage mass in subsequent months did not differ ($P > 0.33$; $\bar{x} > 2,347$ kg ha^{-1}). The interaction of treatment and time period of the study was not significant ($P > 0.10$).

The efficiency of herbage removal was measured in several ways: herbage biomass before and after cattle were stocked, forage allowance (*FA*), and harvest index (*HI*). *HI* describes grazing pressure as the proportion of pre-graze herbage removed by cattle managed with rotational stocking (Equation 3.1).

Herbage biomass (kg ha^{-1}) before and after mob stocking was 3,434 and 2,400 at Blacksburg in May 2014; 5,042 and 4,489 at Blacksburg in September 2014; 4,107 and 3,488 at Raphine in May 2014; and 4,737 and 2,574 at Raphine in September 2014.

Forage allowance (*FA*) differed significantly by treatment ($P < 0.001$) and site ($P = 0.002$); for example, average instantaneous *FA* (kg DM kg BW^{-1}) was 2.7 in continuous, 0.4 in rotational, and 0.02 in mob stocking. Post hoc contrasts indicated that *FA* for continuous stocking was greater than for either rotational or mob, which did not differ from each other. Blacksburg had about 0.5 kg DM kg BW^{-1} greater *FA* than Raphine overall.

Harvest Index (*HI*) varied across time: mean *HI* during rotational stocking at Blacksburg ranged from 0.28 in June to 0.42 in October; *HI* during mob stocking at Blacksburg in 2014 was 0.56 in May and 0.51 in September.

4.1.1.2 Herbage mass at Steeles Tavern.

At Steeles Tavern in 2014, the main effect of stocking treatment on standing herbage mass was not significant (P = 0.218) and the interaction of treatment and month was not significant (P = 0.098). Herbage mass in all paddocks increased from 3,363 kg ha^{-1} in May to 4,145 kg ha^{-1} in June but subsequently decreased during the June to November period to 1,324 kg ha^{-1} (Table 4.1). Grass hay was fed to all herds in September and November as herbage mass became limiting. The pastures with greater relative herbage mass tended to have more grazing days and tended (P = 0.10) to have fewer hay-feeding days. Overall, continuously stocked herds grazed for one week less (Table 4.2) and were fed hay for one week more than mob- and rotationally-stocked herds. Means days of hay feeding were 32, 25, and 25 for continuous, mob, and rotational stocking, respectively.

Date of first stocking of each mob stocked paddock relative to May 4, 2014 was significant as a predictor of herbage mass at subsequent dates (Fig. 4.3a): paddocks averaged 28 kg ha^{-1} more standing herbage during the year for each day after May 4th that mob stocking was initiated. Herbage mass at subsequent dates in rotationally stocked paddocks was not significantly (P = 0.36) predicted by date of first stocking (Fig. 4.3b).

Harvest index in the treatments at Steeles Tavern varied during the July-November period of sampling: during mob stocking HI increased from 0.15 in August to 0.42 in November; with the rotational stocking method, HI ranged from 0.10 in August to 0.29 in October.

4.1.2 Herbage accumulation and disappearance

4.1.2.1 Herbage accumulation and disappearance at Blacksburg and Raphine.

Unique slope coefficients for each month were used to predict rates of herbage accumulation and total disappearance at Blacksburg, Raphine, and Steeles Tavern. An initial regression model with compressed height, month, and the interaction of compressed height and month indicated that the coefficients for month did not differ significantly ($P > 0.10$) from the May coefficient. Therefore, a subset model was fit with compressed height and the interaction of compressed height and month and RPM coefficients (Table 4.3) were calculated as the sum of the compressed height coefficient and the compressed height x month interaction coefficient for each month. The RPM slope coefficient for May was 184 kg ha^{-1} cm^{-1} compressed height and subsequent months differed from this ($P < 0.001$; Table 4.3). The coefficients for July, August, and September did not differ significantly from each other ($P > 0.627$). RPM coefficients ranged from 184 kg ha^{-1} cm^{-1} in June to 319 kg ha^{-1} cm^{-1} in November (R^2 = 0.58 overall). The RPM regression intercept was 734 kg ha^{-1}.

Stocking method did not affect ($P = 0.73$) herbage accumulation rates at Blacksburg and Raphine in 2014 but accumulation rates were 35 kg ha^{-1} d^{-1} greater ($P = 0.035$) at Blacksburg than at Raphine. The effect of month on accumulation rate was significant ($P = 0.036$; Table 4.4); however, post-hoc contrasts between months indicated that accumulation rates did not differ significantly ($P > 0.05$) by month. Accumulation rates in the July-October period tended ($P < 0.10$) to be less by up to 76 kg ha^{-1} d^{-1} relative to May.

The effect of stocking method on ANPP was not significant ($P = 0.34$), although rotationally stocked pastures at Blacksburg and Raphine had opposite trends of ANPP. At Blacksburg ANPP of rotational stocking was greatest relative to the other stocking methods but at Raphine rotational stocking had the least ANPP. Mean ANPP of continuous, mob, and rotational stocking methods was 4,154, 2,380, and 4,194±740 kg ha^{-1}, respectively. Average ANPP in mob-stocked pastures was 1,774±1,573 kg ha^{-1} less (P = 0.39) than continuous stocking (Fig. 4.4a).

The effect of stocking method on annual herbage disappearance was not significant (P = 0.14). Mean annual herbage disappearance of continuous, mob, and rotational stocking methods were -7,711, -6,412, and -8,058±974 kg ha^{-1}, respectively. Continuous stocking dissipated 1,300±2,071 kg ha^{-1} more (P = 0.67) herbage than mob stocking although continuous and rotational stocking were similar (P = 0.97; Fig. 4.4b).

4.1.2.2 Herbage accumulation and disappearance at Steeles Tavern.

Herbage accumulation rates for each stocking method were different in each month at Steeles Tavern: the interaction of stocking method and month was significant (P = 0.022). However, post-hoc contrasts among stocking methods within months did not achieve significance. Rotationally stocked pastures tended to grow faster than mob and continuously stocked pastures in August (P > 0.28) similarly in September and November (P > 0.97), and slower in October (P > 0.44). Pastures overall accumulated herbage faster in October than in August or November (P < 0.046; Table 4.5).

ANPP during the July-November 2014 period at Steeles Tavern did not differ by stocking method (P = 0.34; $\bar{x}$ = 950 kg ha^{-1}). Rotationally stocked paddocks tended (P > 0.39) to have the greatest ANPP: 540 kg ha^{-1} more than continuously stocked paddocks and 518 kg ha^{-1} more than mob stocked paddocks (Fig. 4.5a).

Herbage disappearance during July-November did not differ by stocking method (P = 0.289; $\bar{x}$=1821 kg ha^{-1}). Post hoc contrasts indicated that rotationally stocked paddocks tended (P

> 0.27) to dissipated more herbage: 773 kg ha^{-1} more herbage than mob stocked paddocks and 482 kg ha^{-1} more herbage than continuously stocked paddocks (Fig. 4.5b).

4.1.3 Plant species composition

4.1.3.1 Plant species composition at Blacksburg and Raphine.

Clover cover at Blacksburg and Raphine in 2013-2014 differed significantly ($P < 0.001$) by stocking method; however, each seeded clover species responded differently: white clover cover was significantly greater ($P < 0.001$) in response to continuous stocking relative to mob and rotational stocking, but red clover cover did not differ by stocking method ($P = 0.291$). White clover cover was nearly twice as great in response to continuous stocking relative to mob and rotational stocking overall (Table 4.6). Red clover response differed by location ($P < 0.001$): Blacksburg had 5.9 percentage cover units more red clover than Raphine.

Bare soil cover differed significantly by stocking method ($P = 0.011$; Table 4.6). Bare cover was lesser by 2.3 percentage cover units in response to mob stocking relative to continuous stocking, which represented a 33-95% reduction in bare soil; rotational stocking did not improve bare soil relative to continuous stocking.

The covers of forage, weed, and dead did not differ ($P > 0.10$) among stocking methods: mean cover of forage, weed, and dead were 48, 14, and 24 percent, respectively. However, the proportion of each component varied widely across time (Table 4.6). Cover of clovers and forage generally increased and cover of weeds decreased from the beginning to the end of the study in all treatments. However, clover cover at Raphine declined to 2% in October 2014 after reaching 9% in July 2013. In 2013, clover cover at Raphine in 2013 was less than at Blacksburg. Overall, Blacksburg also had more weed cover and less dead material than Raphine ($P < 0.042$). Forage cover was generally less in May and July of each year relative to October; cover of clovers and dead material were generally greater in May and July and lesser in October (Table 4.7).

4.1.3.2 Plant species composition at Steeles Tavern.

The main effects of stocking method on covers of forage, clover, weed, dead, and bare soil were not significant ($P > 0.36$) at Steeles Tavern in 2014. However, the effects of time on grass, legume, weed, dead, and bare soil cover were significant ($P < 0.05$; Table 4.8): grass, legume, and weed cover decreased from May to July but grass cover later increased from July to October and was greater in October than in May. Dead material increased greatly from May to July. Bare soil decreased from July to October.

4.1.4 Herbage nutritive value

4.1.4.1 Herbage nutritive value at Blacksburg and Raphine.

The main effects of stocking method on ADF, CP, and NDF concentrations in herbage were not significant ($P > 0.13$) at Blacksburg and Raphine in 2013-2014 (Table 4.9). Mean concentrations (g kg^{-1} DM) of ADF, CP, NDF, and TDN were 350, 115, 613, and 438, respectively. The effect of location on nutritive value was significant ($P < 0.003$): herbage at Blacksburg contained 10 g kg^{-1} more CP, 16 g kg^{-1} less ADF, and 34 g kg^{-1} less NDF than herbage at Raphine. Nutritive value of the herbage on offer varied across time: CP was greatest in May, least in July-September, and intermediate in October (Fig. 4.6). Trends for ADF and NDF were similar to CP. ADF and NDF were significantly ($P < 0.001$) positively correlated ($\rho > 0.93$) with each other during the course of the study and fiber constituents and CP were significantly ($P < 0.001$) negatively correlated ($\rho < -0.694$; Table 4.10).

Increased sward biomass and dead material were also correlated with increased ADF and NDF and decreased CP concentrations in herbage DM (Table 4.10).

Clover and dead cover were significant ($P < 0.001$) linear predictors of ADF, CP, and NDF content of clipped herbage at Blacksburg and Raphine in 2013-2014. Simple linear regression models minimized the AIC for the regression of dead material on ADF and NDF (Fig. 4.7b displays the relationship with NDF). A quadratic regression model minimized the AIC for the relationship between total clover cover and CP (Fig. 4.7a).

The NIRS fresh forage equation Global H and Neighborhood H means were 2.2±0.9 and 1.5±0.6, respectively, for the entire population of samples. The equation statistics differed significantly ($P < 0.05$) among periods of the study and tended to differ ($P > 0.06$) among stocking methods. The Global H ranged from 1.4±0.2 in May 2013 to 3.0±0.2 in Oct. 2014. Neighborhood H ranged from 1.0±0.1 in May 2013 to 2.0±0.1 in Oct. 2013. Samples harvested in the spring and summers were generally better predicted by the equation relative to samples harvested in the fall. Samples from mob stocked pastures tended ($P > 0.066$) to have 0.26 greater Global H and 0.16 greater Neighborhood H relative to rotationally stocked pastures; samples from mob and rotational pastures did not differ significantly ($P > 0.16$) from continuously stocked pastures.

4.1.4.2 Herbage nutritive value at Steeles Tavern.

The interactions of stocking method and month were significant ($P < 0.065$) for ADF, CP, and NDF at Steeles Tavern in 2014. CP content of herbage in mob-stocked paddocks was significantly greater ($P < 0.004$) and ADF and NDF contents tended to be less ($P > 0.44$) than herbage in continuously stocked paddocks in September and October (Figures 4.8 and 4.9). Mob and rotationally stocked paddocks did not differ in ADF, CP, and NDF content in September and October ($P > 0.136$).

ADF and NDF were significantly ($P < 0.001$) positively correlated ($\rho = 0.978$) with each other across the course of the study (Table 4.11). CP was also strongly negatively correlated with ADF and NDF ($\rho > -0.876$). Increasing biomass yield was significantly negatively correlated with CP content ($\rho = -0.148$).

The NIRS fresh forage equation Global H and Neighborhood H means were 2.4±0.03 and 1.7±0.03, respectively, for the entire population of samples. The equation statistics differed significantly ($P < 0.001$) among periods of the study and pastures ($P = 0.02$). For Global H the stocking method by month interaction was not significant ($P = 0.06$) but for Neighborhood H the interaction was significant ($P = 0.046$). Global H ranged from 1.31±0.05 in May 2014 to 3.29±0.05 in Oct. 2014. Neighborhood H ranged from 0.90±0.04 in May 2014 to 2.40±0.04 in Aug. 2014. Samples harvested in May and June were better predicted by the equation relative to samples harvested in July through October.

4.1.5 Nutritive value of herbage from esophageal cannula of beef steers

Esophageal extrusa from the two steers was greater in CP concentration relative to clipped pasture samples from all pastures ($P = 0.001$; Table 4.12), but the effects of sampling method on ADF and NDF did not achieve significance. Steers were most selective for CP, moderately selective for NDF, and least selective for ADF relative to nutrient concentrations in clipped pasture samples. The steers did not differ significantly from each other in selectiveness relative to clipped pasture samples ($P > 0.54$).

The selectivity indices varied across the duration of mob stocking in each pasture strip ($0.095 < P < 0.153$ for CP and NDF; $P = 0.411$ for ADF). Steers were generally more selective than hand-plucking (SI for CP: 1.18-1.57) at 0 h, 4 h, and 16 h but were equal to and less selective than hand-plucking (SI for CP: 0.99-1.01) at 8 and 12 h, respectively (Fig. 4.10).

Nutritive value of esophageal extrusa from each treatment had different trends across time (Fig. 4.11). In the first mob stocked paddock CP content decreased by 55% from the pre-stocking level to a minimum at 12 h after initiation of stocking in the first paddock. CP content of herbage harvested by steers in the rotational pasture decreased 33% from the start of the study to 3 d later. CP content of herbage harvested by steers in the continuous stocking pasture increased from the start of the study to 3 d later. Trends for ADF and NDF were similar to CP. Pearson's product-moment correlations among ADF and CP, ADF and NDF, and NDF and CP were -0.77, 0.77, and -0.78, respectively.

Sampling at each 4-h time interval of mob stocking occurred at a different time of day in each of the three pasture strips. Crude protein content of the esophageal extrusa appeared to exhibit diurnal variation. The quadratic regression of crude protein concentration by time of day of sampling was significant ($P = 0.003$, $R^2 = 0.42$; Fig. 4.12).

The NIRS fresh forage equation performed better for the clipped pasture samples than the herbage from esophageal cannula. Mean Global H of clipped and esophageal samples were 3±1 and 6±3, respectively. Mean Neighborhood H of clipped and esophageal samples were 2±1 and 4±2, respectively.

4.2 Discussion

4.2.1 Herbage mass

4.2.1.1 Herbage mass at Blacksburg and Raphine.

Herbage mass was more than 543 kg ha^{-1} greater overall for mob stocking relative to continuous and rotational stocking. This occurred because the mob pastures were grazed in an entirely different way than the continuous and rotational pastures. After mob stocking occurred the mob herds were removed from the project locations. In contrast, the rotational and continuous herds grazed throughout the May-November growing season. Herbage sampling in all pastures occurred throughout May-November. Therefore, the average herbage mass in rotational and continuous pastures each month was calculated with samples from paddocks that were in several intermediate states between grazing and regrowth; for mob stocking none of the samples were harvested from paddocks that were being grazed at the time of sampling. Samples from grazed paddocks lessened the average mass relative to only analyzing samples from paddocks that were not grazed in the period between sampling events. However, limiting the analysis to samples from not-grazed areas was not possible because the continuous pastures had an uninterrupted period of stay during the year. Rest and grazing in rotational pastures occurred on a monthly basis but fully rested mob pastures only occurred twice per year. So comparison of average mass among stocking methods must include a caveat about experimental design. Given that ANPP in 2014 did not differ by stocking method, it is likely that herbage mass would have been similar among stocking methods if pasture had been allocated for season-long mob stocking.

Herbage mass varied from month to month and between locations of the study. Monthly variation would be expected because seasonality in growth rates causes biomass accumulation to exceed harvest and senescence at certain times of the year. Herbage mass during the cattle stocking periods was greater on average than the 1,150 kg ha^{-1} quantity defined as limiting to intake by Whetsell et al (2006). However, because the herbage growth rate slowed during drought conditions in July-August all cattle were removed from the pastures at Raphine on August 30, 2014. In 2013 seasonal destocking occurred on November 1, resulting in 54 more grazing days in 2013 relative to 2014 (Table 3.3). Although average mass was greater than the limiting level, the percent of samples from each pasture at Raphine that contained less than 1,150 kg ha^{-1} DM varied on August 23, 2014. Fourteen, 26, and 41 percent of samples from mob, continuous, and rotationally stocked paddocks, respectively, contained less than 1,150 kg ha^{-1} DM. This result also corresponds with the lesser total herbage accumulation of rotational pastures at Raphine in 2014 relative to rotational pastures at Blacksburg. Given the same rotational stocking density at both locations (18 kg ha^{-1} d^{-1}; stocking rate was equal until early destocking occurred at Raphine), herbage mass reflects the fact that herbage accumulation in the rotationally stocked pastures was lesser overall at Raphine than Blacksburg, perhaps because the climate in Blacksburg is consistently cooler and wetter (Table 3.2).

Mob stocking resulted in greater evenness of herbage mass across the pasture areas at the end of the year. The coefficient of variation (CV) of herbage mass in quadrats sampled at Blacksburg in October 2014 was 54, 51, and 24 in continuous, rotational, and mob-stocked paddocks, respectively, suggesting that evenness of grazing pressure increased with greater stocking density at the same stocking rate applied during the grazing season. CVs at Raphine in August 2014 were 70, 70, and 23, for continuous, rotational, and mob-stocked paddocks. Barnes et al (2008) found that heterogeneity of utilization was positively correlated with paddock size, which suggested that intensive management is associated with even distribution of grazing pressure. Greater evenness of herbage mass may translate into less patchiness and less rejected herbage which may increase the extent of utilization of forage. Comparisons of the CVs in this experiment also includes the caveat that the analysis includes samples from all paddocks in the rotational pasture, grazed and not grazed between sampling events, whereas mob paddocks were only grazed twice each year so each sampling event measured pastures that were not stocked at the time of sampling. The CVs for mob stocking are representative of the effects of mob stocking in May and September. However, continuously stocked pastures had the greatest variation in mass overall, without the influence of variation in biomass between rested and grazed areas within a stocking treatment, indicating the development of grazing patches, which are typical of set stocking (Adler et al, 2001). So although the herbage mass was similar in rotational and continuous pastures on average, some points were grazed more often than others in the continuously stocked pastures.

Forage allowance (*FA*) at the initiation of mob stocking was 3.5% of BW and *FA* after mob stocking was 2.1% of BW. Forage allowance calculations contribute to understanding the temporal dynamics of intake during mob stocking: *FA* in mob-stocked paddocks was less at times than the quantity that others have defined as limiting to intake. Dunn (2013) summarized NRC (2000) data that reported that forage intake was maximized when forage allowance was 4% of BW or 2,250 kg DM ha^{-1} and intake was 60% of the maximum when FA was 2% of BW. The optimum FA described by Dunn corresponds to a stocking density of 56,250 kg BW ha^{-1}, which is 40% less than the stocking density used at Raphine and 65% less than the density used at Blacksburg in this study; herbage mass of 3,750 and 6,428 kg ha^{-1} DM at Raphine and Blacksburg would be needed to provide 4% of cattle BW. Herbage mass at the initiation of mob stocking at Raphine was 26% greater and herbage mass at Blacksburg was 20% less than those quantities, respectively. Based on observations of mob stocking at Blacksburg, herbage mass declined rapidly within eight hours after stocking was initiated but changed less rapidly during the last four-to-eight hours of stocking. Therefore, clipped herbage samples may overestimate the nutritive value of herbage consumed during the last eight hours of the stocking period.

4.2.1.1 Herbage mass at Steeles Tavern.

Standing herbage mass did not differ among stocking methods at Steeles Tavern, likely because the stocking rate was similar for all stocking methods so herbage harvest would be similar. The experimental design permitted monthly sampling of pastures that were in all states of regrowth between currently stocked and fully rested.

Standing herbage mass differed within mob stocked pastures and this effect was linearly related to the date at which paddocks were stocked at the beginning of the growing season. However, herbage mass in rotationally stocked paddocks did not depend on date of initiation of stocking. Several interrelated factors associated with animal stocking density may explain the differing responses of these stocking methods. The extent of defoliation (harvest index) during mob stocking was greater than during rotational stocking. This may have stressed pasture plants and caused root mass to senesce and carbohydrates to mobilize for regrowth, thus limiting regrowth potential at later dates. Also, because cattle were maintained on the mob-strip pastures for seven days, some plants may have been trampled or defoliated more than once. Stressed plants were further weakened by dry weather in June-September (Table 3.2).

Later initiation of stocking has benefitted sward productivity in previous studies of cool-season pastures. For example, Bryan and Prigge (1994), working in West Virginia on set-stocked pastures of bluegrass and white clover, found that herbage mass was 33% more when grazing was initiated 2 weeks later in the spring (late April to early May versus mid- to late-April), although animal gain per hectare during the subsequent 20 weeks was actually 20% greater when grazing was initiated earlier. The pastures at Steeles Tavern are dominated by tall fescue that tends to accumulate lignified stem material with extended rest; therefore, plants in paddocks that were grazed earlier in the season would be grazed to a greater extent than plants in paddocks grazed later and could conceivably produce greater animal weight gain.

The lesser harvest index in the spring relative to the fall in the mob and rotational pastures at Steeles Tavern also could have negatively affected herbage yield at subsequent dates.

Renz and Schmidt (2012), working with perennial ryegrass and tall fescue pastures in Wisconsin, concluded that harvesting less herbage in fall and spring negatively influenced the quantity of biomass on offer in the subsequent fall. Total biomass yield was reduced by 39-60% as residual sward height was increased from 5 to 20 cm. At Steeles Tavern in 2014, seasonal adjustment of stocking rate to correspond to herbage mass on offer might have improved consistency of the harvest index during the growing season and increased season-long yields relative to the stocking methods that were used in 2014.

4.2.2 Herbage accumulation and disappearance

4.2.2.1 Herbage accumulation and disappearance at Blacksburg and Raphine.

ANPP and annual disappearance of mob stocking tended to be less than ANPP and disappearance of continuous stocking. ANPP of rotational stocking was inconsistent but annual disappearance was similar to continuous stocking. Measurements of ANPP and annual disappearance were not biased by the experimental design as were measurements of standing biomass. However, lesser annual disappearance with mob stocking could have contributed to the significantly greater standing herbage mass described in Section 4.2.1.1.

Overall, ANPP and disappearance did not differ significantly by stocking method. At the 12 AUM ha^{-1} stocking rate and with stocking initiation in May, different frequency and intensity of defoliation did not affect subsequent herbage growth rates. Cool-season grasses in the pastures entered the elongation stage of growth before defoliation occurred, if at all, in all stocking treatments. Therefore, an irreversible course of maturation occurred during which resources for growth were diverted to reproduction. Furthermore, because cool-season grass growth rates are greater during spring than summer and fall, the extent of defoliation of all stocking methods was lesser in spring than in summer and fall. Therefore, pasture canopies filled out in the spring and were defoliated in the fall. Extent of light interception of the sward canopy (complete in the spring and incomplete in the fall) may have limited pasture growth. Previous studies of rotational stocking that have produced an advantage in stocking rate or animal days of grazing used a variable stocking rate and maintained a constant level of post-grazing forage mass or stubble height to optimize leaf area (Sollenberger et al, 2012). In these studies, grazing intensity (extent of defoliation episodes) was more important than timing or duration of stocking alone. For example, Holmes et al (1952) found a 33% advantage of rotational stocking compared to set stocking on orchardgrass pastures in the UK. Kuusela and Khalili (2002) found a 26% advantage on a complex cool-season mixture in Finland. Put-and-take methods were used in these studies to equalize the residual herbage mass that results from the same stocking methods over time.

Growth rates were greater at Blacksburg relative to Raphine. Growth rates also varied during the season: rates were generally less in July-October relative to May. Pasture growth would be expected to vary between years and locations depending on temperature and precipitation, but no previous evidence is available in support of an interaction of stocking methods and climate on pasture yield when intensity of defoliations differs among stocking methods and varies haphazardly over time. The rates of herbage accumulation found at Blacksburg and Raphine were within the range found by other studies of cool-season grass pastures in the region. Cool-season grass growth in Virginia is characterized by a "summer slump" of lesser growth rates in the summer relative to the spring and fall periods in response to greater temperature and lesser precipitation in the summer. Rayburn et al (1979) studied tall fescue yield and quality with different accumulation periods in Virginia: growth rate increased in April and May, was lesser in June and August, and intermediate in September and October. Peak fall growth was more than twice the annual minimum rate observed in July. In monoculture swards of orchardgrass and tall fescue in West Virginia, Denison and Perry (1990) found growth rates that ranged from 70 kg ha^{-1} d^{-1} in May to 0 kg ha^{-1} d^{-1} in July. Fall growth rates were less than or equal to early summer growth rates. Burns et al (2002) found growth rates of tall fescue in North Carolina that ranged from 55 kg ha^{-1} d^{-1} in May to 7 kg ha^{-1} d^{-1} in late July. Livestock producers often take advantage of seasonal herbage accumulation by conserving excess herbage as hay rather than leaving it in the fields to mature and senesce. This hay is offered to livestock when pasture growth slows.

Accuracy of accumulation and disappearance measurements could have been influenced by heterogeneous species composition among pastures, which may have resulted in different vertical distributions of biomass characteristic of each species. Tall fescue cover in mob and rotationally stocked pastures was greater ($P < 0.02$) than in continuously stocked pastures (tall fescue covers were 33, 32, and 27%, respectively). Orchardgrass and bluegrass cover did not differ ($P > 0.50$) by stocking method. Accumulation and disappearance measurements are more reliable in monoculture swards; Walters and Evans (1979), for example, concluded that the difference method adequately estimated true intake by sheep on single-variety grass swards. However, estimates of intake tend to be difficult in mixed swards: Casler et al (1998), studied grass pastures established from seed that were stocked rotationally and concluded that tall fescue has the potential to reduce apparent intake on mixed cool-season grass pastures because orchardgrass was grazed to a greater extent than tall fescue at the same level of biomass. However, McLaren et al (1983) found similar total forage growth between orchardgrass-clover and tall fescue-clover pastures set stocked with beef steers in Tennessee. The RPM coefficients developed from a tall fescue pasture may underestimate the post-grazing biomass in an orchardgrass pasture and therefore underestimate animal intake. Because the pastures in this study were composed of mixtures of species and the RPM calibrations were not separated by species, mixed species composition enlarged the confidence intervals around the estimates of accumulation and disappearance for each stocking method.

The RPM slope coefficients determined in this study (174.6 to 293 kg ha^{-1} cm^{-1}, R^2 = 0.56) were in the middle of the range of other studies with tall fescue and orchardgrass. Dunn (2013) estimated standing herbage in tall fescue pastures as 112 kg live DM ha^{-1} cm^{-1}; Rayburn and Rayburn (1998) estimated 452 kg ha^{-1} cm^{-1} (R^2 = 0.52) in tall fescue pastures; and Brink and Soder (2011) estimated 256 kg ha^{-1} cm^{-1} (R^2 = 0.73) in pre- and post-graze pastures of meadow fescue and orchardgrass. Seasonal variation in slope coefficients was consistent with findings by Ferraro (2010) on mixed pastures of tall fescue, bluegrass, and orchardgrass in Ohio and Wisconsin in which slope coefficients were affected (P = 0.002) by time of year and varied from 90-300 kg ha^{-1} cm^{-1} (R^2 = 0.48 to 0.89). The seasonal variation in coefficients at Blacksburg and Raphine likely resulted from several factors, including changes in the proportion of reproductive tillers, amount of refused stem material, and turgor pressure in stems. Stepwise linear regression of RPM coefficients by proportion of each plant species in the sward (orchardgrass vs. tall fescue, for example) could improve estimates of accumulation and removal; however, no species cover data were collected in association with the RPM measurements made in the exclosure cages in the continuously stocked pastures to apply stepwise regression by species cover.

4.2.2.2 Herbage accumulation and disappearance at Steeles Tavern

The overall stocking method by month interaction was significant for rate of herbage accumulation. Rotationally stocked pastures tended to grow faster than mob and continuously stocked pastures in August, similarly in September and November, and slower in October. Overall ANPP tended to be greater and disappearance lesser for rotational stocking relative to continuous and mob stocking. Rotational stocking may have been more productive because it was defoliated to a lesser extent during each stocking period in each paddock. In previous studies of cool-season grass growth, greater residual height has generally resulted in positive responses to dry weather relative to lesser residual height. For example, Karsten and Fick (1999) found poor post-grazing growth of white clover in New York when grazing stress was combined with hot dry weather. The authors recommended decreasing grazing intensity during and after stressful weather. Burns et al (2002) combined intensity and frequency of defoliation of tall fescue during dry weather: in response to short-height, frequent cutting regimes of 11-9 cm and 8-4 cm, pasture growth rate fluctuated over the season from 20 kg ha^{-1} d^{-1} in mid-May to 3 kg ha^{-1} d^{-1} in mid-June but then increased to 18 kg ha^{-1} d^{-1} in November; with higher infrequent cutting regimes of 31-9 cm and 31-5 cm growth rates declined linearly from 23 kg ha^{-1} in May to 8 kg ha^{-1} in November and did not fluctuate within the season. This reinforces the interactive relationship of stocking methods with weather: continuous and rotational stocking could be used successively on the same pasture to benefit yield and persistence depending on the temperature and precipitation regime (Edwards and Chapman, 2011). Pastures might be continuously stocked in the spring to manage residual leaf area and then stocked rotationally during the summer as pasture growth slows in response to seasonal variation in temperature and precipitation.

4.2.3 Plant species composition

4.2.3.1 Plant species composition at Blacksburg and Raphine.

White clover and bare ground cover were greater in continuously stocked areas than in mob stocked areas. These differences may have been biased negatively against mob stocking by the sampling design, as described in Section 4.2.1.1, because areas in varying states of regrowth were not included in the comparison. It is telling that bare ground cover was similar between rotational and continuous stocking methods because bare ground indicates recent disturbance by hooves and grazing. The mob stocking measurements did not include areas that were actively being grazed; therefore, it is not possible to separate the effects of stocking methods from bias of the experimental design, although comparisons between continuous and rotational stocking are not affected by the experimental design in this way.

Red and white clover responded differently to stocking methods at Blacksburg and Raphine: white clover was greater in continuously stocked areas relative to mob and rotationally stocked areas but red clover did not differ by stocking method. Aside from experimental design, differing growth habits of the seeded clover species may explain this response. The prostrate growth habit of white clover likely conferred it tolerance to close and frequent grazing during continuous stocking and intolerance of shading by grasses during mob and rotational stocking. The upright growth habit of red clover likely conferred it tolerance to shading by grasses during mob and rotational stocking. White clover also tends to colonize bare ground, which would explain why continuously stocked areas would have greater white clover cover than mob stocked areas; however, it is not clear, given this reasoning, why in continuous and rotational areas white clover cover was not similar, although bare ground was similar. Competition between clovers and grasses may have influenced the success of each clover species. Grass cover and white and red clover cover were negatively correlated ($\rho < -0.214$). Herbage biomass and white clover cover were also significantly negatively correlated ($\rho = -0.276$) but biomass and red clover cover were not significantly correlated ($\rho = -0.01$), which reflects the ability of red clover to grow taller in response to shading within the canopy, whereas white clover tends to reduce growth in response to shading.

Clover establishment was greater at Blacksburg than at Raphine. Several factors may explain differences in clover establishment between project locations. Hot dry weather in 2014 (Table 3.2) limited clover growth and increased grazing pressure on clovers as total herbage mass became limiting in July 2014. Fertility was similar among sites (Table 3.1) so it is unlikely that fertility could explain location differences in clover cover. Plant residue on the soil surface at Raphine when clover was broadcast seeded may have limited seed-soil contact, which may have limited subsequent germination.

Forage cover increased and weed cover decreased in pastures across time, which is consistent with findings in previous studies. Renz and Schmidt (2012) in rotationally stocked pastures of perennial ryegrass and tall fescue found that weed cover decreased from May to September, regardless of grazing height treatment (5, 10, 15, or 20 cm). Others have found that the plant diversity in fields that contain tall fescue tends to decline across time due to competition from endophyte-infected plants (Clay and Hollah, 1999). At Blacksburg and Raphine, tall fescue cover was greater in mob-stocked areas than continuous and rotationally stocked areas. If monitoring of herbage cover were to continue for several years, mob stocked areas may have lesser weed cover than the other stocking areas because of tall fescue competition with weeds. Standing herbage biomass also generally increased over the duration of the study. Increased biomass may reduce weed populations over time as well. For example, Tracy and Sanderson (2004) suggested that maintaining more than 1,500 kg ha^{-1} of aboveground biomass reduces weed invasion. However, Tracy and Sanderson (2004) also reported that forage diversity and weed abundance were negatively correlated and diversity, weed resistance, and pasture productivity were positively correlated. So increased relative cover of tall fescue may ultimately be at odds with the goal of reducing weeds in pastures.

White clover cover was positively correlated with CP content of herbage DM (ρ = 0.329) and negatively correlated with ADF and NDF content (ρ > -0.387), while dead cover and total biomass were negative predictors of CP content and positive predictors of ADF and NDF contents (Table 4.10). Previous studies have documented the benefits of clover to herbage nutritive value. Bird et al (1989), for example, reported that estimates of ADG on summer perennial ryegrass pastures were better predicted (R^2=0.65) when regressions were based on green mass of subterranean clover (*Trifolium subterraneum* L.) than on total pasture mass (R^2=0.40). At Blacksburg and Raphine red clover cover was not significantly correlated with CP content but was negatively correlated with ADF and NDF content. Red clover tends to mature later in the season than grasses and white clover so may have diluted the fiber content of the herbage DM, although red clover tended to predominate in areas with greater biomass so biomass may have influenced CP content more than red clover cover.

4.2.3.2 Plant species composition at Steeles Tavern.

The grass, legume, weed, dead, and bare soil covers varied seasonally but did not differ significantly among stocking methods. Seasonal variation in plant species composition would be expected based on previous studies (outlined in Section 4.2.3.1). Imbalance between herbage harvest and herbage growth in all stocking methods resulted in accumulation of reproductive tillers of cool season grasses in May-June. The tillers senesced in July and contributed to the cover of dead material in the sward. Clover cover likely declined across time in response to hot dry weather and shading from dead material in the sward.

4.2.4 Herbage nutritive value

4.2.4.1 Herbage nutritive value at Blacksburg and Raphine.

Nutritive value of clipped samples did not differ significantly by stocking method. Samples clipped to the soil surface included dead plant material, as well as the stems of plants, which are more massive and are thought to contain greater structural carbohydrate (ADF and NDF) concentrations and lesser CP concentration relative to plant leaves (Blaser et al, 1986, p. 9). Sheehan et al (1985), for example, found differences in the composition of stem and leaf parts of red clover on Sept. 30th: CP content of leaves was 300 g kg^{-1} DM while stems contained 100 g kg^{-1} DM. If pastures are rested for a greater period of time, as mob stocked pastures would be rested compared to other rotational methods, the relative proportion of leaves tends to be lesser than the proportion of stems in the sward. Nelson and Moser (1994) reported that the leaf:stem ratio of a sward changes from 2:1 at an immature stage to 1:2 at mature stages. Deeper canopy layers exhibit progressively lesser ratios of leaf:stem so swards that are taller and more mature will likely have lesser nutritive value. However, Delegarde et al (2000) reported that DM, CP, and NDF increased in successively deeper layers of a perennial ryegrass pasture. At Blackburg and Raphine continuous and rotational stocked areas had greater variation in herbage mass among the pastures relative to the mob paddocks that were only grazed two times each year. Because the pastures were patchy, herbage nutritive value was an average of points that were recently grazed and points that were passed over for weeks or months before herbage was sampled. Future analysis might examine the range of nutritive value of samples within pastures because the variation within plants and between patches is greater than the variation between pastures.

The nutritive value results were likely influenced by the predictive accuracy of the NIRS equation. Global H and Neighborhood H statistics were 2.2±0.9 and 1.5±0.6, respectively, for the entire population of samples and samples from mob stocked pastures tended ($P > 0.066$) to have

0.26 greater Global H and 0.16 greater Neighborhood H relative to rotationally stocked pastures. Typical acceptance criteria include Global H less than 3.0 and Neighborhood H less than 0.6. Outliers should ideally be analyzed with wet chemistry to expand the equation (Thomas Griggs, personal communication, 20 Jan. 2014). Therefore, some herbage samples were not represented acceptably by the calibration set that was used for equation development. Samples from mob-stocked pastures were predicted less accurately than samples from continuous and rotationally stocked pastures. The results of the nutritive value analysis depended on the performance of the NIRS equation.

Overall, nutritive value of herbage biomass varied during the growing season, as would be expected based on seasonal changes in plant maturity, soil organic matter mineralization, and cover of grass and dead material in the sward. Reproductive maturation of cool-season grasses is associated with increased ADF and NDF content and lesser CP content. Organic matter mineralization is generally greater in spring as increased temperatures and abundant moisture drive turnover of plant residues and release of inorganic nitrogen; therefore, soil nitrogen is assimilated into pasture plants in greater quantities in the spring. However, as reproductive portions of plants develop, nitrogen translocates to growing tissues so seedheads and stems are lesser in nutritive value upon senescence relative to green tissue.

Nutritive value of herbage was greater at Blacksburg relative to Raphine. Several factors may explain this difference. Less precipitation at Raphine relative to Blacksburg (Table 3.2) may have reduced relative plant nutrient uptake and sward growth, resulting in greater proportions of dead material in the swards at Raphine. The dead fraction likely diluted the green plant tissue because forage and clover covers were also lesser at Raphine than Blacksburg. And differences in the relative proportions of different forage species within the green herbage mass may have contributed to differing nutritive value. For example, Sheehan et al (1985) found different crude protein concentrations in regrowth of tall fescue, orchardgrass, and red clover swards in Virginia from September 1st to November 15th: herbage CP concentrations on September 30th, for example, were approximately 200 g kg^{-1} DM in red clover and 140 g kg^{-1} DM in tall fescue. However, clover alone cannot explain differences in herbage nutritive value: although total clover cover differed by stocking method, nutritive value did not differ by stocking method.

Although the project locations differed in herbage nutritive value, nutritive value was less important than herbage mass for secondary pasture productivity. For example, eight percent of the herbage samples from Raphine on Aug. 22, 2014 contained CP less than 80 kg ha^{-1} DM although 28% of herbage mass samples would have been limiting to intake (Whetsell et al, 2006). Herbage intake generally is limited when CP concentrations are less than 60-80 g kg^{-1} DM (NRC, 1987; Moore and Kunkle, 1995). Therefore, small herbage mass would have been a greater limit to livestock production than small CP and energy (i.e. high fiber) content. On a related note, Minson (1982), writes that energy intake from forage is more influenced by DM intake than by DM energy content. Herbage samples clipped to the soil surface generally represent the herbage on offer but livestock tend to select material of greater nutritive value than the material on offer. Therefore, adequate herbage mass to support intake is a greater determinant of diet adequacy than herbage chemistry when herbage mass is small. However, herbage mass and nutritive value tend to be negatively related because of several factors, including dilution of new growth with older biomass and associations among more intense defoliation, less senescent material, and greater clover cover in the sward at later dates. Bryan and Prigge (1994), for example, found that increased grazing intensity increased nutritive value of continuously stocked bluegrass-white clover pastures in West Virginia. Although defoliation at Raphine was more intense than at Blacksburg, lesser precipitation may have set the upper limit for clover growth and nutrient uptake so the study locations did not differ in herbage nutritive value overall.

4.2.4.2 Herbage nutritive value at Steeles Tavern.

Herbage CP content exhibited significant stocking method by month interactions: herbage nutritive value was similar for all stocking methods in May-August; however, CP was greater in September and October in mob stocked pastures relative to continuous and rotational paddocks. ADF and NDF content in September and October tended to be less in mob stocked pastures than in continuous and rotational but differences were not significant ($P > 0.10$). Greater resources for regrowth with extended pasture rest may have improved the growth status of mob stocked pastures and allowed them to resume growth more quickly during the cooler fall conditions relative to continuously stocked paddocks which were not rested. Another explanation is that generally lesser biomass on offer in continuous stocking pastures than in mob and rotational pastures in the fall increased the amount of manure contamination in the harvested samples, which would have increased the ADF and NDF contents of the herbage samples from continuously stocked pastures in the fall, even if lesser biomass favors more nutritious regrowth as Bryan and Prigge (1994) describe. In addition, the presence of trampled senescent seedheads in mob-stocked pastures may have enriched the fiber contents of the pasture samples relative to the green herbage mass on offer.

The nutritive value analysis at Steeles Tavern depended to some extent on the performance of the NIRS fresh forage equation. For the Neighborhood H statistic the stocking method by month interaction was significant ($P = 0.046$). Neighborhood H ranged from 0.90±0.04 in May 2014 to 2.40±0.04 in Aug. 2014. The acceptance criterion for Neighborhood H is 0.6 (Shenk et al, 2007, p. 371). Samples harvested in May and June were better predicted by the equation relative to samples harvested in July through October, although the majority of samples from all months exceeded the acceptance criterion. The stocking method by month interaction for crude protein occurred in the latter part of the year; this interaction may have been affected by the seasonality in accuracy of the NIRS equation.

4.2.5 Nutritive value of herbage sampled from esophageal cannula of beef steers

Steers were selective for CP and fiber constituents relative to clipped pasture samples, although the magnitude of selectivity differed over the duration of mob stocking (possibly as a function of pasture mass): steers were selective at the 0-, 4-, and 16-h timepoints but not selective at 8- and 12-h. Selectivity of steers for greater protein and less NDF content than clipped herbage is consistent with findings by Dubbs et al (2003) on fescue pastures inter-seeded with red clover: concentrations of CP and NDF in clipped forage were less by 4.5 g kg^{-1} OM ($P < 0.01$) and greater by 5.5 g kg^{-1} OM ($P < 0.01$), respectively, relative to ruminal masticate samples collected from steers during April to September. Dunn (2013) also found steers selected for greater CP content relative to clipped samples. CP was 8-21% greater in ruminal masticate samples relative to clipped forage from cool-season grass pasture during June-August. The degree of selectivity in that study did not appear to be associated with seasonal variation in the CP concentration of the herbage on offer. Overall, steers and other growing livestock tend to be more selective relative to cows; therefore, it is conceivable that clipped samples do not differ meaningfully in nutritive value relative to the herbage consumed by the mob of cows. Furthermore, the patterns of selectivity observed at Blacksburg in September may not represent behavior at other times of the year if, for example, swards differ seasonally in relative proportions of leaf and stem. In any case, all samples harvested by the steers in all pastures were greater in CP content than the 80 g kg^{-1} DM limiting level described by the NRC (1987), suggesting that given adequate herbage mass livestock are able to select a diet adequate for maintenance.

The NIRS fresh forage equation performed better for the clipped pasture samples than the herbage from esophageal cannula, although the majority of all samples were outside the acceptance criterion of 3.0 and 0.6 for Global H and Neighborhood H, respectively (Shenk et al, 2007, p. 371). Mean Global H of clipped and esophageal samples were 3±1 and 6±3, respectively. Mean Neighborhood H of clipped and esophageal samples were 2±1 and 4±2, respectively. Because clipped pasture samples tended to have lesser nutritive value but were more accurate than esophageal samples the NIRS equation may have under-predicted the nutritive value of esophageal samples. Steers may have been selective relative to clipped samples for the duration of mob stocking, for example.

Observed temporal variation in nutritive value of esophageal samples is consistent with findings by Seman et al (1999) on tall fescue-alfalfa mixes in Georgia: as the study progressed during five days of stocking and forage mass decreased from 2,100 to 1,000 kg DM ha^{-1}, steer diets exhibited linear decreases in CP ($P < 0.05$) and IVDMD ($P < 0.001$), a linear increase in NDF ($P < 0.05$), and quadratic increases in lignin and cellulose ($P < 0.01$). However, others have found no relationship of nutritive value with length of stocking during shorter timeframes: La Guardia Nave (2012) noted that for rotational stocking of tall fescue in Ohio, residual forage level was not a significant predictor of nutritive value. Defoliation during the first six hours of stocking did not affect nutritive value of the herbage on offer, which suggests that more frequent sampling of nutritive value of the diet selected during rotational grazing at Blacksburg would have provided minimal useful information relative to sampling once daily. However, nutritive value of esophageally-sampled herbage in mob paddocks exhibited diurnal variation: CP was greater in the day than in the evening; therefore harvesting esophageal samples during the day may have overestimated nutritive value of the diet in continuous and rotational pastures relative to mob paddocks which were sampled around the clock.

The timing of herbage intake relative to the harvest of herbage nutritive value samples is unknown but all herds likely spent more time grazing during mornings and evenings. Ideally, herbage samples would have been collected simultaneously with the herds' grazing bouts to represent herbage nutritive value in proportion to the herbage mass consumed in each stocking treatment. This idea corresponds with Minson (1982) who described that energy intake from forages is more closely predicted by mass of herbage consumed than by the chemical composition of the herbage. However, because sward mass changes more rapidly during mob stocking relative to rotational and continuous stocking, rate of herbage intake may decline in proportion to herbage mass on offer which means that mob stocked cattle may have consumed a greater proportion of the herbage of greater nutritive value at the initiation of stocking and consumed less herbage of lesser nutritive value that was available at later points in the duration of mob stocking. So although this work provides a preliminary sense of how the chemical composition of herbage on offer and herbage selected by steers changes during mob stocking, the effects of mob stocking on animal performance over time are still a matter of speculation.

4.3 Conclusions

Intensive stocking management did not benefit pastures at the 12 AUM ha^{-1} beef cattle stocking rate employed in this study. Standing herbage mass was greater overall in the mob stocked pastures at Blacksburg and Raphine; however, extrapolating this observation to net primary productivity would be misleading because herbage production (ANPP) in 2014 did not differ significantly by stocking method. Mob stocking simply leaves more herbage in the field than continuous and rotational stocking. Clover cover was lesser with rotational and mob stocking than continuous stocking, although mob stocking decreased the amount of bare soil. Pasture samples harvested by clipping to the soil surface did not show a response of ADF, CP, or NDF to stocking methods, although herbage samples harvested with esophageally-cannulated steers in September 2014 at Blacksburg indicated that clipped herbage samples underestimated the nutritive value of herbage selected by the steers at certain times. When pasture mass was abundant livestock selected a diet adequate for maintenance; however, diet selected was less nutritious at times with mob stocking relative to continuous and rotational stocking because rapid defoliation and trampling reduced opportunities for selection of nutritious herbage. Rapid fluctuations in nutritive value of the diet would be expected to lessen long-term animal performance.

Within the naturalized cool-season grass pastures with moderate-to-low soil fertility studied in this project, seasonal variation in weather and plant maturity influenced growth and nutritive value of pastures more than stocking management when the beef cattle stocking rate was 12 AUM ha^{-1}. Intense infrequent defoliation produced mixed results: initiating mob stocking earlier in the spring decreased pasture biomass on offer across the growing season; however, after a summer drought mob stocked paddocks were greater in CP concentration in the fall relative to continuous and rotationally stocked paddocks. Past studies that found an advantage of intermittent stocking compared to set stocking managed for consistent pasture mass or height. Pasture management in this study was generally done by the calendar. Perhaps by varying rest periods or stocking rates within a year to achieve specific pasture heights, continuous and intermittent stocking methods may be employed successively to increase pasture productivity and herbage nutritive value.

Future studies should compare the pasture responses to stocking methods at several stocking rates because stocking rate and stocking method interact when determining the responses of productivity, species composition, and herbage nutritive value. Intense frequent defoliations would likely be more damaging to plant growth than intense infrequent defoliations. Species composition responds at moderate stocking rates wherein lesser herbage biomass favors colonial broadleaf species like white clover relative to grasses. Upright broadleaf species like red clover are not as sensitive as white clover to greater herbage biomass, although removing biomass prior to seeding benefits yield of all clovers. Overall, a seasonally adaptive approach to stocking management based on measurable objectives of pasture height may yield more herbage while improving abundance of seeded clovers and supplying nutritious forage for much of the growing season.

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Table 4.1: Least squares means of standing herbage biomass at Steeles Tavern, VA from May-Nov. 2014, averaged among stocking methods.

Month	Herbage biomass
	— $kg\ ha^{-1}$ —
May	3363 d†
June	4145 e
July	2980 cd
August	2598 bc
September	2216 b
October	1865 ab
November	1324 a
SE	208

† Herbage biomass followed by different letters differ based on Tukey's HSD (*P* < 0.05).

Table 4.2: Least squares means of annual days of grazing at Blacksburg, Raphine, and Steeles Tavern, VA by stocking method, averaged among years and pasture replicates.

	Location		
Stocking method	**Blacksburg**	**Raphine**	**Steeles Tavern**
	—— Days of grazing yr^{-1} ——		
Continuous	190 b†	149 b	196 a
Mob	8 a	22 a	202 a
Rotational	190 b	149 b	202 a

† Mean days of grazing followed by different letters differ based on Tukey's HSD (*P* < 0.05).

Table 4.3: Rising plate meter (RPM) coefficients for May-Nov. 2014. RPM calibration samples were harvested at Blacksburg and Raphine, VA, and coefficients were averaged between locations.

Month	**RPM† coefficient**
	kg DM ha^{-1} cm^{-1} compressed herbage height
Intercept	733.6
May	184.4 a‡
June	235.0 b
July	284.1 bc
August	283.7 bc
September	291.4 bcd
October	307.9 cd
November	319.6 d
SE	12.1

† Abbreviations are as follows: DM: dry matter; RPM: rising plate meter.
‡ RPM coefficients followed by different letters differ based on Tukey's HSD ($P < 0.05$).

Table 4.4: Least squares means of rates of herbage accumulation at Blacksburg and Raphine, VA during 5 May-8 Nov. 2014, averaged among locations and stocking methods.

Month	**Accumulation rate**
	— kg ha^{-1} d^{-1} —
May	85.1 b†
June	80.2 ab
July	24.4 ab
August	45.6 ab
September	42.3 ab
October	14.5 a
SE	9.0

† Accumulation rates followed by different letters differ based on Tukey's HSD ($P < 0.10$).

Table 4.5: Least squares means of rates of herbage accumulation at Steeles Tavern, VA during 22 July—22 Nov. 2014, averaged among stocking methods.

Month	Accumulation rate
	— kg ha^{-1} d^{-1} —
August	2.7 a†
September	3.6 a
October	16.2 b
November	0.6 a
SE	4.7

† Growth rates followed by different letters differ based on Tukey's HSD ($P < 0.05$).

Table 4.6: Least squares means of percent cover of white clover, red clover, and bare ground by stocking method at Blacksburg and Raphine, VA during 9 April 2013—8 Nov. 2014, averaged among time and locations.

	Cover type		
Stocking method	**White clover**	**Red clover**	**Bare**
		—% —	
Continuous	7.5 b†	4.2 a	3.3 b
Mob	2.5 a	3.6 a	1.1 a
Rotational	3.0 a	3.1 a	3.3 b
SE	2.0	1.2	1.2

† Percent covers within columns followed by different letters differ based on Tukey's HSD ($P <$ 0.05).

Table 4.7: Least squares means of percent cover of grass, clover, weed, and dead material at Blacksburg and Raphine, VA during 30 April 2013—28 Sept. 2014, averaged among stocking methods and locations.

Cover type	Time period						*SE*
	May 2013	July 2013	Oct. 2013	May 2014	July 2014	Oct. 2014	
Grass (%)	43 a‡	60 c	52 ab	41 a	46 ab	59 bc	3
Clover (%)	3 a	10 ab	8 ab	12 b	9 ab	9 ab	2
Weed (%)	19 a	16 ab	6 b	14 ab	10 ab	16 ab	3
Dead (%)	25 ab	--‡	28 b	27 b	26 ab	10 a	4

† Percent covers within rows followed by different letters differ based on Tukey's HSD ($P < 0.05$).

‡ Dead cover was not observed on 18 July 2013.

Table 4.8: Least squares means of percent cover of grass, legume, weed, and dead material at Steeles Tavern, VA during 27 May –19 Oct. 2014, averaged among stocking methods.

Cover type	Time period			*SE*
	May 2013	July 2014	Oct. 2014	
Grass (%)	73 b†	49 a	86 c	5
Legume (%)	3 b	1 a	1 a	1
Weed (%)	5 b	1 a	2 a	1
Dead (%)	14 a	44 b	10 a	5

† Percent covers within rows followed by different letters differ based on Tukey's HSD ($P < 0.05$).

Table 4.9: Least squares means of acid detergent fiber (ADF), crude protein (CP), neutral detergent fiber (NDF), and total digestible nutrients (TDN) summarized by stocking methods at Blacksburg and Raphine, VA during 2 May 2013—11 Oct. 2014, averaged among time and locations.

	Nutritive value parameter			
Stocking method	**ADF†**	**CP**	**NDF**	**TDN**
	———— g kg^{-1} DM ————			
Continuous	349‡	112	615	437
Mob	351	113	608	442
Rotational	350	118	619	435
SE	14	9	19	13

† Abbreviations are as follows: ADF: acid detergent fiber; CP: crude protein; DM: dry matter; NDF: neutral detergent fiber; TDN: total digestible nutrients.

‡ Nutritive value parameters did not differ significantly by stocking method, based on Tukey's HSD ($P > 0.10$).

Table 4.10: Pearson's product-moment correlation coefficients for complete observations (*n* = 554) of acid detergent fiber (ADF), crude protein (CP), neutral detergent fiber (NDF), herbage biomass, and cover of grass, white clover, red clover, dead material, and bare soil at Blacksburg and Raphine, VA during 15 May 2013-11 Oct. 2014.

Parameter	**ADF†**	**CP**	**NDF**	**Grass**	**White Clover**	**Red Clover**	**Dead**	**Bare**	**Bio-mass**
ADF	1.000								
CP	**-0.697‡**	1.000							
NDF	**0.933**	**-0.694**	1.000						
Grass	**-0.235**	-0.091	**0.336**	1.000					
White Clover	**-0.387**	**0.329**	**-0.436**	**-0.352**	1.000				
Red Clover	**-0.164**	0.119	**-0.226**	**-0.214**	**0.207**	1.000			
Dead	**0.288**	**-0.331**	**0.269**	**-0.236**	**-0.313**	**-0.186**	1.000		
Bare	-0.045	-0.01	-0.087	**-0.272**	0.041	-0.057	**-0.167**	1.000	
Biomass	**0.331**	**-0.336**	**0.316**	**0.163**	**-0.276**	-0.012	**0.333**	**-0.344**	1.000

† Abbreviations are as follows: ADF: acid detergent fiber, CP: crude protein, NDF: neutral detergent fiber.
‡ Bolded coefficients differ significantly from zero ($|t(1, 552)| > 3.88$; $P < 0.001$).

Table 4.11: Pearson's product-moment correlation coefficients for complete observations (n = 463) of acid detergent fiber (ADF), crude protein (CP), neutral detergent fiber (NDF), herbage biomass, date of initiation of stocking, pasture rest period, 15-day soil temperature†, and 15-day accumulated precipitation† at Steeles Tavern, VA during 19 May-18 Nov. 2014.

Parameter	**ADF‡**	**CP**	**NDF**	**Biomass**	**Stocking date**	**Rest period**	**Soil Temp**	**Precip**
ADF	1.000							
CP	**-0.896**§	1.000						
NDF	**0.976**	**-0.872**	1.000					
Biomass	0.080	**-0.167**	0.095	1.000				
Stocking date	0.010	-0.082	-0.001	0.086	1.000			
Rest period	**-0.352**	**0.348**	**-0.345**	**0.201**	**0.509**	1.000		
Soil Temp	**0.655**	**-0.613**	**0.645**	0.137	0.003	**-0.263**	1.000	
Precip	-0.122	0.067	-0.115	**-0.295**	-0.005	-0.130	**-0.524**	1.000

† Source: Natural Resources Conservation Service (NRCS). 2015. Shenandoah Valley Soil Climate Analysis Network (SCAN). In: National Water and Climate Center. http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=2088&state=va (accessed 28 Jan. 2015).

‡ Abbreviations are as follows: ADF: acid detergent fiber; CP: crude protein; NDF: neutral detergent fiber; Soil Temp: Average soil temperature for 15 days prior to sampling; Precip: Cumulative precipitation for 15 days prior to sampling.

§ Bolded coefficients differ significantly from zero (($|t(1, 605)| > 3.63$; $P < 0.001$).

Table 4.12: Least-squares means of concentrations of acid detergent fiber (ADF), crude protein (CP), and neutral detergent fiber (NDF) in herbage sampled by beef steers and hand clipped from continuous, mob, and rotationally stocked pastures at Blacksburg, VA during 28 Sept.—2 Oct. 2014.

	Nutritive value parameter		
Sample	**ADF†**	**CP**	**NDF**
	——— g kg^{-1} DM ———		
Hand-clipped	302 a‡	164 a	591 a
Steer 1	331 a	207 b	562 a
Steer 2	320 a	201 b	550 a
SE	28	22	52

† Abbreviations are as follows: ADF: acid detergent fiber; CP: crude protein; NDF: neutral detergent fiber.
‡ Nutritive value effects within columns followed by different letters differ based on Tukey's HSD ($P < 0.05$).

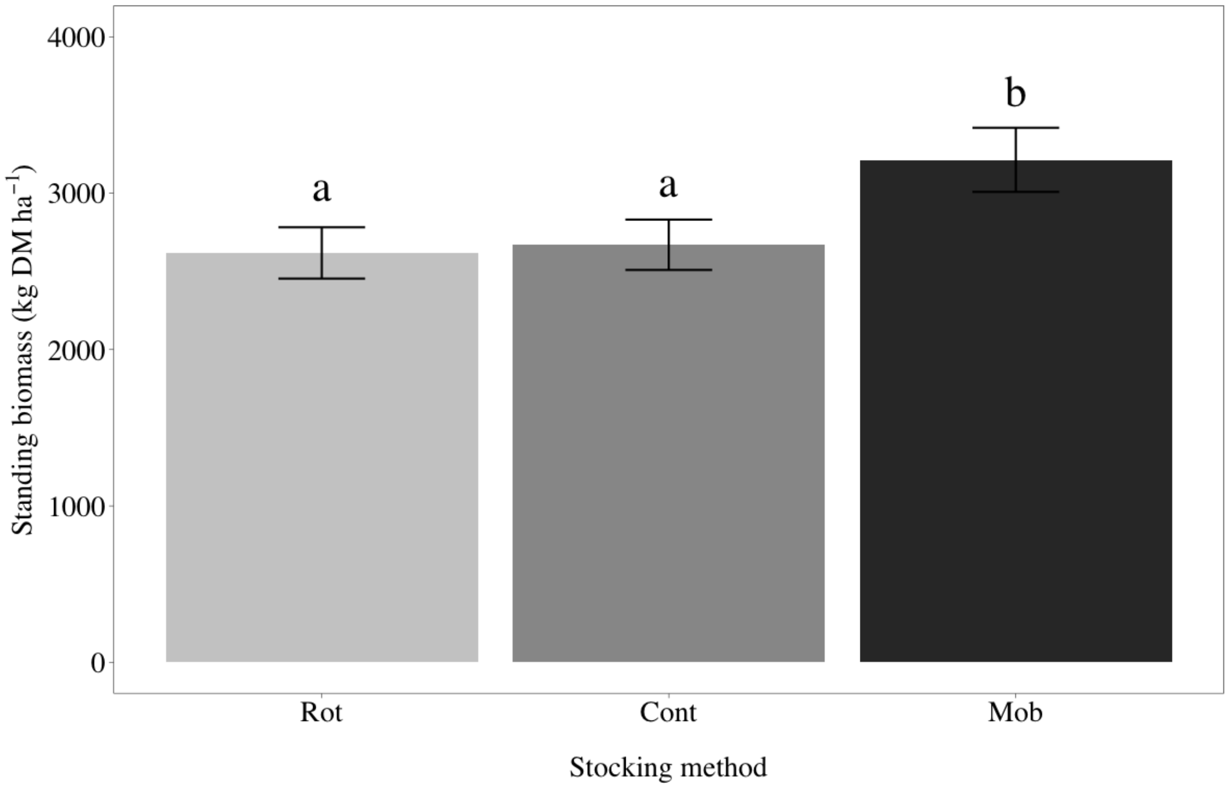

Figure 4.1: Mean standing biomass at Blacksburg and Raphine, VA during 9 April 2013—15 Nov. 2014 by stocking method averaged among sampling periods (n = 13) and locations (n = 2). Error bars show ± *SE*.

† Abbreviations are as follows: Cont: Continuous; DM: dry matter; Rot: Rotational.
‡ Means of standing biomass shown with different letters above error bars were determined to be significantly different using repeated measures ANOVA, $P < 0.05$.

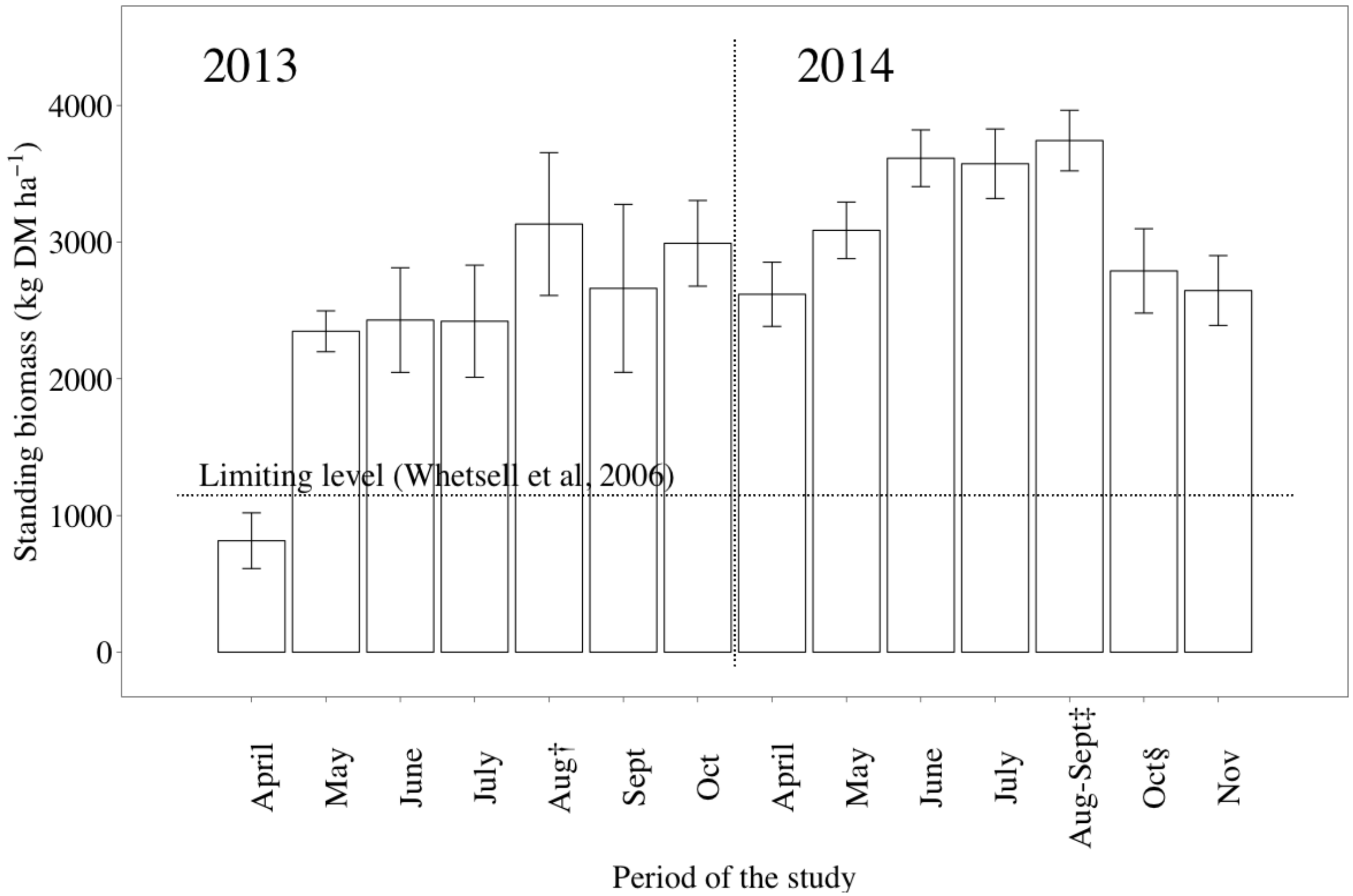

Figure 4.2: Mean standing biomass at Blacksburg and Raphine, VA during 9 April 2013—15 Nov. 2014 by sampling period averaged among locations (n = 2) and stocking methods (n = 3). Error bars show ± *SE*.

† Abbreviations are as follows: Aug: August; DM: dry matter; Sept: September; Nov: November; Oct: October.
‡ Before mob grazing in fall 2014.
§ After mob grazing in fall 2014.
¶ Source: Whetsell, M.S., E.B. Rayburn, and P.I. Osborne. 2006. Evaluation in Appalachian pasture systems of the 1996 (update 2000) National Research Council model for weaning cattle. J. Anim. Sci. 84(5):1265-1270.

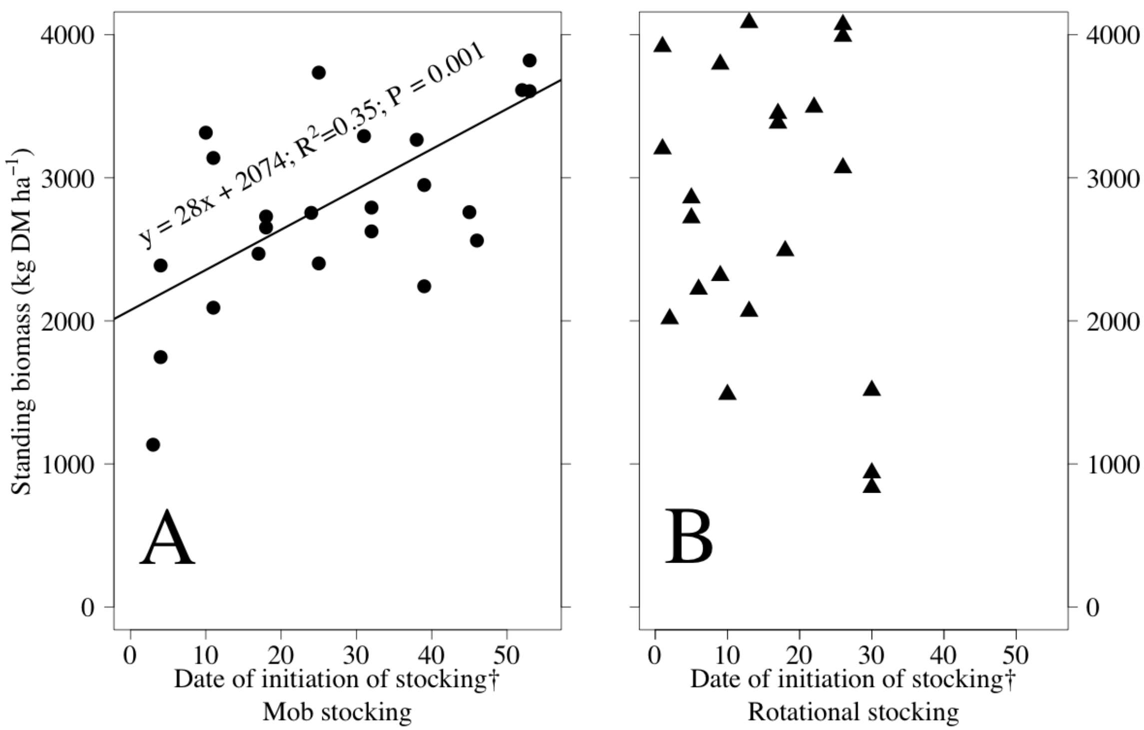

Figure 4.3: Mean standing biomass in paddocks within (A) mob-stocked pastures and (B) rotationally-stocked pastures, at Steeles Tavern, VA, respectively, averaged among samples harvested during 19 May—18 Nov. 2014, as a function of date of initiation of stocking in each paddock. Paddocks designated for hay feeding were excluded from analysis. A linear effect of date of first stocking on mean biomass minimized the sum of squared residual deviations from the mean relative to a quadratic effect. Initiating mob stocking one day later than May 4th increased standing herbage biomass by 28 kg ha^{-1} on average above a 2,074 kg ha^{-1} baseline (R^2 = 0.35; P = 0.001). Linear regression indicated that mean standing biomass in paddocks within rotationally stocked pastures was not significantly (P = 0.36) affected by date of initiation of stocking. †: 0 = 4 May 2014.

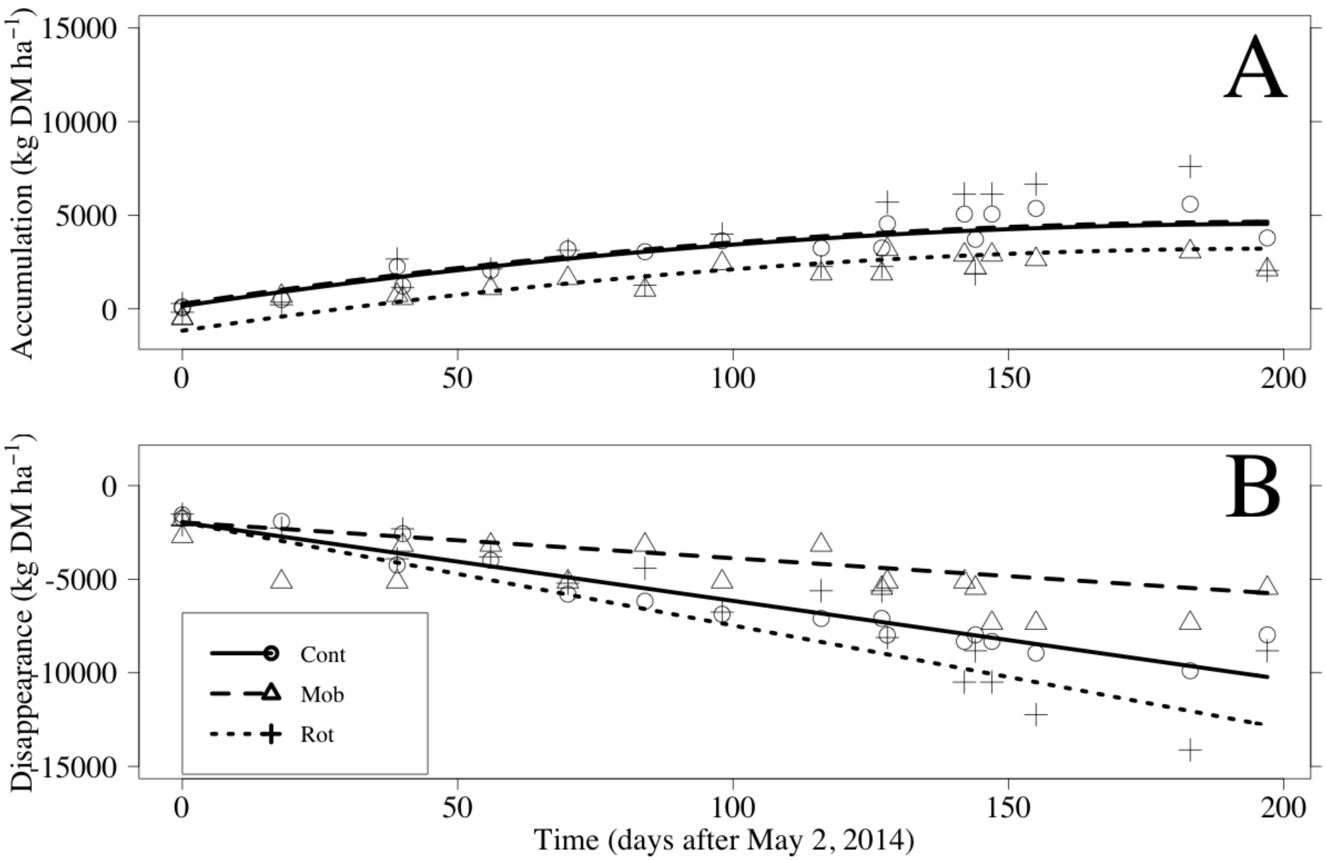

Figure 4.4: (A) Herbage accumulation and (B) herbage disappearance, respectively, during 2 May—15 Nov. 2014 at Blacksburg and Raphine, VA (n = 2). A quadratic effect of time on accumulation (R^2=0.67) minimized the sum of squared residual deviations from the mean relative to a linear effect. A linear effect of time on disappearance (R^2=0.81) was not improved by adding a quadratic effect. The endpoints of A and B represent aboveground net primary production (ANPP) and annual disappearance, respectively.

† Abbreviations are as follows: Cont: Continuous; DM: dry matter; Rot: Rotational.

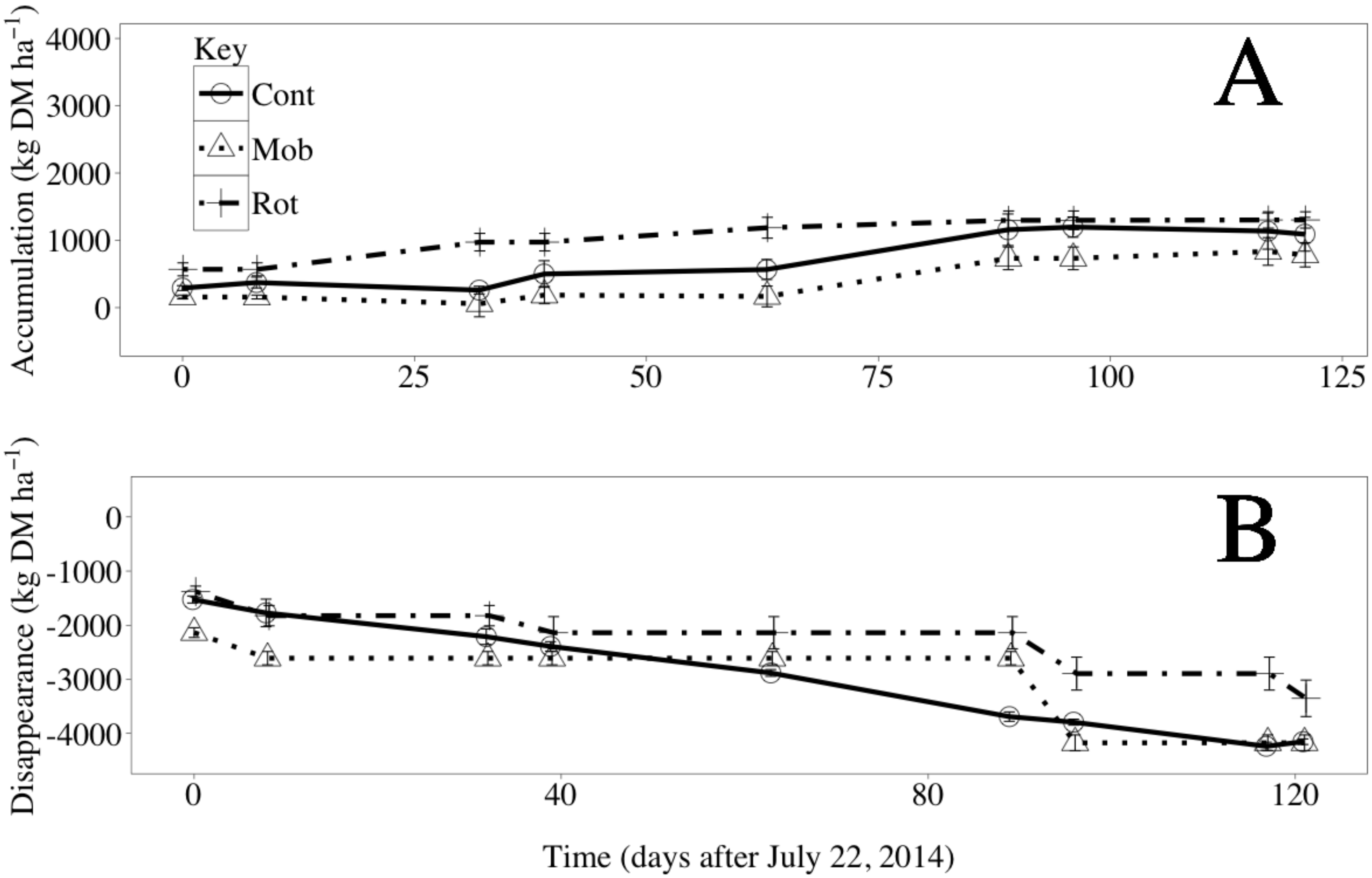

Figure 4.5: (A) Herbage accumulation and (B) herbage disappearance, respectively, during 22 July- 20 Nov. 2014 at Steeles Tavern, VA. Error bars represent ± *SE* (*n*=3). The endpoints of the lines in A and B represent aboveground net primary production (ANPP) and annual disappearance, respectively. † Abbreviations are as follows: Cont: Continuous; DM: dry matter; Rot: Rotational.

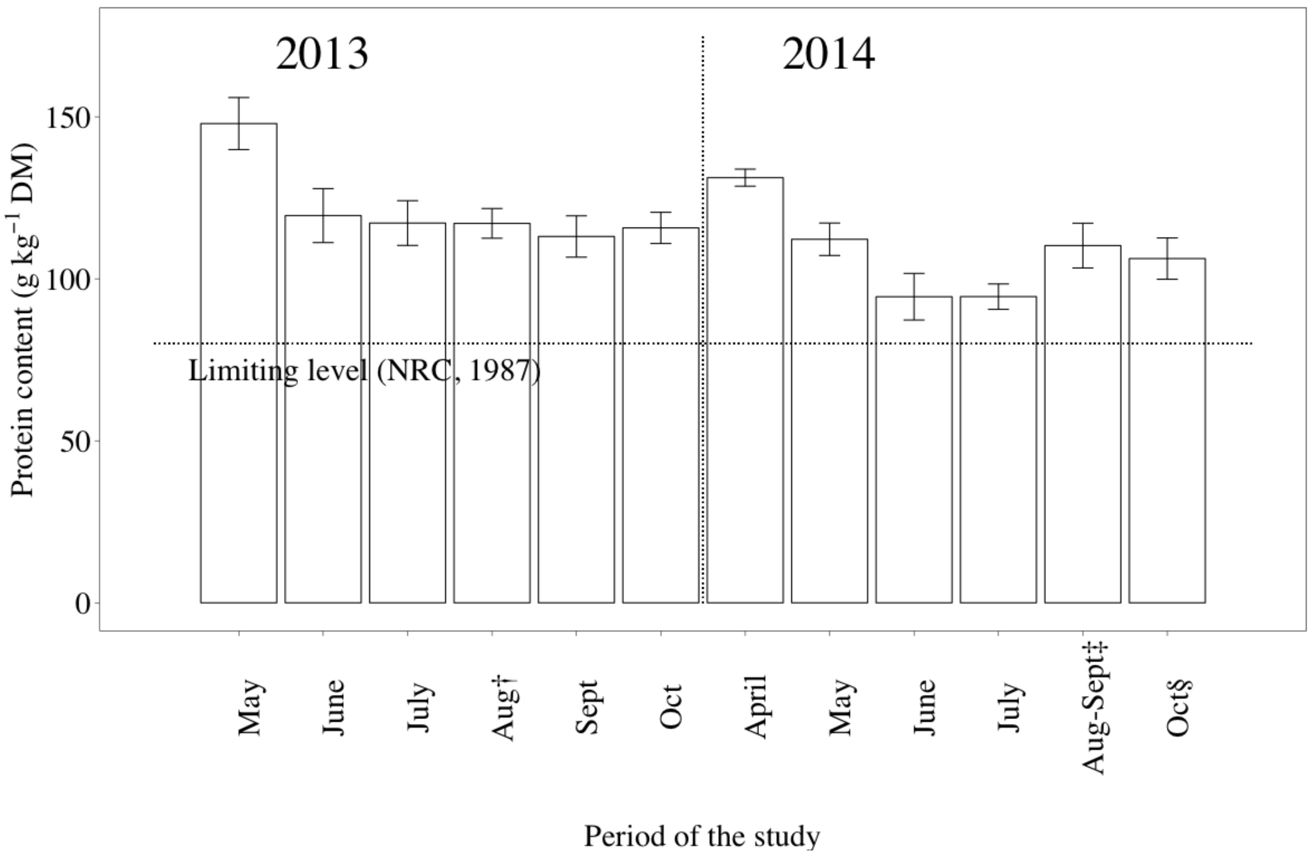

Figure 4.6: Mean crude protein (CP) content of herbage at Blacksburg and Raphine, VA during 2 May 2013-11 Oct. 2014 by month of the study, averaged among locations and stocking treatments. Error bars represent ± *SE*, *n* = 2.

† Abbreviations are as follows: Aug: August; DM: dry matter; Sept: September; Nov: November; Oct: October.
‡ Before mob grazing in fall 2014.
§ After mob grazing in fall 2014.
¶ Source: National Research Council. 1987. Predicting feed intake of food-producing animals. National Academies Press, Washington, D.C.

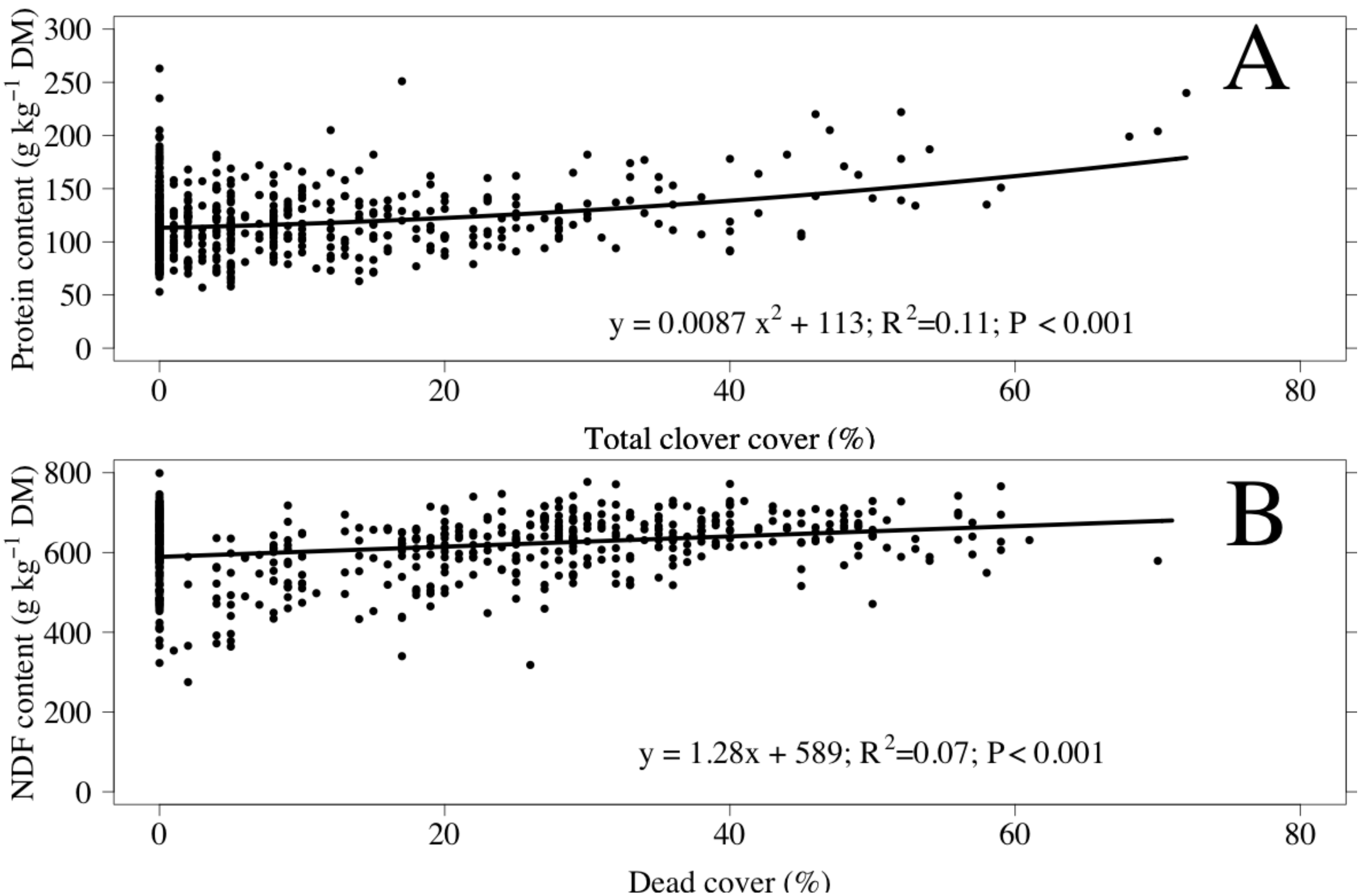

Figure 4.7: (A) Response of crude protein (CP) content of herbage harvested at Blacksburg and Raphine, VA during 15 May 2013—11 Oct. 2014, to the sum of red and white clover cover in sampled quadrats and (B) response of neutral detergent fiber (NDF) content of sampled herbage to dead cover in sampled quadrats. Cover of red and white clovers was observed in two adjacent 0.25 m^2 quadrats and then one of the two quadrats was selected at random and clipped to the soil surface to harvest herbage.

† Abbreviations are as follows: DM: dry matter; NDF: neutral detergent fiber.

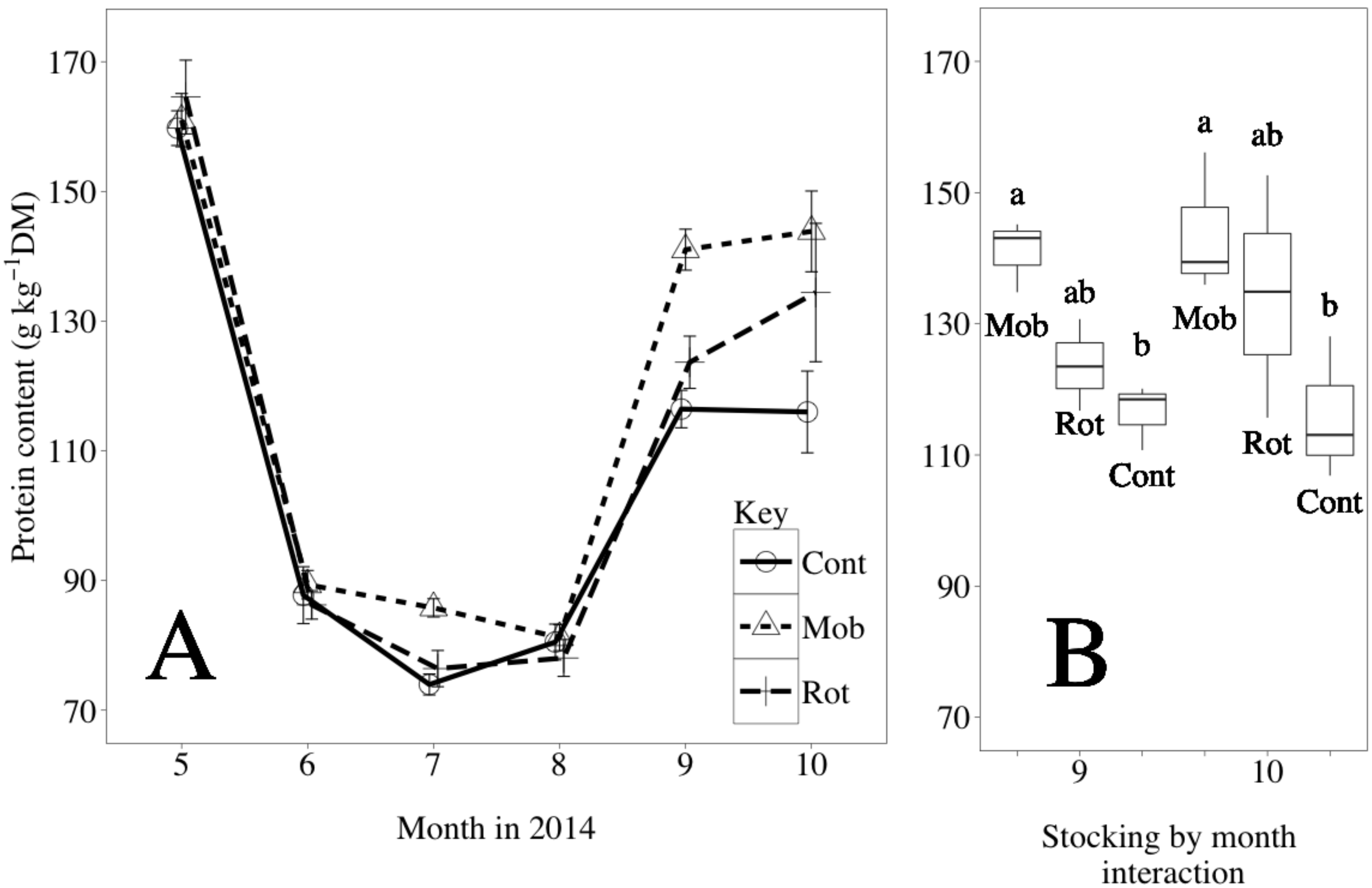

Figure 4.8: (A) Crude protein (CP) content of herbage at Steeles Tavern, VA during 19 May—22 Oct. 2014 by stocking treatment and (B) by month and stocking treatment interaction on September 15 and October 22, 2014. Error bars represent ± *SE*, *n* = 3. Means of CP shown with different letters above error bars were determined to differ significantly using Tukey’s HSD, $P < 0.05$.

† Abbreviations are as follows: Cont: Continuous; DM: dry matter; Rot: Rotational.

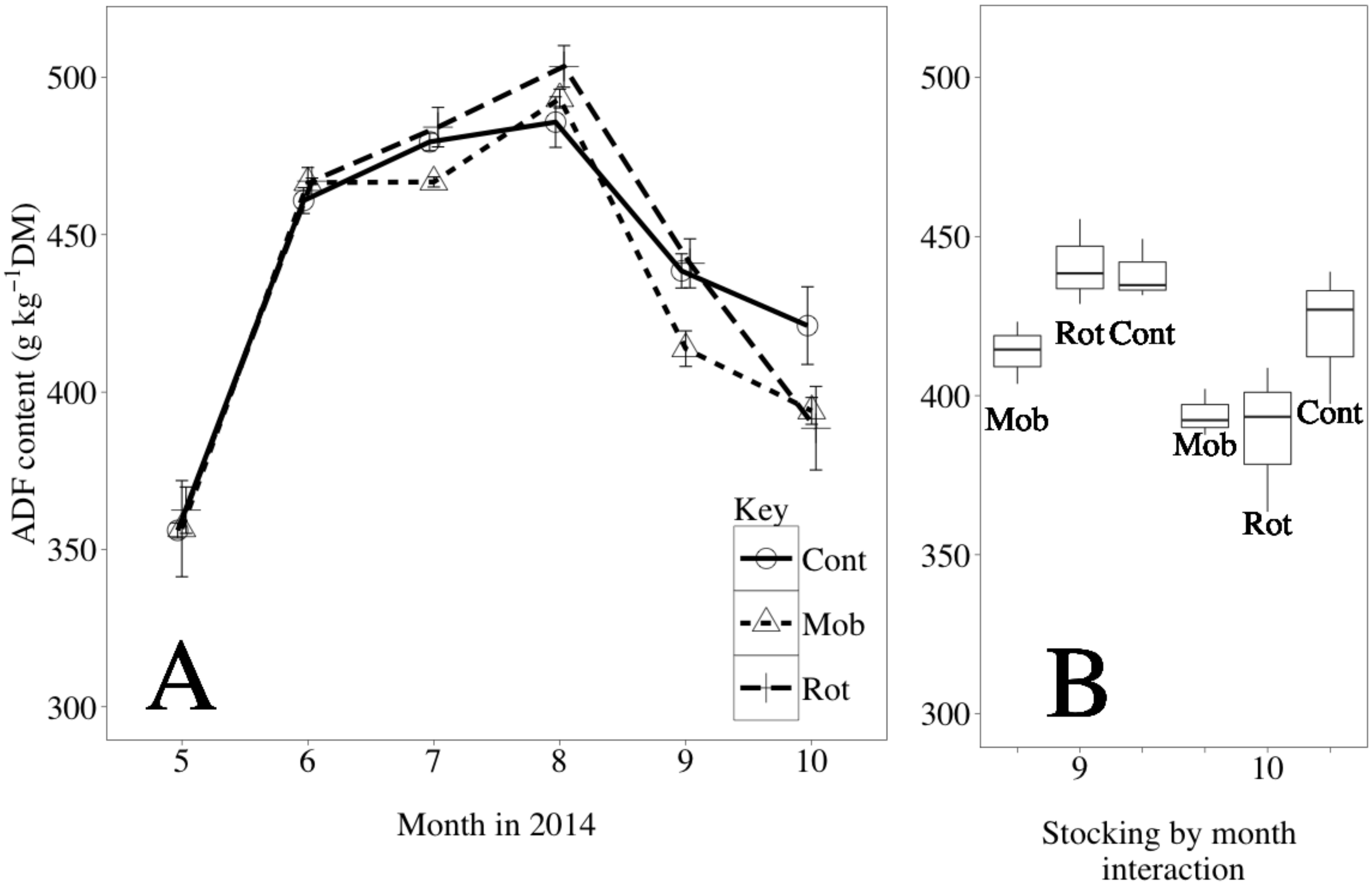

Figure 4.9: (A) Acid detergent fiber (ADF) content of herbage at Steeles Tavern, VA during 19 May-22 Oct. 2014 by stocking treatment and (B) by month and stocking treatment interaction on 15 Sept. and 22 Oct. 2014. Error bars represent ± *SE*, *n* = 3. Means of ADF of stocking treatments within a month did not differ significantly (*P* > 0.10), based on Tukey's HSD.

† Abbreviations are as follows: Cont: Continuous; DM: dry matter; Rot: Rotational.

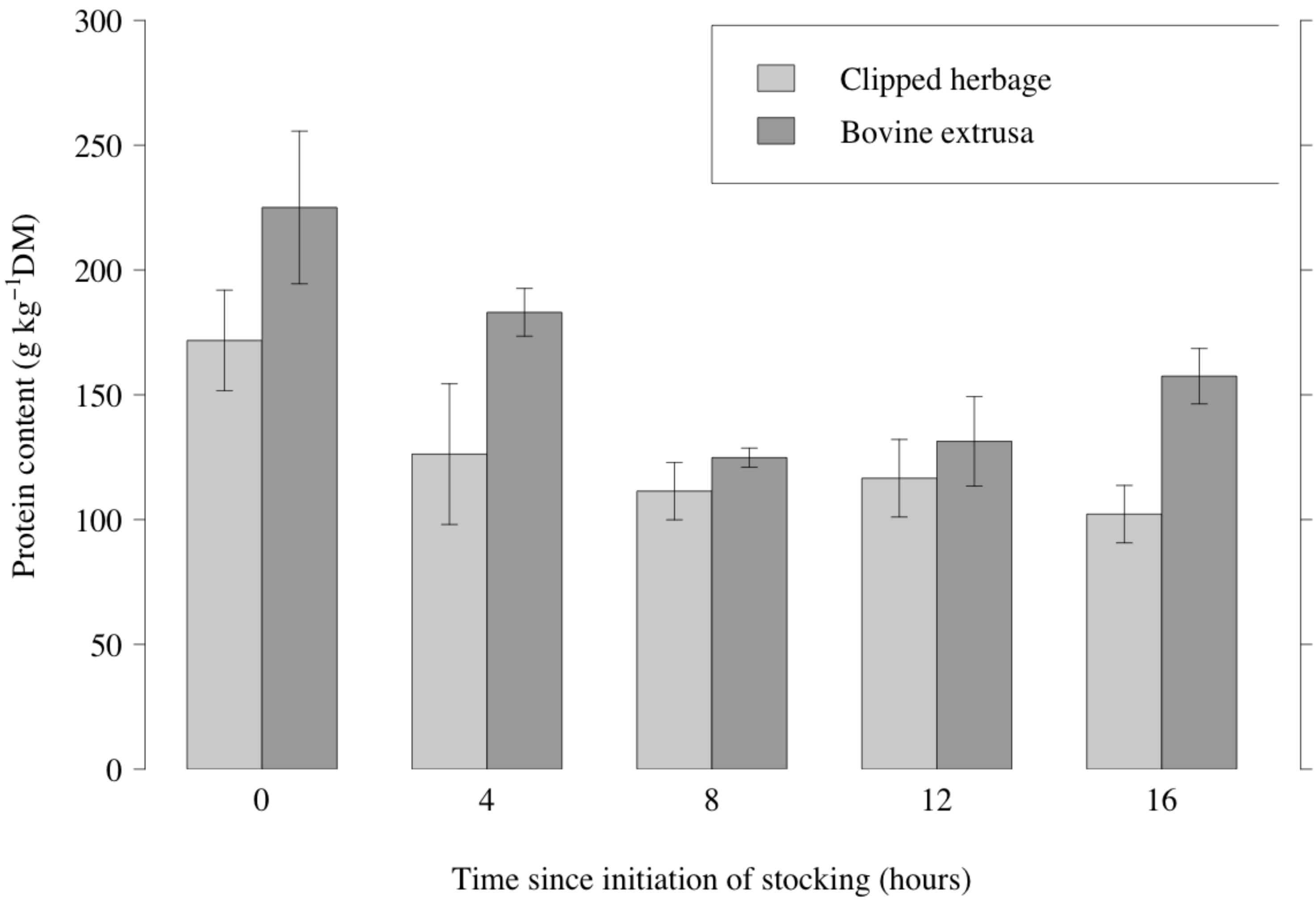

Figure 4.10: Crude protein (CP) content of clipped herbage and bovine esophageal extrusa harvested from mob stocked pasture strips at Blacksburg, VA during 28 Sept.—2 Oct. 2014, averaged among (n = 3) pasture strips and (n = 2) steers.

† Abbreviations are as follows: DM: dry matter.

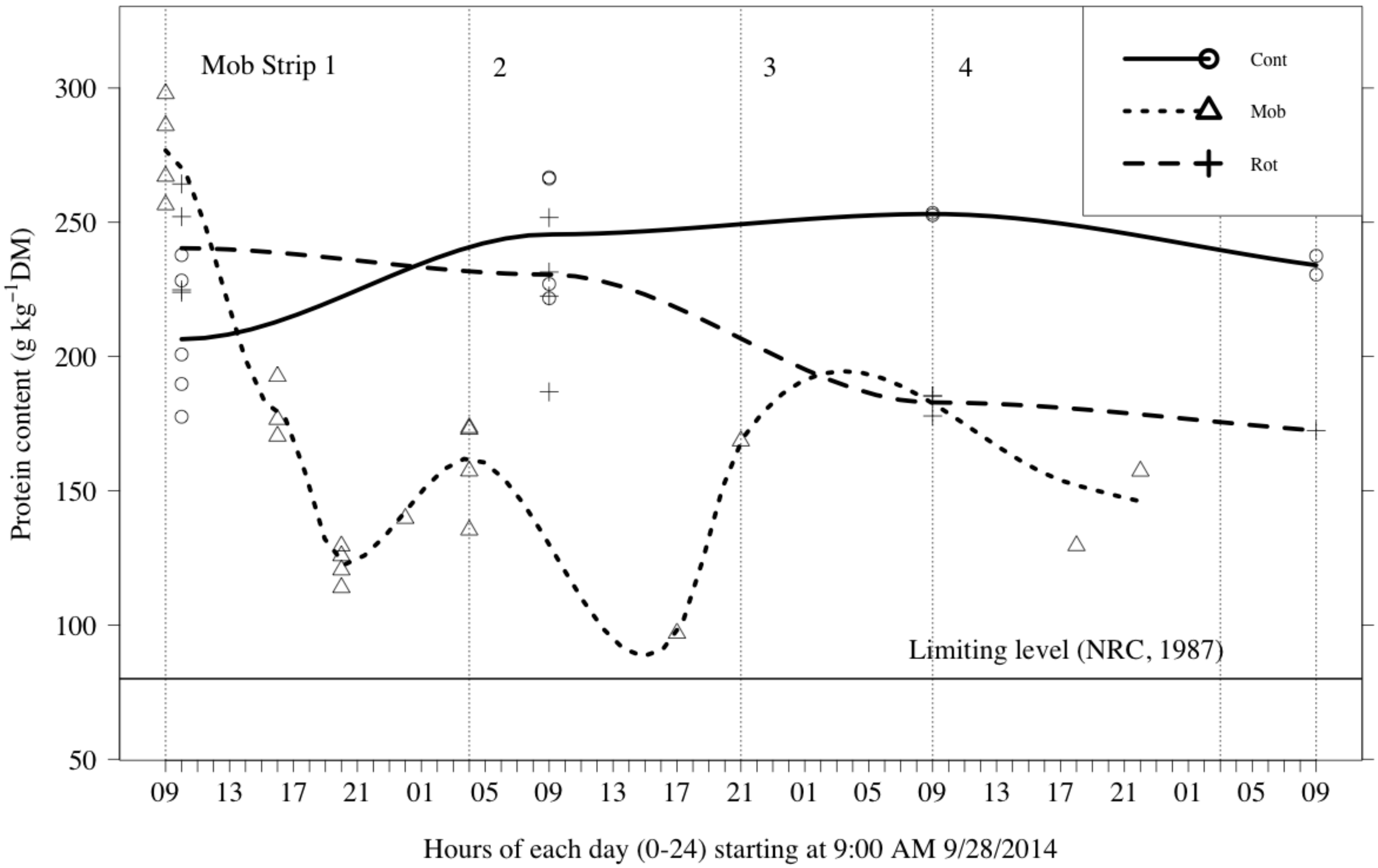

Figure 4.11: Crude protein (CP) content of herbage harvested from esophageal cannulas of beef steers grazing in continuous, mob, and rotational stocking pastures at Blacksburg, VA during 28 Sept.—2 Oct. 2014, fit with unique loess smoothers for each stocking method.

† Abbreviations are as follows: DM: dry matter.
‡ Source: National Research Council. 1987. Predicting feed intake of food-producing animals. National Academies Press, Washington, D.C.

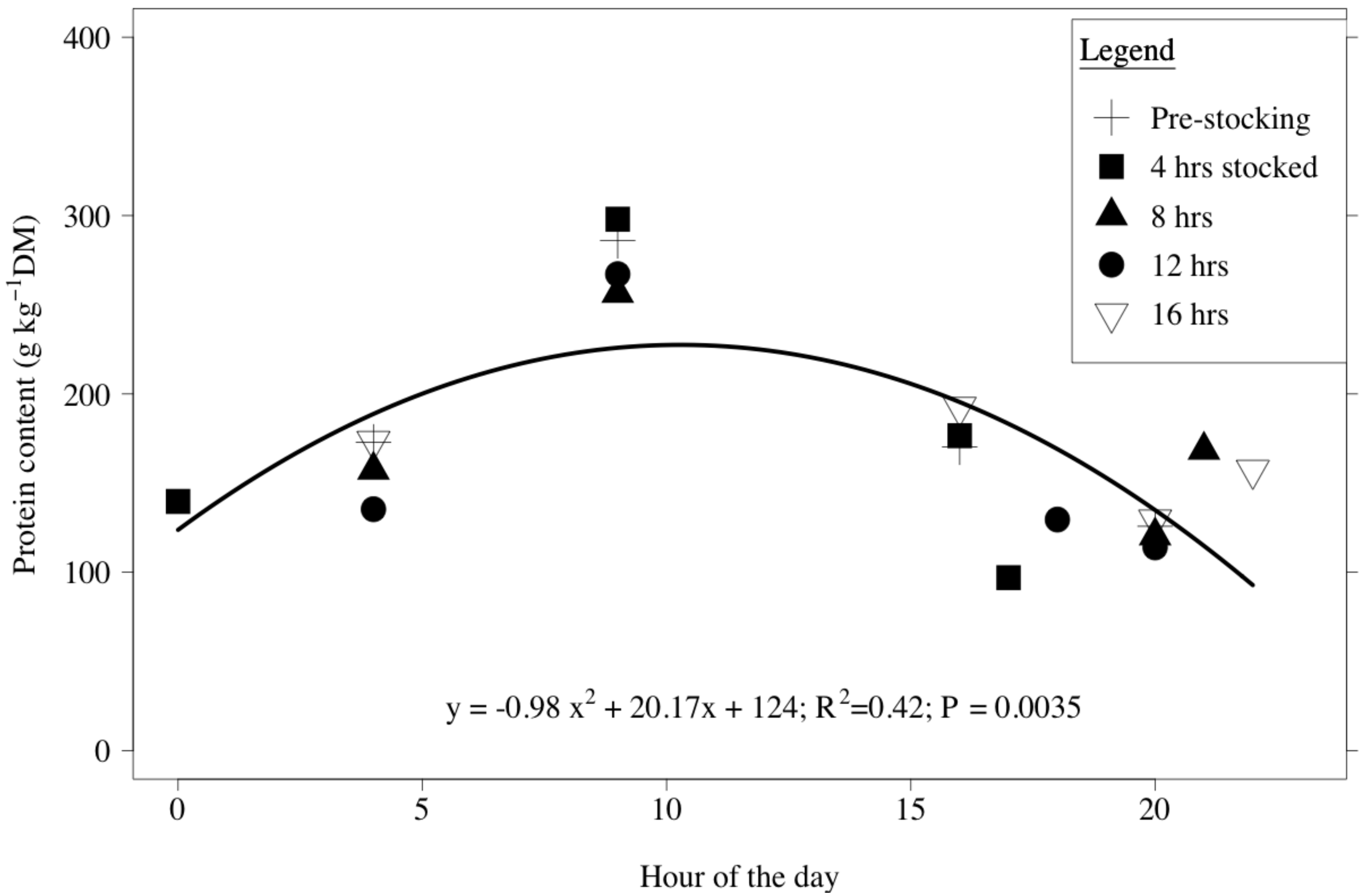

Figure 4.12: Diurnal variation in crude protein (CP) content of herbage harvested from esophageal cannulas of beef steers grazing in mob stocked pastures at Blacksburg, VA during 28 Sept.—2 Oct. 2014. Symbols represent the relative time at which the samples were harvested relative to the mob stocking period in a paddock.

† Abbreviations are as follows: DM: dry matter.