A comparison of runoff quantity and quality among three cattle stocking treatments

Emily Diane Williams

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science

In

Biological Systems Engineering

W. Cully Hession, Chair

Brian L. Benham

Durelle T. Scott

Benjamin F. Tracy

February 10, 2014

Blacksburg, Virginia

Keywords: runoff, water quality, rainfall simulation, pasture, cattle stocking method

A comparison of runoff quantity and quality among three cattle stocking treatments

Emily Diane Williams

ABSTRACT

Measurements of runoff quantity and quality from three cattle stocking treatments applied to pastureland in southwestern Virginia indicate the need for further research to determine treatment effects. Three cattle stocking treatments (1) Continuous, 2) Rotational, and 3) Mob) were applied to three pastures at the Virginia Tech Prices Fork Research Farm. Rainfall simulations were performed over replicated plots in each treatment to induce runoff for collection of runoff quantity and quality data during the 2012 grazing season. Additionally, rainfall simulations were performed prior to applying the grazing treatments to establish initial conditions. Monitored runoff quantity and quality response variables included runoff depth, mean nutrient concentrations, and nutrient mass loss. Response variables were compared among the three pastures for initial conditions and among treatments for post-treatment conditions. Additionally, the trends in response variables within the 2012 season were compared among treatments. Plot and rainfall conditions that were expected to influence responses were also collected and analyzed in relation to response variables. Analyses of the response variables suggested that the variability within treatments likely muted any treatment effect on the response variables. Therefore, we concluded that further research is needed to determine treatment effects on runoff quantity and quality.

Acknowledgements

This project was funded through grants from the United States Department of Agriculture programs. I would like to thank the Virginia Tech Department of Biological Science for the opportunity to attend graduate school and participate in this research.

My committee members: Cully Hession, Durelle Scott, Brian Benham, and Ben Tracy guided the experimental design, field work, data analyses, and thesis writing. Thank you for your support and advice.

Many Virginia Tech staff members, graduate students, and undergraduate students contributed to this work, especially Laura Lehman, Joao Flores, Kinsey Hoffman, Katie Brill, and Nate Jones. This project required collaboration with the VT Beef Center for transporting cattle to and from the study site and staff at the USDA-ARS Pasture Systems and Watershed Management Unit for performing nutrient analysis on the runoff samples collected during this study. Thank you for your professionalism, sincere interest, and efforts.

This work was also supported by my personal friends and family. For his patience, encouragement, and love, I would like to thank my husband, Jason. And to my son, Isaac, you give me hope and inspiration.

All photos by author.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

NPS	non-point source
US-EPA	Environmental Protection Agency
USDA-ARS	United States Department of Agriculture – Agricultural Research Service
USDA	United States Department of Agriculture
USDA-NRCS	United States Department of Agriculture – Natural Resources Conservation Service
CEAP	Conservation Effects Assessment Program
SERA	Southern Extension-Research Activity
SWAT	Soil and Water Assessment Tool
PFRF	Virginia Tech Prices Fork Research Farm
P	phosphorus
TP	total P
DP	dissolved P
PP	particulate p
N	nitrogen
TN	total N
TKN	total Kjeldahl N
NO_3^-	nitrate
NH_4^+	ammonium
NO_2^-	nitrite
NH_3	ammonia
DOC	dissolved organic carbon
ICP-OES	inductively coupled plasma optical emission spectroscopy
GPS	global positioning system
SMC	soil moisture content
SPR	soil penetration resistance
WQ	water quality
UC	coefficient of uniformity
HF	cattle handling facility
DM	dry matter yield
r	correlation coefficient
in	inch
mm	millimeter
cm	centimeter
m	meter
s	second
min	minute
hr	hour
yr	year
hh:mm	time format two digit hour, two digit minute
mm:ss	time format, two digit minute, two digit second

kPa	kilopascal
PSI	pounds per square inch
ha	hectare
µg	microgram
mg	milligram
kg	kilogram
ml	milliliter
L	liter
gal	gallons
ppm	parts per million
AUD	animal unit days
N	north
NE	northeast
E	east
SE	southeast
S	south
SW	southwest
W	west
NW	northwest

Chapter 1. Introduction

1.1 Background and motivation

According to the latest water-quality report, agriculture is the leading source of impairment of rivers and streams, and a major contributor of non-point source (NPS) pollution to other waterbodies in the United States (EPA, 2009). In the eastern US, the Chesapeake Bay is a clear example of the impacts of agriculture on surface-water quality. The Bay is impaired due to high levels of nutrients and sediment, and agriculture has been identified as the largest source these pollutants (EPA, 2010).

Agricultural lands include crop and pasture lands. Much research has been performed to evaluate the impacts of cropland on water-quality (Schnepf and Cox, 2006). Recently, the environmental benefits and water-quality impacts of pastureland have gained considerable interest and are projected to become increasingly important (USDA-ARS, 2012). As compared to cropland, pastureland generally has less soil loss. Pastureland is also more efficient at nutrient recycling than cropland because most of the nutrients removed with forage are returned as animal excreta, rather than taken off-farm as is the case with harvested crops (McDowell, 2008).

As of 2010, six percent (49 million hectares) of US lands were in pasture (USDA, 2013). The majority of US pastureland is located in the eastern US where the climate is conducive to forage growth (fig. 1.1). Globally and within the US, pastureland is an important source of income and food production. In addition to its economic importance, pastureland provides ecosystem services such as water infiltration and carbon sequestration (Nelson, 2012). Poorly managed pastureland contributes to NPS pollution of ground and surface water. There is potential to increase ecosystem services of pastureland if managed well or increase NPS pollution from pastureland, if managed poorly.

Hubbard et al. (2004) provided an overview of environmental and water-quality issues related to grazing animals. Environmental benefits of forage production and livestock grazing include deep root penetration, improved soil characteristics, and carbon sequestration. Environmental problems related to grazing animals include soil and nutrient loss from pastures, as well as pathogen transport. Additionally, an increase in the amount of runoff due to decreased infiltration rates of pastureland is a concern. Dissolved phosphorus in surface runoff is the main environmental concern emanating from pastureland; though nitrate leaching and soil erosion may be site-specific problems (Hubbard et al., 2004). Phosphorus (P) losses from pastureland are a concern for the environmental health of surface waters. Excessive P in surface waters can lead to eutrophication and subsequent water-quality impacts. Excessive nitrate (NO_3^-) losses can create environmental and human-health problems. Excessive NO_3^- in surface waters can contribute to eutrophication and in drinking water can lead to methemoglobinemia (EPA, 2010). Sediment loss from pastureland can contribute to impairment of surface waters by increasing transport of attached pollutants, turbidity, and deposition. Excessive suspended sediment blocks light from reaching the channel bed and decreases the ability of the bed to support aquatic vegetation (EPA, 2010). Deposition impairs aquatic ecosystems by smothering benthic organisms and sediment is a vector for other pollutants such as phosphorus and bacteria (EPA, 2010).

Stocking method (i.e. continuous, rotational, etc.) is an important factor in pasture management. The traditional stocking method for pastures is continuous stocking - where livestock are unmanaged for an allotted grazing season. The goals of continuous stocking are largely animal-production based. Prescribed grazing is a conservation practice that involves managing livestock grazing to achieve conservation goals (USDA-NRCS, 2010). Stocking methods that require managers to move livestock among grazing units and allow periods of rest fall under the umbrella of prescribed grazing. Rotational stocking has been shown to be an effective prescribed grazing system (Nelson, 2012). Mob stocking is method of stocking livestock at high density for a short time with the objective to remove or trample forage rapidly. Though little scientific research has been completed to study the impacts of mob stocking, the system has been promoted as a conservation practice that enhances soil fertility and leads to increased forage and animal production (Gordon 2010; Kidwell, 2010; Tietz, 2011; Thomas, 2012).

This project supports the goals and strategic vision of the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) National Program 215: Pasture, Forage, and Rangeland Systems (USDA-ARS, 2012).

1.2 Research objectives and hypotheses

The goal of this study was to investigate the impacts on surface-water quantity and quality from pastures stocked by three different methods by using a portable rainfall simulator to induce runoff. The stocking methods were applied to pastures in southwestern Virginia as cattle stocking treatments that spanned the grazing season. The cattle stocking treatments were Continuous, Rotational, and Mob stocking treatments. The environmental impacts of the Mob treatment were of particular interest because the method had not been studied previously. Background levels were collected before stocking cattle followed by five sampling periods during the grazing season.

Objective 1: To compare runoff quantity from pastureland among stocking treatments within a grazing season.

Objective 2: To compare mean nutrient concentrations in runoff from pastureland among stocking treatments within a grazing season.

Objective 3: To compare nutrient losses (loads) in runoff from pastureland among stocking treatments within a grazing season.

Hypothesis 1: Runoff quantity was expected to increase throughout the season from the Continuous treatment due to cumulative effects of soil compaction and defoliation. Runoff quantity in the Rotational treatment was expected to remain constant within the grazing season because rest periods allow for some hydrologic recovery and re-vegetation. Runoff quantity for the Mob treatment was expected to be highest directly after stocking followed by a decreasing trend signifying hydrologic recovery and re-vegetation. The Mob and Rotational treatments were expected to yield lower runoff volumes than the Continuous treatment.

Hypothesis 2: Mean nutrient concentrations in runoff from the Continuous treatment were expected to increase within the grazing season. Mean nutrient concentrations in runoff from the Rotational treatment were expected to remain constant for the grazing season. Mean nutrient concentrations in runoff from the Mob treatment were expected to be high directly after stocking and decrease between stocking events.

Hypothesis 3: Nutrient losses from the Continuous treatment were expected to increase throughout the grazing season due to expected increasing concentrations and runoff volumes. From the Rotational treatment, nutrient losses were expected to remain constant throughout the season. Nutrient losses in runoff from the Mob treatment were expected to be highest directly after stocking and decrease between stocking events. Among treatments, it was expected that nutrient losses would be greatest from the Continuous treatment throughout the grazing season and the Rotational treatment would yield the least amount of nutrient losses throughout the grazing season.

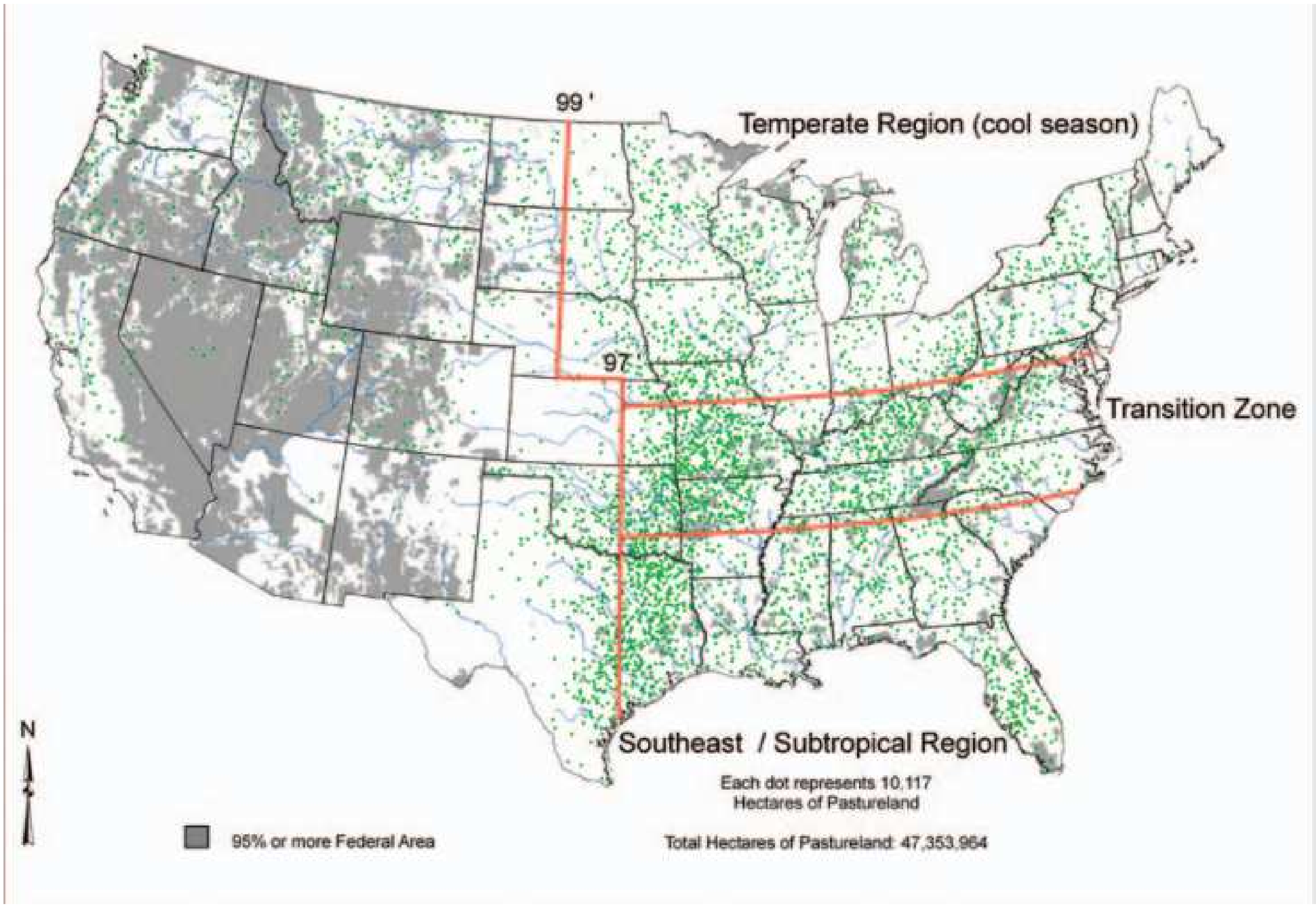


Figure 1.1. Map of pastureland in the U.S. (from Nelson, C. J., ed. 2012. *Conservation Outcomes from Pastureland and Hayland Practices: Assessment, Recommendations, and Knowledge Gaps.* Allen Press, Lawrence, KS. Used under fair use, 2014.)

Chapter 2. Literature Review

2.1 Pasture management

Pasturelands are complex systems of livestock, soils, and vegetation. Pastureland is defined as "land devoted to the production of indigenous or introduced forage for harvest by grazing, cutting, or both" (Allen et al., 2011). Seeding, fertilization, and forage removal are important aspects of pasture management. Managing forage removal from pastures via livestock grazing is a dynamic operation balancing forage availability and livestock requirements. Additionally, land managers may have conservation goals to balance with production goals. Conservation practices of pastureland management, such as Prescribed Grazing, have been established by the United States Department of Agriculture – Natural Resources Conservation Service (USDA-NRCS) to provide guidance for achieving conservation goals (USDA-NRCS, 2010).

Practices of livestock management range from low labor requirements to labor intensive operations. Kothmann (2009) provided an overview of the common stocking practices of continuous, rotational, and deferred stocking and their objectives. Allen et al. (2011) clearly defined terminology related to pasturelands as follows.

2.1.1 Continuous stocking

Continuous stocking is defined as unmanaged stocking, where livestock are allowed to graze uninhibited in an area under the condition that enough forage remains to sustain the heath of the animals. Continuous stocking is the method used most often on pasturelands in the US (Sanderson et al., 2011).

2.1.2 Rotational stocking

Rotational stocking is a practice that divides pastureland into three or more paddocks and livestock are allowed to graze in one paddock at a time for a determined amount of time based on forage availability and environmental conservation goals. In rotational stocking, livestock are moved among paddocks, which allows for the land to "rest" when livestock are not present.

2.1.3 Mob stocking

Mob stocking is a method of stocking livestock at high density for a short time with the objective to remove or trample forage rapidly. It is often termed ‘mob grazing’ or ultra-high stock density grazing in the popular press. Mob stocking was first promoted by Savory in the 1980s as part of a holistic approach to rangeland management (Savory, 1983). Managers use mob stocking to restrict a large number of animals to a small area where they either eat or trample nearly all of the plants before being moved to a new area after a few hours. Mob stocking is usually deferred to start later in the season (e.g., late May/June in Virginia) when the forage is mature. The mob stocking is then followed by a long recovery period –usually 60-90 days. Pastures under mob stocking are grazed just once or twice per season.

2.2 Environmental impacts of pasture management practices

The potential environmental impacts of pastureland management are illustrated in Figure 2.2. Environmental impacts of pasture management practices include effects on runoff quantity and nutrient losses.

2.2.1 Runoff quantity and infiltration rates

An increase in runoff can transport more soil and nutrients away from pastures and into surrounding waterbodies. P losses are closely related to runoff volume (Fleming and Cox, 2001). Also, an increase in runoff in the watershed can impact the morphology of streams (Pizzuto et al., 2000). It is generally accepted that total discharges and peak discharges are higher for grazed lands than for ungrazed lands (Gilley et al., 1996; Mwendera and Saleem, 1997; Chanasyk et al., 2003). Grazing intensity and stocking method may be important management factors that influence runoff quantity; these factors and their effects are discussed below in Sections 2.3.1 and 2.3.2.

Likewise, infiltration rates have long been an area of concern for grazing lands and many studies support the theory that livestock grazing significantly decreases infiltration rates (Gamougoun et al., 1984; Pluhar et al., 1987; Wilcox and Wood, 1988; Wood and Wood, 1988;

Mwendera and Saleem, 1997). Treading damage was shown to reduce the infiltration rates of plots receiving simulated rainfall in a New Zealand cattle treading experiment (Nguyen et al., 1998). While stocking rate has been shown to be a primary factor in determining infiltration rates (Thurow et al., 1988), stocking density may also have a significant effect (Warren et al., 1986). Though not significantly different, mob stocked pastures averaged a higher infiltration rate (93.98 mm hr^{-1}) than rotationally stocked pastures (81.03 mm hr^{-1}) in a three year study conducted in Iowa (Dietzel, 2012). Rotationally stocked pastures (which included both management-intensive grazing and mob grazing treatments) had highest of all infiltration rates at four of six locations compared to row crops or continuously stocked pastures (Dietzel, 2012). Some rangeland studies concluded that rotational systems have significantly lower infiltration rates than continuous grazing (Gamougoun et al., 1984; Pluhar et al., 1987).

2.2.2 Sediment

Erosion from poor forage stands or heavy animal traffic can lead to sedimentation in local waterbodies. Studies have shown a trend for increasing sediment loads with grazing pressure (Warren et al., 1986; Wood and Wood, 1988; Wilcox and Wood, 1988; Owens et al., 1989; Naeth and Chanasyk, 1996; Haan et al., 2006). Excessive suspended sediment blocks light from reaching the channel bed and decreases the ability of the bed to support aquatic vegetation (EPA, 2010). Deposition impairs aquatic ecosystems by smothering benthic organisms and sediment is a vector for other pollutants such as phosphorus and bacteria (EPA, 2010). Grazing studies have shown a linear relationship between concentrations of sediment in runoff with the fraction of bare ground (Elliott et al., 2002; Elliott and Carlson, 2004), and Elliott et al. (2002) suggested a minimum of two months for concentrations of sediment in runoff and infiltration rates to recover to background levels. As compared to continuous systems, rotationally time-controlled grazing systems increase the amount of ground cover (Earl and Jones, 1996; Sanjari et al. 2009) and reduce the amount of sediment lost in surface runoff (Sanjari et al., 2009). In contrast, Wood and Wood (1988) found that a short-duration grazing treatment produced the highest amount of sediment compared to continuous treatments stocked at a moderate and heavy density on rangeland. Sediment production was also less from pastures continuously stocked at a moderate rate than from pastures stocked at a heavy rate employing a rotational system (Pluhar et al., 1987). Gamougoun et al. (1984) also found that sediment production was higher from a rotational grazing system as compared to moderately or heavily stocked continuous systems on rangeland. Still other studies found no differences in sediment production among rotational and continuous grazing systems (Lambert et al., 1985; Naeth and Chanasyk, 1996; O'Reagain et al., 2005).

2.2.3 Nutrients

The nutrients of concern in loss pathways from pastureland are nitrogen (N) and phosphorus (P). Nitrogen and phosphorus are essential elements to living organisms. In pasture systems, N and P are used by the livestock, forage, and soil organisms in a cyclical fashion as shown in Figure 2 and 2.Figure 2. Livestock consume the forage and incorporate some of the N and P into their body tissues, but most of the nutrients are excreted in the feces and urine (McDowell, 2008). Excreta supplies nutrients and energy to the soil microbes that mineralized N and P, making them available for plant uptake (Bellows, 2001). External to this nutrient cycle are inputs and losses of N and P. External inputs of N include fertilizer application and nitrogen fixation; loss pathways of N are the volatilization of ammonia and via water movement (Bellows, 2001). External inputs of P are from fertilizer application; loss pathways of P are via soil loss and water movement (Bellows, 2001). When the amount of N and P in the soil exceeds the amount required for plant growth, the nutrients may be transported to surface waters during a runoff event (Bellows, 2001). Additionally, P losses in runoff from pastures can be an environmental concern even when soil P levels are below the agronomic requirements (McDowell et al., 2007). Balancing nutrient inputs and animal production while minimizing nutrient losses is a complicated task of conservation-minded land managers.

Nitrogen in soils is organic-N or inorganic-N. The majority of nitrogen found in pastureland soils is within the organic matter and pasturelands typically have high levels of organic matter (Bellows, 2001; McDowell, 2008). Inorganic nitrogen in the forms of nitrate, ammonium, and nitrite also exists in pastureland soils. The levels of organic-N and forms of inorganic-N are dictated by nitrogen inputs, biological conversions among forms, and nitrogen losses. Total N (TN) is the sum of dissolved N and sediment-bound N. Nitrogen is highly soluble; therefore, the majority of TN is in the dissolved form (McDowell, 2008). Dissolved N comprises of dissolved organic N, nitrate (NO_3^-), ammonium (NH_4^+), and nitrite (NO_2^-). Typical laboratory analysis of water quality includes determining Total Kjeldahl Nitrogen (TKN) which is the sum of organic N, ammonia (NH_3), and NH_4^+. TN is then determined by adding TKN, NO_3^-, and NO_2^-. Excessive NO_3^- losses can create environmental and human health problems. Excessive NO_3^- in surface waters can contribute to eutrophication and in drinking water can lead to methemoglobinemia (EPA, 2010). Nitrate accumulation in pastureland soils may occur under conditions where urine and dung inputs exceed sward growth requirements, such as in the late growing season or in times of drought (McDowell, 2008; Nelson, 2012). Concentrations of greater than 10 mg L^{-1} NO_3^- in groundwater have been documented as a result of grazing (Hubbard et al., 2004). The United States Environmental Protection Agency (EPA) has set 10 mg L^{-1} NO_3^- to be the highest concentration acceptable for safe drinking water.

Like nitrogen, phosphorus also exists in soil in organic and inorganic forms. Unlike nitrogen, the inorganic pool of P in agricultural lands is usually more than 50% of the total P (Whitehead, 2000). Inorganic P is usually bound to the finer fraction of soils, but also exists in soil solution as phosphate ions available for plant uptake or to losses in runoff. Dung and forage residue are the major P inputs to pastureland soils, but in some cases, inorganic P fertilizers may also be used. P losses from pastureland are P bound to soil eroded from the site and dissolved forms of P in surface runoff. Sources of P losses in runoff from pastures are 1) dung deposits (20-40%), 2) inorganic fertilizer (10-50%), 3) vegetation (20%), and 4) soil (remaining source) (Kleinman et al., 2011).

P losses from pastureland are a concern for the environmental health of surface waters. Excessive P in surface waters can lead to eutrophication and subsequent water quality impacts. P may be transported in surface runoff as dissolved P (DP) or particulate P (PP). Total phosphorus (TP) is the sum of DP and PP. On pasture sites, DP dominates the mobilized P in runoff (Sharpley et al., 1994; Jones et al., 2009). Mundy et al. (2003) concluded that P losses in runoff are due to defoliation rather than defecation. This result was also supported by Elliott and Carlson's (2004) findings that nutrient concentrations in surface runoff from rainfall simulations were highly correlated to the percentage of bare ground. P losses from dung and fertilizer on pastureland are typically highest directly after deposition and decrease with time, returning to background levels after several months (Kleinman et al., 2011). The initial values of P concentrations in runoff are typically a function of the rate of manure or fertilizer application (Kleinman et al., 2011).

2.3 Conservation practices for livestock management

The Conservation Effects Assessment Program (CEAP) began in 2003 as an effort to evaluate the effectiveness of specific USDA conservation programs, including grazing management, at the watershed scale (Osmond et al., 2012). In 2006, the USDA Agricultural Research Service (USDA-ARS) produced a comprehensive bibliography of scientific studies of environmental effects of conservation practices on grazed lands (USDA-ARS, 2006). In 2007 and revised in 2010, USDA-NRCS published a Conservation Practice Standard for Prescribed Grazing. Prescribed Grazing is "managing the harvest of vegetation with grazing and/or browsing animals" to achieve a number of conservation goals including "to improve or maintain surface and/or subsurface water quality and quantity" (USDA-NRCS, 2010). Much research has been completed to assess the effectiveness of Prescribed Grazing practices on grazing lands (Briske, 2011; Nelson, 2012). The CEAP-Pastureland initiative began in 2008 with results documented in a literature synthesis in 2012 (Sanderson et al., 2011; Nelson, 2012). Overwhelmingly, grazing intensity is the most important variable in achieving conservation goals, but stocking method, shade and water positioning, and timing of runoff event have also been shown to influence results (Haan et. al., 2006; Briske, 2011; Sanderson et al., 2011; Nelson, 2012).

2.3.1 Grazing intensity and its effects on runoff volume and nutrient losses

Grazing intensity has been reported as the most important management factor influencing soil, animal, and vegetation responses in pastureland (Sanderson et al., 2011; Nelson, 2012). Grazing intensity is often measured by stocking rate (animal unit per land area per time) or post-grazing stubble height. Some studies have shown a significant increase in the amount of runoff with stocking rate (Rhoades et al., 1964; Naeth and Chanasyk, 1996; Mwendera and Saleem, 1997), while others do not (Chanasyk et al., 2003; O'Reagain et al., 2005). Typically, systems with high stocking rates destroy soil properties related to hydrologic function, thereby decreasing infiltration and increasing runoff. Grazing intensity affects the nutrient-cycling process by manipulating excrement inputs and vegetation removal. Grazing livestock significantly influenced the concentrations of NO_3^- and DP in surface runoff as compared to ungrazed lands (Schepers and Francis, 1982; Schepers et al., 1982). Additionally, an increase in the stocking rate significantly increased runoff concentrations of NH_4^+, NO_3^-, TP, and total organic carbon (TOC) (Schepers et al., 1982). Similarly, Nguyen et al. (1998) concluded that runoff from plots with increasing treading damage increased levels of TKN and TP in runoff. P losses in runoff derived from dung deposits depends on stock type and stocking rate (Kleinman et al., 2011). Lambert et al. (1985) and Stout et al. (2000a) also concluded that stocking rate may significantly influence nutrient losses from pastureland.

2.3.2 Stocking method and its effects on runoff volume and nutrient losses

While it is generally accepted that grazing intensity influences nutrient losses from pastureland, the results from studies of the effect of stocking method on runoff quantity and nutrient losses have been inconclusive. The most common method practiced is continuous stocking, often with an interest in profitability and without regard to environmental impacts (Sanderson et al., 2011). Rotational systems can increase animal and forage productivity and decrease environmental impacts of grazing animals (Nelson, 2012). Though little scientific research has been completed to study the impacts of mob stocking, the system has been promoted as a conservation practice that enhances soil fertility and leads to increased forage and animal production (Gordon 2010; Kidwell, 2010; Tietz, 2011; Thomas, 2012).

Soil hydrologic functions can recover with adequate rest; therefore, rotational systems may maintain higher soil hydrologic function than continuous stocking (Briske, 2011). Studies comparing runoff originating from natural rainfall from pastures treated with rotational and continuous stocking found that there was no effect on the amount of runoff due to grazing method (Lambert et al., 1985; Kuykendall et al., 1999). Yet another watershed-natural rainfall study deduced that rotational grazing significantly reduces runoff as compared to continuous grazing (Sanjari et al., 2009). Runoff from simulated rainfall on plots treated with continuous grazing and twice-over rotational grazing was not significantly different (Gilley et al., 1996). Rotational systems also reduce the amount of bare soil and maintain vegetation cover compared to continuous stocking systems (Lodge et al., 2003; Haan et al., 2006).

Rotational stocking has been promoted as a conservation practice that may influence livestock excreta distribution and, subsequently, affect soil characteristics. More uniform deposition of excreta has occurred with an increase in the number of paddocks corresponding to a decrease in paddock size and increase in frequency of rotation (Peterson and Gerrish, 1996; Lory and Roberts, 2000). Some researchers believe livestock distribution (and hence effected soil characteristics) are more closely related to shade and water positions than stocking method in warm climates (Matthews et al., 1994). Concentrations of TKN and TP in runoff from continuously-grazed lands were significantly higher than from rotationally grazed lands (Olness et al., 1975). O'Reagain et al. (2005) did not detect a difference in TN and TP levels in runoff among five stocking methods. Grazing methods (continuous, weekly rotational, and frequent rotational) were not determined to be a major factor in determining NO_3^- levels of leaching or surface runoff (Owens et al., 2012). No effect of grazing method (rotational stocking vs. continuous) was shown on quality of runoff from natural rainfall events (Kuykendall et al., 1999). Simulated rainfall induced runoff from plots managed under continuous stocking had significantly higher P loads than from plots in pastures managed under ungrazed, hayed, or rotationally grazed treatments (Haan et al., 2006).

Since mob stocking is a fairly new practice, little research has been performed related to the effect on vegetation, livestock, or the environment. A conclusion from one of the few published studies on mob stocking was that nitrate leaching may be a concern from pastures managed under high animal densities on Pennsylvania dairies (Stout et al., 2000b).

2.3.3 Timing of runoff event

Several studies have concluded that the timing of the runoff event is also a significant factor affecting nutrient losses from pasturelands. In a study conducted at the Iowa State University Rhodes Research and Demonstration Farm, Haan et al. (2006) showed that the highest amount of sediment and P lost in runoff from grazed plots receiving simulated rainfall was during the wet season. The proportion of P present in the particulate form decreased during each runoff season and was highest in the wettest year in a study conducted in southern Australia (Cox, 2001). An increase in the time since grazing when runoff is produced decreased P concentrations in surface runoff from dairy pastures in Australia (Dougherty et al., 2008).

2.4 Methods of studying runoff and nutrient losses from pastureland

Historically, nutrient losses from grazing lands have been studied in runoff generated from rainfall simulation or naturally occurring rainfall events. Spatial scales of studies range widely from indoor box plots to field plots to watersheds. Runoff and nutrient losses from pastureland may also be simulated using computerized hill-slope and watershed models. Animal grazing is most often implemented, but may be simulated (Teany, 2004; McDowell et al., 2007; Gali et al. 2012).

2.4.1 Rainfall simulation

Rainfall simulations provide a way of inducing runoff in a more uniform and controlled manner than natural rainfall because rainfall intensity can be controlled using a rainfall simulator, whereas intensity may vary among natural events (Suszkiw, 2001). Rainfall simulations on pastureland typically occur at the plot or field scale, but indoor box plots have also been used (McDowell et al., 2007; Burkitt et al., 2010; Cournane et al., 2011). Installing runoff plots *in situ* allows for realistic grazing conditions and defines a standardized area for runoff collection. Unlike box plots, field plots maintain hydrologic properties of the surface (Srinivasan et al., 2007). Different types of rainfall simulators are available including portable (Sharpley and Kleinman, 2003) and stationary constructions (Dillaha et al., 1988). The National Phosphorus

Runoff Project (NPRP) rainfall simulation protocol was developed to provide guidance for field plot studies of P losses in runoff using a portable rainfall simulator (SERA-17, 2008; Suszkiw, 2001). Many studies have used modified versions of the protocol to study runoff water quality from different management scenarios or land conditions (Srinivasan et al., 2007).

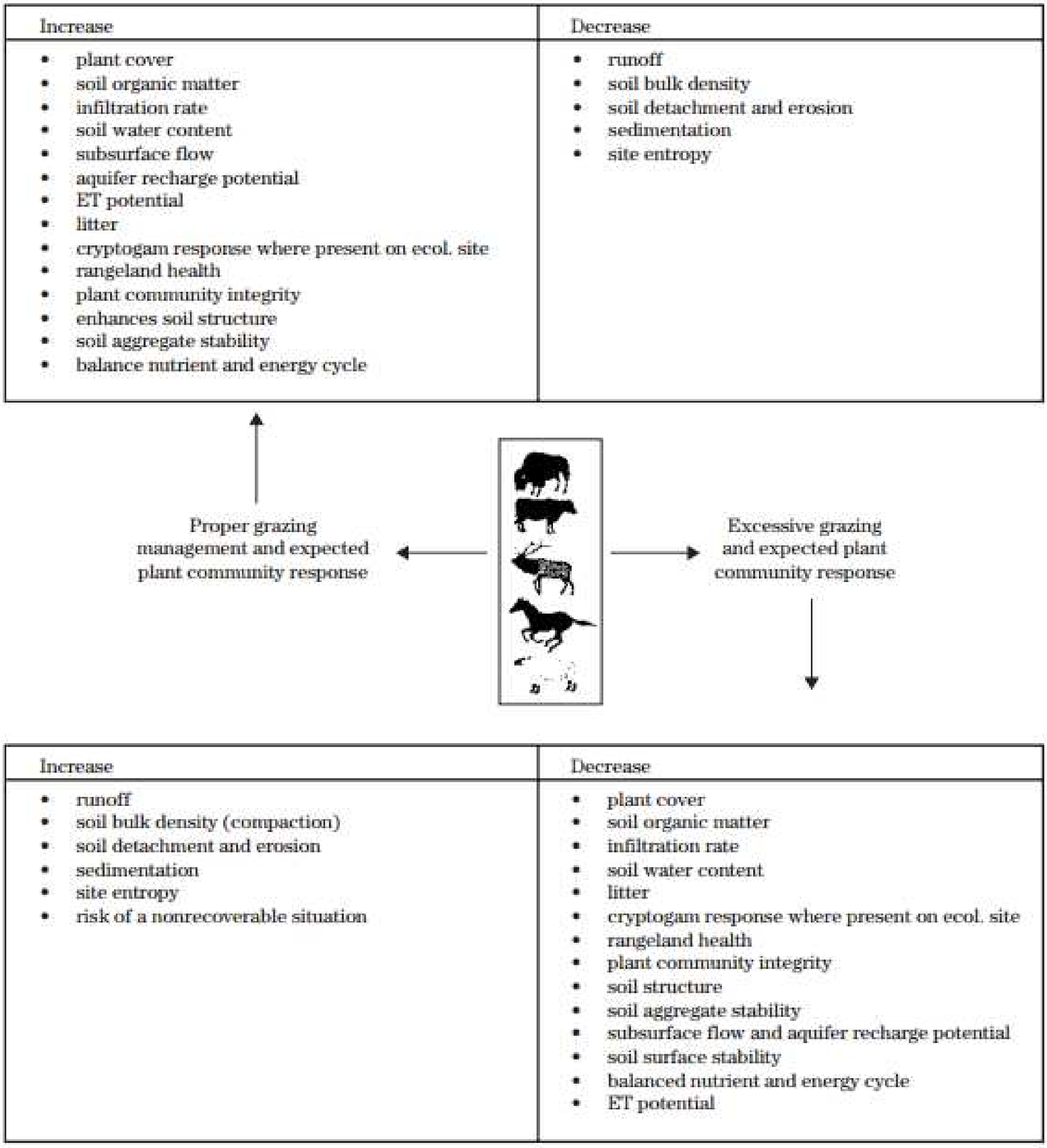
2.4.2 Natural rainfall

Plots have been established in pastures to quantify the effects of management on nutrient losses in runoff induced by natural rainfall (McDowell et al., 2003; Dougherty et al., 2008). Runoff from natural rainfall events may also be monitored at the watershed scale and many studies have been performed attempting to determine the effectiveness of management practices (Park et al., 1994; Edwards et al., 1996; Brannan et al., 2000). Watershed monitoring projects provide insight into cumulative effects of management practices, but often the effects of individual conditions and management practices cannot be deconvoluted (Srinivasan et al., 2007). Isolated watersheds have been instrumented to study nutrient losses from range and pasture under different management scenarios (Olness et al., 1975; Schepers and Francis, 1982; Kuykendall et al., 1999; Sanjari et al., 2009; Owens et al., 2012).

2.4.3 Computer models for grazing management effects on water quality

Hydrologic and erosion models have been developed for rangeland (Nearing et al., 2011; Weltz et al., 2011), but processed-based model development for pastureland is lacking (Nelson, 2012). The Soil and Water Assessment Tool (SWAT) has been used to model hydrology and nutrient losses from watersheds under different grazing management scenarios (Chaubey et al., 2010; Chiang et al., 2010; White et al., 2010). Grazing intensity significantly affected nutrient losses from the Lincoln Lake watershed (Chaubey et al., 2010; Chiang et al., 2010). Pasture management practices (including grazing management) increased vegetative cover and reduced sediment loads from simulations of the Wister Lake watershed (White et al., 2010). SWAT modeling of pastures is limited by the fact that a) soil compaction is not modeled, b) pastures are modeled as monoculture, whereas in reality, pastures are typically species diverse, and c) animal distribution is modeled as uniform, but in reality, animal distribution is highly variable.

Model development of land management options, including grazing management, is needed as well as standards for model application (Osmond et al., 2012).



Increase	Decrease
• plant cover • soil organic matter • infiltration rate • soil water content • subsurface flow • aquifer recharge potential • ET potential • litter • cryptogam response where present on ecol. site • rangeland health • plant community integrity • enhances soil structure • soil aggregate stability • balance nutrient and energy cycle	• runoff • soil bulk density • soil detachment and erosion • sedimentation • site entropy

Increase	Decrease
• runoff • soil bulk density (compaction) • soil detachment and erosion • sedimentation • site entropy • risk of a nonrecoverable situation	• plant cover • soil organic matter • infiltration rate • soil water content • litter • cryptogam response where present on ecol. site • rangeland health • plant community integrity • soil structure • soil aggregate stability • subsurface flow and aquifer recharge potential • soil surface stability • balanced nutrient and energy cycle • ET potential

Figure 2.1**.** Environmental impacts of management on pastureland (from USDA-NRCS and U. S. Grazing Lands Technology Institute, 2003).

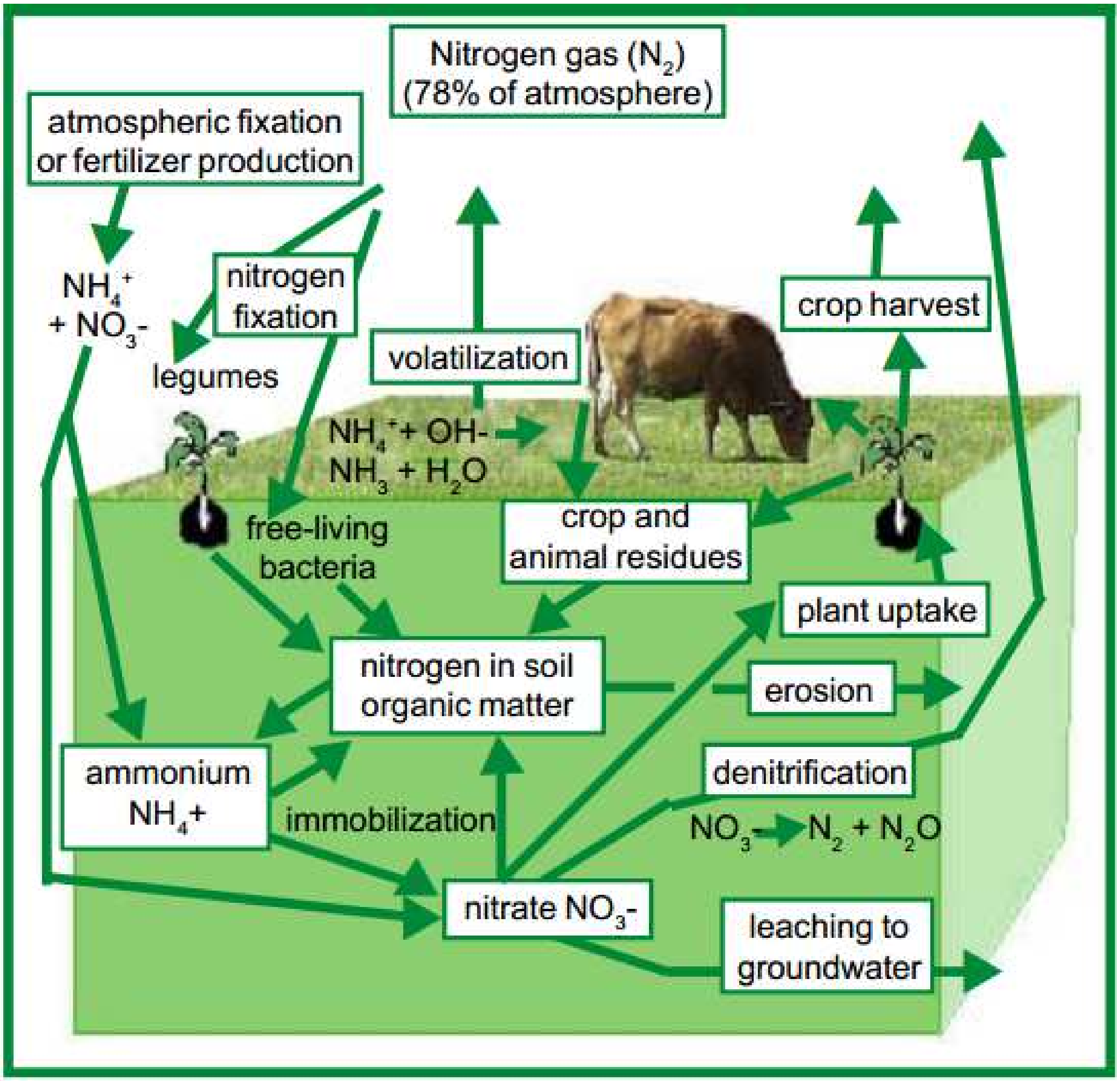


Figure 2.2**.** The N cycle in pasture systems (from Bellows, B. 2001. *Nutrient cycling in pastures. Livestock systems guide.* Available at https://attra.ncat.org/attra-pub/summaries/summary.php?pub=240. Accessed 02 May 2013. Used under fair use, 2014).

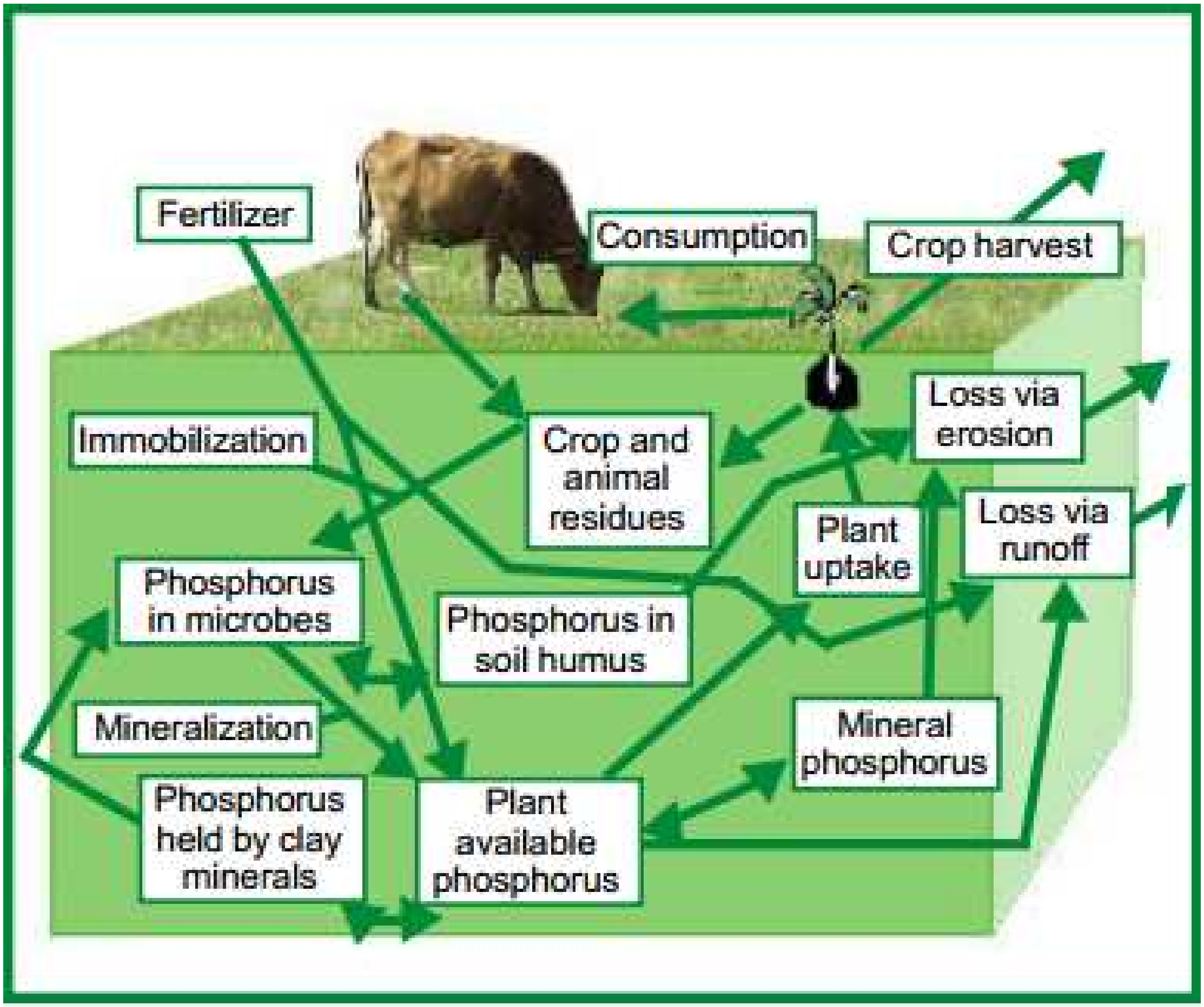


Figure 2.3**.** The P cycle in pasture systems (from Bellows, B. 2001. *Nutrient cycling in pastures. Livestock systems guide.* Available at https://attra.ncat.org/attra-pub/summaries/summary.php?pub=240. Accessed 02 May 2013. Used under fair use, 2014).

Chapter 3. Methods

Rainfall simulations were used to produce runoff from replicated plots in three pastures managed under three different cattle stocking treatments; 1) continuous stocking, 2) rotational stocking, and 3) mob stocking. Runoff was collected for each rainfall event and water quality analysis was performed to determine nutrient and sediment content in the plot runoff. The experiment began in May of 2012. Data were collected for the 2012 and 2013 grazing seasons. Data from 2012 are the focus of this thesis. Fertilizer application, cattle stocking periods, and the timing of simulated and natural rainfall events for the 2012 season are listed in Table 3.1 and presented as a timeline in Figure 3.1.

3.1 Study site

The study site is located at the Virginia Tech Prices Fork Research Farm (PFRF) west of Blacksburg, Virginia (fig. 3.2). Blacksburg has a temperate climate with average annual rainfall of 104 cm (40 in). The climate is conducive to a grazing season from approximately May 1 through November 1.The site has three small watersheds that are 1.4, 2.4, and 3.1 ha in size. These watersheds (fig 3.3) were used for USDA Soil Conservation Service (now NRCS) research between 1951 and 1967 (Burford et al., 1981). For the past 20 years, the watersheds have been hayed once or twice a year and fertilized rarely[1]. The site had also been used for other VT research (*i.e.* Mendez et al., 1999; Habersack, 2002; Soupir, 2003; Teany, 2004; Mishra et al., 2006). Generally, the site has Groseclose silt loam soils and uniform density cool season grasses, primarily tall fescue. Slopes range from 0% to 50% at the site and average 12%.

3.2 Experimental design

This experiment was designed to gather runoff induced by simulated rainfall events to produce runoff quantity and quality data from the three cattle stocking treatments within a grazing season. The pastureland at PFRF had not previously been grazed with livestock; therefore, it

---

[1] See Teany (2004) for composition and application rates of fertilization in 2002. Undocumented fertilization (with 10-10-10) also occurred in 2006 (Laura Lehman, VT-BSE, personal communication 31 January 2014).

was necessary to install fences and an animal watering system. To determine initial hydrological, soil, and vegetative conditions, measurements were recorded before applying stocking treatments. The stocking treatments were designed to achieve specific forage production goals. The rainfall simulations followed the National Research Project for Simulated Rainfall - Surface Runoff Studies protocol (SERA-17, 2008) using a Tlaloc 3000 Rainfall Simulator. Runoff plot borders and collection pans were available from a previous study (Teany, 2004). The locations of runoff plots and were established to achieve, as much as possible, consistent slopes for all plots. The number of runoff plots was limited to ten, based on the number of simulated rainfall events that could be performed over two consecutive days.

3.2.1 Pasture layout

Three pastures that corresponded to the natural watershed boundaries were defined using high-tensile wire fencing. All three watersheds were included within a permanent perimeter fence (fig. 3.4 and 3.5). Pasture 1 (3.1 ha) was used for continuous stocking. Pasture 2 (2.4 ha) was divided into four paddocks of equal area and used for rotational stocking. Pasture 3 (1.4 ha) was divided into three paddocks of equal area and used for mob stocking. Paddocks were defined using temporary posts and fencing. To meet animal needs, drinking water was available in each pasture and a mineral supplement was available in Pastures 1 and 2. A lined pond located on the property was used as the source water for drinking water troughs. The pond was refilled as needed from an on-site groundwater well.

3.2.2 Stocking treatments

Mixed breed mature beef cows each weighing approximately 635 kg were used in this research. A stocking rate of 333 animal unit days (AUD) ha^{-1} (one animal per acre per season) was held constant across the three cattle stocking treatments. Stocking density (animals per unit area) and length of stocking time (duration) were variable among the treatments. Stocking treatments were applied for the entire grazing season (June 1 through November 1) and stocking events were specific to each treatment. The particulars of each treatment are shown in Figure 3.5. Due to space constraints, the stocking treatments were not replicated.

The continuous stocking treatment (CONT) was applied to Pasture 1 (fig. 3.6). Continuous stocking is defined as livestock management where animals have unrestricted and uninterrupted access to the entire pasture throughout the time when grazing is allowed. Seven cows were stocked on Pasture 1 on June 1, 2012 and removed on November 1, 2012. Continuous stocking is a traditional method for managing livestock.

The rotational stocking treatment (ROT) was applied to Pasture 2 (fig. 3.7). Rotational stocking is defined as recurring periods of grazing and rest among three or more paddocks in a grazing management unit. Five cows were stocked on Pasture 2 on June 1, 2012 and removed on November 1, 2012. From June 1, 2012 to November 1, 2012, the cows were moved between the Pasture 2 paddocks every three to four days during the spring and every five to six days during the summer. The rest period for the paddocks was determined by forage availability. The goal of rotational stocking in this experiment was to allow cattle to graze the paddock to a stubble height of 7 to 10 cm and enter the next paddock with a sward height of 20 to 25 cm.

The mob stocking treatment (MOB) was applied to Pasture 3 (fig. 3.8). Two mob stocking events (Mob 1 and Mob 2) occurred during the season. Mob stocking is defined as high grazing pressure for a short period to remove forage rapidly. The goal of mob stocking for this experiment was to graze 50% of the forage, trample 40%, and leave 10% standing. In this experiment the stocking density of the mob stocking practice was 63,000 kg ha^{-1} (56,000 lb ac^{-1}), which is on the lower range of suggested mob stocking densities. The first mob stocking event (Mob 1) occurred early in the season when forty cows were stocked on Pasture 3 on June 23, 2012 and removed on June 25, 2012. From June 25, 2012 to October 28, 2012, Pasture 3 was not stocked and forage grew to maturity. The second mob stocking event (Mob 2) occurred when forty cows were stocked on Pasture 3 on October 28, 2012 and removed on November 1, 2012. During stocking events, the cows were moved between paddocks daily.

3.2.3 Baseline measurements

Prior to applying stocking treatments, soils and vegetation were sampled throughout the site using a 30 by 30 m grid (fig. 3.9). In May of 2012, the site was sampled for soil fertility, soil moisture content, soil penetration resistance, and vegetation dry matter and species composition. Site maps were created using Kriging in ArcGIS 10.0 (ESRI, 2010; fig. 3.10-3.13). Based on the results from the soil fertility tests and the Virginia recommendations for soil fertility, commercial fertilizer (0-100-80) was applied to the site on May 17, 2012 at a rate of 392 kg ha^{-1} (Maguire and Heckendorn, 2013). Baseline runoff characteristics for each pasture were established by performing simulated rainfall events over runoff plots prior to introducing livestock (Simulation 1, fig. 3.1.) An automatic rainfall and temperature gauge unit was installed on site to record local weather data (fig. 3.9).

3.2.4 Runoff plot locations and runoff event timing

Runoff plot sites were chosen in each pasture to achieve a slope of approximately 15% for each plot (fig. 3.14). LiDAR topographic mapping data from 2005 at 762 by 762 m (2500 by 2500 ft) resolution were used to create a digital elevation model of the site, from which suitable plot locations were identified. An aspect map was created and overlaid on the slope map in an effort to identify locations of similar slope and aspect. It was not possible to establish plot locations in each pasture that had both similar slope and aspect, therefore aspect was variable among plots. The maximum number of simulated rainfall events that could be performed over two-day consecutive period was ten. Therefore, ten plots sites were established: three in each Pasture 1 and Pasture 3 and four in Pasture 2 (fig. 3.14). Final plot locations were geo-located using a hand-held global positioning system (GPS) unit. Plot slopes were verified in the field using a clinometer. In order to observe seasonal changes in runoff quantity and quality, rainfall simulations were planned to occur monthly during the grazing season and once after the removal of livestock.

3.3 Rainfall simulations

A total of 54 rainfall simulation events were performed in a series of six simulations (6 simulations x 3 treatments x 3 plots). A rainfall simulation was performed at each plot pre-stocking, then approximately monthly after cattle had been introduced, and once after cattle were removed (fig. 3.1). Rainfall was simulated over Plot 6 in Pasture 2 only to collect baseline conditions (Simulation 1). Due to time constraints, rainfall was not simulated over Plot 9 for the final simulation (Simulation 6). A blank record sheet showing data collected during simulated rainfall events is shown in Figure 3.17. The on-site groundwater well was used as the source-water for rainfall simulations.

3.3.1 Runoff plot construction

Runoff plots were constructed as described in Teany (2004). Runoff plots (2 by 2 m in area) were designated by steel borders driven at least 10 cm into the ground (fig. 3.15). At the downslope edge of the plots, galvanized runoff collection pans were installed. Collection pans were triangular-shaped pieces of stainless steel sheet metal with outer edges molded to channel flow to an outlet. Each collection pan was fitted with a garden hose bibb at the outlet. Plot corners were geo-located using a Topcon (Livermore, CA) GR-3 GPS survey instrument (fig. 3.14) and runoff plot slopes were calculated (table 3.3).

Plot borders and runoff collection pans were installed prior to each simulated rainfall event. Plot borders and pans were removed between events so as to not interfere with cattle behavior. Runoff plots were pre-wetted the day before each event by uniformly applying water to the surface of each plot using a hose until runoff occurred. Pre-wetting was necessary because of the unusually dry conditions during 2012. Pre-wetting was also used in an attempt to normalize soil moisture among plots.

3.3.2 Initial conditions and preparation for simulated rainfall

Immediately prior to each event, the following plot condition data was collected: visual estimation of ground cover percentage, volumetric soil moisture content (SMC) using a Hydrosense Soil Water Measurement System (Cambell Scientific, Inc., Logan, UT), and soil penetration resistance (SPR) using a FieldScout SC-900 Soil Compaction Meter (Spectrum Technologies, Inc., Plainfield, IL). To avoid disturbing the plots, SMC was measured at two sites adjacent to and one site within each plot. Likewise, SPR was measured to a depth of 20 cm adjacent to each plot. The three measurement were averaged to obtain an average SMC and average SPR. Additionally, forage samples were collected for dry matter yield determination for Simulations 3, 4, 5, and 6 at locations adjacent to the plots.

Prior to initiating rainfall at each plot, five 150 mL non-recording rain gauges were placed inside the plot (one in each corner and one in the center of the plot) to collect applied rainfall. The runoff collection pan was cleaned of debris and capped to avoid collecting rain that fell directly onto the pan. The rainfall simulator was centered over then plot (fig. 3.15). Water from the on-site well was pumped into two 1,325 L tanks and transported to the runoff plots to be used as the simulated rainfall source water (fig. 3.16). An Echo Water Pump 100 was used to pump the water from the tank to the simulator.

3.3.3 Rainfall simulation and event data collection

Uniform rainfall intensity was ensured by maintaining 76 kPa (11 PSI) at the simulator nozzle. A test rainfall simulation was performed prior to the study and established that 76 kPa corresponded to an intensity of 9.1 cm hr^{-1} (3.6 in hr^{-1}), which is close to the intensity (8.9 cm hr^{-1}) of a 60 min - 1000 yr storm for the Blacksburg area. Other rainfall simulation studies use similar intensities (Suszkiw, 2001). To prevent wind effects, simulations were performed under calm conditions. Rainfall intensities and wind effects were also calculated as described in Section 3.6.1.

The time of day was recorded at the initiation of rainfall simulation, as well as the time of day when runoff initiated. The volume of water pumped to the simulator nozzle was recorded using an inline flow meter mounted on the rainfall simulator. Rainfall collected in the rain gauges was measured and recorded.

3.3.4 Runoff collection

After 2.5 min of continuous runoff, a 1 L sample was collected (water quality (WQ) sample). Likewise, WQ samples were collected at 12.5, 22.5, and 32.5 min after runoff was initiated. Runoff that was not collected for detailed chemical analysis was collected through a garden hose connected to the collection pan and into a series of 19.4 L buckets (flow samples). After the final WQ sample was collected, rainfall was halted. Runoff collection continued until the flow was no longer steady at which time the duration of runoff was recorded. Grab samples were collected from the rainfall source water for each day of rainfall simulation and processed for water quality analysis.

3.4 Sample processing

Samples were processed in the field on the same day of collection. A blank record sheet of data collected during sampling processing is shown in Figure 3.18. Flow samples and the empty buckets were weighed. WQ samples were weighed and prepared for water quality analysis by mixing the WQ sample and portioning four 250 mL samples, two unfiltered (raw) and two filtered at 0.45 µm pore diameter. A Geotech Geopump was used with 0.45 µm disposable filters to filter runoff samples. The weights of the empty WQ bottles were then measured. WQ samples were stored on ice and transported to the Virginia Tech Biological Systems Engineering Watershed Analysis Laboratory within 24 h where they were frozen. One raw and one filtered sample from each WQ sample and rainfall simulator source samples were frozen and shipped to the United States Department of Agriculture – Agricultural Research Service (USDA-ARS), Pasture Systems and Watershed Management Research Unit in University Park, PA for nutrient analysis. One raw and one filtered sample from each WQ sample and source samples were frozen for sediment and carbon analysis in the Water Analysis Laboratory at Virginia Tech.

3.5 Laboratory analysis

WQ samples sent to the USDA-ARS lab were analyzed for concentrations of total phosphorus (TP), dissolved P (DP), total nitrogen (TN), and dissolved N (DN). Nutrient analyses were performed using standard procedures. TN (the sum of organic N, ammonium, nitrate, and nitrite in unfiltered samples) was determined by alkaline persulfate digestion following the method of Patton and Kryskalla (2003). To determine TP concentrations, a portion of each of the raw samples was digested by aqua regia following EPA standard method 200.2 (EPA, 1994). The filtrate was then analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES) to measure TP concentrations. Concentrations of dissolved P were determined by ICP-OES analysis of filtered samples (Buda et al., 2010). Dissolved N (nitrate and ammonium) concentrations were determined by analyzing a portion of the filtered samples using a Lachat QuikChem FIA + 8000 Series autoanalyzer (Church et al., 2011). Results of nutrient analyses were analyzed as described in Section 3.7 and are summarized in Chapter 4.

Analysis for concentrations of dissolved organic carbon and total suspended solids was performed in the VT Water Analysis Lab. Filtered samples were thawed, portioned, and analyzed for dissolved organic carbon (DOC) using a Shimadzu TOC-V CPH. DOC concentrations are reported in Tables A.1 and A.2 in Appendix A. Raw samples were thawed and analyzed for total suspended solid concentration by following Method 2540 D., Total Suspended Solids Dried at 103-105°C (APHA, 1995). Because samples were frozen and then thawed prior to filtration, calcium carbonate precipitated upon thawing. Calcium carbonate precipitate levels could not be separated from sediment levels. Therefore, results from the TSS analysis were discarded.

3.6 Calculations

Event and post-stocking average data were calculated as described in the following sections. A summary of measured and calculated values is presented in Table 3.4.

3.6.1 Event runoff depth, runoff ratio, average runoff rate, rainfall intensity, and wind factor

Event runoff mass was calculated by summing the masses of the runoff samples and WQ samples and subtracting the sum of masses of the empty containers. Event runoff volume was calculated by dividing the event runoff mass by the density of water (1 kg L^{-1}). Event runoff depth was calculated by dividing runoff volume by the area of the plot. Runoff ratio was calculated by dividing the event runoff depth by the average rainfall depth. Average runoff rate was calculated by dividing the event runoff volume by runoff duration. Intensity of the storm event was calculated by dividing the average rainfall depth by the total rainfall time. Average rain volumes were calculated by averaging the depths from the five rain gauges and then multiplying by the area of the plot. A wind factor for each event was calculated by subtracting from unity the ratio of the applied rain volume to the volume of water pumped to the simulator nozzle.

3.6.2 P and N concentrations and loads

TP and TN concentrations were determined by analysis of digested raw samples. Equations 1 and 2 were applied to results, respectively, to obtain nutrient concentrations in the units of µg ml^{-1}.

TP concentrations were determined by aqua regia digestion and ICP-OES analysis. Equation 1 was applied to the results from the ICP-OES analysis to obtain concentrations in units of µg ml^{-1}.

$$\frac{\mu g\ P}{ml} = \left[\left(\frac{\mu g\ P}{ml\ of\ extract}\right) - \left(\frac{\mu g\ P}{ml\ of\ blank}\right)\right] * \left(\frac{25\ ml}{10\ ml\ sample}\right) \qquad (1)$$

TN concentrations were determined by alkaline persulfate digestion and flow injection analysis colorimetery. Equation 2 was applied to the results from the colorimeter to obtain concentrations in units of µg ml^{-1}.

$$\frac{\mu g\ N}{ml\ of\ sample} = \left(\frac{\mu g\ N}{ml\ of\ digest}\right) * \left(\frac{15\ ml\ of\ digest}{10\ ml\ of\ sample}\right) \qquad (2)$$

Event mean TP, DP, TN and DN concentrations were calculated by averaging the concentrations of the WQ samples for each event.

Event TP and TN loads were calculated by applying Equation 3 which assumes that concentrations of the WQ samples represent concentrations prior to each sample and that the runoff nutrient load after the forth WQ sample was negligible. An example calculation of event nutrient load by summation of incremental nutrient loads is shown in Table 3.5.

$$Event\ Load = \sum_{i=0}^{3} \Delta Time_i * Concentration_i * Runoff\ rate \qquad (3)$$

3.6.3 Treatment average-event nutrient loads and runoff depths

For each plot, cumulative nutrient loads were calculated by summing event nutrient loads for Simulations 2 through 6, likewise cumulative runoff depths were determined by summing event runoff depths for Simulations 2 through 6. In order to compare among stocking treatments, it was necessary to normalize the values on a per event basis because rainfall was not simulated over Plot 9 during Simulation 6. Means and standard deviations of the average-event nutrient loads and runoff depths were then calculated for each treatment.

3.6.4 Rainfall uniformity coefficient

A coefficient of uniformity (UC) was calculated for each simulated rainfall event using the method described in Teany (2004). The following equation was applied

$$UC = 1 - \frac{x}{y} \tag{4}$$

where *UC* is Uniformity Coefficient, *x* is the absolute deviation of rainfall depths from mean depth (mm), and *y* is the average rainfall depth (mm). Uniformity coefficients are listed in Table B.1 in Appendix B.

3.7 Data analyses

Due to the lack of replication of stocking treatments, statistical hypothesis testing for differences of response variables among treatments was not possible. Means, standard deviations, and coefficients of variation of response variables, plot conditions, and rainfall/runoff variables were summarized within each pasture/treatment, within each simulation, and for post-stocking conditions.

Initial conditions of the site were analyzed by, first, defining a “margin of variability” for each response variable in each pasture and, second, by comparing the values within the margins of variability among pastures. The margins of variability were defined as plus or minus one standard deviation around the mean of each response variable. Differences in response variables occurred among pastures if the margins of variability did not overlap. When the margins of variability overlapped, it was determined that there was no difference in response among pastures. Additionally, the coefficients of variation of the response variables from Simulation 1 were compared among pastures. An analysis of correlation was performed to determine if there were significant relationships between various plot condition variables and the response variables. Correlation analysis involved determining the degree to which to variables were linearly related, represented as the correlation coefficient (r), and applying a statistical test (t-test) to determine significance. Correlations were significant when p-values were less than 0.01. Data was plotted for significantly correlated variables and analyzed for clusters of data from each pasture.

Response variables were compared among treatments for three data sets 1) average-event responses for post-stocking conditions, 2) values at the end of the season, and 3) trends within the season. Average-event response variables for post-stocking conditions were calculated by averaging response variables per event for Simulations 2 through 6. Treatments were compared by using the margins of variability as described previously. Trends were analyzed by first calculating a margin variability for each trend line segment for each treatment and then comparing the values among treatments. Margins of variability for each trend line segment were defined by the maximum and minimum slopes between the margins of variability for each response variable between simulation numbers. If the margins of variability of for each segment of the trend line overlapped, no difference was detected among treatments. Correlation tests for data from post-stocking conditions were also performed and included a test for correlations with simulation date. The effect of source water nutrient concentrations as well as sampling times on nutrient concentrations in surface runoff was also addressed.

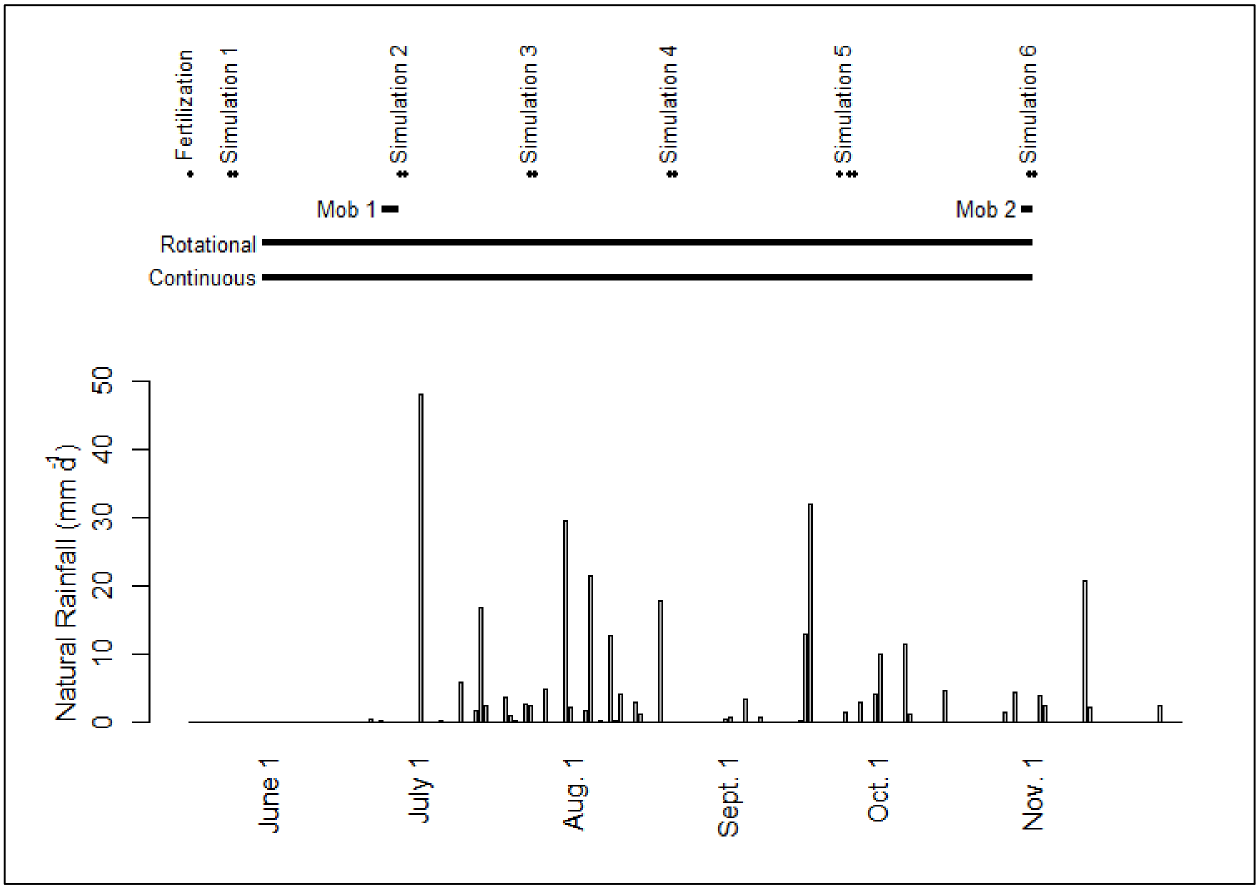


Figure 3.1. Timeline of events for the 2012 season showing daily natural rainfall depths, stocking events, and simulated rainfall dates.

Figure 3.2. Location of Virginia Tech Prices Fork Research Farm.

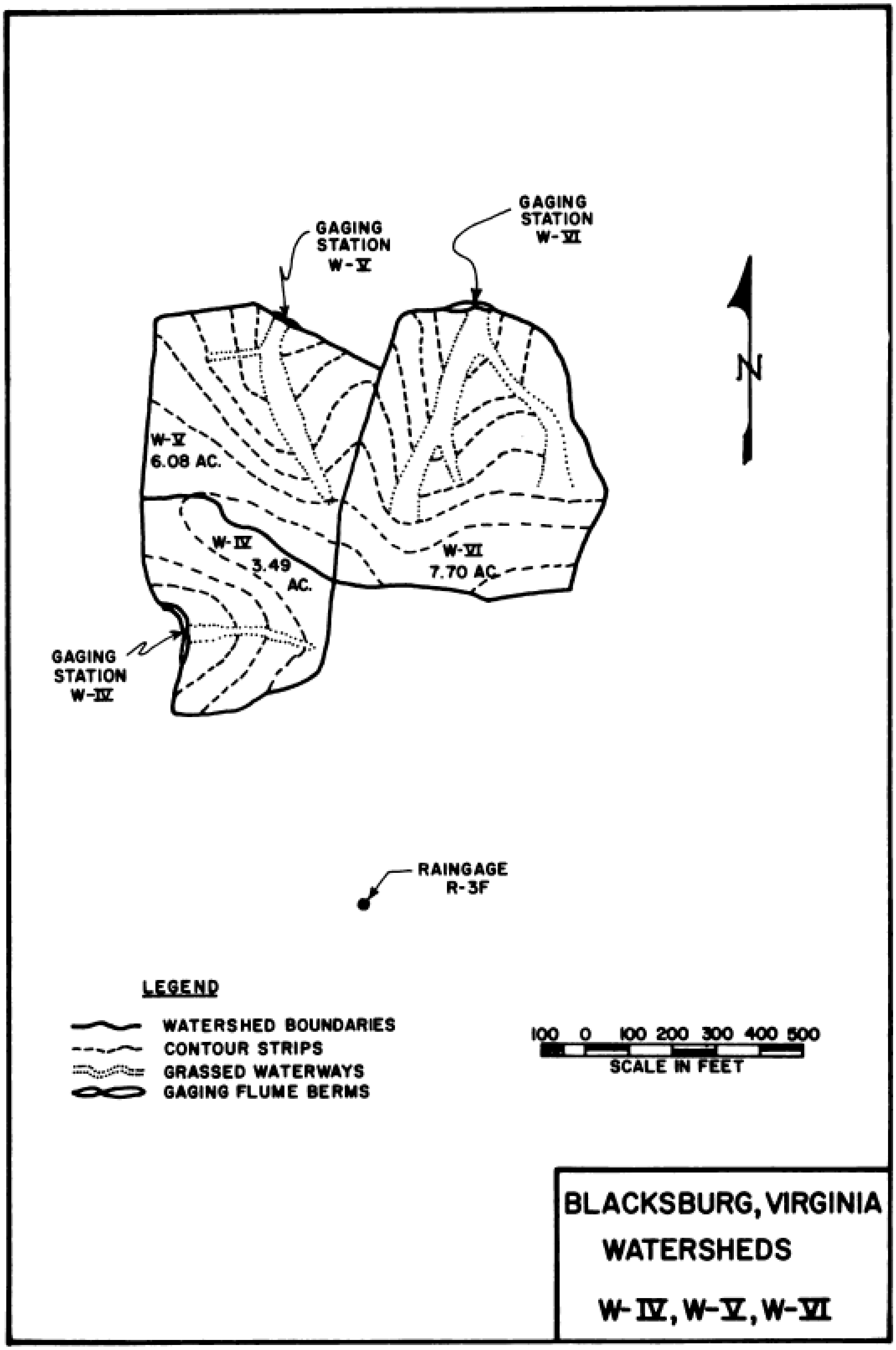


Figure 3.3. Soil Conservation Service watersheds from Hobbs and Crammatte (1965).

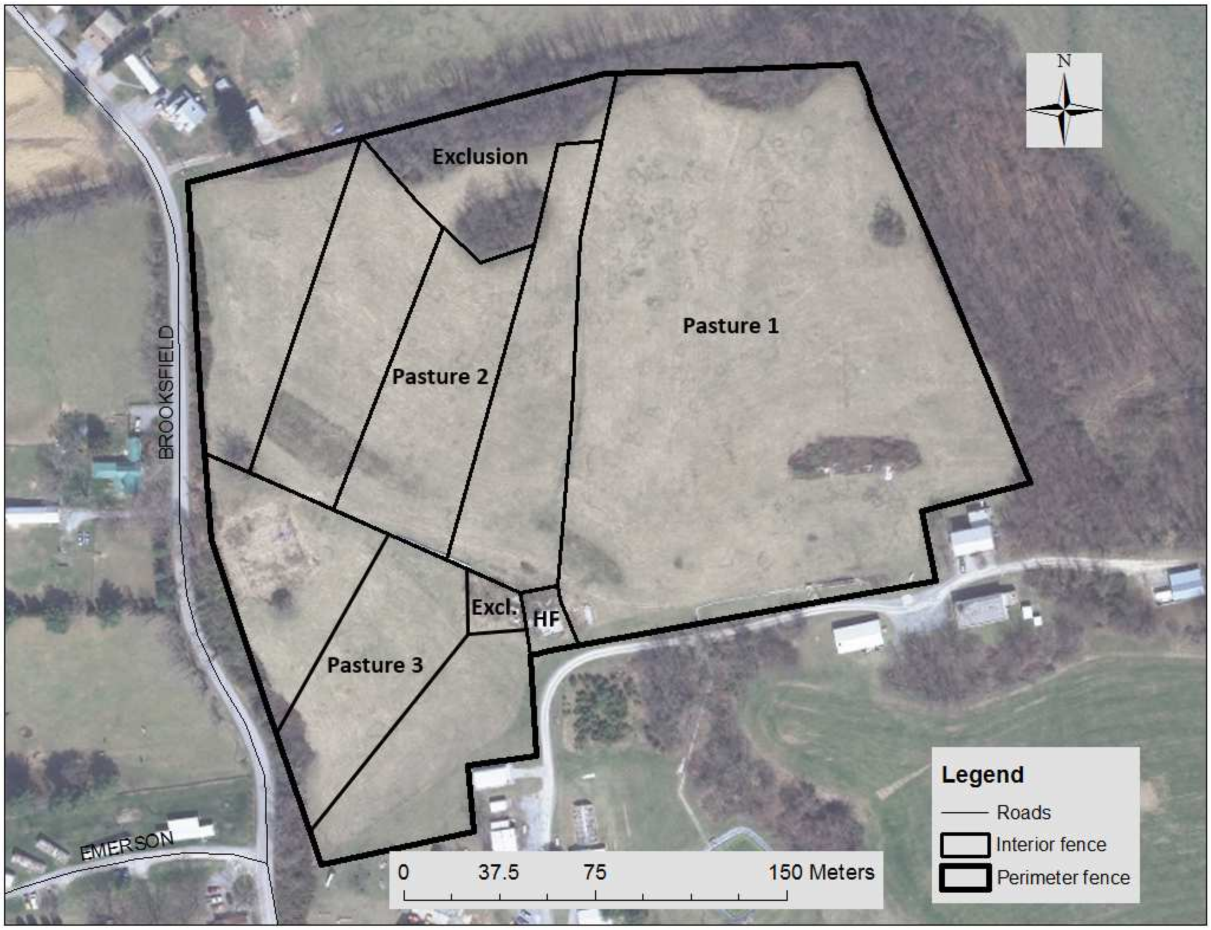


Figure 3.4. Aerial photograph and fence boundaries at Prices Fork Research Farm. Interior fences designated pastures, paddocks within Pastures 2 and 3, exclusion areas, and cattle handling facility (HF).

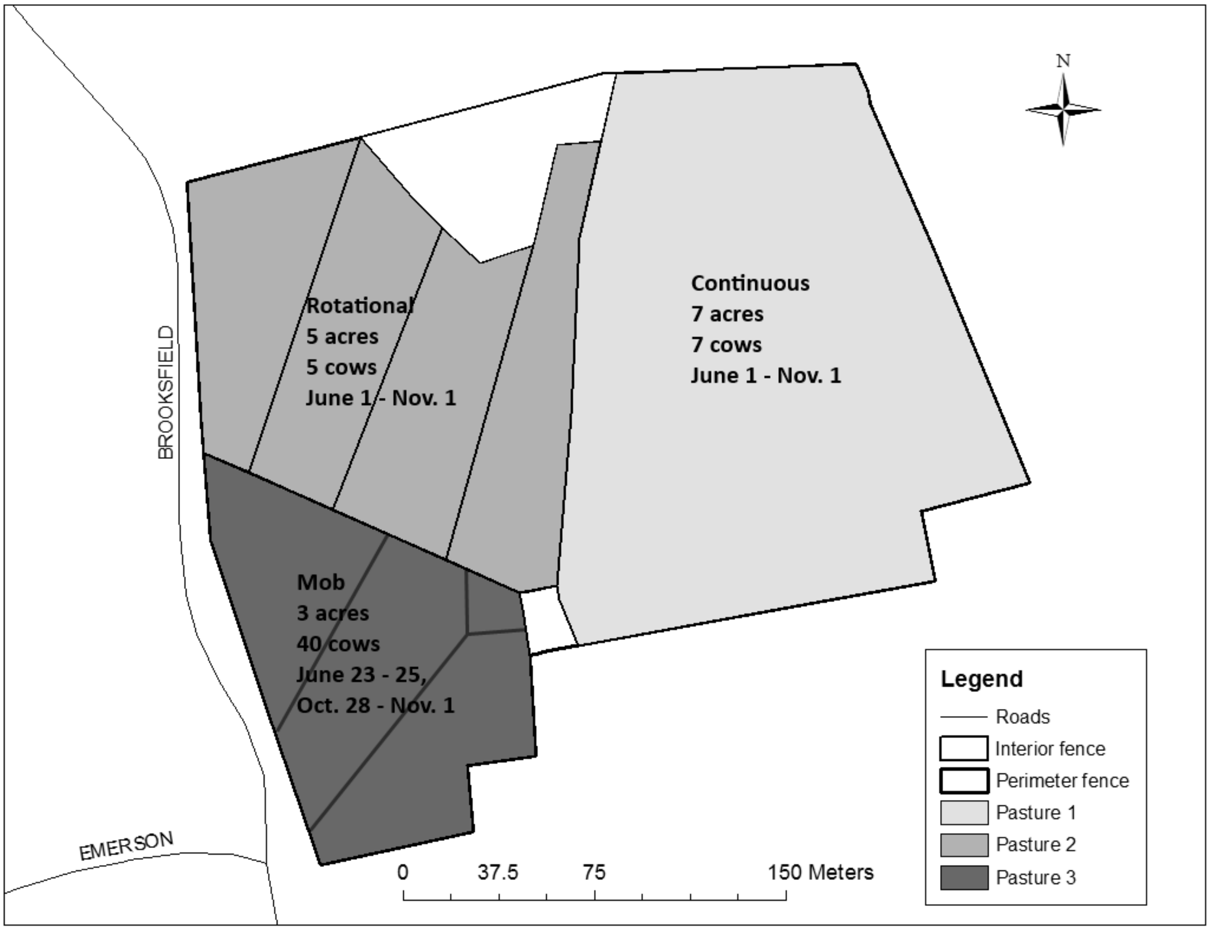


Figure 3.5. Stocking treatments as applied to pastureland at PFRF for the 2012 season.

Figure 3.6. Pasture 1, continuous stocking. Looking east (06/28/2012).

Figure 3.7. Pasture 2, rotational stocking. Looking north (06/28/2012).

Figure 3.8. Pasture 3, mob stocking. Looking west (06/28/2012).

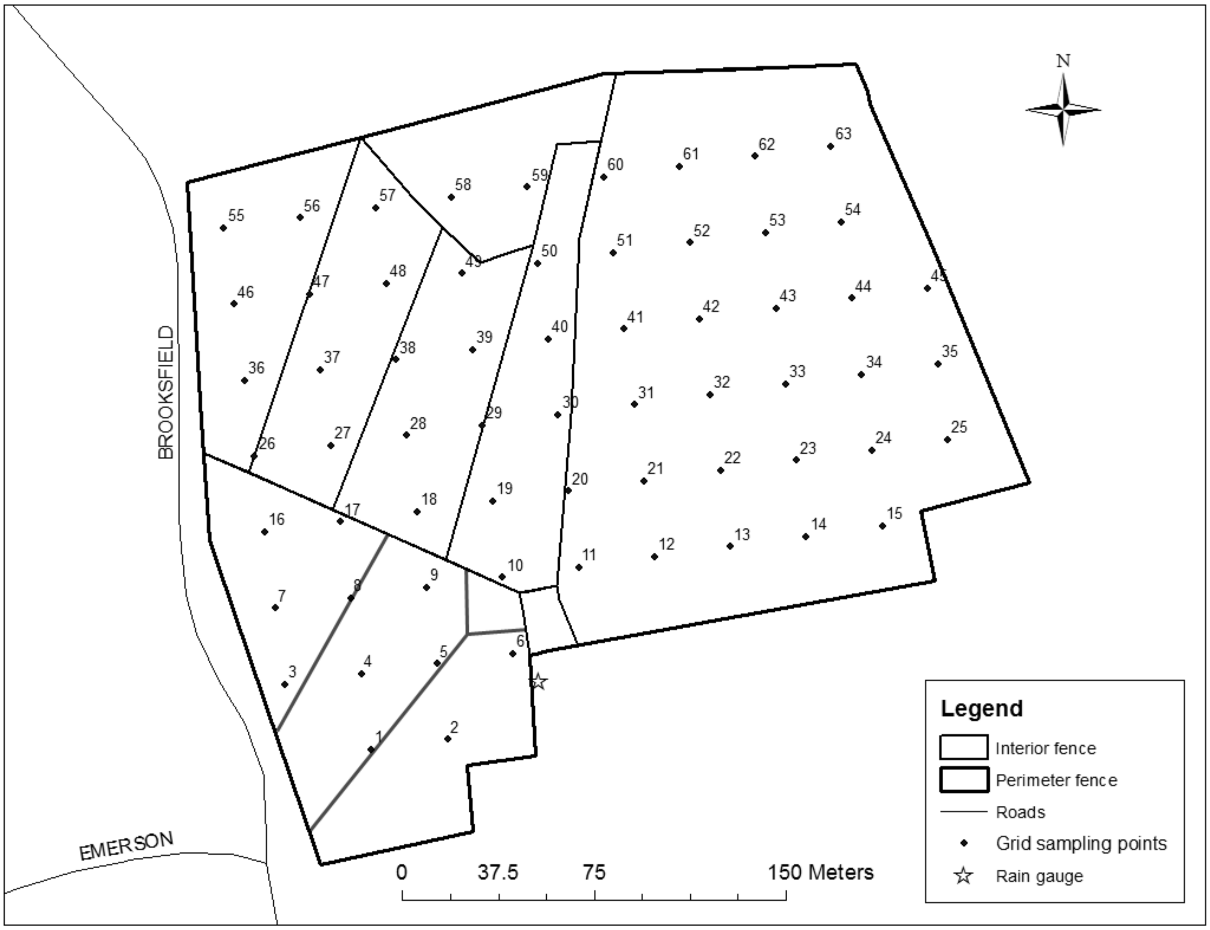


Figure 3.9. A 30 x 30 m grid for spatial vegetation and soil sampling. Points (1 through 63) indicate sampling locations. Star shows location of rain and temperature gauge.

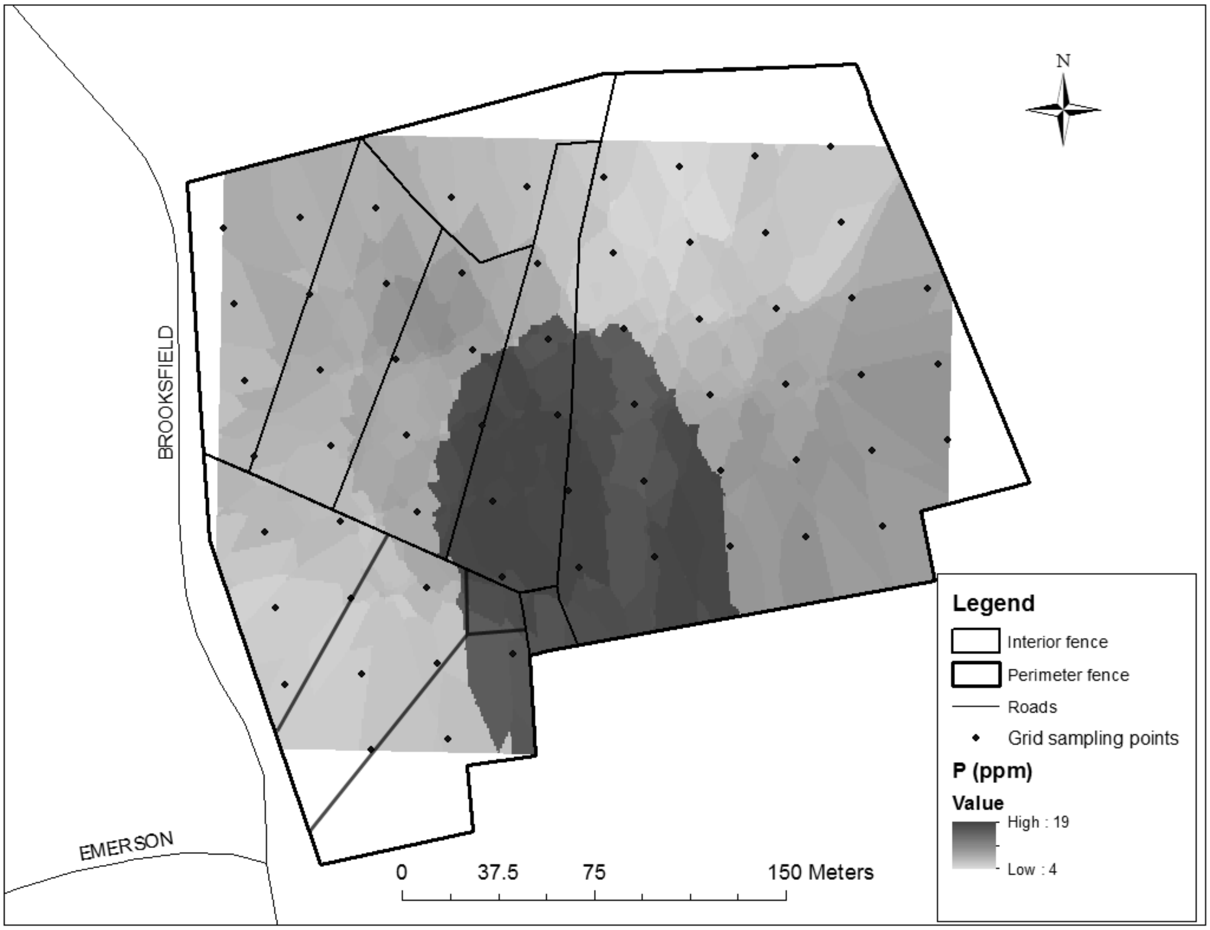


Figure 3.10. Interpolated values of soil P (ppm) from May 2012 samples.

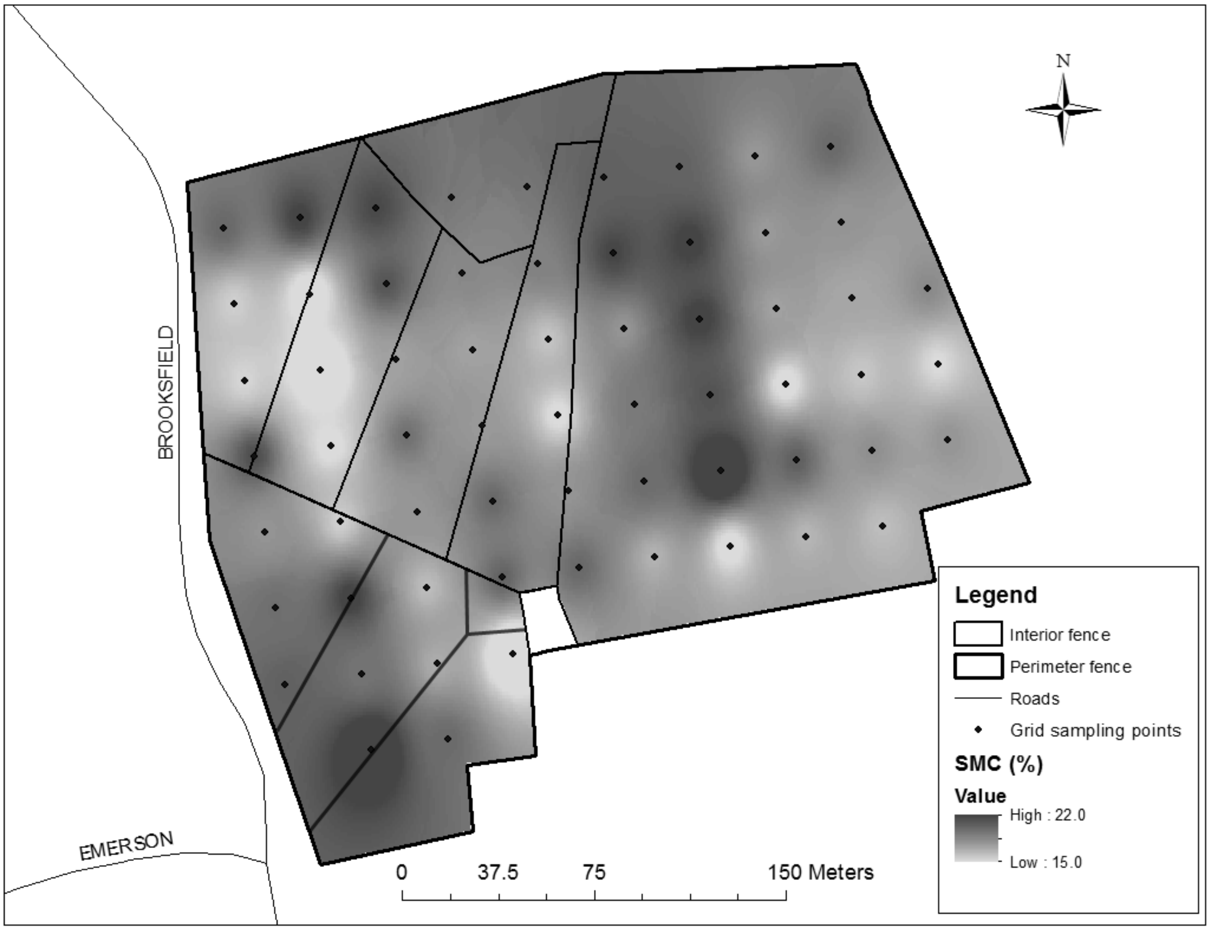


Figure 3.11. Interpolated values of soil moisture content (%) from May 2012 samples.

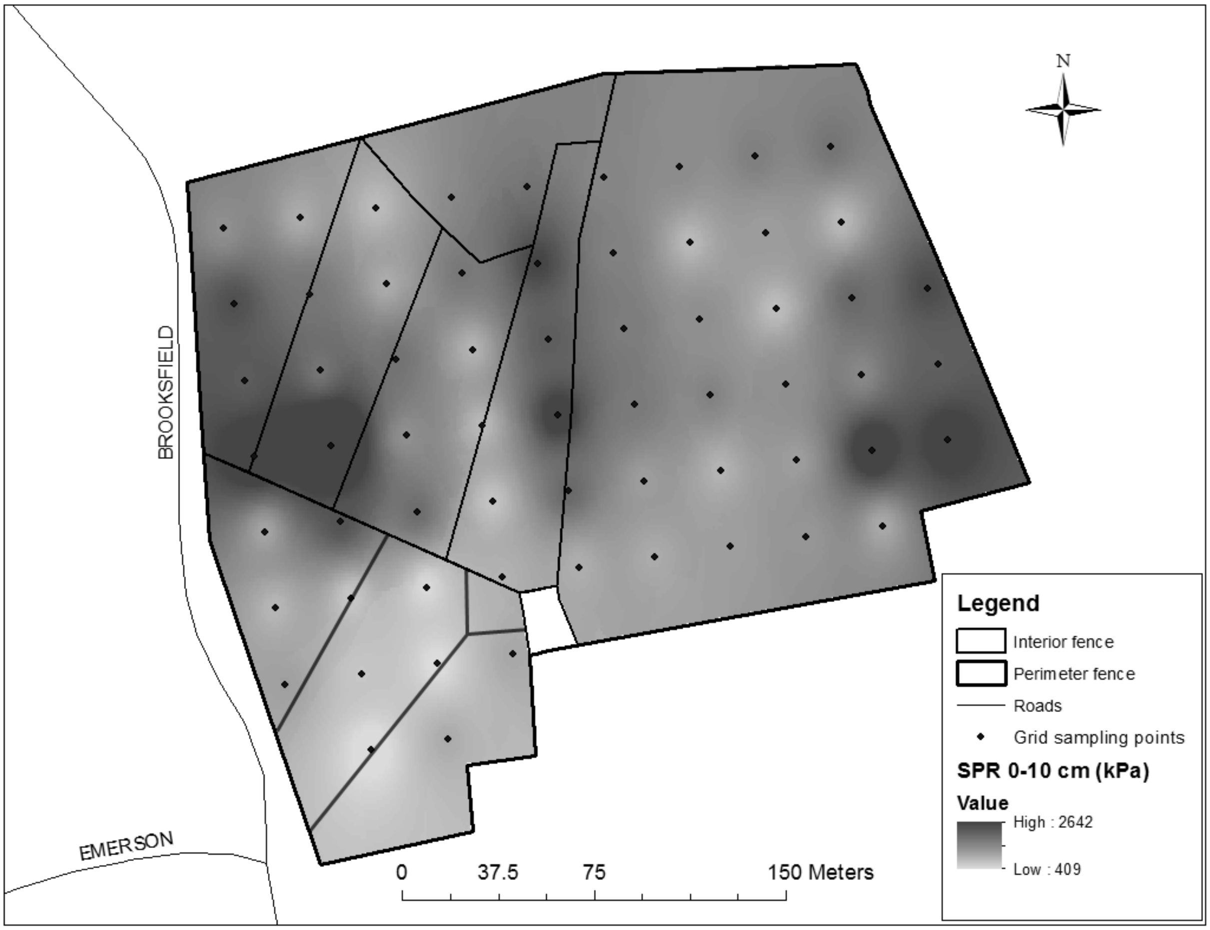


Figure 3.12. Interpolated values of average surface (0 - 10 cm) soil penetration resistance (SPR) from May 2012 samples.

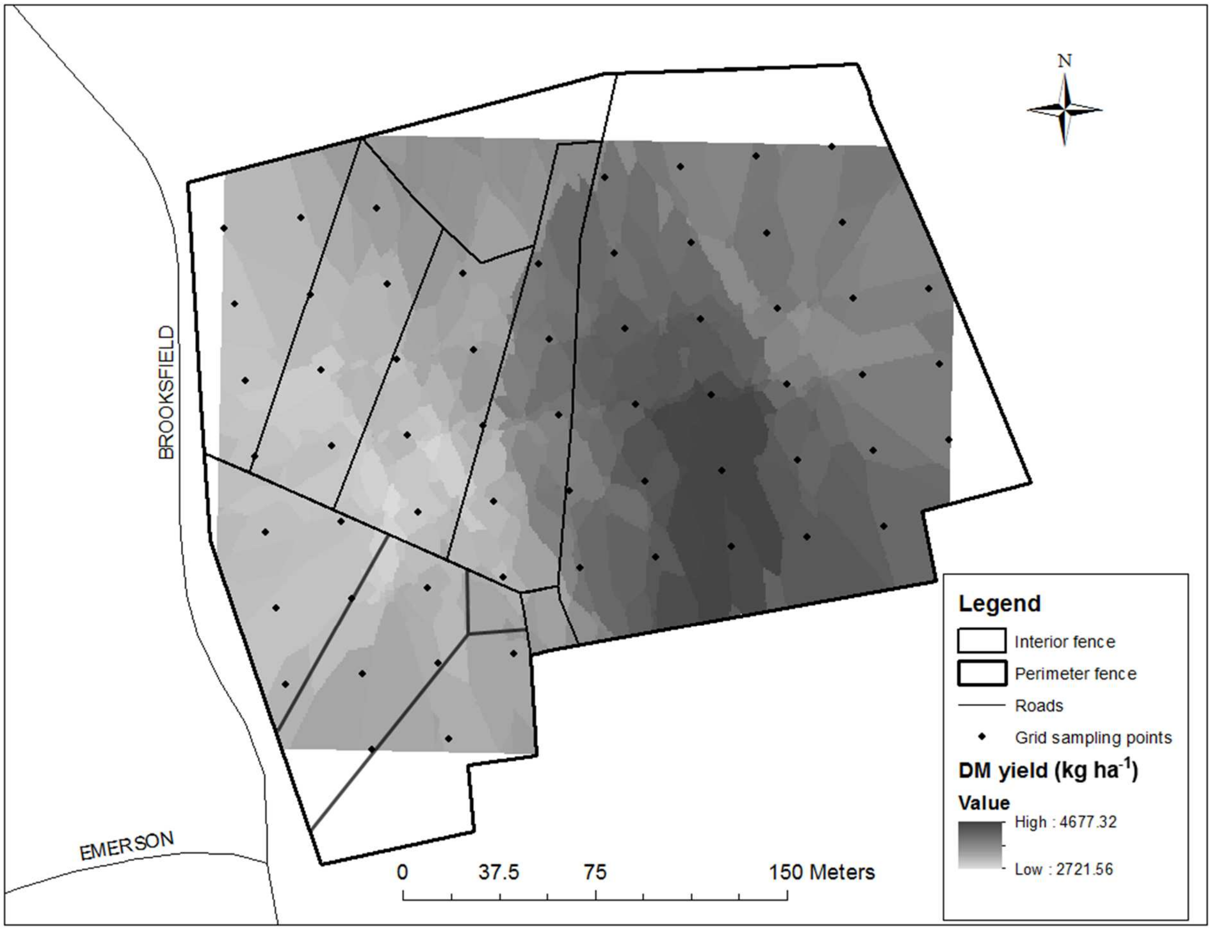


Figure 3.13. Interpolated values of dry matter yield (kg ha^{-1}) from May 2012 samples.

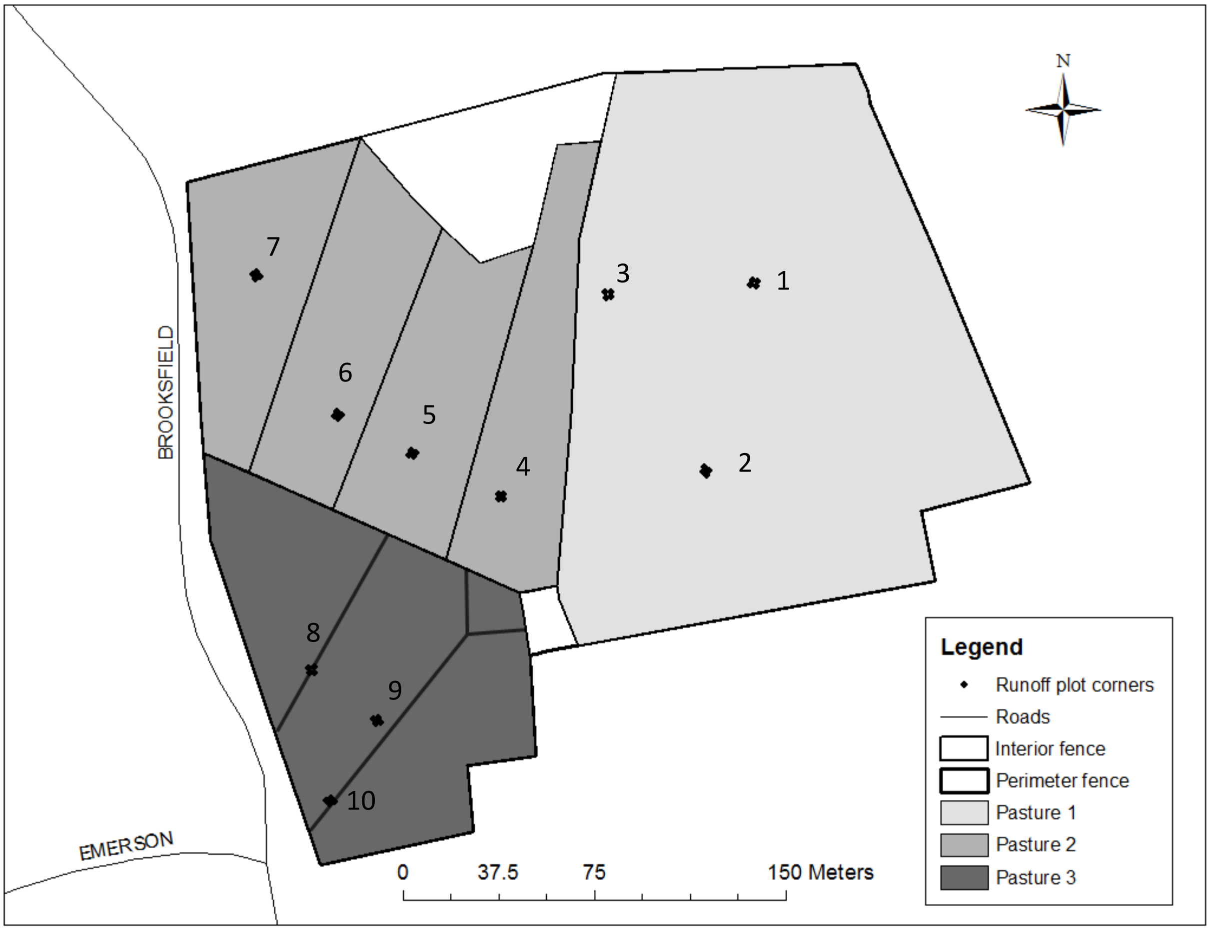
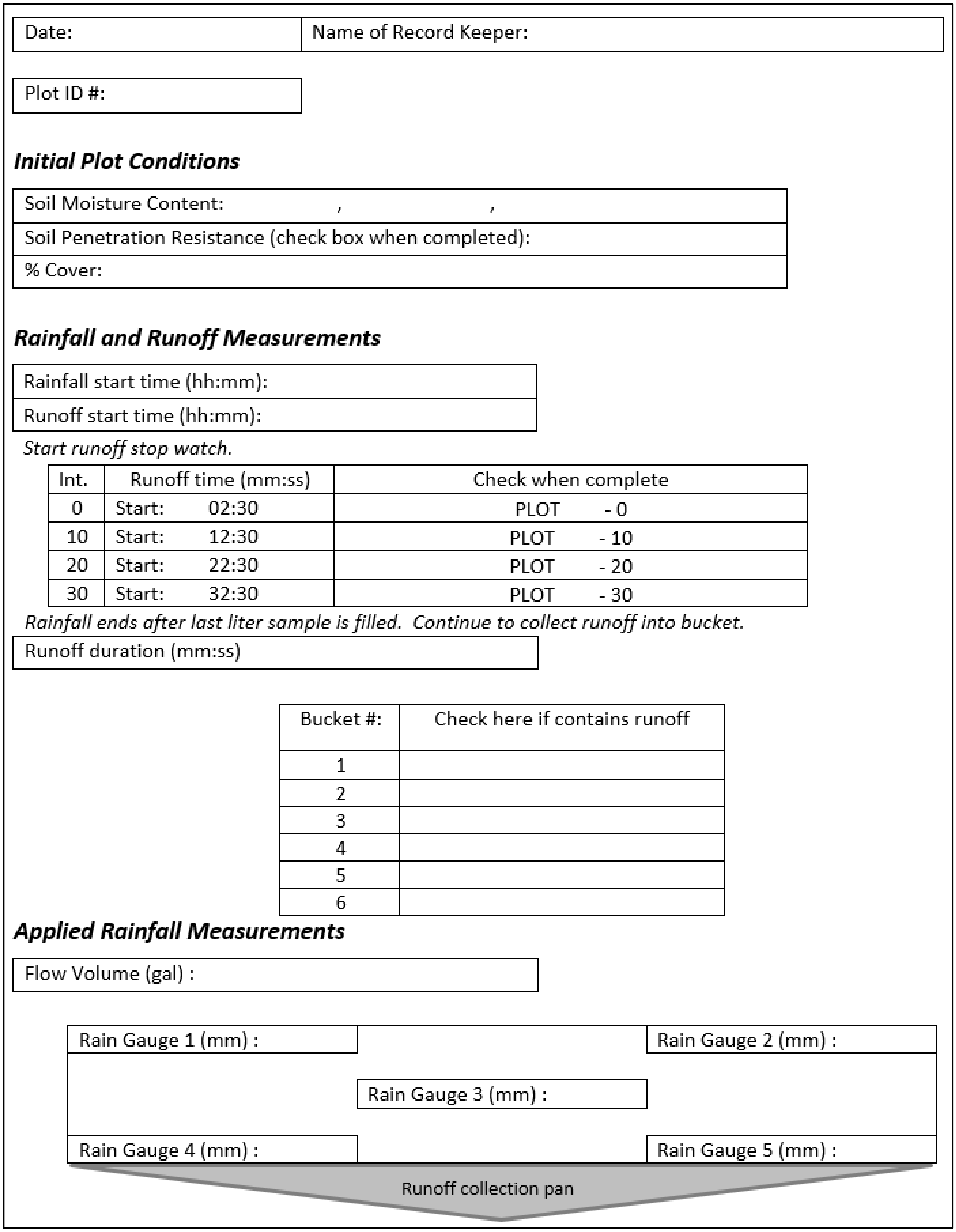


Figure 3.14. Runoff plot locations. Runoff was collected at Plot 6 for initial conditions (Simulation 1) and selected at random to be excluded from the rest of the study.

Figure 3.15. Runoff plot borders, collection flume, and rain gauges within frame of rainfall simulator.


Figure 3.16. Rainfall simulation. Tank of source water (left), simulator (right).



Date:	Name of Record Keeper:

Plot ID #:

Initial Plot Conditions

Soil Moisture Content: , ,
Soil Penetration Resistance (check box when completed):
% Cover:

Rainfall and Runoff Measurements

Rainfall start time (hh:mm):
Runoff start time (hh:mm):

Start runoff stop watch.

Int.	Runoff time (mm:ss)	Check when complete
0	Start: 02:30	PLOT - 0
10	Start: 12:30	PLOT - 10
20	Start: 22:30	PLOT - 20
30	Start: 32:30	PLOT - 30

Rainfall ends after last liter sample is filled. Continue to collect runoff into bucket.

Runoff duration (mm:ss)

Bucket #:	Check here if contains runoff
1	
2	
3	
4	
5	
6	

Applied Rainfall Measurements

Flow Volume (gal) :

Rain Gauge 1 (mm) :

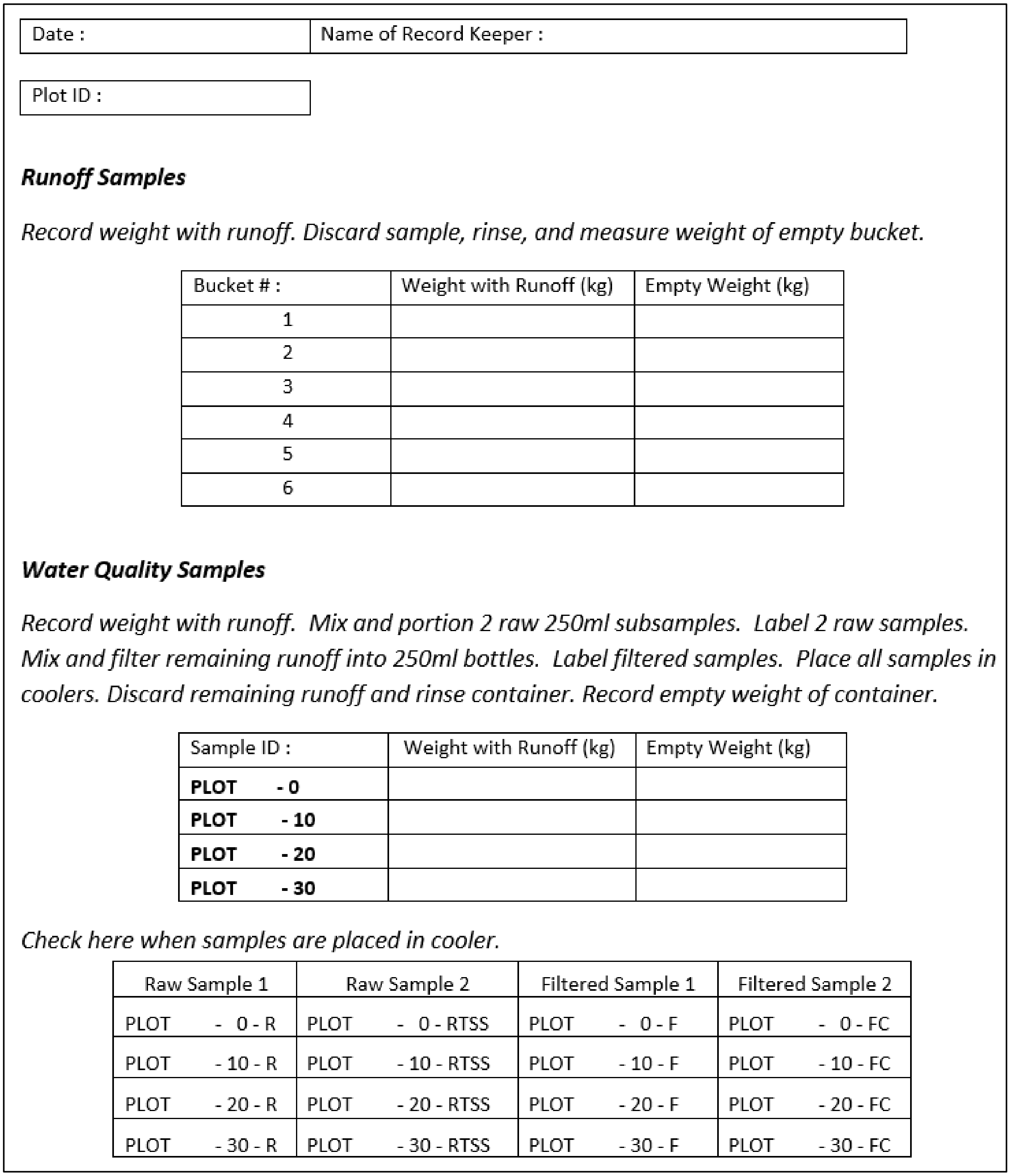
Rain Gauge 2 (mm) :

Rain Gauge 3 (mm) :

Rain Gauge 4 (mm) :

Rain Gauge 5 (mm) :

Figure 3.17. Record sheet showing data collected during runoff events.



Date :	Name of Record Keeper :

Plot ID :

Runoff Samples

Record weight with runoff. Discard sample, rinse, and measure weight of empty bucket.

Bucket # :	Weight with Runoff (kg)	Empty Weight (kg)
1		
2		
3		
4		
5		
6		

Water Quality Samples

Record weight with runoff. Mix and portion 2 raw 250ml subsamples. Label 2 raw samples. Mix and filter remaining runoff into 250ml bottles. Label filtered samples. Place all samples in coolers. Discard remaining runoff and rinse container. Record empty weight of container.

Sample ID :	Weight with Runoff (kg)	Empty Weight (kg)
PLOT - 0		
PLOT - 10		
PLOT - 20		
PLOT - 30		

Check here when samples are placed in cooler.

Raw Sample 1	Raw Sample 2	Filtered Sample 1	Filtered Sample 2
PLOT - 0 - R	PLOT - 0 - RTSS	PLOT - 0 - F	PLOT - 0 - FC
PLOT - 10 - R	PLOT - 10 - RTSS	PLOT - 10 - F	PLOT - 10 - FC
PLOT - 20 - R	PLOT - 20 - RTSS	PLOT - 20 - F	PLOT - 20 - FC
PLOT - 30 - R	PLOT - 30 - RTSS	PLOT - 30 - F	PLOT - 30 - FC

Figure 3.18. Record sheet showing data collected during sample processing.

Table 3.1. Table of management events for the 2012 season.

Date (mm/dd/yyyy)	Event	Plots
05/17/2012	Fertilizer Application	
05/25/2012	Simulation 1	1, 2, 3
05/26/2012	Simulation 1	4, 5, 6, 7, 8, 9, 10
05/30/2012	Grid forage and soil sampling	
06/01/2012	Continuous and rotational stocking began	
06/19/2012	Automatic rain and temperature gauge installed	
06/25/2012	Mob 1 stocked	
06/28/2012	Mob 1 removed, Simulation 2	1, 2, 3, 4, 5, 7
06/29/2012	Simulation 2	8, 9, 10
07/19/2012	Cattle removed for TB testing	
07/24/2012	Simulation 3	4, 5, 7, 8,
07/25/2012	Simulation 3, cattle return	1, 2, 3, 9, 10
08/21/2012	Simulation 4	4, 5, 7, 8, 9, 10
08/22/2012	Simulation 4	1, 2, 3
09/24/2012	Simulation 5	1, 2, 3
09/26/2012	Simulation 5	4, 5, 7, 8
09/27/2012	Simulation 5	9, 10
10/02/2012	2 cows removed from each treatment	
10/30/2012	Mob 2 stocked	
11/01/2012	All cattle removed, Simulation 6	1, 2, 3
11/02/2012	Simulation 6	4, 7, 8, 10

Table 3.2. Natural rainfall at Prices Fork Research Farm.

Date (mm/dd/yyyy)	Total Daily Depth (mm d^{-1})	Recording Device
05/29/2012	13.00	Manual Rain gauge
06/02/2012	11.18	Manual Rain gauge
06/04/2012	0.75	Manual Rain gauge
06/05/2012	2.79	Manual Rain gauge
06/06/2012	12.19	Manual Rain gauge
06/07/2012	0.25	Manual Rain gauge
06/12/2012	12.00	Manual Rain gauge
06/18/2012	6.00	Manual Rain gauge
06/22/2012	0.51	Tipping Bucket
06/24/2012	0.25	Tipping Bucket
06/29/2012	0.25	Tipping Bucket
07/02/2012	48.01	Tipping Bucket
07/06/2012	0.25	Tipping Bucket
07/10/2012	5.84	Tipping Bucket
07/13/2012	1.78	Tipping Bucket
07/14/2012	16.76	Tipping Bucket
07/15/2012	2.54	Tipping Bucket
07/19/2012	3.81	Tipping Bucket
07/20/2012	1.02	Tipping Bucket
07/21/2012	0.25	Tipping Bucket
07/23/2012	2.79	Tipping Bucket
07/24/2012	2.54	Tipping Bucket
07/27/2012	5.08	Tipping Bucket
07/31/2012	29.46	Tipping Bucket
08/01/2012	2.29	Tipping Bucket
08/04/2012	1.78	Tipping Bucket
08/05/2012	21.59	Tipping Bucket
08/07/2012	0.25	Tipping Bucket
08/09/2012	12.7	Tipping Bucket
08/10/2012	0.25	Tipping Bucket
08/11/2012	4.32	Tipping Bucket
08/14/2012	3.05	Tipping Bucket
08/15/2012	1.27	Tipping Bucket
08/19/2012	17.78	Tipping Bucket
09/01/2012	0.51	Tipping Bucket
09/02/2012	0.76	Tipping Bucket
09/05/2012	3.56	Tipping Bucket
09/08/2012	0.76	Tipping Bucket
09/16/2012	0.25	Tipping Bucket
09/17/2012	12.95	Tipping Bucket

09/18/2012	32.00	Tipping Bucket
09/25/2012	1.52	Tipping Bucket
09/26/2012	0.25	Tipping Bucket
09/28/2012	3.05	Tipping Bucket
10/01/2012	4.32	Tipping Bucket
10/02/2012	10.16	Tipping Bucket
10/07/2012	11.43	Tipping Bucket
10/08/2012	1.27	Tipping Bucket
10/15/2012	4.83	Tipping Bucket
10/27/2012	1.52	Tipping Bucket
10/29/2012	4.57	Tipping Bucket
11/03/2012	4.06	Tipping Bucket
11/04/2012	2.54	Tipping Bucket
11/12/2012	20.83	Tipping Bucket
11/13/2012	2.29	Tipping Bucket
11/27/2012	2.54	Tipping Bucket
Total Natural Rainfall (mm)	311.91	

Table 3.3. Runoff plot slopes (%) and aspects (cardinal direction, enumeration).

Plot ID	Slope (%)	Aspect
1	14.4	NW, 8
2	15.2	NW, 8
3	14.1	NE, 2
4	14.2	N, 1
5	15.0	NE, 2
6	14.0	NE, 2
7	11.6	NE, 2
8	13.6	S, 5
9	13.6	SW, 6
10	17.0	NW, 8
Average Slope =	14.0	

Table 3.4. Summary of measure and calculated values for response variables, plot conditions, and rainfall/runoff variables.

Measured Value	Calculated Value
	Response variables
Runoff mass (kg)	Runoff depth (mm)
Incremental TP concentrations in runoff (mg L^{-1})	Event mean TP concentration in runoff (mg L^{-1})
Incremental TN concentrations in runoff (mg L^{-1})	Event mean TN concentration in runoff (mg L^{-1})
Runoff mass (kg), runoff start time (mm:ss), runoff end time (mm:ss), incremental TP concentrations (mg L^{-1})	Event TP load (kg ha^{-1})
Runoff mass (kg), runoff start time (mm:ss), runoff end time (mm:ss), incremental TP concentrations (mg L^{-1})	Event TN load (kg ha^{-1})
	Plot condition variables
DM yield	Average DM yield (kg ha^{-1})
SMC (%)	Average SMC (%)
SPR (0 - 20 cm) (kPa)	Average SPR (0 - 10 cm) (kPa)
Ground coverage (%)	
	Rainfall/runoff variables
Runoff start time (hh:mm)	Time to runoff (min)
Rainfall start time (hh:mm), runoff start time (hh:mm), rainfall depths (mm)	Rainfall intensity (mm hr^{-1})
Runoff mass (kg), runoff duration (mm:ss)	Runoff rate (s)
Runoff mass (kg), rainfall depths (mm)	Runoff ratio (mm mm^{-1})
Flow volume (gal), rainfall depths (mm)	Wind factor (L L^{-1})
Rainfall depths (mm)	Applied rain volume (L)
Rainfall start time (hh:mm), runoff start time (hh:mm)	Rainfall duration (min)
Runoff duration (mm:ss)	
Rainfall start time (hh:mm)	
Rainfall depths (mm)	Uniformity coefficient (mm mm^{-1})

Table 3.5. Example calculations for total TP load for an event.

Increment	ΔTime (s)	TP (mg L^{-1})	Time*TP	Runoff rate (L s^{-1} ha^{-1})	TP load (kg ha^{-1})
0	150	1.1	164	130	0.0213
1	600	1.2	741	130	0.0961
2	600	0.8	500	130	0.0649
3	600	0.7	440	130	0.0571
				Total TP load =	0.239

Chapter 4. Results and Discussion

4.1 Initial (pre-stocking) conditions

Prior to introducing livestock in May 2012, for 20 years, the pastureland at PFRF had largely been undisturbed, being hayed once or twice a year. As described in Chapter 3, baseline soil and vegetation characteristics were determined by sampling the PFRF pastures on a 30 by 30 m grid prior to initiating stocking treatments (fig. 3.9-3.13). The following variables were measured at each grid point: soil fertility, soil penetration resistance, soil moisture content, dry matter yield, and species composition.

To establish baseline runoff characteristics, simulated rainfall events were conducted over each runoff plot prior to initiating stocking treatments. The first simulated rainfall events (Simulation 1) occurred over two consecutive days (5/25/12 and 5/26/12), with the first rainfall event occurring eight days after the PFRF pasture had been fertilized. During the soil penetration resistance measurements, Plot 3 was found to have a gravelly subsurface layer which was unique among the plots. Equipment failed during the Plot 10 rainfall simulation. The simulation began and runoff was initiated and soon after the simulator pump failed. Data from runoff collected for this small time period was discarded. Once the pump was replaced, the simulation was restarted and runoff was collected according to the sampling protocol. Data from Plot 6 was also discarded because it would have made for an unbalanced comparison among pastures.

Across all the runoff plots, runoff depths (hereafter referred to simply as runoff) averaged 19.5 mm. Runoff was highly variable within pastures and across all plots (fig. 4.1 and table 4.1). Averaging runoff within pastures shows that Pasture 2 yielded the greatest average runoff and Pasture 1 the least (table 4.1). There was no difference in runoff among pastures since the margins of variability overlap across pastures (table 4.1). Runoff was most variable from Pasture 1 (CV = 0.95) and least variable from Pasture 3 (CV = 0.62).

Plot condition (table 4.2) and rainfall/runoff variables (table 4.3) were generally less variable than runoff. The influence of measured physical variables on runoff variability was investigated by performing correlation analyses between runoff, plot conditions, and other rainfall/runoff variables (tables 4.4 and 4.5). Because no significant correlations were found, we concluded that the hydrology of the runoff plots was variable due to 1) factors that were not measured during our study (e.g., the presence of macropores) and/or 2) non-linear relationships between factors and runoff. The pastureland at PFRF overlays karst rock and had evidence of subterranean rodent activity (groundhog burrows), both of which may have formed macropores that increased infiltration. Non-linear relationships or combinations of condition variables might also explain the variation in runoff. There were no significant correlations between runoff and plot condition variables, but as expected runoff was significantly correlated with runoff rate and runoff ratio (table 4.5). Runoff and the time to runoff (fig. 4.2) were the most variable responses, but cannot be explained by a linear relationship with the plot conditions or rainfall/runoff characteristics measured. Applied rain, intensity of rainfall, and dry matter yield were consistent among plots and pastures. Soil moisture content (fig. 4.3) and surface soil penetration resistance (fig. 4.4) were also variable within pastures.

Across all runoff plots, the mean concentrations in runoff for TP and TN were 1.9 mg L^{-1} and 5.0 mg L^{-1}, respectively. Mean TP and TN concentrations were variable within pastures and across all plots (table 4.1 and fig. 4.5), but there was no difference in mean nutrient concentrations among pastures (fig. 4.6). A smaller CV for TN concentrations than for TP concentrations indicates that there was less of a plot effect for TN concentrations than for TP concentrations (table 4.1). Total nutrient concentrations in runoff were significantly correlated with their dissolved counterparts (table 4.5) and nutrients were transported completely in their dissolved forms (table 4.1).

Across all plots, TP loads averaged 0.24 kg ha^{-1} and TN loads averaged 0.70 kg ha^{-1}. Pasture 1 had the lowest average loads, but nutrient loads did not differ among pastures (fig. 4.7). While TN load was significantly correlated with runoff, TP load closely followed runoff ($r = 0.76$), but was not significant at a 0.01 level (tables 4.4 and 4.5). Primarily due to the variability in runoff, nutrient loads were variable across plots and within pastures (fig. 4.8).

4.2 Comparison of runoff quantity from stocking treatments

No differences were found among treatments for average-event runoff, runoff at the end of the season, or trends in runoff. Within the grazing season (Simulations 2 through 6), mean runoff tended to increase for all treatments. Runoff within one standard deviation surrounding the mean from initial conditions (Simulation 1) overlap the values of one standard deviation surrounding the mean from the first post-stocking events (Simulation 2); therefore, runoff did not differ between initial conditions and the first post-stocking simulation. The differences in trends of runoff was not affected by stocking treatment (table 4.6; fig. 4.9). Over time, runoff variability tended to decrease within the season and overall was least variable in the data collected from runoff plots in the Mob treatment and most variable from the Rotational treatment (table 4.7). Considering the results from Simulation 6 to represent a full season of stocking treatment, mean runoff from the Mob treatment (26.9 mm) was lower that of the other two treatments (38.0 mm and 43.0 mm for Continuous and Rotational, respectively), but the margins of variability overlapped among the treatments. Average-event runoff for each treatment were calculated by summing event runoff for each plot for Simulations 2 through 6, dividing by the number of simulated rainfall events, and then averaging within stocking treatment. A graph of average-event runoff and their standard deviations does not show large differences among treatments (fig. 4.10). Dry matter yield and time to runoff were the most variable conditions overall (table 4.8 and 4.9). Additionally, Figure 4.11 illustrates that runoff variability persists among plots and treatments throughout the season.

Correlation coefficients and p-values between runoff and other variables are shown in Tables 4.10 and 4.11. As expected, runoff was highly correlated with runoff rate and runoff ratio. Further investigation into significantly correlated relationships did not yield discernable treatment effects (fig. 4.12). An investigation into seasonal patterns of SMC showed lower values for Simulation 2 than the other simulations, which could have contributed to the lower runoff from Simulation 2 (fig. 4.13). The decreasing trend in DM yield for Simulations 4, 5, and 6 in the Continuous and Rotational treatments could help explain the increasing trend in runoff from those treatments (table 4.8). An increase in SPR between Simulations 1 and 2 for all pastures/treatments was observed and corresponded to cattle stocking (fig. 4.14). SPR for

Simulation 4 was lower for all treatments which was coincidental with higher SMC values for Simulation 4.

Runoff ratios were similar to other studies of runoff from pastureland induced by rainfall simulation (table 4.12). The fact that the Rotational treatment had the most variation in runoff overall may be partially a result of the design of the experiment. Plots in the Rotational treatment were distributed across paddocks to sample within the entire treated area. Within each simulation, paddocks were expected to have more variable DM yield, SPR, and other physical variables which may have influenced runoff than the other treatments due to the periods of rest and grazing in the Rotational treatment design.

In summary, the spatial variability of runoff quantity within treatments likely masked any treatment effect. The impact of treatment on average-event runoff quantity, runoff quantity at the end of the grazing season, and trends in runoff quantity within the season was indeterminate in this study and is in need of continued research.

4.3 Comparison of mean nutrient concentrations in runoff from stocking treatments

No differences were found among treatments for average-event TP concentrations or trends in mean TP concentrations; however, there were differences among treatments for mean TP concentrations at the end of the season. Though not different when considering the margins of variability among treatments, Mean TP concentrations in runoff tended to decrease during the grazing season (Simulations 2 through 6), except from runoff plots in the Mob treatment which showed an increase between Simulations 5 and 6 (fig. 4.15). Mean TP concentrations were higher from the Mob treatment at the end of the season (Simulation 6) than the other treatments.

No differences were found among treatments for average-event TN concentrations, mean TN concentrations at the end of the season, or trends in TN concentrations across the grazing season. Within the season, mean concentrations of TN in runoff were less variable than mean TP concentrations (table 4.7), but showed a similar decreasing trend through Simulation 4 (fig. 4.16). Runoff from plots in the Mob treatment had a higher mean TN concentration than the other treatments during Simulation 6, but also had a large margin of variability.

On average 63% of TP was transported in the dissolved form and DN comprised 53% of TN. The ratios of DP to TP and DN to TN were consistent across treatments within the grazing season. There was a decrease in the percentage of total nutrient concentration that was dissolved between the initial conditions (Simulation 1) and the first post-stocking simulation (Simulation 2).

The mean TP and TN concentrations in runoff in this study were similar to nutrient concentrations in runoff from pastureland in other studies where runoff was induced by rainfall simulation, but well above EPA suggested levels (EPA, 2002) for waterbodies in Aggregate Ecoregion XI, in which PFRF is located (table 4.12). Mean TP and TN concentrations may not be the best representation for each plot because sampling time was found to be a significant factor (see Appendix C, which also includes a discussion of sampling time effects on nutrient loads).

Average total nutrient concentrations were significantly correlated with runoff and their respective dissolved fractions (table 4.11). Additionally, mean TP concentrations in runoff were significantly correlated with mean TN concentrations, SMC, rainfall start time, and simulation date. No data clusters associated with stocking treatment were discovered in an investigation into significantly correlated relationships (fig. 4.17). The negative correlation between mean TP concentrations in runoff and simulation date may be due to fertilizer washout early in the study. The negative correlation between TP concentrations and SMC was exemplified with the increase in mean TP concentrations from Simulation 4 to 5 for all pastures, which is coincidental with the decrease in SMC. Drier conditions for Simulation 5 might have left more P on the surface, available to runoff under rainfall simulations.

The difference in mean TP concentration among treatments at the end of the season may be due to stocking method. The second mob stocking event (Mob 2) occurred immediately prior to Simulation 6, which may have deposited a high density of manure deposits on the land surface, making P readily available to runoff. The decrease in the ratio of dissolved nutrient concentration to total nutrient concentration in runoff from all treatments between Simulation 1 and 2 may be an effect of the cattle disturbing the land. A higher level of nutrient bound to particulates may be an effect of erosion due to cattle traffic. More variation in TP concentrations than TN concentrations may have been caused by variations in soil P levels (fig. 3.10), presence of manure deposits, or sediment production. Though sediment data was not available for analysis, variable sediment production may have led to variations in TP concentrations because P tends to bind to sediment.

While, mean TP concentrations in runoff were much higher than source-water concentrations, source-water concentrations of TN were approximately half of TN concentrations in runoff (table 4.13). Though simulated rainfall may have been a large source of N in runoff, the same source water was used for all events in each simulation, therefore would not have effected measureable differences in N concentrations among pastures or treatments.

In summary, no differences were found among treatments for average-event nutrient concentrations, TN concentrations at the end of the season, or trends of mean nutrient concentrations in runoff. The differences in mean TP concentrations at the end of the season among treatments may be partially attributed to treatment effect. Mean TP concentrations in runoff during Simulation 6 were higher from the Mob treatment (1.1 mg L^{-1} TP) than from the Continuous (0.4 mg L^{-1} TP) or Rotational (0.5 mg L^{-1} TP) treatments. Results of the analysis of mean nutrient concentrations among treatments were inconclusive in this study; further research is necessary to determine treatment impacts on mean nutrient concentrations.

4.4 Comparison of nutrient losses (loads) in runoff from stocking treatments

There was no difference among treatments for average-event nutrient loads, loads at the end of the season, or the trends across the grazing season. Average-event nutrient loads did not differ among treatments (fig. 4.10). Though within the margin of variability, mean TP loads in runoff at the end of the season (Simulation 6) were higher from the Mob treatment (0.22 kg ha^{-1}) than the Continuous (0.14 kg ha^{-1}) or the Rotational (0.16 kg ha^{-1}) treatments. TP load trends within the grazing season were similar across treatments. Lowest loads occurred during Simulations 2, 3, and 4 and loads increased between Simulations 4 and 5 (fig. 4.18). All treatments showed an increasing trend in TN loads within the grazing season (fig. 4.19) and TN loads did not differ among treatments at the end of the season (table 4.6).

TN load was highly correlated with runoff (table 4.10). Though TP load was significantly correlated with runoff (table 4.11), trends in TP load did not follow runoff as closely as TN load due to more variability in TP concentrations than TN concentrations within the season. Nutrient loads were not correlated with mean nutrient concentrations. Of particular interest is a comparison of TP loads, mean TP concentrations, and runoff for Simulation 6, which occurred immediately after Mob 2. Though plots in the Mob treatment have the lowest mean runoff, due to their relatively high TP concentrations in runoff, the mean TP load was highest from the Mob treatment; therefore, stocking treatment may have affected mean TP loads for Simulation 6.

In summary, there was no difference among treatments in average-event nutrient loads, the trends of nutrient loads, or nutrient loads at the end of the season. Any treatment impacts were likely muted by the variability in nutrient loads within treatments. Further research should seek to reduce the margins of variability to making treatment effects determinable.

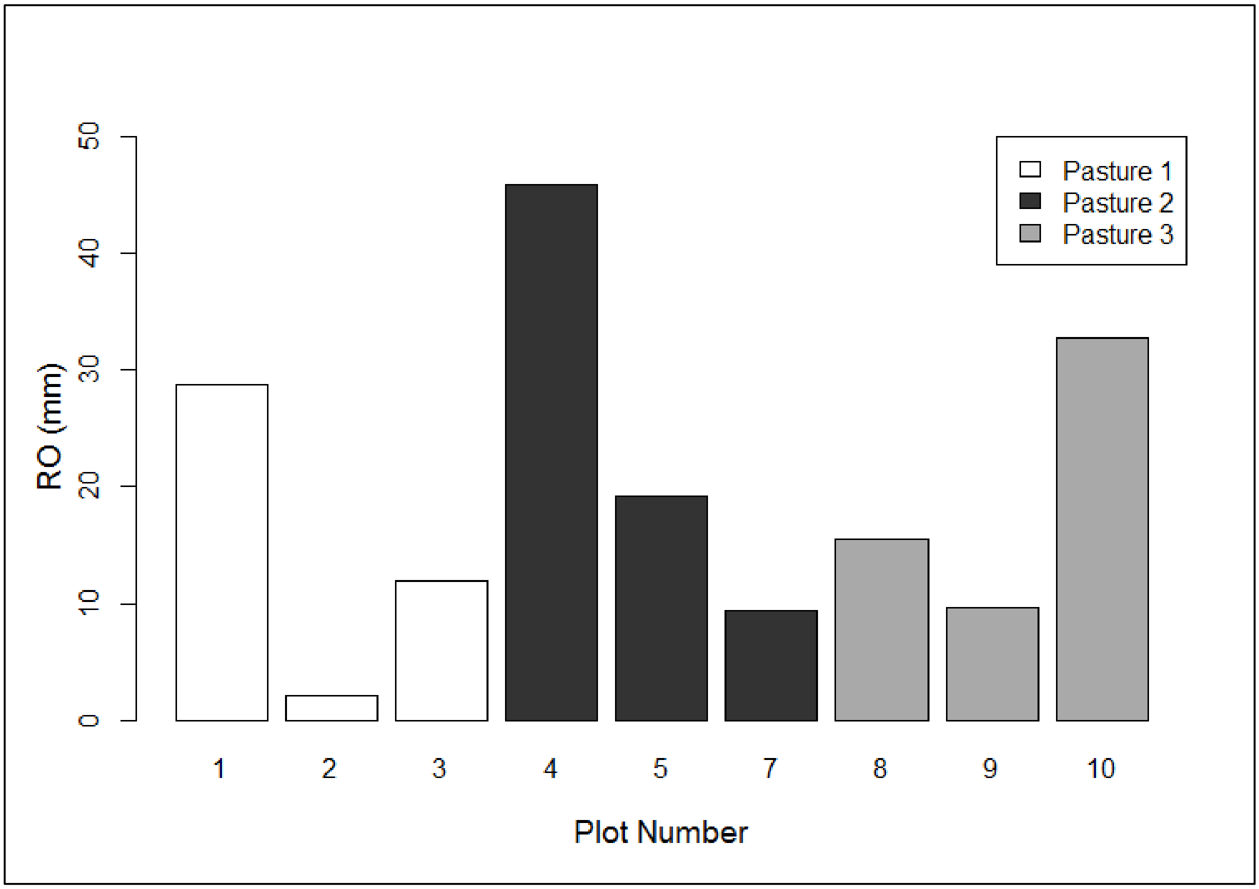


Figure 4.1. Initial conditions (Simulation 1) runoff (mm) by plot and pasture.

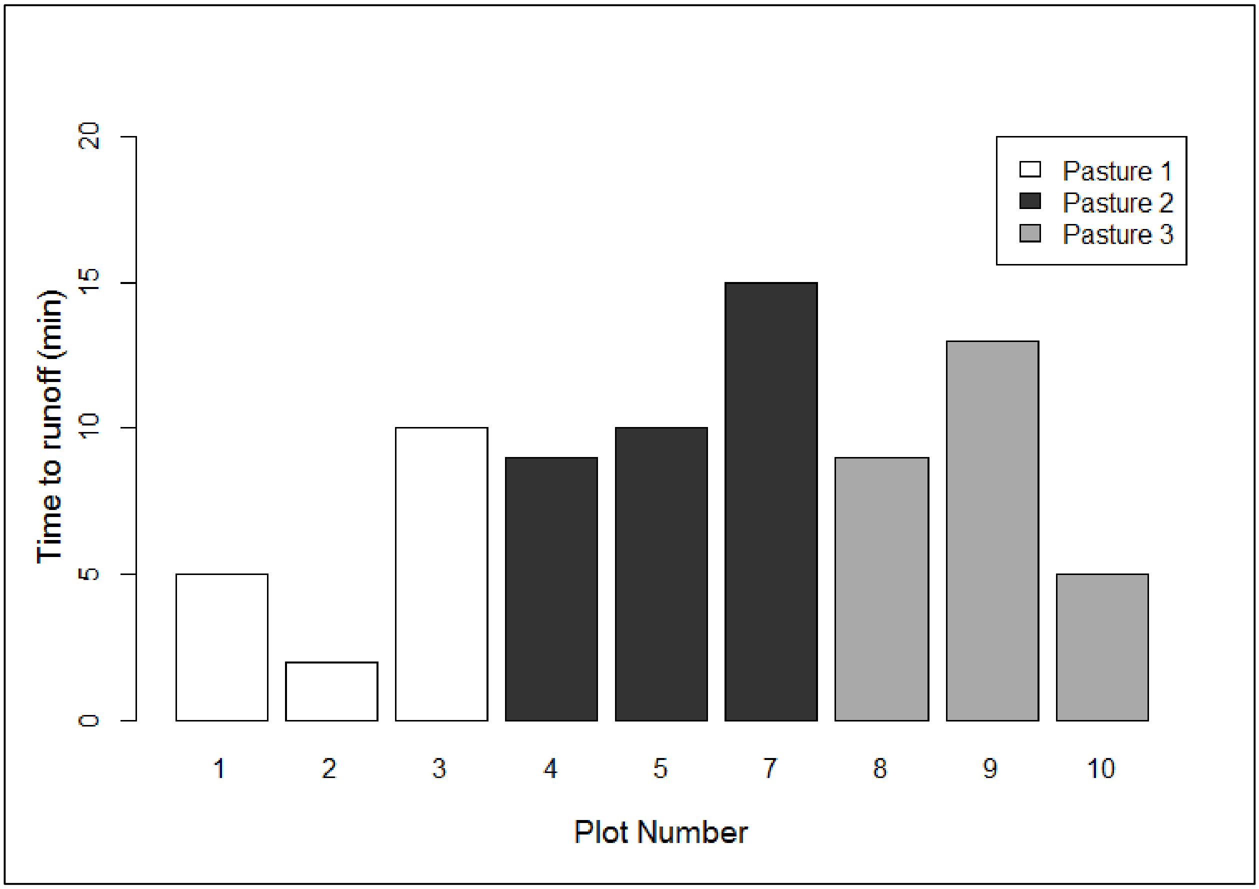


Figure 4.2. Initial conditions (Simulation 1) time to runoff (min) by plot and pasture.

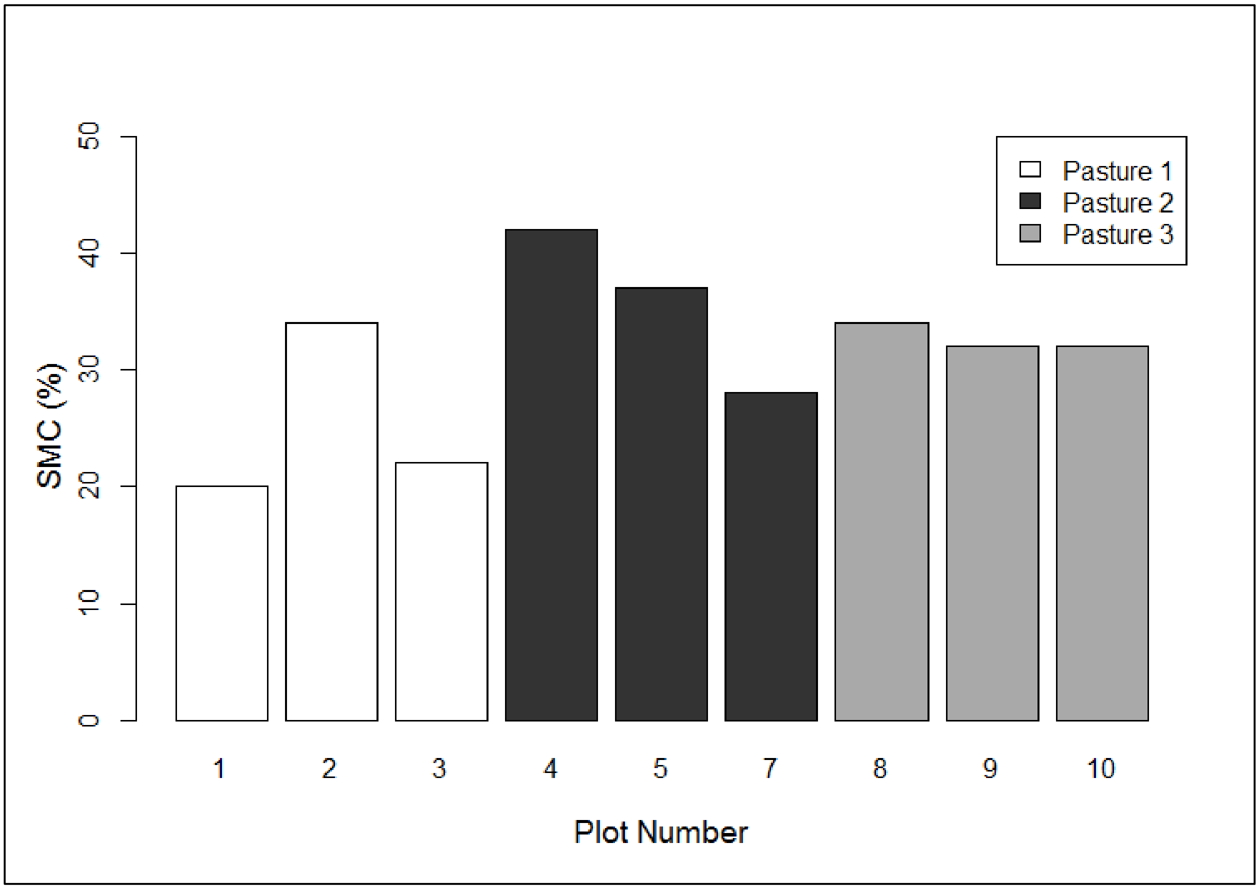


Figure 4.3. Initial conditions (Simulation 1) soil moisture content (SMC) (%) by plot and pasture.

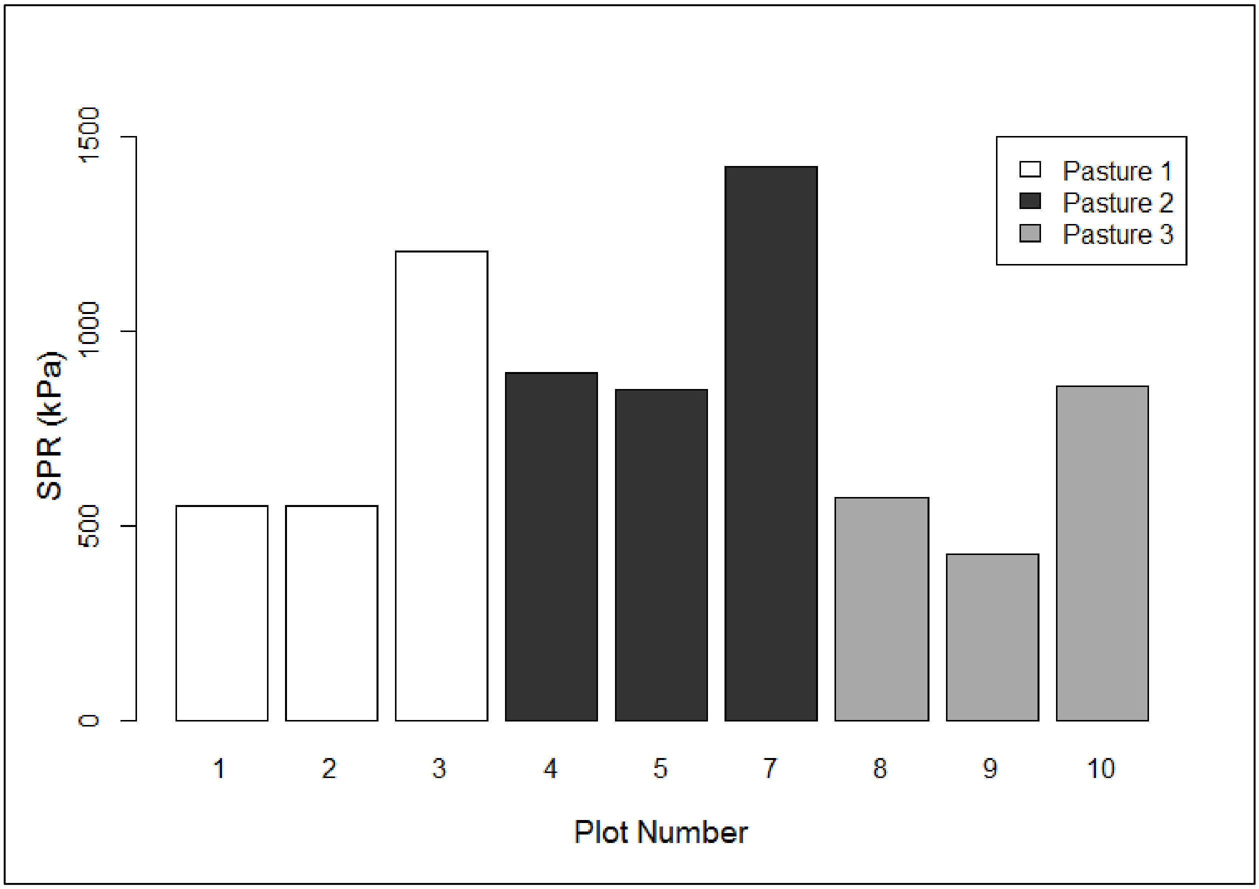


Figure 4.4. Initial conditions (Simulation 1) soil penetration resistance (SPR) (0-10 cm) (kPa) by plot and pasture.

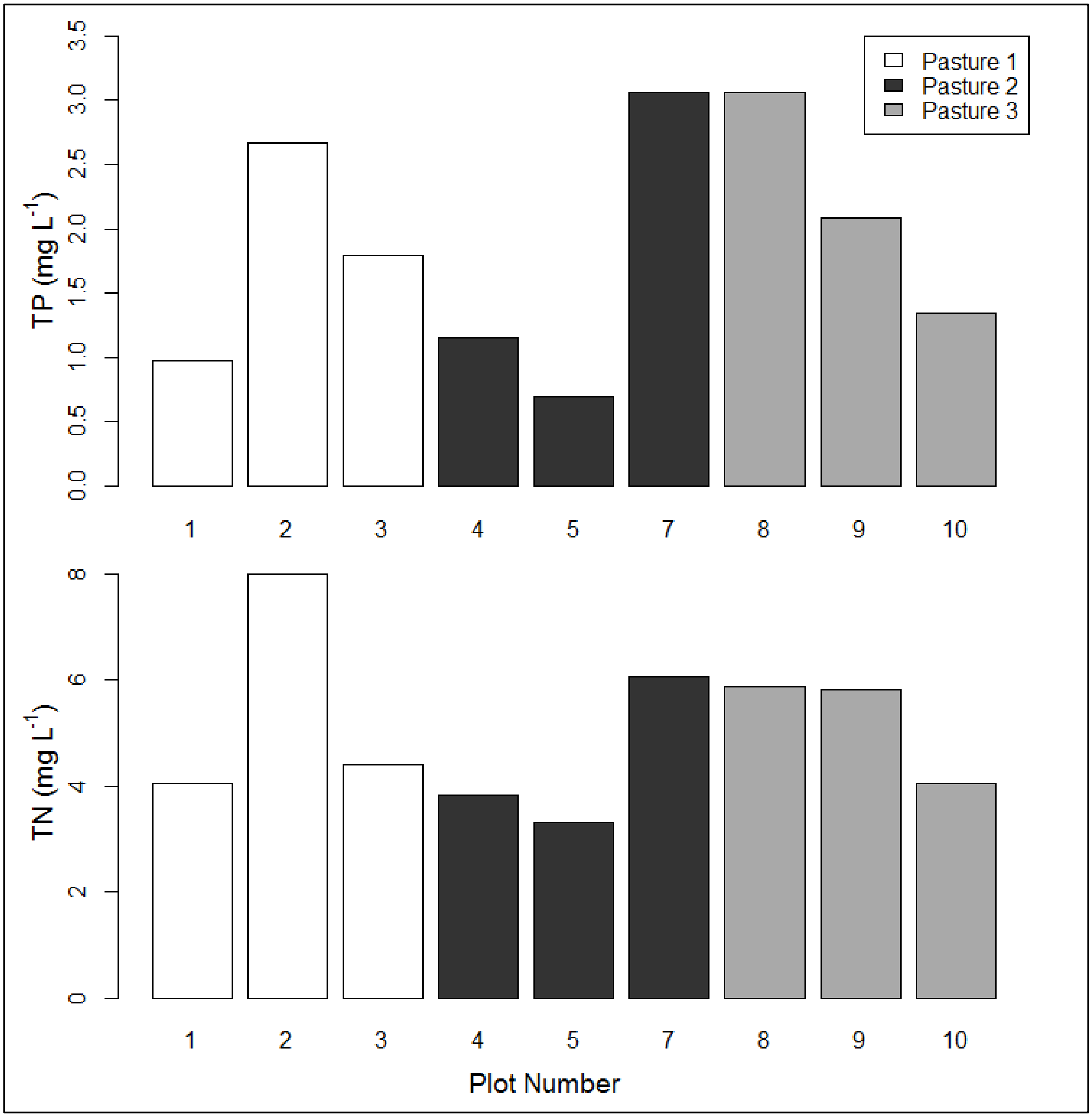


Figure 4.5. Initial conditions (Simulation 1) mean (N = 4) TP and TN concentrations (mg L^{-1}) in runoff by plot and pasture.

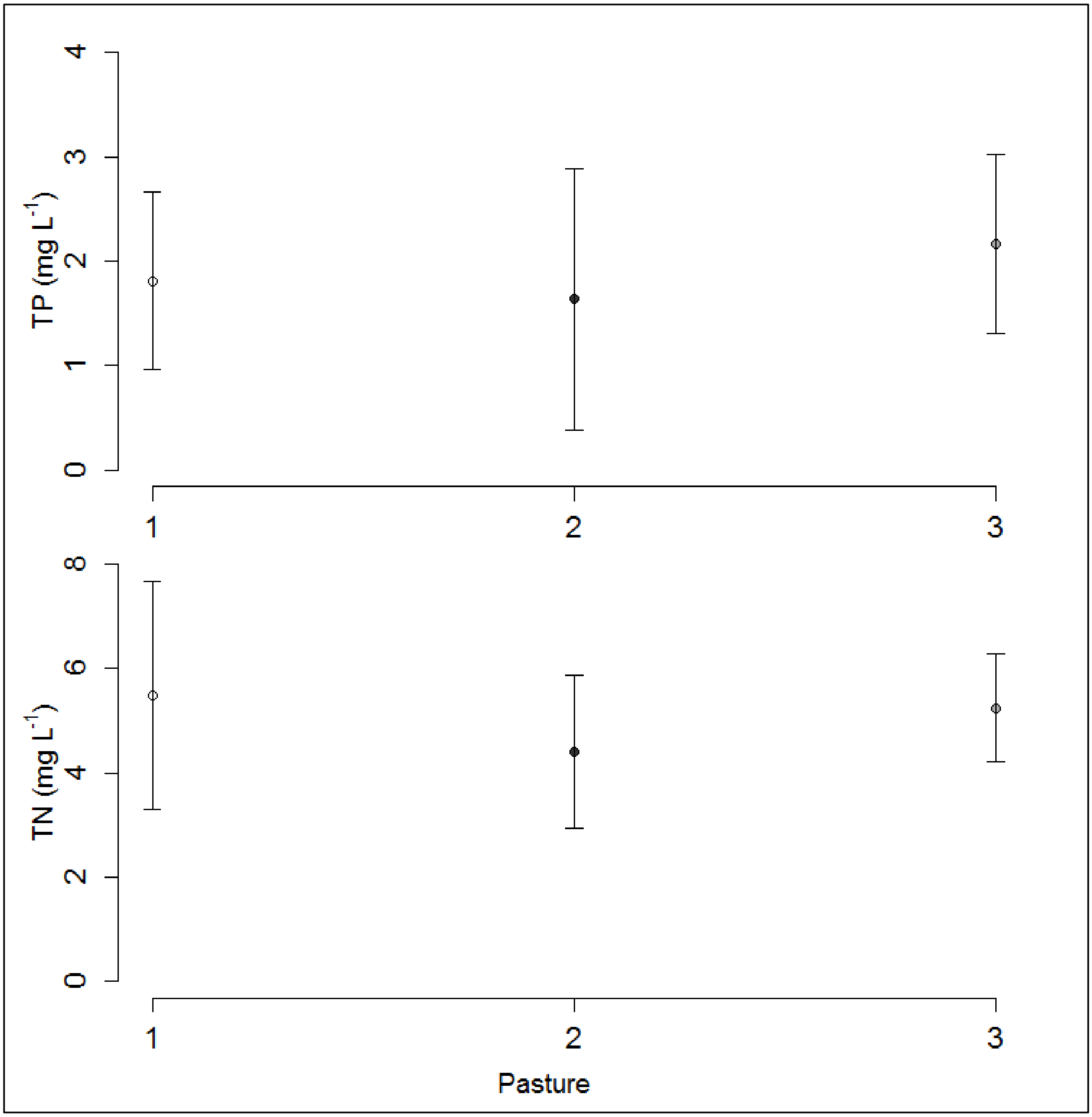


Figure 4.6. Initial conditions (Simulation 1) mean (N = 3) nutrient concentrations (mg L^{-1}) in runoff by pasture. Whiskers signify plus or minus one standard deviation.

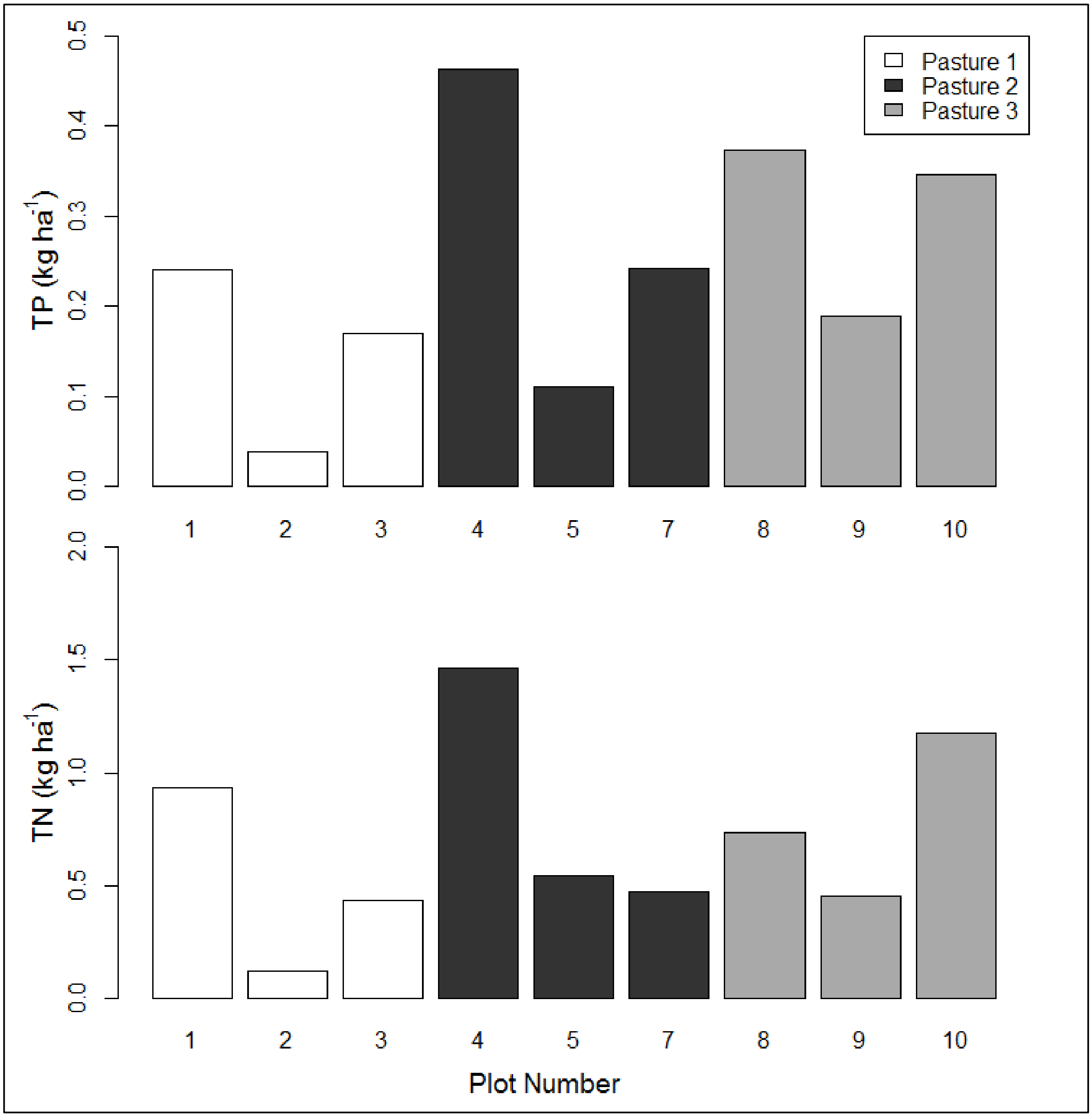


Figure 4.7. Initial conditions (Simulation1) nutrient loads (kg ha^{-1}) by plot and pasture.

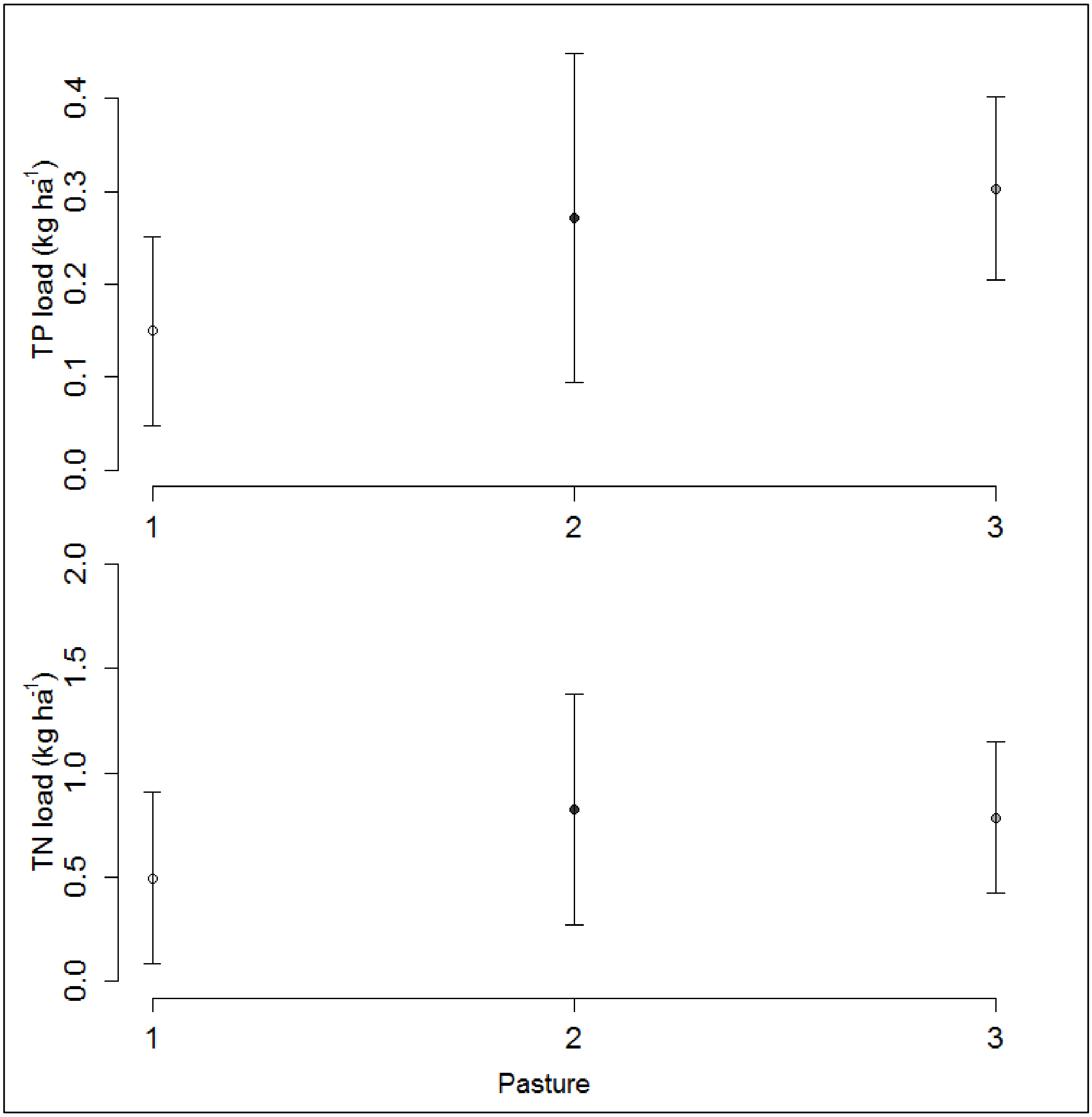


Figure 4.8. Initial conditions (Simulation 1) mean (N = 3) nutrient loads (kg ha^{-1}) in runoff by pasture. Whiskers signify plus or minus one standard deviation.

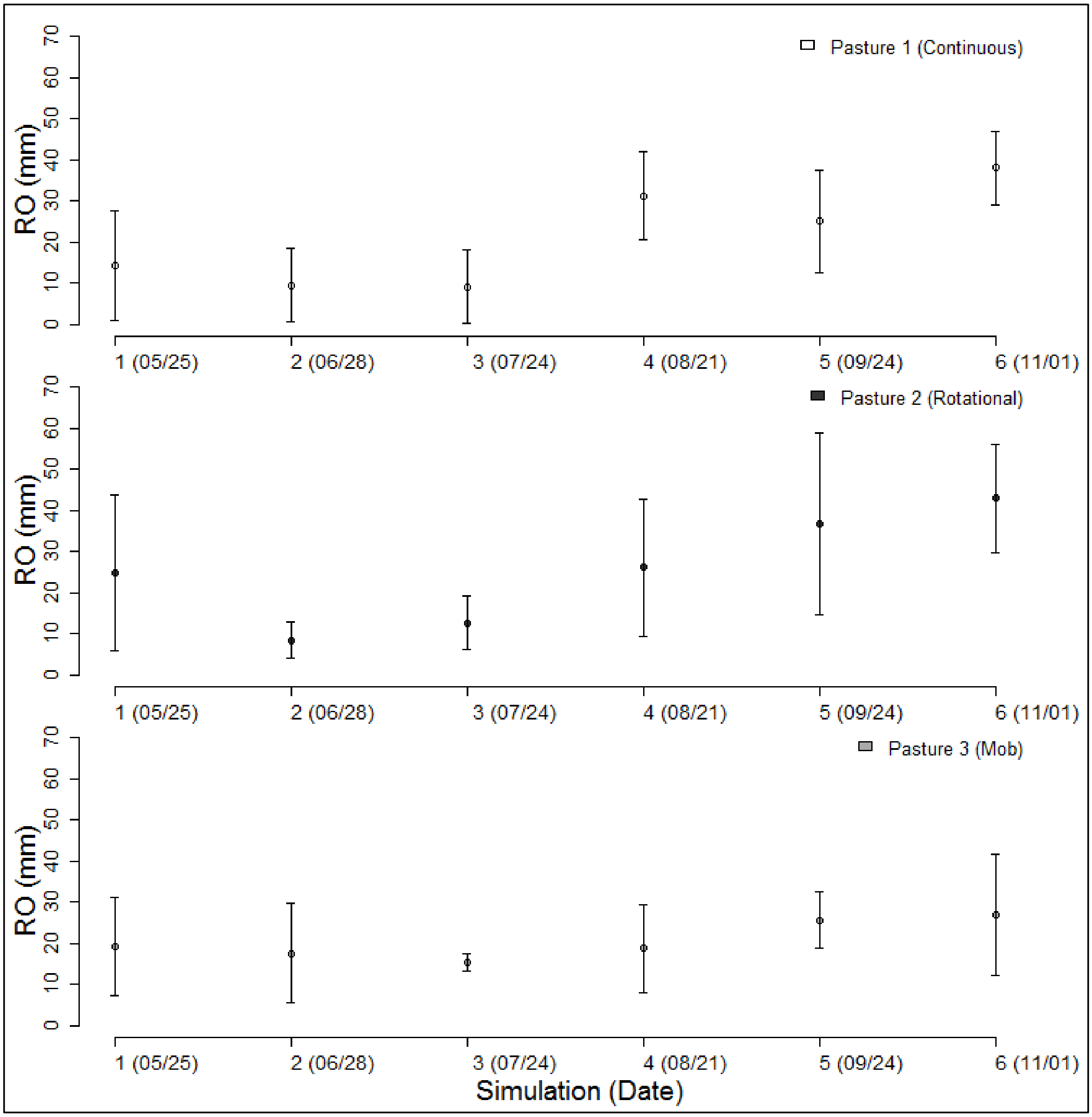


Figure 4.9. Runoff (mm) for initial conditions (Simulation 1) and post-stocking conditions (Simulations 2 through 6). Mob stocking occurred immediately prior to Simulations 2 and 6. (N = 3, except for Simulation 6 in Mob treatment where N = 2).

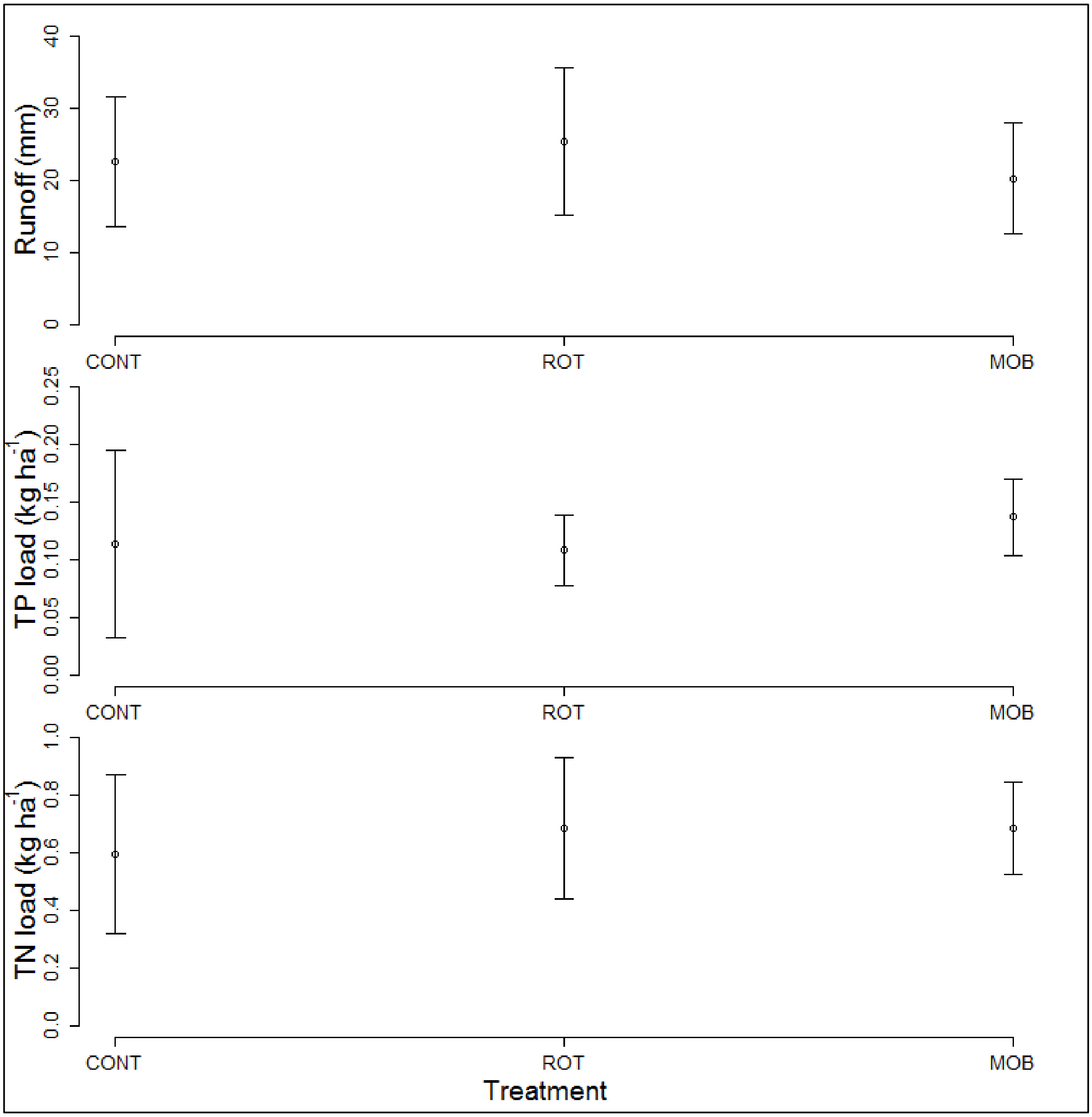


Figure 4.10. Average-event runoff (mm) and nutrient loads (kg ha^{-1}) for each stocking treatment.

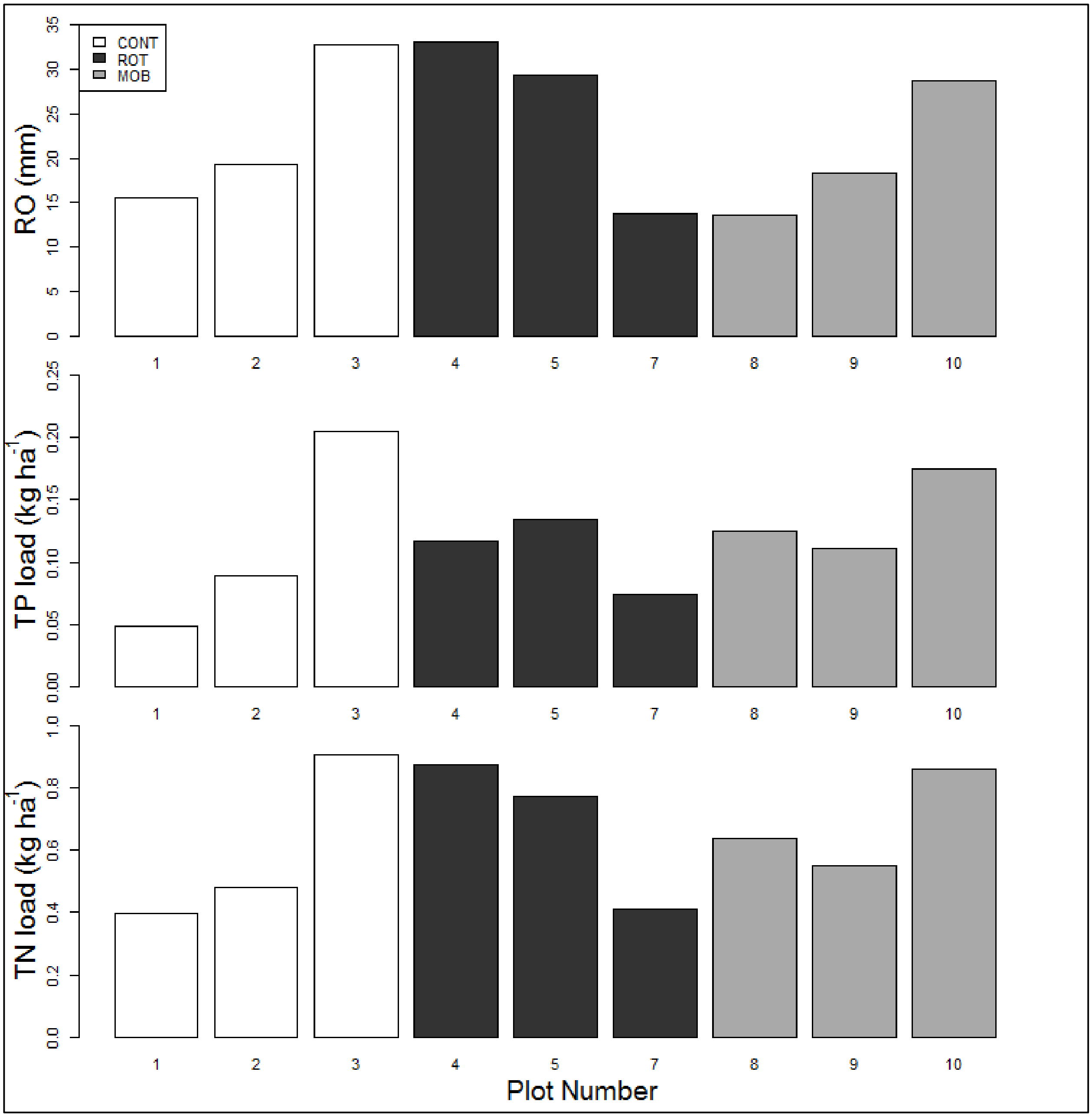


Figure 4.11. Average-event runoff and nutrient loads for post-stocking conditions (Simulations 2 through 6) by plot.

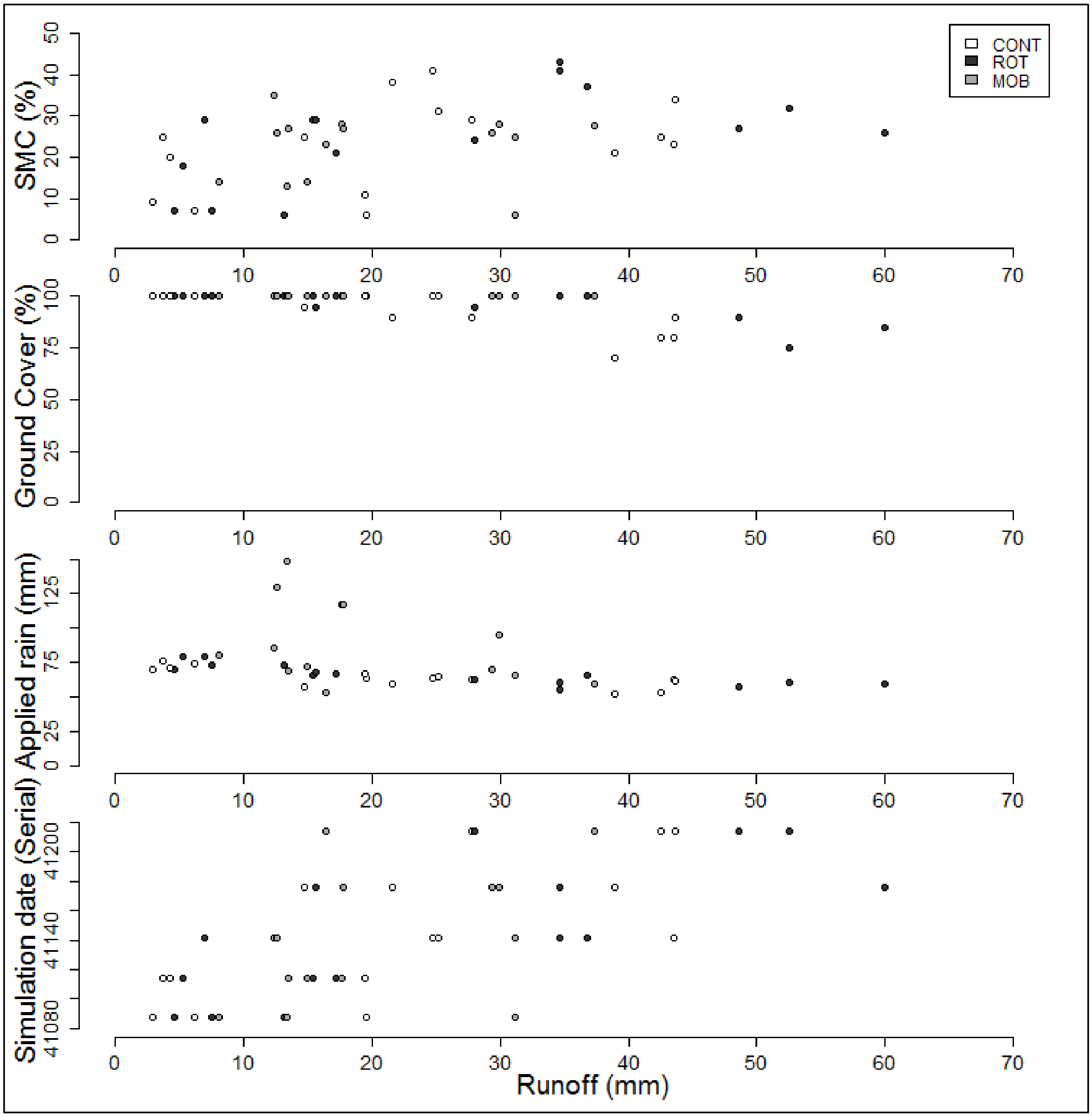


Figure 4.12. A pairwise comparison of runoff (mm) and significantly correlated variables for post-stocking conditions (Simulations 2 through 6).

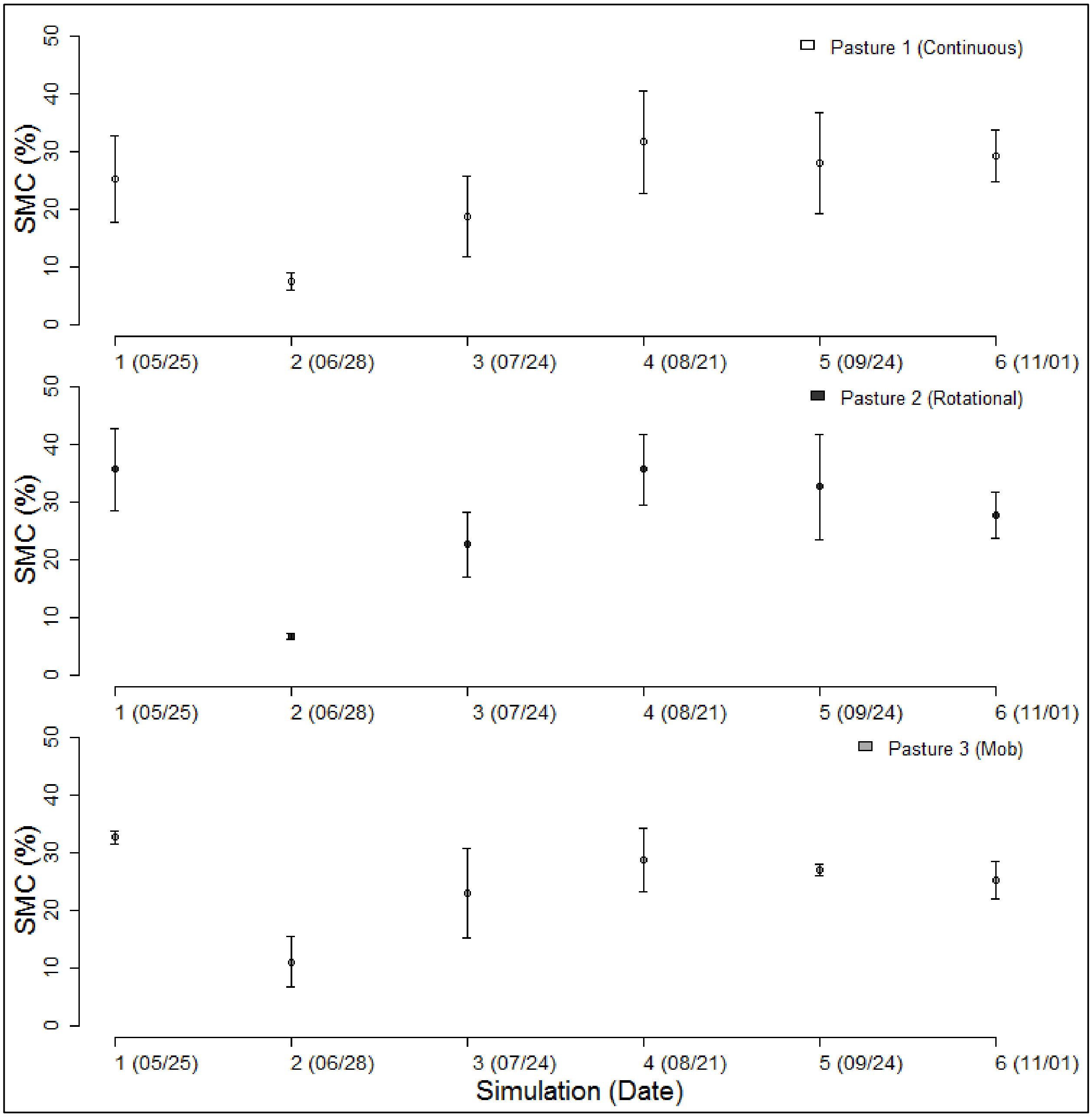


Figure 4.13. Soil moisture content (%) by simulation and pasture/treatment. (N = 3, except for Simulation 6 in the Mob treatment where N =2).

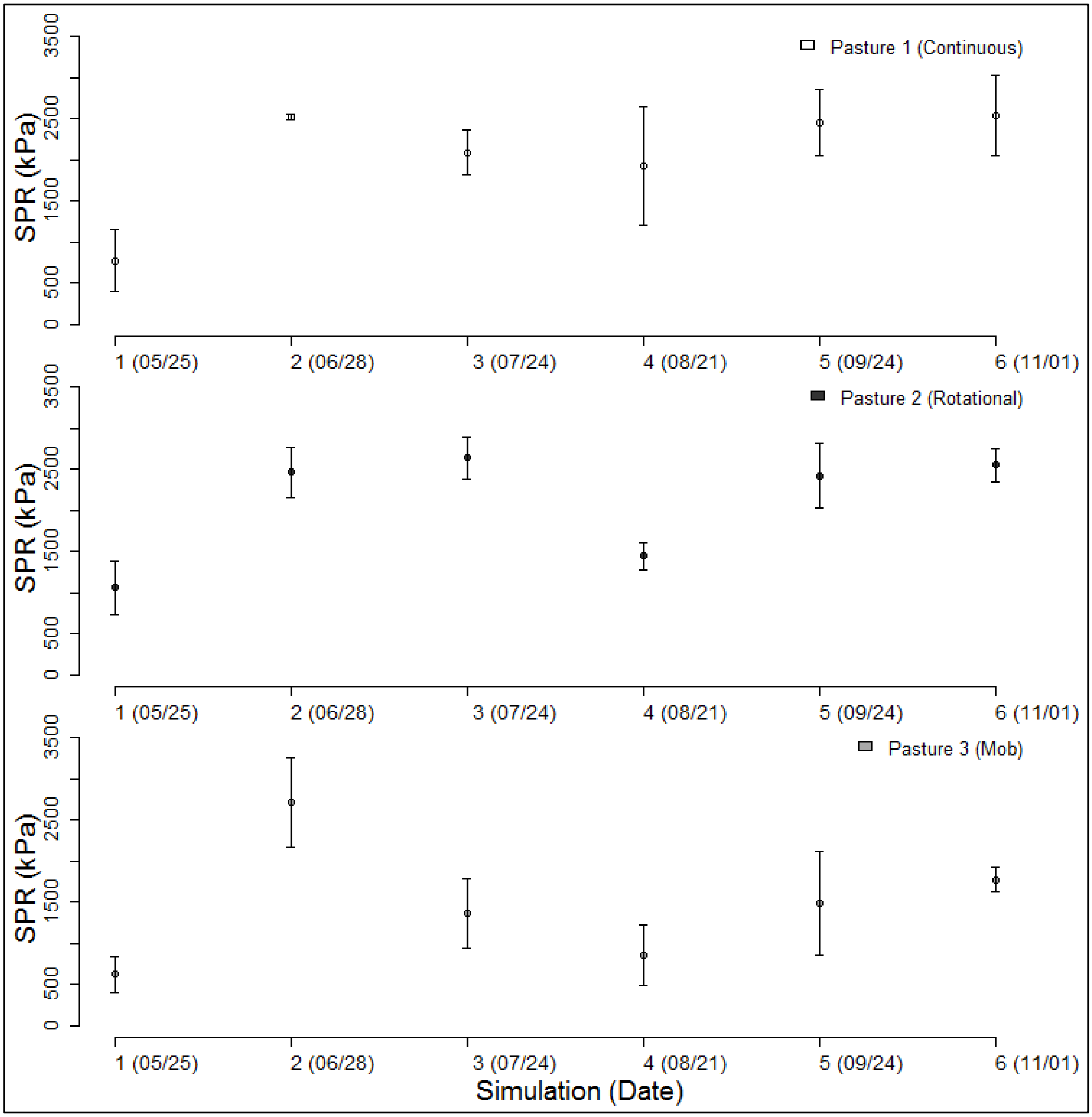


Figure 4.14. Soil penetration resistance (kPa) by simulation and pasture/treatment.

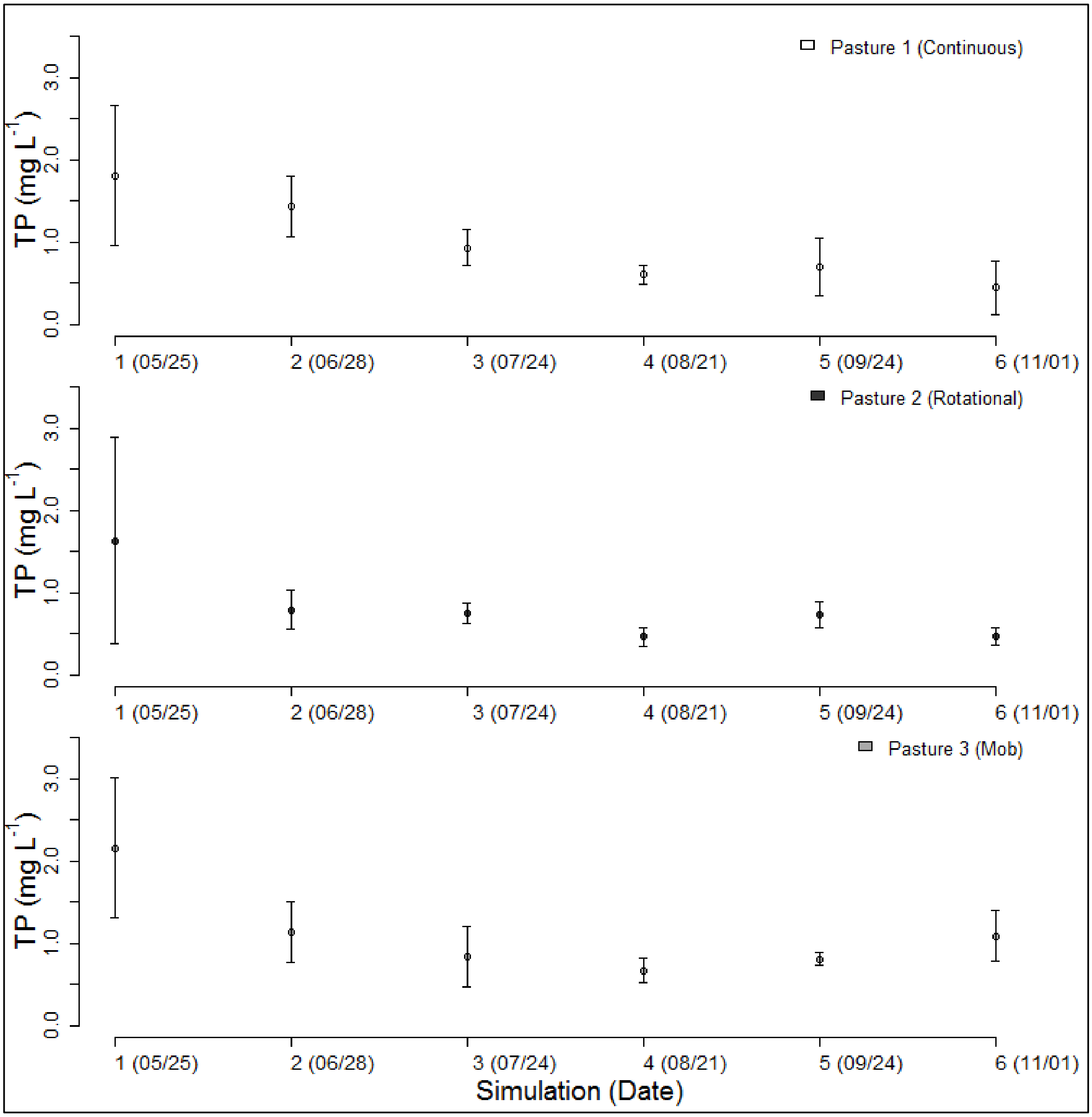


Figure 4.15. Event mean TP concentrations (mg L^{-1}) in runoff for initial conditions (Simulation 1) and post-stocking conditions (Simulations 2 through 6). Mob stocking occurred immediately prior to Simulations 2 and 6. (N = 3, except for Simulation 6 from the Mob treatment where N = 2.)

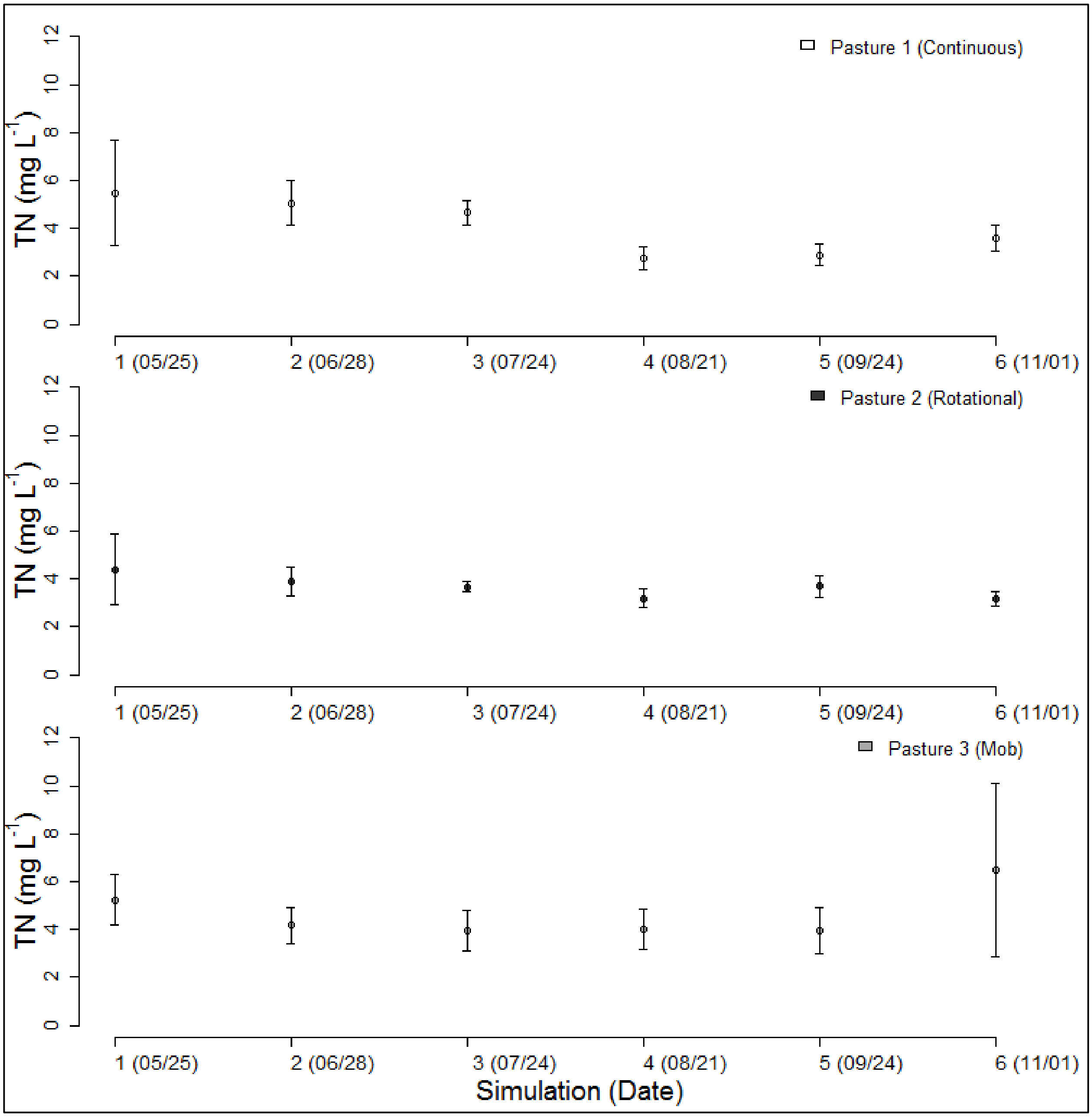


Figure 4.16. Event mean TN concentrations (mg L^{-1}) in runoff for initial conditions (Simulation 1) and post-stocking conditions (Simulations 2 through 6). Mob stocking occurred immediately prior to Simulations 2 and 6. (N = 3, except for Simulation 6 from the Mob treatment where N = 2.)

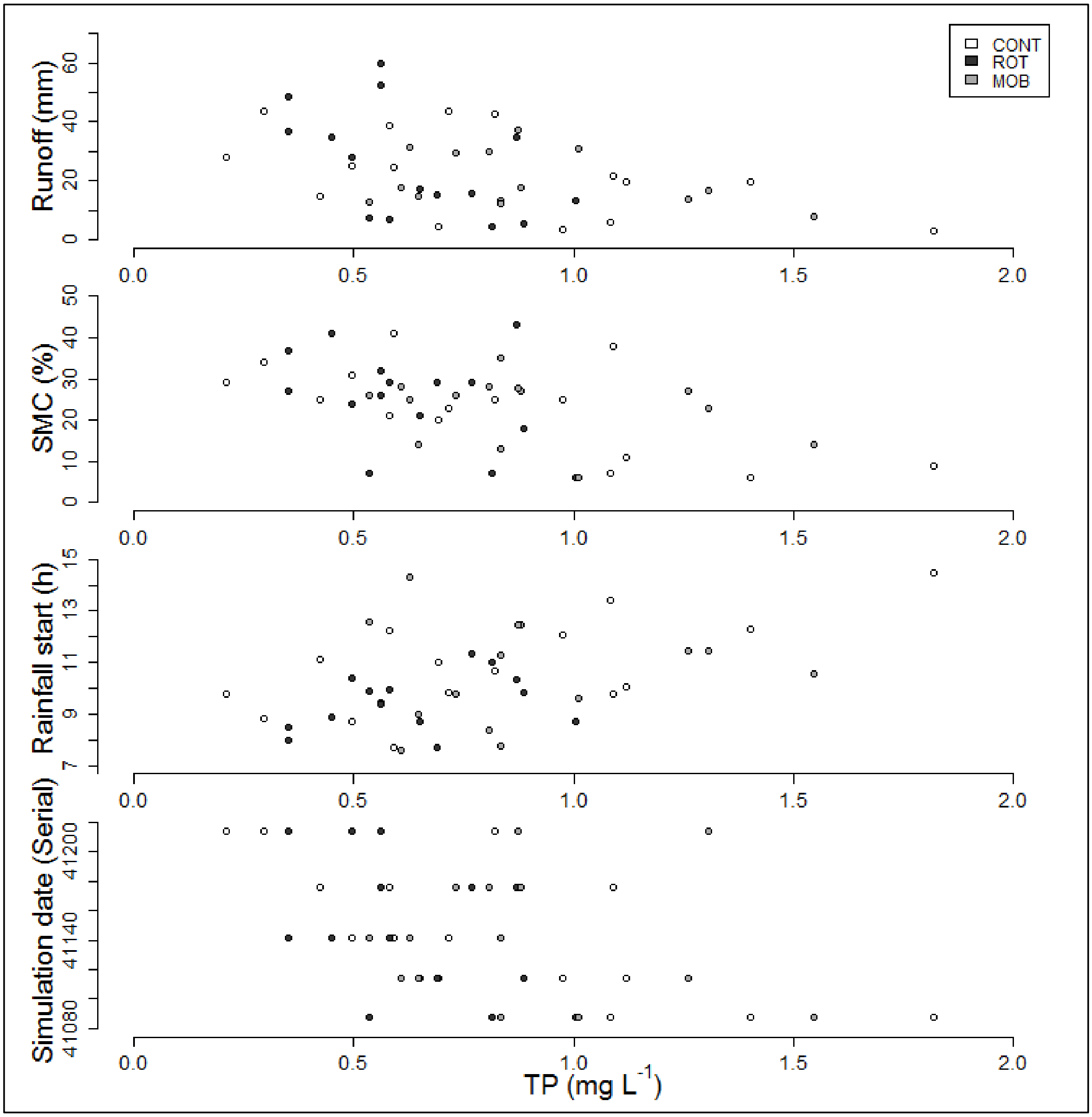


Figure 4.17. A pairwise comparison of mean TP concentrations (mg L^{-1}) in runoff and significantly correlated variables for post-stocking conditions (Simulations 2 through 6). Points are colored by stocking treatment. (N = 3, except for Simulation 6 from the Mob treatment where N = 2.)

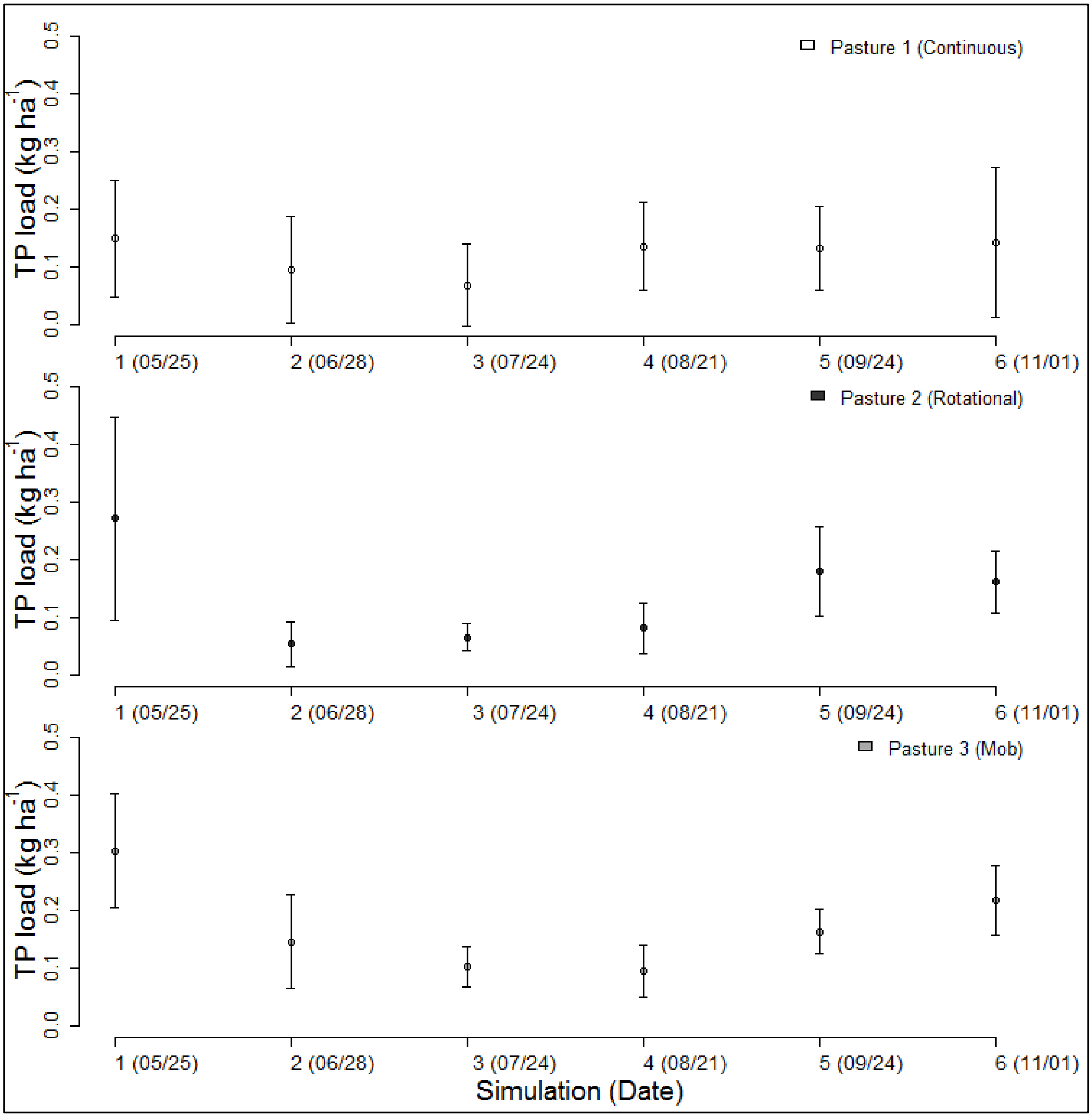


Figure 4.18. TP load (kg ha^{-1}) for initial conditions (Simulation 1) and post-stocking conditions (Simulations 2 through 6). Mob stocking occurred immediately prior to Simulations 2 and 6. (N = 3, except for Simulation 6 from the Mob treatment where N = 2.)

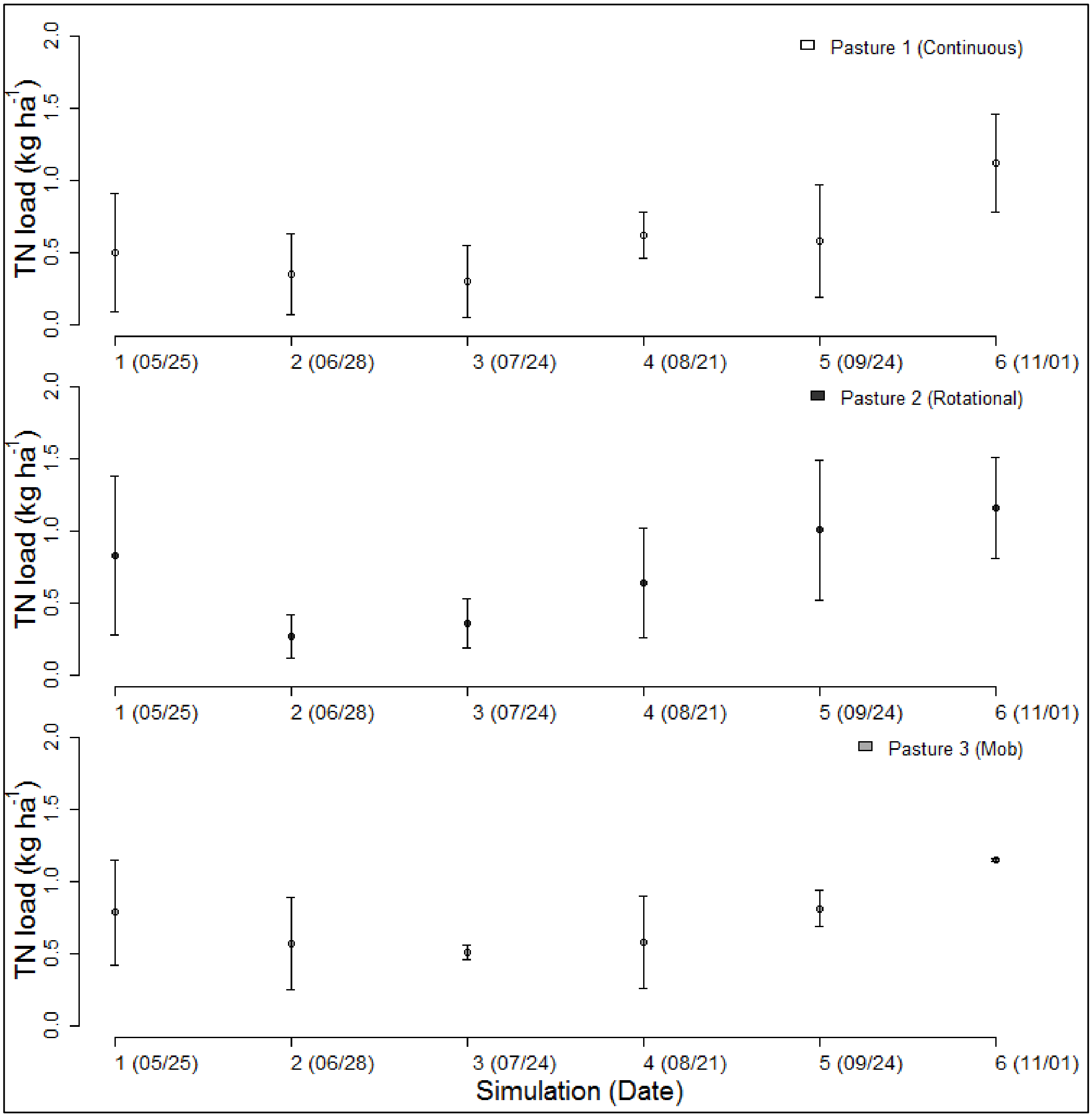


Figure 4.19. TN load (kg ha^{-1}) for initial conditions (Simulation 1) and post-stocking conditions (Simulations 2 through 6). Mob stocking occurred immediately prior to Simulations 2 and 6. (N = 3, except for Simulation 6 from the Mob treatment where N = 2.)

Table 4.1. Response variable means (μ), standard deviations (σ), and coefficient of variations (CV) from initial conditions (Simulation 1).

Variable	Pasture	μ	σ	CV
Runoff (mm)	All	19.5	13.8	0.71
	1	14.3	13.5	0.95
	2	24.8	18.9	0.76
	3	19.3	12.0	0.62
Mean TP concentration (mg L^{-1})	All	1.9	0.9	0.48
	1	1.8	0.8	0.47
	2	1.6	1.3	0.77
	3	2.2	0.9	0.40
Mean DP concentration (mg L^{-1})	All	1.98	0.94	0.47
	1	2.04	0.97	0.48
	2	1.71	1.32	0.77
	3	2.20	0.81	0.37
Mean TN concentration (mg L^{-1})	All	5.04	1.50	0.30
	1	5.48	2.19	0.40
	2	4.40	1.47	0.33
	3	5.24	1.04	0.20
Mean DN concentration (mg L^{-1})	All	5.41	2.19	0.40
	1	6.51	3.54	0.54
	2	5.16	1.61	0.31
	3	4.57	1.09	0.24
TP load (kg ha^{-1})	All	0.24	0.13	0.55
	1	0.15	0.10	0.68
	2	0.27	0.18	0.65
	3	0.30	0.10	0.33
TN load (kg ha^{-1})	All	0.70	0.42	0.60
	1	0.50	0.41	0.83
	2	0.83	0.55	0.67
	3	0.79	0.36	0.46

Table 4.2. Plot condition means (μ), standard deviations (σ), and coefficient of variations (CV) for initial conditions (Simulation 1).

Variable	Pasture	μ	σ	CV
Dry matter yield[a] (kg ha^{-1})	All	1405.0	223.4	0.16
	1	1661.1	216.3	0.13
	2	1242.3	36.5	0.03
	3	1311.6	18.2	0.01
Soil moisture content (%)	All	31	7	0.23
	1	25	8	0.32
	2	36	7	0.19
	3	33	1	0.03
Soil penetration resistance (kPa)	All	815	332	0.41
	1	770	377	0.49
	2	1057	320	0.30
	3	620	219	0.35
Ground coverage (%)	All	100	0	0.00
	1	100	0	0.00
	2	100	0	0.00
	3	100	0	0.00
Slope (%)	All	14.3	1.4	0.10
	1	14.6	0.5	0.03
	2	13.6	1.5	0.11
	3	14.8	1.7	0.11

[a]Dry matter yield for Simulation 1 was estimated using results from the grid sampling.

Table 4.3. Rainfall and runoff characteristic means (μ), standard deviations (σ), and coefficient of variations (CV) from initial conditions (Simulation 1).

Variable	Pasture	μ	σ	CV
Time to runoff (min)	All	8.7	4.1	0.47
	1	5.7	4.0	0.71
	2	11.3	3.2	0.28
	3	9.0	4.0	0.44
Rainfall intensity (mm hr^{-1})	All	103.1	7.3	0.07
	1	106.2	6.7	0.06
	2	103.7	3.8	0.04
	3	99.5	10.9	0.11
Runoff rate (L ha^{-1} s^{-1})	All	89.4	65.4	0.73
	1	64.4	61.1	0.95
	2	114.6	89.3	0.78
	3	89.2	59.4	0.67
Runoff ratio (mm mm^{-1})	All	0.14	0.10	0.71
	1	0.10	0.10	1.00
	2	0.17	0.13	0.76
	3	0.14	0.09	0.64
Wind factor (L L^{-1})	All	0.59	0.08	0.14
	1	0.61	0.07	0.11
	2	0.60	0.13	0.22
	3	0.56	0.04	0.07
Applied rain (mm)	All	70	5	0.06
	1	67	3	0.05
	2	76	3	0.04
	3	68	1	0.01
Rainfall duration (s)	All	2470	246	0.10
	1	2290	242	0.11
	2	2630	193	0.07
	3	2490	240	0.10
Runoff duration (s)	All	2230	112	0.05
	1	2286	161	0.07
	2	2197	70	0.03
	3	2208	112	0.05
Start Time (h)	All	12.1	2.5	0.21
	1	12.3	1.9	0.15
	2	9.6	1.8	0.19
	3	14.2	1.3	0.09

Table 4.4. Correlation coefficients for measurements during initial conditions (Simulation 1).

	Runoff	Mean TP conc	Mean DP conc	Mean TN conc	Mean DN conc	TP load	TN load	DM	SMC	SPR	Coverage	Time to runoff	Intensity	Runoff rate	Runoff ratio	Wind Factor	Applied rain	Rain duration	Runoff duration	Rainfall start time
Runoff																				
Mean TP conc	-0.66																			
Mean DP conc	-0.71	0.98																		
Mean TN conc	-0.74	0.84	0.91																	
Mean DN conc	-0.68	0.63	0.74	0.90																
TP load	**0.76**	-0.07	-0.17	-0.39	-0.56															
TN load	**0.98**	-0.51	-0.58	-0.66	-0.68	0.87														
DM	-0.51	0.27	0.37	0.59	0.70	-0.60	-0.56													
SMC	0.29	-0.05	-0.08	0.01	0.06	0.29	0.28	-0.34												
SPR	0.01	0.09	0.05	-0.21	-0.07	0.09	0.01	-0.16	-0.17											
Coverage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA										
Time to runoff	-0.17	0.23	0.18	-0.12	-0.21	0.14	-0.11	-0.57	0.01	0.48	NA									
Intensity	0.44	-0.43	-0.41	-0.20	0.04	0.01	0.35	0.23	0.07	-0.03	NA	-0.79								
Runoff rate	**1.00**	-0.66	-0.71	-0.73	-0.67	0.76	0.98	-0.50	0.30	0.02	NA	-0.18	0.44							
Runoff ratio	**1.00**	-0.66	-0.71	-0.73	-0.69	0.76	0.98	-0.49	0.26	-0.02	NA	-0.20	0.44	1.00						
Wind Factor	0.72	-0.36	-0.29	-0.15	-0.05	0.48	0.71	0.04	0.18	-0.24	NA	-0.37	0.43	0.72	0.73					
Applied rain	0.26	-0.14	-0.20	-0.45	-0.33	0.26	0.24	-0.68	0.11	0.76	NA	0.69	-0.11	0.25	0.21	-0.12				
Rain duration	-0.17	0.23	0.18	-0.12	-0.21	0.14	-0.11	-0.57	0.01	0.48	NA	1.00	-0.79	-0.18	-0.20	-0.37	0.69			
Runoff duration	-0.73	0.55	0.67	0.88	0.92	-0.65	-0.74	0.64	-0.03	-0.33	NA	-0.16	-0.12	-0.73	-0.73	-0.04	-0.44	-0.16		
Rainfall start time	-0.41	0.37	0.35	0.29	0.01	-0.13	-0.29	0.26	-0.39	-0.05	NA	-0.06	-0.28	-0.40	-0.37	-0.54	-0.44	-0.06	0.05	
Slope	0.35	-0.55	-0.54	-0.29	-0.23	-0.04	0.29	0.18	0.18	-0.37	NA	-0.76	0.64	0.37	0.38	0.20	-0.47	-0.76	-0.25	0.24

Table 4.5. Correlation test p-values for measurements during initial conditions (Simulation 1).

	Runoff	Mean TP conc	Mean DP conc	Mean TN conc	Mean DN conc	TP load	TN load	DM	SMC	SPR	Coverage	Time to runoff	Intensity	Runoff rate	Runoff ratio	Wind Factor	Applied rain	Rain duration	Runoff duration	Rainfall start time
Runoff																				
Mean TP conc	0.05																			
Mean DP conc	0.03	**<0.01**																		
Mean TN conc	0.02	<0.01	<0.01																	
Mean DN conc	0.05	0.07	0.02	**<0.01**																
TP load	**0.02**	0.86	0.65	0.30	0.11															
TN load	**<0.01**	0.16	0.10	0.05	0.04	<0.01														
DM	0.16	0.49	0.32	0.09	0.04	0.09	0.12													
SMC	0.45	0.91	0.85	0.98	0.87	0.45	0.46	0.37												
SPR	0.98	0.81	0.90	0.59	0.85	0.82	0.98	0.67	0.65											
Coverage	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA										
Time to runoff	0.66	0.55	0.64	0.76	0.58	0.73	0.77	0.11	0.98	0.19	NA									
Intensity	0.24	0.25	0.28	0.61	0.92	0.98	0.36	0.56	0.86	0.94	NA	0.01								
Runoff rate	**<0.01**	0.05	0.03	0.02	0.05	0.02	<0.01	0.17	0.43	0.96	NA	0.65	0.23							
Runoff ratio	**<0.01**	0.05	0.03	0.03	0.04	0.02	<0.01	0.18	0.50	0.95	NA	0.60	0.23	<0.01						
Wind Factor	0.04	0.39	0.49	0.72	0.91	0.22	0.05	0.92	0.67	0.56	NA	0.36	0.29	0.04	0.04					
Applied rain	0.51	0.71	0.60	0.22	0.39	0.50	0.54	0.04	0.78	0.02	NA	0.04	0.78	0.51	0.58	0.77				
Rain duration	0.66	0.55	0.64	0.76	0.58	0.73	0.77	0.11	0.98	0.19	NA	<0.01	0.01	0.65	0.60	0.36	0.04			
Runoff duration	0.03	0.13	0.05	<0.01	<0.01	0.06	0.02	0.06	0.94	0.38	NA	0.68	0.75	0.02	0.03	0.93	0.23	0.68		
Rainfall start time	0.27	0.33	0.36	0.45	0.97	0.74	0.45	0.50	0.31	0.89	NA	0.88	0.47	0.29	0.32	0.16	0.24	0.88	0.90	
Slope	0.35	0.13	0.13	0.46	0.56	0.93	0.45	0.64	0.64	0.33	NA	0.02	0.06	0.33	0.31	0.64	0.20	0.02	0.52	0.53

Table 4.6. Response variable means (μ) and standard deviations (σ) from post-treatment conditions (Simulations 2 through 6).

		Simulation number											
		2		3		4		5		6		Post-stocking Simulations	
Variable	Treatment	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Runoff (mm)	**All**	**11.8**	**8.9**	**12.4**	**6.2**	**25.3**	**12.5**	**29.1**	**14.4**	**37.1**	**12.2**	**22.8**	**14.5**
	CONT	9.5	8.8	9.1	8.9	31.2	10.7	25.0	12.5	38.0	8.8	22.6	14.7
	ROT	8.4	4.3	12.6	6.4	26.2	16.6	36.7	22.3	43.0	13.2	25.4	18.3
	MOB	17.5	12.1	15.4	2.1	18.7	10.8	25.6	6.8	26.9	14.7	20.4	9.3
Mean TP concentration (mg L^{-1})	**All**	**1.1**	**0.4**	**0.8**	**0.2**	**0.6**	**0.1**	**0.7**	**0.2**	**0.6**	**0.4**	**0.8**	**0.4**
	CONT	1.4	0.4	0.9	0.2	0.6	0.1	0.7	0.3	0.4	0.3	0.8	0.5
	ROT	0.8	0.2	0.7	0.1	0.5	0.1	0.7	0.2	0.5	0.1	0.6	0.3
	MOB	1.1	0.4	0.8	0.4	0.7	0.2	0.8	0.1	1.1	0.3	0.9	0.3
Mean TN concentration (mg L^{-1})	**All**	**4.39**	**0.85**	**4.10**	**0.67**	**3.31**	**0.77**	**3.52**	**0.75**	**4.16**	**2.02**	**3.89**	**1.13**
	CONT	5.06	0.95	4.65	0.52	2.75	0.47	2.89	0.44	3.59	0.53	3.79	1.09
	ROT	3.91	0.60	3.68	0.19	3.18	0.39	3.69	0.45	3.18	0.29	3.53	0.46
	MOB	4.18	0.74	3.97	0.84	4.01	0.86	3.97	0.97	6.49	3.63	4.39	1.51
TP load (kg ha^{-1})	**All**	**0.10**	**0.08**	**0.08**	**0.05**	**0.10**	**0.06**	**0.16**	**0.06**	**0.17**	**0.09**	**0.12**	**0.07**
	CONT	0.09	0.09	0.07	0.07	0.14	0.08	0.13	0.07	0.14	0.13	0.11	0.08
	ROT	0.05	0.04	0.07	0.02	0.08	0.04	0.18	0.08	0.16	0.05	0.11	0.07
	MOB	0.15	0.08	0.10	0.04	0.09	0.05	0.16	0.04	0.22	0.06	0.14	0.06
TN load (kg ha^{-1})	**All**	**0.40**	**0.26**	**0.39**	**0.18**	**0.61**	**0.26**	**0.80**	**0.37**	**1.14**	**0.26**	**0.66**	**0.38**
	CONT	0.35	0.28	0.30	0.25	0.62	0.16	0.58	0.39	1.12	0.34	0.59	0.39
	ROT	0.27	0.15	0.36	0.17	0.64	0.38	1.01	0.49	1.16	0.35	0.69	0.46
	MOB	0.57	0.32	0.51	0.05	0.58	0.32	0.81	0.12	1.15	0.01	0.69	0.29

Table 4.7. Coefficients of variation (CV) for data from post-stocking simulations (Simulations 2 through 6).

		Simulation Number					
Variable	Treatment	2	3	4	5	6	Post-stocking Simulations
Runoff	**All**	**0.75**	**0.50**	**0.49**	**0.49**	**0.33**	**0.63**
	CONT	0.93	0.98	0.34	0.50	0.23	0.65
	ROT	0.51	0.51	0.64	0.61	0.31	0.72
	MOB	0.69	0.14	0.58	0.27	0.55	0.46
Mean TP concentration	**All**	**0.36**	**0.28**	**0.25**	**0.27**	**0.60**	**0.50**
	CONT	0.26	0.23	0.18	0.50	0.75	0.63
	ROT	0.30	0.17	0.25	0.21	0.23	0.50
	MOB	0.33	0.44	0.23	0.09	0.28	0.33
Mean TN concentration	**All**	**0.19**	**0.16**	**0.23**	**0.21**	**0.49**	**0.29**
	CONT	0.19	0.11	0.17	0.15	0.15	0.29
	ROT	0.15	0.05	0.12	0.12	0.09	0.13
	MOB	0.18	0.21	0.22	0.24	0.56	0.34
TP load	**All**	**0.78**	**0.58**	**0.53**	**0.38**	**0.51**	**0.58**
	CONT	0.98	1.07	0.56	0.56	0.93	0.73
	ROT	0.72	0.38	0.54	0.43	0.33	0.64
	MOB	0.56	0.35	0.48	0.24	0.28	0.43
TN load	**All**	**0.67**	**0.46**	**0.43**	**0.46**	**0.23**	**0.58**
	CONT	0.81	0.84	0.26	0.67	0.30	0.66
	ROT	0.56	0.47	0.60	0.48	0.30	0.67
	MOB	0.56	0.10	0.56	0.15	0.01	0.42

Table 4.8. Plot condition means (μ) and standard deviations (σ) for post-treatment conditions (Simulations 2 through 6). Forage was not sampled during Simulations 2 and 3.

		Simulation number																	
		2			3			4			5			6			Post-stocking Simulations		
Variable	Treatment	μ	σ	CV	μ	σ	CV	μ	σ	CV	μ	σ	CV	μ	σ	CV	μ	σ	CV
Dry matter yield (kg ha^{-1})	**All**							**2140.4**	**1370.2**	**0.64**	**2160.8**	**2476.1**	**1.15**	**1142.8**	**1318.5**	**1.15**	**1840.5**	**1809.6**	**0.98**
	CONT							1102.2	917.6	0.83	208.9	201.7	0.97	277.5	108.7	0.39	529.5	639.5	1.21
	ROT							1694.0	1128.8	0.67	891.2	642.5	0.72	607.2	308.5	0.51	1064.2	826.9	0.78
	MOB							3625.0	415.2	0.11	5382.4	607.7	0.11	3244.2	127.8	0.04	4188.8	1076.5	0.26
Soil moisture content (%)	**All**	**8**	**3**	**0.38**	**21**	**6**	**0.29**	**32**	**7**	**0.22**	**29**	**7**	**0.24**	**28**	**4**	**0.14**	**24**	**10**	**0.42**
	CONT	7	2	0.29	19	7	0.37	32	9	0.28	28	9	0.32	29	5	0.17	23	11	0.48
	ROT	7	1	0.14	23	6	0.26	36	6	0.17	33	9	0.27	28	4	0.14	25	12	0.48
	MOB	11	4	0.36	23	8	0.35	29	6	0.21	27	1	0.04	25	3	0.12	23	8	0.35
Soil penetration resistance (kPa)	**All**	**2588**	**359**	**0.14**	**1937**	**649**	**0.34**	**1411**	**624**	**0.44**	**2124**	**637**	**0.30**	**2352**	**461**	**0.20**	**2058**	**674**	**0.33**
	CONT	2524	40	0.02	2093	274	0.13	1933	721	0.37	2458	407	0.17	2540	492	0.19	2310	480	0.21
	ROT	2467	306	0.12	2642	258	0.10	1443	169	0.12	2425	391	0.16	2550	209	0.08	2267	526	0.23
	MOB	2712	545	0.20	1363	422	0.31	856	369	0.43	1491	634	0.43	1773	149	0.08	1629	768	0.47
Ground coverage (%)	**All**	**100**	**0**	**0**	**100**	**0**	**0**	**98**	**7**	**0.07**	**92**	**10**	**0.11**	**90**	**9**	**0.10**	**96**	**8**	**0.08**
	CONT	100	0	0	100	0	0	93	12	0.13	85	13	0.15	87	6	0.07	93	10	0.11
	ROT	100	0	0	100	0	0	100	0	0.00	90	7	0.08	87	10	0.11	96	8	0.08
	MOB	100	0	0	100	0	0	100	0	0.00	100	0	0.00	100	0	0.00	100	0	0.00

Table 4.9. Rainfall and runoff characteristic means (μ) and standard deviations (σ) from post-treatment conditions (Simulations 2 through 6).

		Simulation number												
		2		3		4		5		6		Post-stocking Simulations		
Variable	Treatment	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	CV
Time to runoff (min)	**All**	**12.9**	**14.9**	**13.0**	**9.6**	**13.2**	**14.9**	**13.6**	**16.4**	**6.6**	**2.7**	**12.0**	**12.6**	**1.05**
	CONT	6.0	1.0	7.0	0.0	4.7	0.6	5.3	1.2	4.3	0.6	5.5	1.2	0.22
	ROT	8.7	3.2	12.3	9.3	8.3	6.7	6.7	3.8	6.7	1.5	8.5	5.2	0.61
	MOB	24.0	24.4	19.7	12.6	26.7	20.8	28.7	23.4	10.0	2.8	22.7	17.5	0.77
Rainfall intensity (mm hr^{-1})	**All**	**105.8**	**6.1**	**100.8**	**10.7**	**99.4**	**4.1**	**92.7**	**8.1**	**90.8**	**9.8**	**98.1**	**9.5**	**0.10**
	CONT	108.0	9.8	108.0	7.4	102.6	2.7	89.4	8.3	96.5	7.5	100.9	9.8	0.10
	ROT	105.5	5.3	95.7	8.9	100.3	3.5	93.5	4.4	92.5	5.2	97.5	7.0	0.07
	MOB	103.7	3.3	98.7	14.3	95.3	2.4	95.1	12.2	79.7	12.1	95.6	11.2	0.12
Runoff rate (L ha^{-1} s^{-1})	**All**	**52.0**	**39.9**	**54.8**	**27.9**	**111.5**	**56.3**	**129.5**	**60.2**	**167.4**	**58.0**	**101.6**	**64.9**	**0.64**
	CONT	40.9	37.8	39.0	37.7	136.8	50.2	112.1	52.6	170.1	37.5	99.8	65.4	0.66
	ROT	36.7	17.8	54.0	27.3	116.5	74.9	159.4	93.6	199.8	63.6	113.3	82.8	0.73
	MOB	78.4	55.0	71.4	12.6	81.1	46.6	117.2	31.3	114.6	62.5	91.0	40.8	0.45
Runoff ratio (mm mm^{-1})	**All**	**0.08**	**0.07**	**0.08**	**0.05**	**0.19**	**0.11**	**0.23**	**0.14**	**0.31**	**0.10**	**0.18**	**0.13**	**0.72**
	CONT	0.07	0.07	0.07	0.07	0.25	0.09	0.23	0.13	0.32	0.09	0.19	0.13	0.68
	ROT	0.06	0.03	0.09	0.05	0.20	0.14	0.31	0.19	0.36	0.12	0.21	0.16	0.76
	MOB	0.11	0.11	0.09	0.01	0.12	0.10	0.15	0.07	0.23	0.11	0.13	0.09	0.69
Wind factor (L L^{-1})	**All**	**0.51**	**0.03**	**0.53**	**0.04**	**0.55**	**0.02**	**0.57**	**0.03**	**0.58**	**0.05**	**0.55**	**0.04**	**0.07**
	CONT	0.52	0.04	0.51	0.02	0.53	0.01	0.58	0.04	0.55	0.04	0.54	0.04	0.07
	ROT	0.51	0.02	0.56	0.03	0.54	0.03	0.57	0.02	0.58	0.02	0.55	0.03	0.05
	MOB	0.50	0.02	0.53	0.06	0.56	0.02	0.55	0.05	0.63	0.06	0.55	0.06	0.11
Applied rain (mm)	**All**	**80**	**26**	**76**	**16**	**75**	**22**	**70**	**22**	**59**	**4**	**72**	**20**	**0.28**
	CONT	69	5	71	5	64	1	56	4	59	5	64	7	0.11
	ROT	72	2	71	7	68	10	61	6	60	3	66	7	0.11
	MOB	98	45	86	27	94	33	94	24	56	5	88	29	0.33
Rainfall duration (s)	**All**	**2723**	**896**	**2730**	**574**	**2743**	**896**	**2763**	**984**	**2348**	**163**	**2669**	**754**	**0.28**
	CONT	2310	60	2370	0	2230	35	2270	69	2210	35	2278	71	0.03
	ROT	2470	193	2690	557	2450	399	2350	227	2350	92	2462	312	0.13
	MOB	3390	1466	3130	755	3550	1245	3670	1401	2550	170	3309	1050	0.32
Runoff duration (s)	**All**	**2281**	**68**	**2269**	**143**	**2285**	**64**	**2231**	**71**	**2232**	**90**	**2260**	**91**	**0.04**
	CONT	2331	23	2305	40	2289	76	2212	79	2228	31	2273	66	0.03
	ROT	2273	62	2344	213	2263	60	2293	62	2162	88	2267	114	0.05
	MOB	2239	88	2159	81	2304	75	2188	30	2343	9	2240	89	0.04
Start Time (h)	**All**	**10.8**	**2.2**	**9.7**	**1.6**	**10.1**	**2.2**	**10.5**	**1.4**	**10.2**	**1.3**	**10.3**	**1.8**	**0.17**
	CONT	13.4	1.1	11.0	1.0	8.7	1.1	11.0	1.2	9.8	0.9	10.8	1.8	0.17
	ROT	9.9	1.2	8.8	1.1	8.9	1.0	10.4	1.0	9.4	1.0	9.5	1.1	0.12
	MOB	9.3	1.4	9.3	1.9	12.7	1.5	10.2	2.1	12.0	0.7	10.6	2.0	0.19

Table 4.10. Correlation coefficients for measurements during post-treatment conditions (Simulation 2 through 6).

	Runoff	Mean TP conc	Mean DP conc	Mean TN conc	Mean DN conc	TP load	TN load	DM	SMC	SPR	Coverage	Time to runoff	Intensity	Runoff rate	Runoff ratio	Wind Factor	Applied rain	Rain duration	Runoff duration	Rainfall start time	Simulation date
Runoff																					
Mean TP conc	-0.45																				
Mean DP conc	-0.34	0.93																			
Mean TN conc	-0.44	0.65	0.56																		
Mean DN conc	-0.37	0.51	0.41	0.90																	
TP load	**0.73**	0.13	0.22	-0.09	-0.12																
TN load	**0.91**	-0.27	-0.18	-0.10	-0.03	0.80															
DM	-0.39	0.37	0.46	0.39	0.52	-0.07	-0.18														
SMC	0.43	-0.47	-0.33	-0.30	-0.31	0.18	0.36	-0.12													
SPR	0.25	0.03	-0.17	-0.12	-0.15	0.24	0.21	-0.71	-0.39												
Coverage	-0.67	0.28	0.28	0.32	0.33	-0.47	-0.56	0.65	-0.20	-0.47											
Time to runoff	-0.30	0.05	0.08	0.13	0.27	-0.17	-0.22	0.69	-0.04	-0.43	0.28										
Intensity	-0.29	0.00	-0.11	-0.24	-0.19	-0.42	-0.48	-0.07	-0.28	0.14	0.30	-0.17									
Runoff rate	1.00	-0.46	-0.35	-0.44	-0.37	0.72	0.91	-0.40	0.44	0.25	-0.67	-0.30	-0.29								
Runoff ratio	0.98	-0.41	-0.32	-0.38	-0.36	0.72	0.91	-0.53	0.41	0.34	-0.73	-0.43	-0.33	0.98							
Wind Factor	0.21	0.07	0.16	0.35	0.26	0.31	0.39	0.03	0.31	-0.11	-0.30	0.21	-0.92	0.21	0.27						
Applied rain	-0.39	0.04	0.02	0.02	0.18	-0.30	-0.37	0.68	-0.14	-0.34	0.37	0.93	0.19	-0.38	-0.52	-0.18					
Rain duration	-0.30	0.05	0.08	0.13	0.27	-0.17	-0.22	0.69	-0.04	-0.43	0.28	1.00	-0.17	-0.30	-0.43	0.21	0.93				
Runoff duration	-0.17	0.21	0.19	0.22	0.09	-0.09	-0.17	0.13	-0.24	0.00	0.14	-0.01	0.03	-0.23	-0.13	0.04	0.00	-0.01			
Rainfall start time	-0.27	0.46	0.48	0.47	0.42	-0.04	-0.15	0.29	-0.28	-0.13	0.02	0.03	-0.18	-0.28	-0.21	0.29	-0.07	0.03	0.26		
Simulation date	0.66	-0.44	-0.29	-0.12	-0.08	0.44	0.71	-0.23	0.62	0.01	-0.53	-0.14	-0.57	0.66	0.67	0.57	-0.33	-0.14	-0.22	-0.03	
Slope	0.27	-0.03	0.01	-0.11	-0.10	0.27	0.24	0.11	0.04	0.10	0.01	-0.32	0.21	0.27	0.27	-0.26	-0.24	-0.32	-0.05	0.11	0.02

Table 4.11. Correlation test p-values for measurements during post-treatment conditions (Simulations 2 through 6).

	Runoff	Mean TP conc	Mean DP conc	Mean TN conc	Mean DN conc	TP load	TN load	DM	SMC	SPR	Coverage	Time to runoff	Intensity	Runoff rate	Runoff ratio	Wind Factor	Applied rain	Rain duration	Runoff duration	Rainfall start time	Simulation date
Runoff																					
Mean TP conc	<0.01																				
Mean DP conc	0.03	**<0.01**																			
Mean TN conc	<0.01	<0.01	<0.01																		
Mean DN conc	0.01	<0.01	<0.01	**<0.01**																	
TP load	**<0.01**	0.39	0.15	0.58	0.42																
TN load	**<0.01**	0.07	0.23	0.53	0.86	<0.01															
DM	0.05	0.07	0.02	0.05	<0.01	0.73	0.38														
SMC	**<0.01**	<0.01	0.03	0.05	0.04	0.24	0.02	0.57													
SPR	0.11	0.88	0.30	0.45	0.36	0.14	0.20	<0.01	0.01												
Coverage	<0.01	0.07	0.07	0.04	0.03	<0.01	<0.01	<0.01	0.20	<0.01											
Time to runoff	0.05	0.73	0.62	0.41	0.08	0.27	0.14	<0.01	0.78	<0.01	0.07										
Intensity	0.06	0.99	0.47	0.12	0.23	<0.01	<0.01	0.73	0.06	0.38	0.05	0.27									
Runoff rate	<0.01	<0.01	0.02	<0.01	0.01	<0.01	<0.01	0.04	<0.01	0.11	<0.01	0.05	0.05								
Runoff ratio	<0.01	<0.01	0.03	0.01	0.02	<0.01	<0.01	<0.01	<0.01	0.03	<0.01	<0.01	0.03	<0.01							
Wind Factor	0.18	0.68	0.31	0.02	0.09	0.04	<0.01	0.89	0.05	0.51	0.05	0.19	<0.01	0.18	0.08						
Applied rain	<0.01	0.78	0.88	0.88	0.25	0.05	0.01	<0.01	0.36	0.03	0.02	<0.01	0.22	0.01	<0.01	0.25					
Rain duration	0.05	0.73	0.62	0.41	0.08	0.27	0.14	<0.01	0.78	<0.01	0.07	<0.01	0.27	0.05	<0.01	0.19	<0.01				
Runoff duration	0.28	0.16	0.21	0.16	0.58	0.58	0.26	0.54	0.12	0.99	0.39	0.94	0.83	0.14	0.39	0.78	1.00	0.94			
Rainfall start time	0.08	<0.01	<0.01	<0.01	<0.01	0.82	0.34	0.15	0.07	0.42	0.90	0.84	0.24	0.06	0.18	0.06	0.66	0.84	0.09		
Simulation date	**<0.01**	**<0.01**	0.06	0.45	0.59	<0.01	<0.01	0.27	<0.01	0.94	<0.01	0.37	<0.01	<0.01	<0.01	<0.01	0.03	0.37	0.16	0.83	
Slope	0.08	0.84	0.95	0.50	0.52	0.08	0.11	0.59	0.80	0.55	0.93	0.04	0.17	0.08	0.07	0.10	0.11	0.04	0.75	0.49	0.91

Table 4.12. Comparison of runoff quantity (runoff ratio) and nutrient concentrations in runoff between this study, other similar studies, and EPA suggested nutrient levels.

Variable	This study	Other studies	EPA suggested levels, lakes and reservoirs[c]	EPA suggested levels, rivers and streams[c]
Runoff ratio	0.06 - 0.36	0.21 - 0.54[a] 0.064 – 0.104[b]		
TP in runoff (mg L^{-1})	0.2 - 3.1	0.124 – 2.2[a] 0.06 - 0.80[b]	0.008	0.010
TN in runoff (mg L^{-1})	2.4 - 9.1	1.2 – 10.7[a] 0.35 - 2.38[b]	0.46	0.31

[a] From Elliott and Carlson (2004), where TN is reported as TKN
[b] From Jones et al. (2009)
[c] From EPA (2002)

Table 4.13. Simulated rainfall source water mean nutrient concentrations for each simulation.

Simulation Number	TP (mg L^{-1})	TN (mg L^{-1})
1	0.1	2.68
2	0.0	2.36
3	0.0	2.33
4	0.0	1.63
5	0.0	1.69
6	0.0	2.36
Average	**0.0**	**2.03**

Chapter 5. Conclusions and Recommendations

5.1 Conclusions

Conclusions related to each objective and hypothesis (Chapter 1) pair are described below.

Objective 1: To compare runoff quantity from pastureland among stocking treatments within a grazing season.

Hypothesis 1: Runoff quantity was expected to increase throughout the season from the Continuous treatment due to cumulative effects of soil compaction and defoliation. Runoff quantity in the Rotational treatment was expected to remain constant within the grazing season because rest periods allow for some hydrologic recovery and re-vegetation. Runoff quantity for the Mob treatment was expected to be highest directly after stocking followed by a decreasing trend signifying hydrologic recovery and re-vegetation. The Mob and Rotational treatments were expected to yield lower runoff quantities than the Continuous treatment.

Conclusion 1: No differences were found among treatments for average-event runoff, runoff at the end of the season, or trends in runoff. Runoff quantity increased throughout the season for all stocking methods and was not significantly correlated with soil compaction or dry matter yield, but was significantly correlated with soil moisture content. Runoff quantity was also significantly correlated with ground coverage and applied rainfall, however the small variations in these values (CV = 0.08 and 0.28, respectively) resulted in minimal impact on overall runoff. Runoff quantity from the Mob treatment was not affected by the stocking events that occurred immediately prior to Simulations 2 and 6. Additionally, runoff do not differ between initial conditions (Simulation 1) and the first post-stocking events (Simulation 2). The initial conditions of the hydrology of the pastureland at PFRF varied widely across plots and within pastures. The variability in runoff depth decreased over time across the grazing season, but this decrease in variability was lowest for the Mob treatment.

Objective 2: To compare mean nutrient concentrations in runoff from pastureland among stocking treatments within a grazing season.

Hypothesis 2: Mean nutrient concentrations in runoff from the Continuous treatment were expected to increase during the grazing season. Mean nutrient concentrations in runoff from the Rotational treatment were expected to remain constant over the grazing season. Mean nutrient concentrations in runoff from the Mob treatment were expected to be high directly after stocking and decrease between stocking events.

Conclusion 2: No differences were found among treatments for average-event TP concentrations or trends in mean TP concentrations; however, there were differences among treatments for mean TP concentrations at the end of the season. The differences in mean TP concentrations among treatments at the end of the season may be partially attributed to stocking method effect. Mean TP concentrations were higher from the Mob treatment at the end of the season than the Rotational or Continuous treatments. Higher mean TP concentrations from the Mob treatment at the end of the season may be due to the mob stocking event which occurred immediately prior to Simulation 6. No differences were found among treatments for average-event TN concentrations, mean TN concentrations at the end of the season, or trends in TN concentrations across the grazing season. Mean nutrient concentrations in runoff decreased for the first three post-stocking simulations (Simulations 2 through 4) for all treatments. Additionally, there was a decrease in the percentage of total nutrient concentration that was dissolved between the initial conditions (Simulation 1) and the first post-stocking simulation (Simulation 2).

Objective 3: To compare nutrient losses (loads) in runoff from pastureland among stocking treatments within a grazing season.

Hypothesis 3: Nutrient losses from the Continuous treatment were expected to increase throughout the grazing season due to expected increasing concentrations and runoff quantities. From the Rotational treatment, nutrient losses were expected to remain constant throughout the season. Nutrient losses in runoff from the Mob treatment were expected to be highest directly after stocking and decrease between stocking events. Among treatments, it was expected that nutrient losses would be greatest from the Continuous treatment throughout the grazing season and the Rotational treatment would yield the least amount of nutrient losses throughout the grazing season.

Conclusion 3: There was no difference among treatments for average-event nutrient loads, loads at the end of the season, or the trends across the grazing season. However, the overall trends in TP and TN loads across the season did differ: TN loads mimic runoff more closely than TP loads. The difference between TP and TN loads is due to the fact that TP concentrations were more variable than TN concentrations. Directly after Mob 2 (Simulation 6), though mean values are within the margin of error among treatments, mean TP load was the highest from the Mob treatment, due to its highest TP concentrations among treatments.

In summary, analyses of the response variables suggested that the large margins of variability within treatments made detection of effects on response variables across treatments impossible. Therefore, future efforts will require additional within treatment samples (or plots) or more effort to control the variability of response variables within treatments (e.g. slope, aspect, soil moisture content). Additionally, there may be a stocking density threshold, under which, treatment effects are minimal. Mob stocking densities have been suggested to approach 224,170 to 560,425 kg ha^{-1} (200,000 to 500,000 lb ac^{-1}) in order to effectively increase production (Salatin, 2008; Gordon, 2010; Kidwell, 2010). The stocking density used in 2012 was 63,000 kg ha^{-1} (56,000 lb ac^{-1}), which may have been below the threshold of creating a treatment effect.

5.2 Recommendations

<u>Recommendations related to cattle stocking treatments and pasture management:</u>

1) Replicate treatments.
   Treatments were not replicated at PFRF because space was limited. Replicating the stocking treatments is essential for statistical hypothesis testing. There is potential for replication at the Benson Farm, a farm in the Shenandoah Valley that VT has recently begun leasing for livestock management.
2) Increase Mob treatment stocking density.

Mob stocking densities have been suggested to approach 224,170 to 560,425 kg ha^{-1} (200,000 to 500,000 lb ac^{-1}) in order to effectively increase production (Salatin, 2008; Gordon, 2010; Kidwell, 2010). The stocking density used in 2012 was 63,000 kg ha^{-1} (56,000 lb ac^{-1}), which may have been below the threshold of creating a treatment effect. Increasing the stocking density of the Mob treatment, while maintaining a constant stocking rate among treatments, could be achieved by dividing the Mob treatment into more paddocks paired with appropriately timing cattle rotation.

3) Investigate animal behavior patterns within the Mob treatment.
   Animal behavior of the Mob treatment may have been impacted by transporting the cows to PFRF. Stress in cattle associated with transportation has been shown to affect animal behavior during and after transit (Swanson and Morrow-Tesch, 2001). Therefore, results from the Mob treatment as implemented at PFRF may differ from studies where cattle are kept on-site.
4) Design experiments to investigate the implications of site fertilization.
   Though fertilization may have been recommended to increase forage growth, we suspect that the decreasing trend in nutrient concentrations was partly due to fertilizer washout. Therefore, it is recommended that in situations where fertilization is necessary, runoff be collected from areas excluded from grazing so that fertilizer effect may be analyzed separately from grazing effects. Mowing or haying would be necessary in cattle exclusions used for runoff collection.

Recommendations related to within-treatment experimental units (e.g. plots):

1) Adjust experimental units by
   a. increasing the number of runoff plots per treatment
      The margins of variability of the data collected in 2012 were too large to determine a response signal. Increasing the number of runoff plots within each treatment would likely reduce the margins of variability, thereby increasing our power to detect differences across treatment. However, this would require a significant increase in infrastructure, and personnel, and time.
   b. increasing the size of the plots, or

Increasing the size of the runoff plots may help to average out small-scale local variability in soils (surface and subsurface) and, thereby, reduce the margins of variability within treatments. Increasing the size of the plots would require redesigning the plots and using a rainfall simulator with a larger footprint. Optimizing the size of the plot by experimentation would take considerable time and effort and may not lead to the desired result of reducing spatial variability while maintaining sufficient sample size.

c. instrumenting the entire sub-watersheds.

   An additional option is to instrument the three watersheds at their outlets with runoff quantity and quality data collection devices. This could be done in addition to conducting plot studies. Instrumenting the watersheds at the outlets would rely on natural rainfall to produce measurable runoff at the outlets, which historically has been rare (Burford et al., 1981). Instrumentation would also increase temporal variability and variability in rainfall amounts, duration, and distribution. Spatial variability of the treatments would be immeasurable for instrumented watersheds; therefore, data collected at the outlet of instrumented watersheds would require different analyses than were described in this study. Because of the rarity of natural runoff, it would probably take many years to collect enough data to make meaningful comparisons between treatments.

Additionally, for plot studies it is recommended to

2) Automate borders and pans installation.

   In 2012 borders and pans were installed by hand, which contributed to the variability among plots. For further studies that use these borders and pans, automating installation would likely reduce the variability among plots.

3) Investigate an experimental design with unique plot locations or,

   Returning to the same plot location for each simulation may have a cumulative effect of decreasing the amount of nutrients available to runoff with each simulation. We observed a decrease in nutrient concentrations across simulation date and attributed this to fertilizer washout. This decrease may also have been partly due to raining at the same location across simulation dates. To resolve the question of cumulative effects of rainfall application, it is recommended that the design of a study that has unique plot locations be investigated.

4) Maintain plots *in situ* throughout the grazing season.

   Maintaining plots *in situ* throughout the grazing season would allow for repeated measures analysis (if treatments were replicated), but it would be necessary to use a different plot design than was used in 2012. The plot design in 2012 was available from a previous study. It was necessary to remove and reinstall the plot borders and pans prior to each simulation so as to not disturb cattle behavior. Reinstalling the borders and pans for each simulation disturbed the land surface immediately prior to simulation and may have affected responses. The area of the plots was affected by reinstalling the borders and pans in the same locations throughout the season. When the collection pans were installed, it was necessary to insert the up-slope edge of the pans under the soil surface about 5 cm to ensure that runoff flowed into the pan. After the pans were removed (between simulations), cattle trampled the down-slope edge of the plot which made it necessary to refinish before the next simulation. Refinishing the down-slope edge of the plot reduced the plot area for each subsequent rainfall simulation. It must be noted that it was impossible to simply shift the up-slope edge of the plot because this would have created a preferential flow pathway where the border had been installed previously.

Recommendations for rainfall simulation protocol:

5) Include sediment sampling and analyses. Sediment is another water pollutant that may be affected by stocking method. Though water quality samples were collected for total suspended solids analysis (TSS) in 2012, data from the TSS analysis were unusable because calcium carbonate precipitate levels were not removed from overall suspended sediment levels. In future studies, it is recommended not to freeze samples before TSS analysis to prevent precipitate from forming.

6) Measure flow rates temporally within runoff events. Measuring flow rates within runoff events would allow comparison of an event hydrograph among treatments and also result in more accurate nutrient loads. The time it takes to fill each water quality sample should be recorded.

References

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

American Public Health Association (APHA). 1995. *Standard methods for the examination of water and wastewater.* American Public Health Association, American Water Works Association, and Water Pollution Control Federation. 19th edition, Washington, D.C.

Bellows, B. 2001. *Nutrient cycling in pastures. Livestock systems guide.* Available at https://attra.ncat.org/attra-pub/summaries/summary.php?pub=240. Accessed 02 May 2013.

Brannan, K. M., S. Mostaghimi, P. W. McClellan, and S. Inamdar. 2000. Animal waste BMP impacts on sediment and nutrient losses in runoff from the Owl Run watershed. *Trans. ASAE* 43(5): 1155-1166.

Briske, D.D., ed. 2011. *Conservation Benefits of Rangeland Practices: Assessment, Recommendations, and Knowledge Gaps.* United States Department of Agriculture, Natural Resources Conservation Service.

Buda, A. R., C. Church, P. J. A. Kleinman, L. S. Saporito, B. G. Moyer, and L. Tao. 2010. Using Rare Earth Elements to Control Phosphorus and Track Manure in Runoff. *J. Environ. Qual.* 39:1028–1035.

Burford, J. B., J. L. Delashmutt, and R. T. Roberts. 1981. *Hydrologic data for experimental agricultural watersheds in the United States, 1972. Misc. Pub. No. 1412*. Beltsville, Maryland: Water Data Laboratory, Beltsville Agricultural Research Center.

Burkitt, L. L., W. J. Dougherty, S. M. Carlson, and D. J. Donaghy. 2010. Effect of variable soil phosphorus on phosphorus concentrations in simulated surface runoff under intensive dairy pastures. *Aust. J. Soil Res.* 48: 231-237.

Chanasyk, D. S., E. Mapfumo, and W. Willms. 2003. Quantification and simulation of surface runoff from fescue grassland watersheds. *Ag. Water Manag.* 59: 137-153.

Chaubey, I., L. Chiang, M. W. Gitau, and S. Mohamed. 2010. Effectiveness of best management practices in improving water quality in a pasture-dominated watershed. *J. Soil and Water Cons.* 65(6): 424-437.

Chiang, L., I. Chaubey, M. W. Gitau, and J. G. Arnold. 2010. Differentiating impacts of land use changes from pasture management in a CEAP watershed using the SWAT mode. *Trans. ASABE* 53(5): 1569-1584.

Church, C. D., T. L. Veith, G. J. Fomar, A. R. Buda, G. W. Feyereisen, R. B. Bryant, J. P. Schmidt, C. J. Dell, and P. J. A. Kleinman. 2011. U.S. Department of Agriculture Agricultural Research

Service Mahantango Creek Watershed, Pennsylvania,United States: Long-term water quality database. *Water Resour. Res.* 47: W08704.

Cournane, F. C., R. McDowell, R. Littlejohn, and L. Condron. 2011. Effects of cattle, sheep and deer grazing on soil physical quality and losses of phosphorus and suspended sediment losses in surface runoff. *Ag., Ecosys. and Environ.* 140: 264-272.

Cox, J. W. 2001. Carbon and phosphorus losses from dairy pasture in South Australia. *Aust. J. Soil Res.* 39(5): 969-978.

Dietzel, K. 2012. Comparison of steady-state, water infiltration rates among farming systems, final report. *Practical Farmers*.

Dillaha, T. A., B. B. Ross, S., Mostaghimi, C. D. Heatwole, V. O. Shanholtz, and F. B. Givens. 1988. Rainfall simulation: A tool for best management practice education. *J. Soil and Water Conserv*. 43(4): 288–290.

Dougherty, W. J., P. J. Nicholls, P. J. Milham, E. J. Havilah, and R. A. Lawrie. 2008. Phosphorus fertilizer and grazing management effects on phosphorus in runoff from dairy pastures. *J. Environ. Qual.* 37(2): 417-428.

Earl, J. M., and C. E. Jones. 1996. The need for a new approach to grazing management - Is cell grazing the answer? *Rangel. J.* 18(2): 327-350.

Edwards, D. R., T. C. Daniel, H. D. Scott, J. F. Murdoch, M. J. Habiger, and H. M. Burks. 1996. Stream quality impacts of best management practices in a northwestern Arkansas basin. *Wat. Res. Bull.* 32(3): 499-509.

Elliott, A. H., and W. T. Carlson. 2004. Effects of sheep grazing episodes on sediment and nutrient loss in overland flow. *Aust. J. of Soil Res*. 42(2): 213-220.

Elliot, A. H., Y. Q. Tian, J. C. Rutherford, and W. T. Carlson. 2002. Effect of cattle treading on interrill erosion from hill pasture modelling concepts and analysis of rainfall simulator data. *Aust. J. of Soil Res.* 40 (6): 963-976.

EPA. 1994. *Standard Method 200.2. Sample Preparation procedure for spectrochemical determination of total recoverable elements: Revision 2.8.* U.S. EPA Office of Research and Development, Cincinatti, Ohio.

EPA. 2002. *Summary Table for the Nutrient Criteria Documents*. Available at http://www2.epa.gov/nutrient-policy-data/ecoregional-criteria-documents. Accessed 26 Jan 2014.

EPA. 2009. *National water quality inventory: Report to congress, 2004 reporting cycle: Findings.* Available at http://water.epa.gov/lawsregs/guidance/cwa/305b/upload/2009_05_20_305b_2004report_report2004pt3.pdf. Accessed 30 October 2013.

EPA. 2010. Chesapeake Bay Total Maximum Daily Load for nitrogen, phosphorus, and sediment. U.S. Environmental Protection Agency. EPA. Available at: http://www.epa.gov/reg3wapd/tmdl/ChesapeakeBay/tmdlexec.html. Accessed 31 October 2013.

Fleming, N. K., and J. W. Cox. 2001. Carbon and phosphorus losses from dairy pasture in South Australia. *Aust. J. Soil Res.* 39: 969-978.

Gali, R. K., M. L. Soupir, and S. Mostaghimi. 2012. A comparison of nutrient losses from two simulated pastureland management scenarios. *J. Environ. Monit.* 14:2421.

Gamougoun, N. D., R. P. Smith, M. K. Wood, and R. D. Pieper. 1984. Soil, vegetation, and hydrologic responses to grazing management at Fort Stanton, New Mexico. *J. Range Manage.* 37(6): 538-541.

Gilley, J. E., B. D. Patton, P. E. Nyren, and J. R. Simanton. 1996. Grazing and haying effects on runoff and erosion from a former Conservation Reserve Program site. *Appl. Eng. in Ag.* 12(6): 681-684.

Gordon, K. 2010. Mastering mob grazing: Ultra-high stock densities can yield impressive results. *Angus*. August: 80-81.

Haan, M. M., J. R. Russell, W. J. Powers, J. L. Kovar, and J. L. Benning. 2006. Grazing management effects on sediment and phosphorus in surface runoff. *Range. Eco. Manage.* 59(6): 607-615.

Habersack, M. J. 2002. Evaluation of nutrient and pathogen losses from various poultry litter storage methods. MS thesis. Blacksburg, Virginia: Virginia Tech, Department of Biological Systems Engineering.

Hobbs, H. W., and F. B. Crammatte. 1965. *Hydrologic Data for Experimental Agricultural Watershed in the United States 1960-61. Misc. Pub. No. 994.* Washington, D. C.: U.S. Dept. of Agriculture.

Hubbard, R. K., G. L. Newton, and G. M. Hill. 2004. Water quality and the grazing animal. J. *Anim. Sci.* 82 E-Suppl: E255-263.

Jones, M. G., R. W. Vervoort, and J. Cattle. 2009. Nutrient losses under simulated rainfall from pasture plots in the Great Lakes District, New South Wales. *Aust. J. of Soil Res.* 47(6): 555-564.

Kidwell, B. 2010. Mob grazing: High-density stocking builds profits back into the cattle business. *Angus*. March: 28-29.

Kleinman, P. J., A. N. Sharpley, R. W. McDowell, D. N. Flaten, A. R. Buda, L. Tao, L. Bergstrom, and Q. Zhu. 2011. Managing agricultrual phosphorus for water quality protection: principle for progress. *Plant Soil*. 349: 169-182.

Kothmann, M. 2009. Grazing methods: A viewpoint. *Rangelands* 31(5): 5-10.

Kuykendall, H. A., M. L. Cabrera, C. S. Hoveland, M. A. McCann, and L. T. West. 1999. Stocking method effects on nutrient runoff from pastures fertilized with broiler litter. *J. Environ. Qual.* 28(6): 1886-1890.

Lambert, M. G., B. P. Devantier, P. Nes, and P. E. Penny. 1985. Losses of nitrogen, phosphorus, and sediment in runoff from hill country under different fertilizer and grazing management regimes. *New Zealand J. of Ag. Res.* 28(3): 371-379.

Lodge, G. M., S. R. Murphy, and S. Harden. 2003. Effects of grazing and management on herbage mass, persistence, animal production and soil water content of native pastures. 1. A redgrass-wallaby grass pasture, Barraba, North West Slopes, New South Wales. *Aust. J. Experim. Ag.* 43: 875-890.

Lory, J., and C. Roberts. 2000. Managing nutrients in pastures to improve profitability and water quality. In: G. J. Bishop-Hurley, S.A. Hamilton, and R. Kallenbach (eds.) *Missouri Dairy Grazing Manual.* Missouri University Extension. University of Missouri. Columbia, MO.

Maguire. R. O., and S. E. Heckendorn. 2013. *Soil Test Recommendations for Virginia.* Virginia Cooperative Extension. Available at http://www.soiltest.vt.edu/PDF/recommendation-guidebook.pdf. Accessed 6 Nov 2013.

Matthews, B. W., L. E. Sollenberger, V. D. Nair, and C. R. Staples. 1994. Impact of grazing management on soil nitrogen, phosphorus, potassium, and sulfur distribution. *J. Environ. Qual.* 23: 1006-1013.

McDowell, R. W, ed. 2008. *Environmental Impacts of Pasture-based Farming.* Cambridge, MA. CABI.

McDowell, R. W., D. M. Nash, and F. Robertson. 2007. Sources of phosphorus lost from a grazed pasture receiving simulated rainfall. *J. Environ. Qual.* 36: 1281-1288.

McDowell, R. W., J. J. Drewry, R. W. Muirhead, and R. J. Paton. 2003. Cattle treading and phosphorus and sediment loss in overland flow from grazed cropland. *Aust. J. Soil Res.* 41: 1521-1532.

Mendez, A., T. Dillaha, and S. Mostaghimi. 1999. Sediment and nitrogen transport in grass filter strips. *JAWRA* 35(4): 867-875.

Mishra, A., B. L. Benham, and S. Mostaghimi. 2006. Sediment and nutrient losses from field-scale cropland plots treated with animal manure and inorganic fertilizer. *Water, Air, and Soil Poll.* 175: 61-76.

Mundy, G. N., K. J. Nexhip, N. R. Austin, and M. D. Collins. 2003. The influence of cutting and grazing on phosphorus and nitrogen in irrigation runoff from perennial pasture. *Aust. J. Soil Res.* 41(4): 675-685.

Mwendera, E. J., and M. A. M. Saleem. 1997. Hydrologic response to cattle grazing in the Ethiopian highlands. *Ag. Ecosys. Environ.* 64:33-41.

Naeth, M. A., and D. S. Chanasyk. 1996. Runoff and sediment yield under grazing in foothills fescue grasslands of Alberta. *Water Res. Bul.* 32(1): 89-95.

Nearing, M. A., H. Wei, J. J. Stone, F. B. Pierson, K. E. Spaeth, M. A. Weltz, D. C. Flanagan, and M. Hernandez. 2011. A rangeland hydrology and erosion model. *Trans. ASABE* 54(3): 1-8.

Nelson, C. J., ed. 2012. *Conservation Outcomes from Pastureland and Hayland Practices: Assessment, Recommendations, and Knowledge Gaps.* Allen Press, Lawrence, KS.

Nguyen, M. L., G. W. Sheath, C. M. Smith, and A. B. Cooper. 1998. Impact of cattle treading on hill land: 2. Soil physical properties and contaminant runoff. *New Zealand J. Ag. Res.* 41(2): 279-290.

Olness, A., S. J. Smith, E. D. Rhoades, and R. G. Menzel. 1975. Nutrient and Sediment Discharge from Agricultural Watersheds in Oaklahoma. *J. Environ. Qual.* 4(3): 331-336.

O'Reagain, P. J., J. Brodie, G. Fraser, J. J. Bushell, C. H. Holloway, J. W. Faithful, and D. Haynes. 2005. Nutrient loss and water quality under extensive grazing in the upper Burdekin river catchment, North Queensland. *Marine Poll. Bull.* 51:037-50.

Osmond, D.L., D.W. Meals, D. LK. Hoag, and M. Arabi, eds. 2012. *How to Build Better Agricultural Conservation Programs to Protect Water Quality: The National Institute of Food and Agriculture–Conservation Effects Assessment Project Experience.* Ankeny, IA: Soil and Water Conservation Society.

Owens, L. B., D. J. Barker, S. C. Loarch, M. J. Shipitalo, J. V. Bonta, and R. M. Sulc. 2012. Inputs and losses by surface runoff and subsurface leaching for pastures managed by continuous or rotational stocking. *J. Environ. Qual.* 41: 106-113.

Owens, L. B., W. M. Edwards, and R. W. Van Keuren. 1989. Sediment and nutrient losses from unimproved, all-year grazed watershed. *J. Environ. Qual.* 18(2): 232-238.

Park, S. W., S. Mostaghimi, R. A. Cooke, and P. W. McClellan. 1994. BMP impacts on watershed runoff sediment, and nutrient yields. *Wat. Res. Bull.* 30(6): 1011-1023.

Patton, C. J., and J. R. Kryskalla. 2003. Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Evaluation of alkaline persulfate digestion as an alternative to Kjeldahl digestion for determination of total dissolved nitrogen and phosphorus in water: U*.S. Geological survey Water-Resources Investigations Report 03-4174*, 33 p.

Peterson, P. R., and J. R. Gerrish. 1996. Grazing systems and spatial distribution of nutrients in pastures: Livestock management considerations. In: R.E. Joost and C.A. Roberts (eds.) *Nutrient Cycling in Forage Systems.* Potash and Phosphate Institute and Foundation of Agronomic Research. Manhattan, KS.

Pizzuto, J. E., W. C. Hession, and M. McBride. 2000. Comparing gravel-bed rivers in paired urban and rural catchments of southeastern Pennsylvania. *Geology* 28(1): 79-82.

Pluhar, J. J., R. W. Knight, and R. K. Heitschmidt. 1987. Infiltration rates and sediment production as influenced by grazing systems in the Texas Rolling Plains. *J. Range Manage.* 40(3): 240-243.

Rhoades, E. D., L. F. Locke, H. M. Taylor, and E. H. McIlvain. 1964. Water intake on a sandy range as affected by 20 years of differential cattle stocking rates. *J. Range Manage.* 185-190.

Salatin, J. 2008. An aggressive approach to controlled grazing: Tall grass mob stocking. *Acres U.S.A.* 38(5).

Sanderson, M. A., A. Franzluebbers, S. Gosless, J. Kiniry, L. Owens, K. Spaeth, J. Steiner, and T. Veith. 2011. Pastureland Conservation Effects Assessment Project: Status and expected outcomes. *J. Soil and Water Cons.* 66(5): 140a-145a.

Sanjari, G., B. Yu, H. Ghadiri, C. A. A. Ciesiolka, and C. W. Rose. 2009. Effects of time-controlled grazing on runoff and sediment loss. *Aust. J. of Soil Res.* 47(8): 796-808.

Savory, A. 1983. The Savory grazing method or holistic resource management. *Rangelands* 5: 155–159.

Schepers, J. S., and D. D. Francis. 1982. Chemical water quality of runoff from grazing land in Nebraska: I. Influence of grazing livestock. *J. Environ. Qual.* 11(3): 351-354.

Schepers, J. S., B. L. Hackes, and D. D. Francis. 1982. Chemical water quality of runoff from grazing land in Nebraska: II. Contributing factors. *J. Environ. Qual.* 11: 355-359.

Schnepf, M., and C. Cox (ed.) 2006. *Environmental benefits of conservation on croplands: the status of our knowledge*. Soil Water Conservation Society, Ankeny, IA.

Sharpley, A., and P. Kleinman. 2003. Effect of rainfall simulator and plot scale on overland flow and phosphorus transport. *J. Environ. Qual.* 32: 2172-2179.

Sharpley, A. N., S. C. Chapra, R. Wedepohl, J. T. Sims, T. C. Daniel, and K. R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and Options. *J. Environ. Qual.* 23: 437-451.

Soupir, M. L. 2003. Release and transport of bacteria and nutrients from livestock manure applied to pastureland. MS thesis. Blacksburg, Virginia: Virginia Tech, Department of Biological Systems Engineering.

Southern Extension-Research Activity (SERA-17). 2008. National Research Project for Simulated Rainfall - Surface Runoff Studies. Available at http://www.sera17.ext.vt.edu/Documents/National_P_protocol.pdf Accessed 13 December 2013.

Srinivasan, M. S., P. Kleinman, A. Sharpley, T. Buob, and W. Gburek. 2007. Hydrology of small field plots used to study phosphorus runoff under simulated rainfall. *J. Environ. Qual.* 36: 1833-1842.

Stout, W. L., S. L. Fales, L. D. Muller, R. R. Schnabel, G. F. Elwinger, and S. R. Weaver. 2000. Assessing the effect of management intensive grazing on water quality in the Northeast U. S. *J. Soil and Water Cons.* 55(2): 238-243.

Stout, W. L., S. L. Fales, L. D. Muller, R. R. Schnabel, and S. R. Weaver. 2000. Water quality implication of nitrate leaching from intensively grazed pasture swards in the northeast US. *Ag., Ecosyst., and Environ.* 77: 203-210.

Suszkiw, J. 2001. Rainfall simulators target runoff. *Ag. Research*. Oct: 18-20.

Swanson, J. C., and J. Morrow-Tesch. 2001. Cattle transport: Historical, research, and future perspectives. *J. Anim. Sci.* 79: E102-E109.

Teany, L. E. 2004. Phosphorus losses from simulated dairy management intensive grazing forage system. MS thesis. Blacksburg, Virginia: Virginia Tech, Department of Biological Systems Engineering.

Thomas, H. S. 2012. Ranchers sing the praises of mob grazing of cattle. *Beef.* February. Available at http://beefmagazine.com/pasture-range/ranchers-sing-praises-mob-grazing-cattle. Accessed 21 November 2013.

Thurow, T. L., W. H. Blackburn, and C. A. Taylor. 1988. Infiltration and interrill erosion responses to selected livestock grazing strategies, Edwards Plateau, Texas. *J. Range Manage.* 41(4): 296-302.

Tietz, N. 2011. Mob grazing produces prime pastures. Hay and Forage. February. Available at http://hayandforage.com/grazing/grading-mob-grazing-0501. Accessed 21 November 2013.

USDA. 2013. Summary Report: 2010 National Resources Inventory, Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available at http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1167354.pdf Accessed 30 Jan 2014.

USDA-ARS. 2006. *Environmental Effects of Conservation Practices on Grazing Lands: A Conservation Effects Assessment Project (CEAP) Bibliography. SRB 2006-02.* Beltsville, Maryland: National Agricultural Library.

USDA-ARS. 2012. NP 215 Action Plan for 2013-2018 Pasture, Forage and Rangeland Systems. Available at http://www.ars.usda.gov/SP2UserFiles/Program/215/NP215%20Action%20plan%20Final%20May%202013.pdf. Accessed 16 November 2013.

USDA-NRCS. 2010. Conservation Practice Standard: Prescribed grazing. Code 528. Natural Resources Conservation Service. Available at http://efotg.sc.egov.usda.gov/references/public/NE/NE528.pdf. Accessed 30 October 2013.

USDA-NRCS and U.S. Grazing Lands Technology Institute. 2003. *National range and pasture handbook*. Fort Worth, Texas: U.S. Dept. of Agriculture, Natural Resources Conservation Service, Grazing Lands Technology Institute.

Warren, S. D., W. H. Blackburn, and C. A. Taylor. 1986. Soil hydrologic response to number of pastures and stocking density under intensive rotation grazing. *J. Range Manage.* 39(6): 500-504.

Weltz, M. A., L. Jolley, D. Goodrich, K. Boykin, M. Nearing, J. Stone, P. Guertin, M. Hernandez, K. Spaeth, F. Pierson, C. Morris, and B. Kepner. 2011. Techniques for assessing the environmental outcomes of conservation practices applied to rangeland watersheds. *J. Soil and Water Cons.* 66(5): 154A-162A.

White, M. J., D. E. Storm, P. Busteed, S. Stoodley, and S. J. Phillips. 2010. Evaluating conservation program success with Landsat and SWAT. *Environ. Manag.* 45: 1164-1174.

Whitehead, D. C. 2000. *Nutrient Elements in Grassland: Soil-Plant-Animal Relationships*. CAB International, Wallingford, UK.

Wilcox, B. P., and M. K. Wood. 1988. Hydrologic impacts of sheep grazing on steep slopes in semiarid rangelands. *J. Range Manage.* 41(4): 303-306.

Wood, J., and M. Wood. 1988. Infiltration and water quality on range sites at Fort Stanton, New Mexico. *AWRA Water Resources Bulletin* 24 (2): 317-323.

Appendix A. Carbon Concentrations in Runoff

Table A.1. Dissolved organic carbon (DOC) concentrations (mg L^{-1}) in runoff.

Simulation	Plot	Sampling Time (min)	DOC (mg L^{-1})
1	1	2.5	21.5
1	1	12.5	13.8
1	1	22.5	11.4
1	1	32.5	9.5
1	2	2.5	30.5
1	2	12.5	20.7
1	2	22.5	14.1
1	2	32.5	15.8
1	3	2.5	20.1
1	3	12.5	12.4
1	3	22.5	10.7
1	3	32.5	9.0
1	4	2.5	19.0
1	4	12.5	11.0
1	4	22.5	8.8
1	4	32.5	7.6
1	5	2.5	12.7
1	5	12.5	10.0
1	5	22.5	7.8
1	5	32.5	7.0
1	6	2.5	16.2
1	6	12.5	10.9
1	6	22.5	7.4
1	6	32.5	7.0
1	7	2.5	21.0
1	7	12.5	15.2
1	7	22.5	11.8
1	7	32.5	10.6
1	8	2.5	44.8
1	8	12.5	25.9
1	8	22.5	16.8
1	8	32.5	14.4
1	9	12.5	16.7
1	9	22.5	15.7
1	9	32.5	14.8
1	10	2.5	17.4
1	10	12.5	10.2
1	10	22.5	7.1
1	10	32.5	5.9
2	1	2.5	40.8
2	1	12.5	24.5

2	1	22.5	16.4
2	1	32.5	14.9
2	2	2.5	66.9
2	2	12.5	33.7
2	2	22.5	28.0
2	2	32.5	24.3
2	3	2.5	40.7
2	3	12.5	23.4
2	3	22.5	17.0
2	3	32.5	13.1
2	4	2.5	31.4
2	4	12.5	19.4
2	4	22.5	16.2
2	4	32.5	11.0
2	5	2.5	20.6
2	5	12.5	14.2
2	5	22.5	11.1
2	5	32.5	10.4
2	7	2.5	23.4
2	7	12.5	15.6
2	7	22.5	12.9
2	7	32.5	10.0
2	8	2.5	79.7
2	8	12.5	57.1
2	8	22.5	42.5
2	8	32.5	32.1
2	9	2.5	20.6
2	9	12.5	20.5
2	9	22.5	18.5
2	9	32.5	16.7
2	10	2.5	30.9
2	10	12.5	19.6
2	10	22.5	15.7
2	10	32.5	13.4
3	1	2.5	13.8
3	1	12.5	10.0
3	1	22.5	8.3
3	1	32.5	7.8
3	2	2.5	14.0
3	2	12.5	10.6
3	2	22.5	8.7
3	2	32.5	6.9
3	3	2.5	14.7
3	3	12.5	8.2
3	3	22.5	4.7
3	3	32.5	4.6

3	4	2.5	11.3
3	4	12.5	7.2
3	4	22.5	4.4
3	4	32.5	4.0
3	5	2.5	16.2
3	5	12.5	9.9
3	5	22.5	6.6
3	5	32.5	6.1
3	7	2.5	10.4
3	7	12.5	8.2
3	7	22.5	7.1
3	7	32.5	6.0
3	8	2.5	13.7
3	8	12.5	11.1
3	8	22.5	11.8
3	8	32.5	5.7
3	9	2.5	5.8
3	9	12.5	5.7
3	9	22.5	5.5
3	9	32.5	4.4
3	10	2.5	10.2
3	10	12.5	5.6
3	10	22.5	4.4
3	10	32.5	3.6
4	1	2.5	24.0
4	1	12.5	14.1
4	1	22.5	10.3
4	1	32.5	8.7
4	2	2.5	26.2
4	2	12.5	11.9
4	2	22.5	7.8
4	2	32.5	6.2
4	3	2.5	20.0
4	3	12.5	10.5
4	3	22.5	7.3
4	3	32.5	6.5
4	4	2.5	15.1
4	4	12.5	7.3
4	4	22.5	5.6
4	4	32.5	5.0
4	5	2.5	18.9
4	5	12.5	10.0
4	5	22.5	8.0
4	5	32.5	5.3
4	7	2.5	23.8
4	7	12.5	18.6

4	7	22.5	14.9
4	7	32.5	12.4
4	8	2.5	29.7
4	8	12.5	23.4
4	8	22.5	15.4
4	8	32.5	14.2
4	9	2.5	15.6
4	9	12.5	13.1
4	9	22.5	9.7
4	9	32.5	10.4
4	10	2.5	31.1
4	10	12.5	15.5
4	10	22.5	11.4
4	10	32.5	8.9
5	1	2.5	20.5
5	1	12.5	10.2
5	1	22.5	7.9
5	1	32.5	6.5
5	2	2.5	21.1
5	2	12.5	12.0
5	2	22.5	7.7
5	2	32.5	7.3
5	3	2.5	20.5
5	3	12.5	9.8
5	3	22.5	7.6
5	3	32.5	6.1
5	4	2.5	14.4
5	4	12.5	7.9
5	4	22.5	5.6
5	4	32.5	5.7
5	5	2.5	20.3
5	5	12.5	8.0
5	5	22.5	7.5
5	5	32.5	6.1
5	7	2.5	16.5
5	7	12.5	13.3
5	7	22.5	9.8
5	7	32.5	8.1
5	8	2.5	26.7
5	8	12.5	17.4
5	8	22.5	11.9
5	8	32.5	10.6
5	10	2.5	25.7
5	10	12.5	0.0
5	10	22.5	10.4
5	10	32.5	8.1

6	1	2.5	11.8
6	1	12.5	6.4
6	1	22.5	4.8
6	1	32.5	4.2
6	2	2.5	10.5
6	2	12.5	5.5
6	2	22.5	4.1
6	2	32.5	3.3
6	3	2.5	13.8
6	3	12.5	15.4
6	3	22.5	10.8
6	3	32.5	7.5
6	4	2.5	15.3
6	4	12.5	6.4
6	4	22.5	4.7
6	4	32.5	4.0
6	5	2.5	11.3
6	5	12.5	5.8
6	5	22.5	4.5
6	5	32.5	4.3
6	7	2.5	11.5
6	7	12.5	9.0
6	7	22.5	6.7
6	7	32.5	5.6
6	8	2.5	71.0
6	8	12.5	46.0
6	8	22.5	32.3
6	8	32.5	29.6
6	10	2.5	28.0
6	10	12.5	20.3
6	10	32.5	12.0

Table A.2. Dissolved organic carbon (DOC) ($mg L^{-1}$) in source water samples.

Simulation	Date (mm/dd)	Source	DOC ($mg L^{-1}$)
1	05/25	Well	0.0
1	05/26	Well	0.0
1	06/28	Well	1.8
3	07/24	Well	3.8
3	07/25	Well	1.3
4	08/21	Well	1.5
4	08/22	Well	1.9
5	09/24	Mixed	2.6
5	09/24	Town	1.9
5	09/24	Well	2.6
5	09/26	Well	2.3
5	09/27	Well	1.8
6	11/02	Well	1.0

Appendix B. Rainfall Uniformity Coefficients (UC)

Table B.1. Rainfall uniformity coefficients (UC) for simulated rainfall events in 2012.

Simulation	Date	Plot	Rain1 (mm)	Rain2 (mm)	Rain3 (mm)	Rain4 (mm)	Rain5 (mm)	UC
1	05/25/12	1	80	62	97	62	42	0.77
1	05/25/12	2	70	38	75	69	65	0.84
1	05/25/12	3		78	73	55	73	0.89
1	05/26/12	4	70	70	72	80	75	0.96
1	05/26/12	5	76	60	75	83	80	0.92
1	05/26/12	6	65	77	75	75	87	0.93
1	05/26/12	7	88	79	83	73	70	0.93
1	05/26/12	8	68	74	70	59	68	0.95
1	05/26/12	9	46	80	80	65		0.82
1	05/26/12	10	70	70	74	65	68	0.97
2	06/28/12	1	89	70	80	58		0.86
2	06/28/12	2	95	63	88		32	0.68
2	06/28/12	3	34	63	83		76	0.76
2	06/28/12	4	60		82		67	0.88
2	06/28/12	5	71	69	80	74		0.95
2	06/28/12	7	50	83	91		70	0.82
2	06/29/12	8	76	73	90		81	0.93
2	06/29/12	9	190	157			100	0.78
2	06/29/12	10	80	68	77		38	0.79
3	07/25/12	1	91	64	87	68	43	0.79
3	07/25/12	2	81	73	90	72	65	0.90
3	07/25/12	3	45	66	83		72	0.83
3	07/24/12	4	65	48	70	82	63	0.87
3	07/24/12	5	65	47	83	79	61	0.83
3	07/24/12	7	104	75	115	76	26	0.69
3	07/24/12	8	35	79	100	43	89	0.65
3	07/25/12	9	145	147.5	98	77		0.75
3	07/25/12	10	90	80	85	74	32	0.78
4	08/22/12	1	71	66	71	57	56	0.90
4	08/22/12	2	66	57	68	64	65	0.96
4	08/22/12	3	69	60	69	58	56	0.92
4	08/21/12	4	71	57	64	67	67	0.94
4	08/21/12	5	60	55	67	64	55	0.93
4	08/21/12	7	74	82	90	77	72	0.93
4	08/21/12	8	87	89	98	74	81	0.92
4	08/21/12	9	128	138	140	124	120	0.94
4	08/21/12	10	66	66	75	65	57	0.94
5	09/24/12	1	65	51	74	58	41	0.84
5	09/24/12	2	77	44	68	62	45	0.80
5	09/24/12	3	44	53	70	37	55	0.83
5	09/26/12	4	63	54	67		54	0.91
5	09/26/12	5	66	45	65	55	47	0.86
5	09/26/12	7	65	69	77	65	64	0.94

5	09/26/12	8	122	128	140	87	108	0.87
5	09/27/12	9	98	106	106	82	83	0.89
5	09/27/12	10	75	71	76	66	61	0.93
6	11/02/12	1	68	59	74	63	48	0.89
6	11/02/12	2	67	63	78	59	42	0.85
6	11/02/12	3	60	28	68	68	44	0.74
6	11/03/12	4	68	33	81	66	38	0.70
6	11/03/12	5	62	44	82	64	52	0.83
6	11/03/12	7	65	50	75	70	55	0.87
6	11/03/12	8	44	60	80	23	57	0.71
6	11/03/12	10	61	45	75	60	57	0.88
							Average UC	0.86

Appendix C. Analysis of Sampling Time Effect on Nutrient Concentrations and Loads

For initial conditions (Simulation 1), there was a decreasing trend in TP and TN concentrations in runoff across sampling time for all pastures (table C.1, figs. C.1 and C.2). The decreasing trend in concentrations is most evident in data from Pasture 1. Therefore, sampling time may have affected event mean concentrations, particularly for Pasture 1. Incremental loads tended to increase between 2.5 and 12.5 mins of runoff, and then decrease for the rest of the event (table C.2, figs. C.5 and C.6). Sampling time had less of an effect on event loads because the initial samples, which generally had the highest concentrations, were used to calculate 2.5 minutes of loading, whereas samples throughout the rest of the runoff event were each used to calculate 10 minutes of loading.

During post-stocking conditions (Simulations 2 through 6), incremental TP and TN concentrations in runoff tend to decrease with sampling time for all treatments (figs. C.3 and C.4, table C.3). Variation in incremental TP concentrations was greatest from the Continuous treatment and, for all treatments, variation tended to decrease with simulation number. Incremental TN concentrations were less variable than incremental TP concentrations. Like event loads, incremental loads increased within the season (table C.4; figs. C.7 and C.8).

Correlation coefficients and p-values between sampling time and incremental nutrient concentrations and loads are shown in Table C.5. Correlation was tested for significance at the 0.01 level for initial conditions (Simulation 1), post-stocking conditions (Simulations 2 through 6), and all simulations. Sampling time was most strongly correlated with nutrient concentrations.

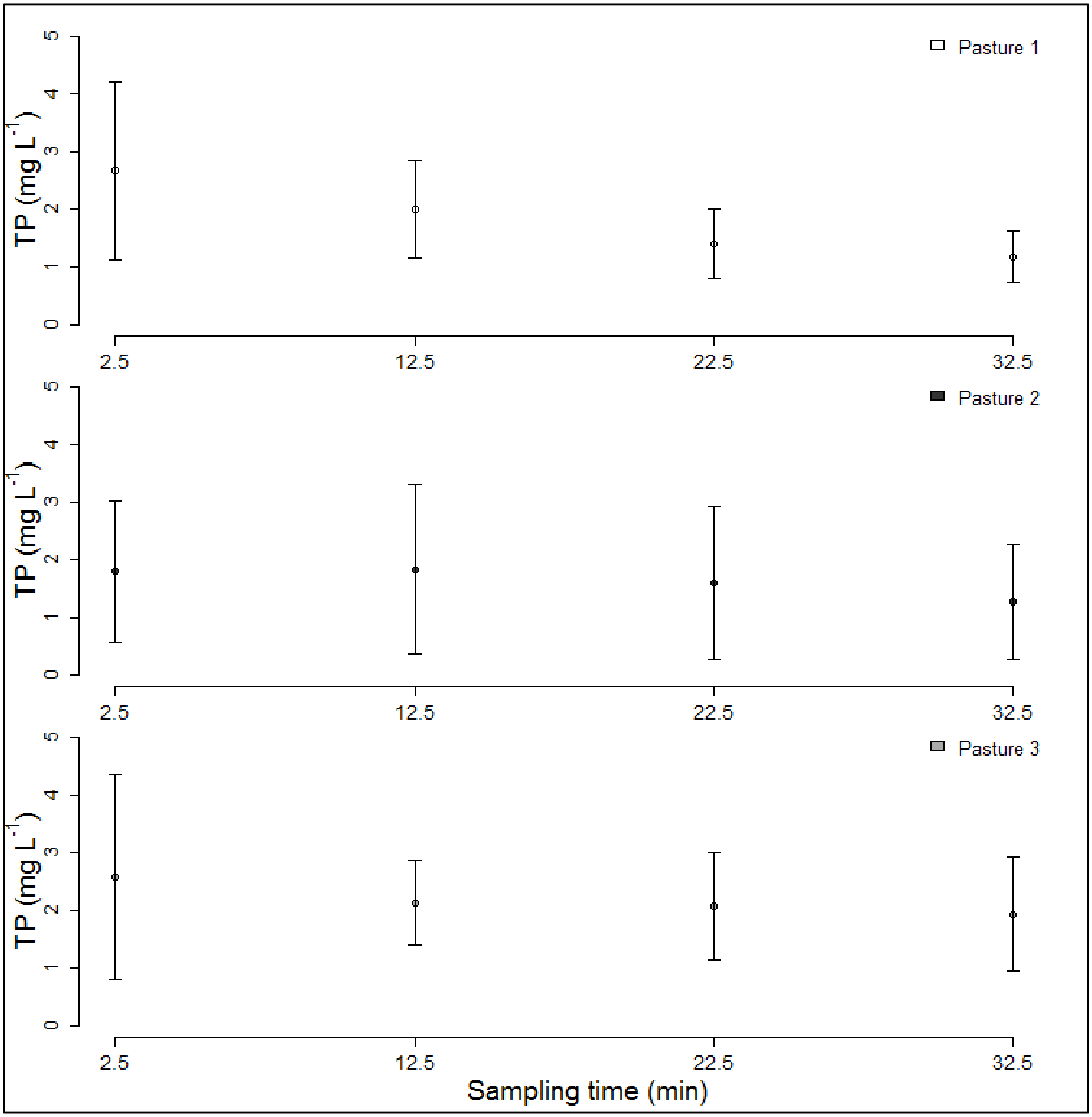


Figure C.1. Initial conditions (Simulation 1) TP concentrations (mg L^{-1}) in runoff by sampling time (min), averaged within pasture (N = 3). Whiskers extend plus or minus one standard deviation from the mean.

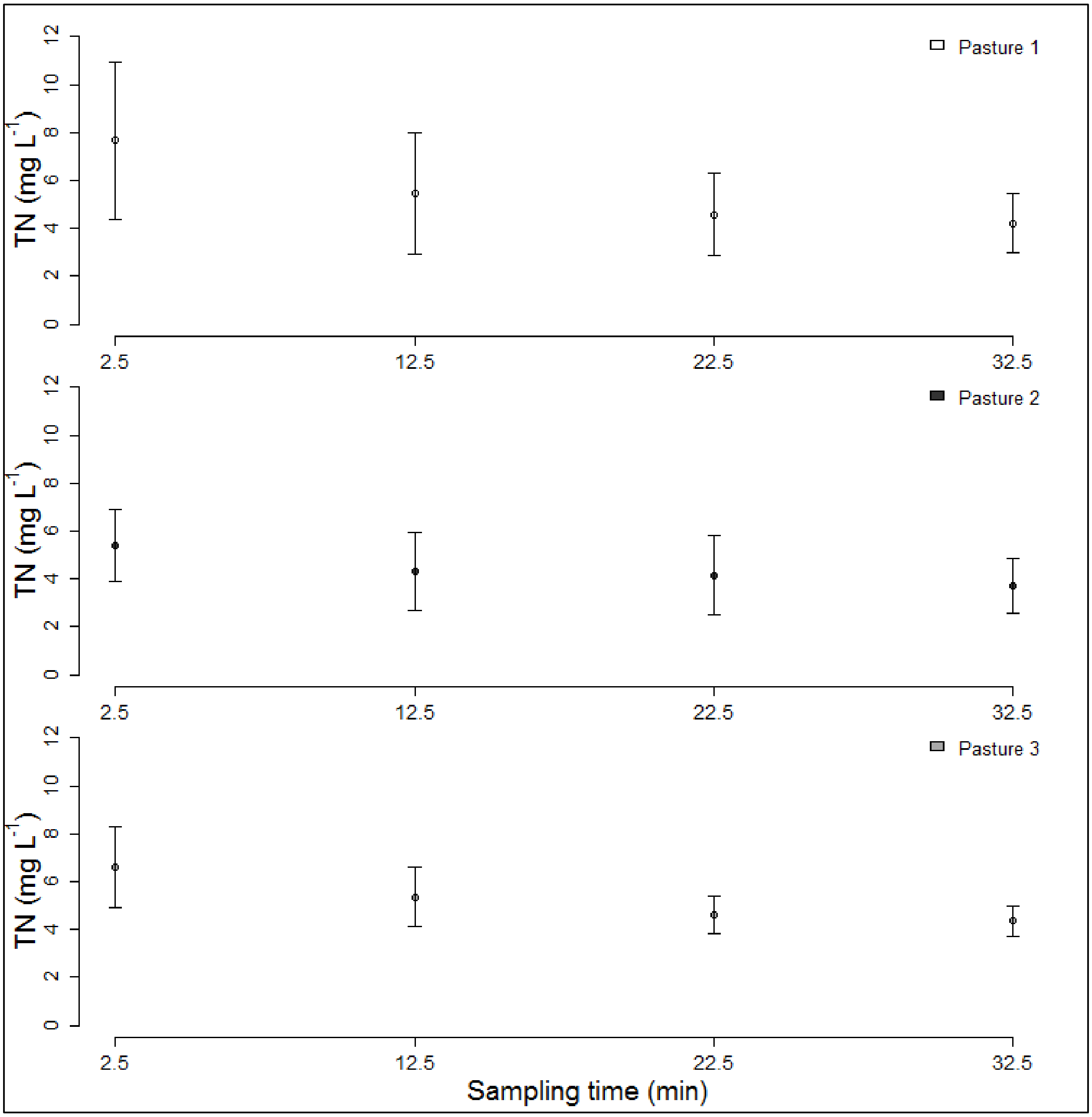


Figure C.2. Initial conditions (Simulation 1) TN concentrations (mg L^{-1}) in runoff by sampling time (min), averaged within pasture (N = 3). Whiskers extend plus or minus one standard deviation from the mean.

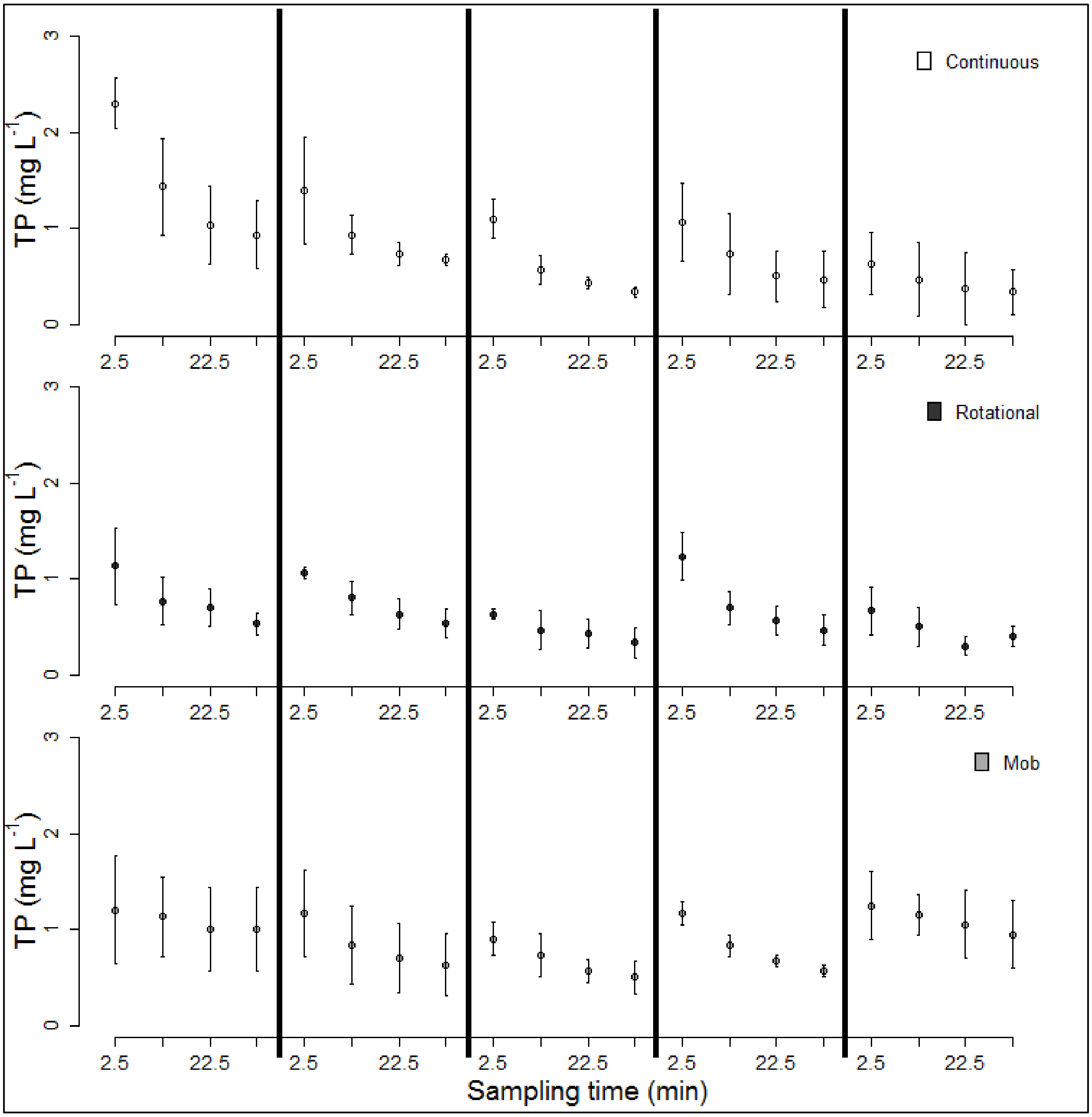


Figure C.3. Mean incremental TP concentrations (mg L^{-1}) for post-stocking conditions (Simulations 2 through 6 as denoted with vertical bars). Whiskers extend plus or minus one standard deviation from the mean.

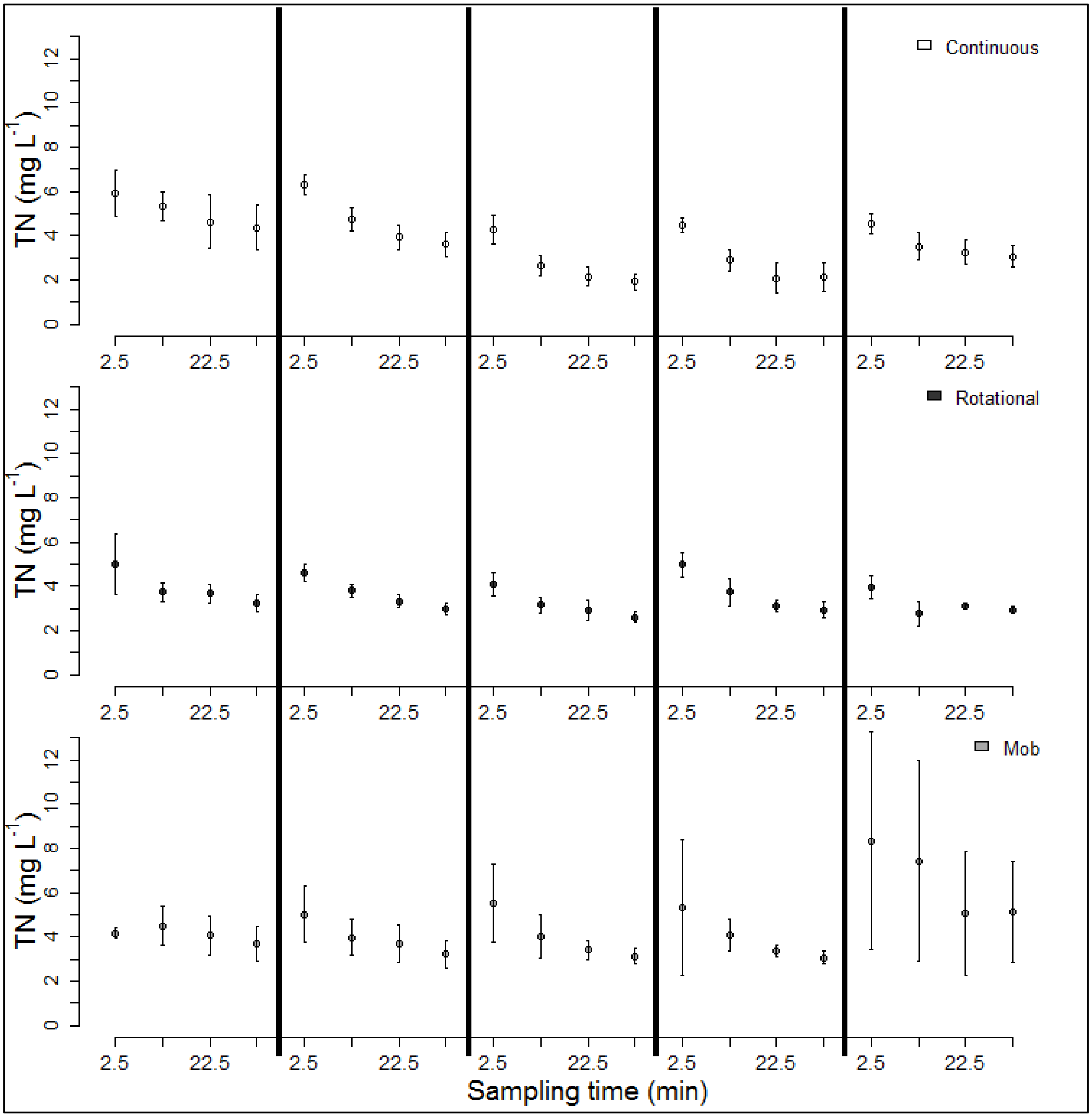


Figure C.4. Mean incremental TN concentrations (mg L^{-1}) for post-stocking conditions (Simulations 2 through 6 as denoted with vertical bars). Whiskers extend plus or minus one standard deviation from the mean.

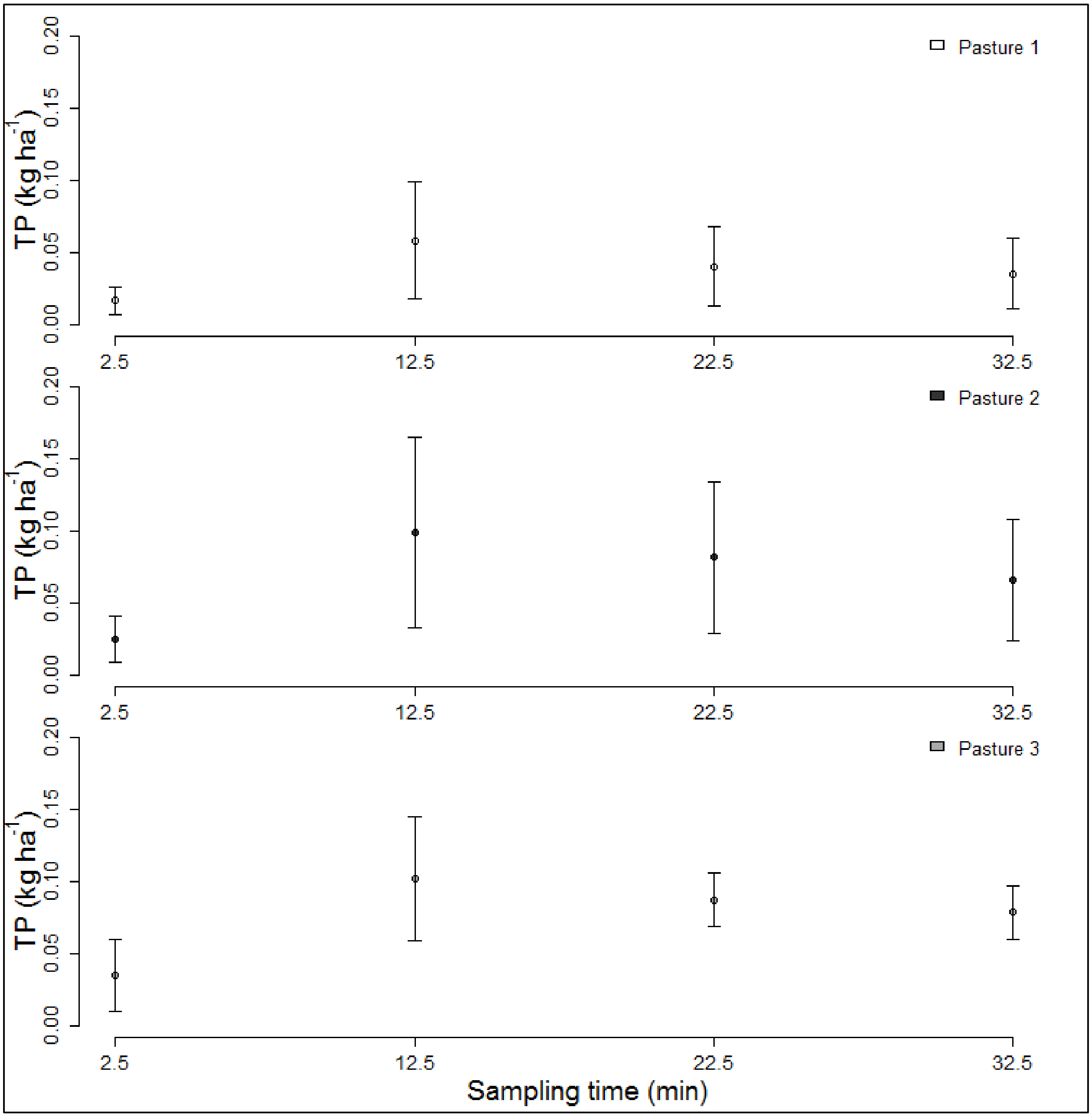


Figure C.5. Mean (N =3) incremental TP loads (kg ha^{-1}) for each pasture across sampling time (min) for initial conditions (Simulation 1).

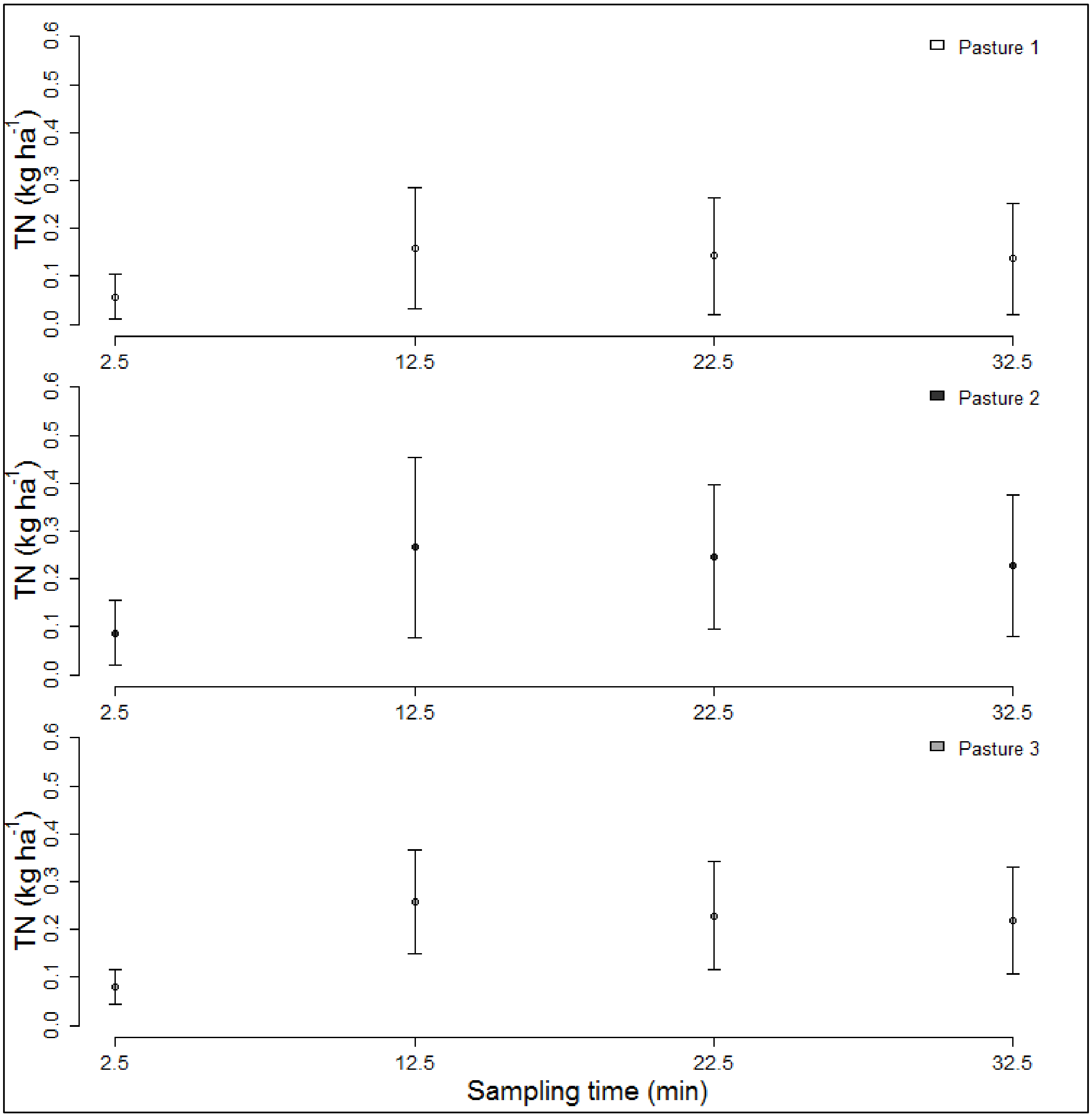


Figure C.6. Mean (N = 3) incremental TN loads (kg ha^{-1}) for each pasture across sampling time (min) for initial conditions (Simulation 1).

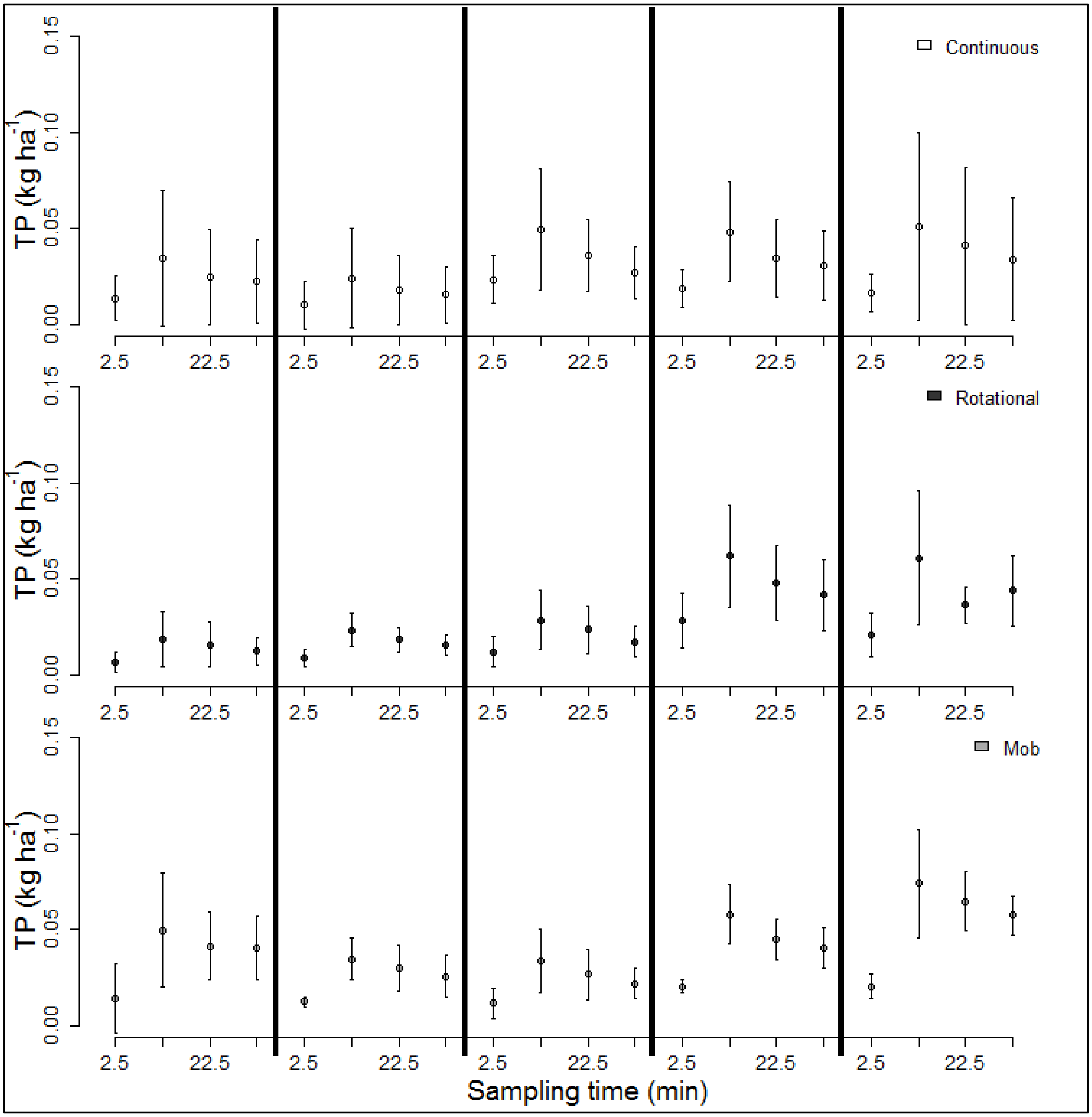


Figure C.7. TP loads (kg ha^{-1}) for each treatment across sampling time (min) for post-stocking conditions (Simulations 2 through 6 as denoted with vertical bars). (N = 3, except for Simulation 6 from the Mob treatment where N = 2).

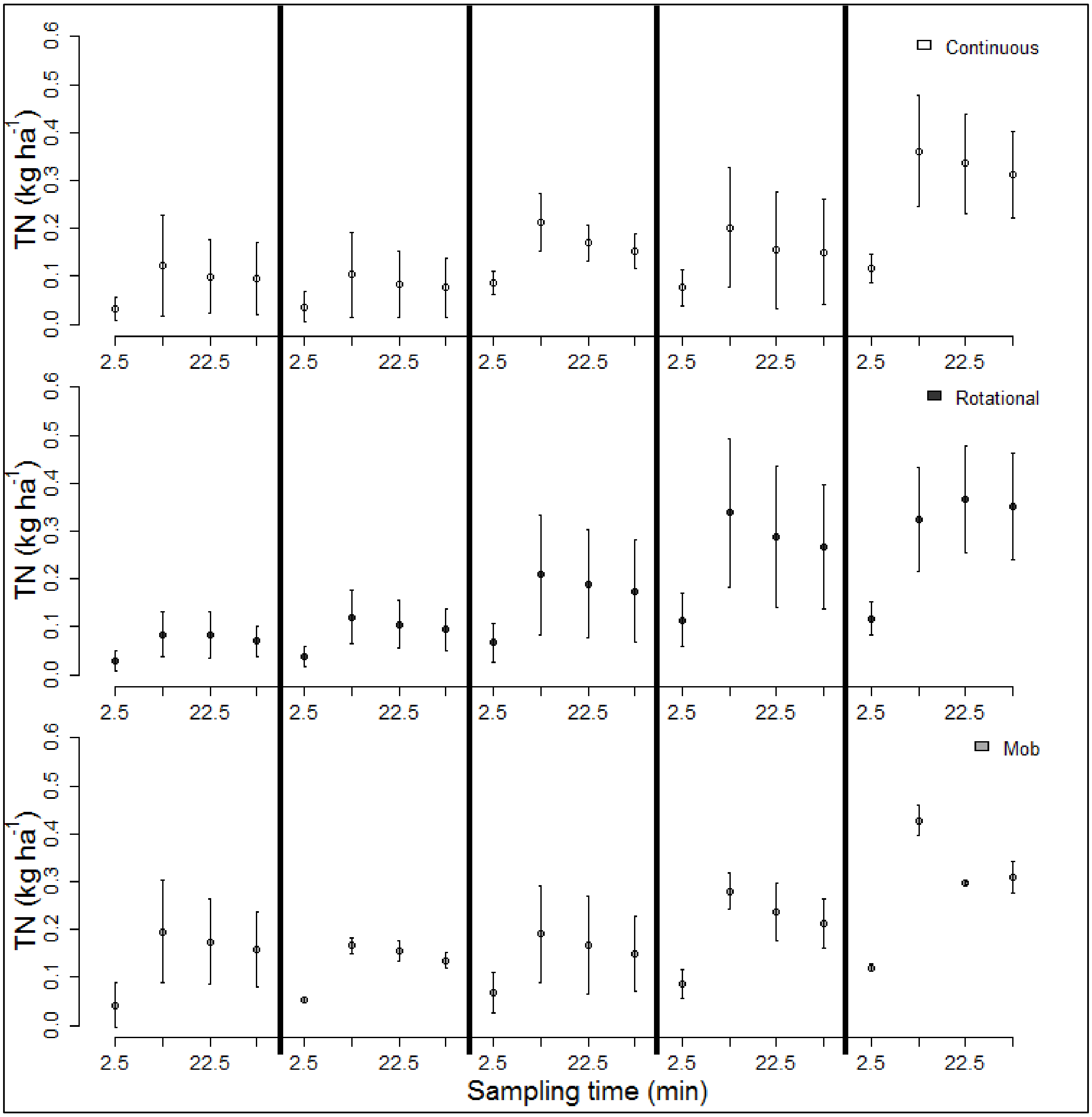


Figure C.8. TN loads (kg ha^{-1}) for each treatment across sampling time (min) for post-stocking conditions (Simulations 2 through 6 as denoted with vertical bars). (N = 3, except for Simulation 6 from the Mob treatment where N = 2).

Table C.1. Means and standard deviations of incremental nutrient concentrations for initial conditions (Simulation 1).

			Initial conditions	
Variable	Pasture	Sampling time (min)	μ	σ
TP concentration (mg L^{-1})	**All**	**Mean**	**1.9**	**1.0**
	1	**Mean**	**1.8**	**1.0**
		2.5	2.6	1.5
		12.5	2.0	0.8
		22.5	1.4	0.6
		32.5	1.2	0.5
	2	**Mean**	**1.6**	**1.1**
		2.5	1.8	1.2
		12.5	1.9	1.5
		22.5	1.6	1.3
		32.5	1.3	1.0
	3	**Mean**	**2.2**	**1.0**
		2.5	2.6	1.8
		12.5	2.1	0.8
		22.5	2.0	0.9
		32.5	1.9	1.0
TN concentration (mg L^{-1})	**All**	**Mean**	**5.04**	**1.81**
	1	**Mean**	**5.48**	**2.42**
		2.5	7.66	3.27
		12.5	5.47	2.53
		22.5	4.58	1.70
		32.5	4.21	1.25
	2	**Mean**	**4.40**	**1.43**
		2.5	5.39	1.52
		12.5	4.33	1.63
		22.5	4.15	1.64
		32.5	3.72	1.15
	3	**Mean**	**5.24**	**1.35**
		2.5	6.62	1.68
		12.5	5.36	1.24
		22.5	4.62	0.78
		32.5	4.36	0.64

Table C.2. Means of incremental nutrient loads for initial conditions (Simulation 1).

Variable	Pasture	Sampling time (min)	μ	σ
TP load (kg ha^{-1})	1	Mean Event Load	0.15	0.10
		2.5	0.02	0.01
		12.5	0.06	0.04
		22.5	0.04	0.03
		32.5	0.03	0.02
	2	Mean Event Load	0.27	0.18
		2.5	0.02	0.02
		12.5	0.10	0.07
		22.5	0.08	0.05
		32.5	0.07	0.04
	3	Mean Event Load	0.30	0.10
		2.5	0.04	0.03
		12.5	0.10	0.04
		22.5	0.09	0.02
		32.5	0.08	0.02
TN load (kg ha^{-1})	1	Mean Event Load	0.50	0.14
		2.5	0.06	0.05
		12.5	0.16	0.13
		22.5	0.14	0.12
		32.5	0.14	0.12
	2	Mean Event Load	0.83	0.55
		2.5	0.09	0.07
		12.5	0.27	0.19
		22.5	0.24	0.15
		32.5	0.23	0.15
	3	Mean Event Load	0.79	0.36
		2.5	0.08	0.04
		12.5	0.26	0.11
		22.5	0.23	0.11
		32.5	0.22	0.11

Table C.3. Means and standard deviations of incremental and mean event nutrient concentrations within stocking treatments for post-stocking conditions (Simulations 2 through 6).

			Simulation number											
			2		3		4		5		6		Post-stocking Simulations	
Variable	Treatment	Sampling time (min)	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
TP concentration (mg L^{-1})	CONT	**Mean event**	**1.4**	**0.7**	**0.9**	**0.4**	**0.6**	**0.3**	**0.7**	**0.4**	**0.4**	**0.3**	**0.8**	**0.5**
		2.5	2.3	0.3	1.4	0.5	1.1	0.2	1.1	0.4	0.6	0.3	1.3	0.7
		12.5	1.4	0.5	0.9	0.2	0.6	0.2	0.7	0.4	0.5	0.4	0.8	0.5
		22.5	1.0	0.4	0.7	0.1	0.4	0.1	0.5	0.3	0.4	0.4	0.6	0.3
		32.5	0.9	0.4	0.7	0.1	0.3	0.0	0.5	0.3	0.3	0.3	0.5	0.3
	ROT	**Mean event**	**0.8**	**0.3**	**0.7**	**0.2**	**0.5**	**0.2**	**0.7**	**0.3**	**0.5**	**0.2**	**0.6**	**0.3**
		2.5	1.1	0.4	1.1	0.1	0.7	0.1	1.2	0.2	0.7	0.3	0.9	0.3
		12.5	0.8	0.2	0.8	0.2	0.5	0.2	0.7	0.1	0.5	0.2	0.6	0.2
		22.5	0.7	0.2	0.6	0.2	0.4	0.2	0.5	0.2	0.3	0.1	0.5	0.2
		32.5	0.5	0.1	0.5	0.2	0.3	0.1	0.5	0.1	0.4	0.1	0.4	0.1
	MOB	**Mean event**	**1.1**	**0.4**	**0.8**	**0.4**	**0.7**	**0.2**	**0.8**	**0.3**	**1.1**	**0.3**	**0.9**	**0.3**
		2.5	1.2	0.6	1.2	0.5	0.9	0.2	1.2	0.1	1.3	0.3	1.1	0.3
		12.5	1.2	0.4	0.8	0.4	0.7	0.2	0.8	0.1	1.1	0.2	0.9	0.3
		22.5	1.0	0.4	0.7	0.4	0.6	0.1	0.6	0.1	1.0	0.3	0.8	0.3
		32.5	1.0	0.4	0.6	0.3	0.5	0.1	0.6	0.1	0.9	0.4	0.7	0.3
TN concentration (mg L^{-1})	CONT	**Mean event**	**5.06**	**1.06**	**4.65**	**1.18**	**2.75**	**1.06**	**2.89**	**1.12**	**3.59**	**0.75**	**3.79**	**1.37**
		2.5	5.93	1.04	6.32	0.47	4.29	0.66	4.47	0.30	4.53	0.46	5.11	1.03
		12.5	5.32	0.64	4.74	0.54	2.65	0.46	2.90	0.49	3.51	0.62	3.82	1.17
		22.5	4.63	1.19	3.93	0.54	2.14	0.43	2.09	0.68	3.26	0.56	3.21	1.20
		32.5	4.37	1.01	3.62	0.57	1.91	0.34	2.12	0.65	3.05	0.49	3.01	1.10
	ROT	**Mean event**	**3.91**	**0.96**	**3.68**	**0.69**	**3.18**	**0.67**	**3.69**	**0.93**	**3.18**	**0.59**	**3.53**	**0.81**
		2.5	5.00	1.40	4.61	0.39	4.08	0.50	4.98	0.57	3.95	0.55	4.52	0.80
		12.5	3.74	0.43	3.79	0.28	3.14	0.38	3.74	0.63	2.75	0.53	3.43	0.58
		22.5	3.66	0.45	3.33	0.31	2.91	0.47	3.11	0.27	3.07	0.12	3.22	0.40
		32.5	3.25	0.38	2.98	0.27	2.60	0.23	2.92	0.35	2.94	0.15	2.94	0.33
	MOB	**Mean event**	**4.11**	**0.74**	**3.97**	**1.05**	**4.01**	**1.31**	**3.97**	**1.64**	**6.49**	**3.26**	**4.37**	**1.84**
		2.5	4.17	0.24	5.02	1.29	5.52	1.75	5.35	3.07	8.34	4.92	5.59	2.47
		12.5	4.51	0.90	3.97	0.83	3.99	0.98	4.11	0.72	7.45	4.52	4.62	1.87
		22.5	4.07	0.90	3.69	0.86	3.41	0.44	3.37	0.26	5.07	2.80	3.84	1.11
		32.5	3.70	0.77	3.21	0.61	3.13	0.35	3.06	0.27	5.11	2.29	3.54	1.04

Table C.4. Means and standard deviations of incremental and mean event nutrient loads within treatments for post-stocking conditions (Simulations 2 through 6). Event loads are summations of incremental loads. Mean event loads are event loads averaged within each treatment.

			Simulation number											
			2		3		4		5		6		Post-stocking	
Variable	Treatment	Sampling time (min)	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
TP load (kg ha^{-1})	CONT	**Mean event**	**0.09**	**0.09**	**0.07**	**0.07**	**0.14**	**0.08**	**0.13**	**0.07**	**0.14**	**0.13**	**0.11**	**0.08**
		2.5	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01
		12.5	0.03	0.04	0.02	0.03	0.05	0.03	0.05	0.03	0.05	0.05	0.04	0.03
		22.5	0.02	0.02	0.02	0.02	0.04	0.02	0.03	0.02	0.04	0.04	0.03	0.02
		32.5	0.02	0.02	0.02	0.01	0.03	0.01	0.03	0.02	0.03	0.03	0.03	0.02
	ROT	**Mean event**	**0.05**	**0.38**	**0.07**	**0.02**	**0.08**	**0.04**	**0.18**	**0.08**	**0.16**	**0.05**	**0.11**	**0.07**
		2.5	0.01	0.01	0.01	0.00	0.01	0.01	0.03	0.01	0.02	0.01	0.02	0.01
		12.5	0.02	0.01	0.02	0.01	0.03	0.02	0.06	0.03	0.06	0.04	0.04	0.03
		22.5	0.02	0.01	0.02	0.01	0.02	0.01	0.05	0.02	0.04	0.01	0.03	0.02
		32.5	0.01	0.01	0.02	0.01	0.02	0.01	0.04	0.02	0.04	0.02	0.03	0.02
	MOB	**Mean event**	**0.15**	**0.08**	**0.10**	**0.36**	**0.09**	**0.04**	**0.16**	**0.04**	**0.22**	**0.06**	**0.14**	**0.06**
		2.5	0.01	0.02	0.01	0.00	0.01	0.01	0.02	0.00	0.02	0.01	0.02	0.01
		12.5	0.05	0.03	0.03	0.01	0.03	0.02	0.06	0.02	0.07	0.03	0.05	0.02
		22.5	0.04	0.02	0.03	0.01	0.03	0.01	0.04	0.01	0.06	0.02	0.04	0.02
		32.5	0.04	0.02	0.03	0.01	0.02	0.01	0.04	0.01	0.06	0.01	0.04	0.02
TN load (kg ha^{-1})	CONT	**Mean event**	**0.35**	**0.28**	**0.30**	**0.25**	**0.62**	**0.16**	**0.58**	**0.39**	**1.12**	**0.34**	**0.59**	**0.39**
		2.5	0.03	0.02	0.04	0.03	0.09	0.02	0.08	0.04	0.12	0.03	0.07	0.04
		12.5	0.12	0.10	0.10	0.09	0.21	0.06	0.20	0.13	0.36	0.12	0.20	0.13
		22.5	0.10	0.08	0.08	0.07	0.17	0.04	0.15	0.12	0.33	0.10	0.17	0.12
		32.5	0.10	0.08	0.08	0.06	0.15	0.04	0.15	0.11	0.31	0.09	0.16	0.11
	ROT	**Mean event**	**0.27**	**0.15**	**0.36**	**0.17**	**0.64**	**0.38**	**1.01**	**0.49**	**1.16**	**0.35**	**0.69**	**0.46**
		2.5	0.03	0.02	0.04	0.02	0.07	0.04	0.11	0.06	0.12	0.03	0.07	0.05
		12.5	0.08	0.05	0.12	0.06	0.21	0.12	0.34	0.16	0.32	0.11	0.21	0.14
		22.5	0.08	0.05	0.11	0.05	0.19	0.11	0.29	0.15	0.37	0.11	0.21	0.14
		32.5	0.07	0.03	0.09	0.04	0.17	0.11	0.27	0.13	0.35	0.11	0.19	0.13
	MOB	**Mean event**	**0.57**	**0.32**	**0.51**	**0.05**	**0.58**	**0.32**	**0.81**	**0.12**	**1.15**	**0.01**	**0.69**	**0.29**
		2.5	0.04	0.05	0.05	0.01	0.07	0.04	0.09	0.03	0.12	0.01	0.07	0.04
		12.5	0.20	0.11	0.17	0.02	0.19	0.10	0.28	0.04	0.43	0.03	0.24	0.11
		22.5	0.17	0.09	0.16	0.02	0.17	0.10	0.24	0.06	0.30	0.00	0.20	0.08
		32.5	0.16	0.08	0.14	0.02	0.15	0.08	0.21	0.05	0.31	0.03	0.18	0.08

Table C.5. Correlation coefficients (r) and p-values for relationships between sampling time and incremental nutrient concentrations and loads.

	Initial conditions (Simulation 1)		Post-stocking conditions (Simulations 2 – 6)		All Simulations	
Variable	Sampling time		Sampling time		Sampling time	
	r	p	r	p	r	p
Incremental TP concentrations	-0.33	0.05	-0.49	**<0.01**	-0.33	**<0.01**
Incremental TN concentrations	-0.50	**<0.01**	-0.49	**<0.01**	-0.47	**<0.01**
Incremental TP loads	0.24	0.16	0.16	0.04	0.16	0.02
Incremental TN loads	0.31	0.06	0.28	<0.01	0.29	<0.01