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Soil Quality in Rhode Island Pastures Grazed by Different Types of Livestock

Alissa H. Becker
University of Rhode Island, alibba@my.uri.eduAlissa

SOIL QUALITY IN RHODE ISLAND PASTURES GRAZED BY DIFFERENT TYPES OF LIVESTOCK

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ALISSA H. BECKER

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ALISSA H. BECKER

APPROVED:

Thesis Committee:

Major Professor José A. Amador

Mark Stolt

Rebecca Brown

Nasser H. Zawia
DEAN OF THE GRADUATE SCHOOL

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ABSTRACT

Historically, much of the New England landscape was converted to pasture for grazing animals and harvesting hay. Today, consumer demand for local, sustainably produced food, the number of livestock farms and the land area used for farming are increasing in Rhode Island. In order to make sound management decisions, it is important to characterize the effects of livestock on the quality of pasture soils. Although pastures remain a fairly common part of the New England landscape, little research has been published on the effects of grazing animals on pasture soil quality. To assess this, I examined soil quality in farms raising beef cattle, sheep, and horses, using hayed pastures as a control. All pastures were situated on ablation till. Three pastures per livestock type and three control hayed pastures were sampled in May, August and October 2012. I interviewed farmers about their management practices, made soil profile descriptions to a 50-cm depth, and characterized vegetation species. I established a 10 m × 10 m sampling area in each pasture and assessed soil quality based on measurement of physical (aggregate stability, bulk density, soil organic matter, infiltration, soil structure, texture and penetration resistance), chemical (soil pH, electrical conductivity, extractable N and P) and biological (active C, earthworm numbers, soil respiration) parameters, according to general agricultural recommendations in the Cornell Soil Health Training Assessment Manual. The effects of livestock type and sampling date on soil quality parameters were analyzed using a one-way ANOVA on ranks. Penetration resistance, bulk density, aggregate stability, organic matter content and extractable phosphate differed significantly ($P<0.05$) among pasture type. Hay and sheep pastures had significantly lower penetration

resistance and bulk density than horse or beef pastures, whose values were in the ideal range for bulk density, but in the acceptable and problematic ranges for surface penetration resistance, according to general agricultural recommendations. For aggregate stability, hay pastures had the highest fraction of water-stable aggregates, followed by sheep and beef pastures, though all values for all pastures fell within the ideal range for agricultural soils. Horse and hay farms had significantly lower extractable phosphate concentrations than beef or sheep farms, with approximately 25% of horse pasture values within the problematic ranges for soil phosphate, according to agricultural soil guidelines. The remaining soil quality parameters (active C, vegetation, electrical conductivity, pH, extractable N, infiltration rate, and earthworm numbers) did not vary significantly among pasture types or season. Soil pH and extractable NO_3^- values were problematic in all pasture types, whereas values for surface penetration resistance, active carbon levels, vegetation and earthworm counts were problematic in beef and horse pastures. Extractable PO_4^{3-} was problematic in all pastures except hay. Penetration resistance and bulk density values were inversely correlated with organic matter content, aggregate stability and earthworm counts, whereas soil respiration was correlated with temperatures and soil moisture.

Overall mean soil quality values, calculated by converting values for each parameter to a % score and calculating the mean % score, were highest for hayed pastures (78), followed by sheep (74), with horse pastures having the lowest soil quality score (69), which was similar to that for beef pasture (70). Pasture soils generally sustain the greatest damage from traffic during wet conditions, which may explain why soil quality was lower in continuously grazed pastures, regardless of soil moisture conditions, whereas hay is generally harvested in warmer months when soil and vegetation are fairly dry. In addition, sheep are smaller than either horse or beef cattle, and exert less pressure per hoof print, which may lead to better soil quality in pasture. Soil quality could be improved in all pastures by liming soil, preventing traffic during wet soil conditions, and preventing overgrazing by rotating animals off pasture when vegetation height is reduced to 7-12 cm. By implementing these practices, farmers can address a variety of physical, biological and chemical soil quality issues, ultimately leading to better pasture production, which could lower animal feed costs considerably.

The results of my study provide baseline data on the effect different types of livestock have on pasture soil quality in Rhode Island, which may be useful in making sound land use and agricultural management decisions.

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CHAPTER 1

INTRODUCTION

Agriculture has become an increasingly important aspect of the New England landscape. Both the number of farms and the amount of land farmed in Rhode Island increased markedly between 2002 and 2007 (USDA, 2009), a change likely fueled by the rise in consumer interest in homesteading, local foods, and grass-fed meat and animal products. Grazing animals require pasture, either directly for grazing, or indirectly for hay production. Pasture provides many ecosystem services, and enhances both historic and aesthetic aspects and values of New England landscapes. Nearly 16% of Rhode Island's farmland (over 10,500 acres) is grazed (USDA, 2009), yet little research has been conducted on livestock grazing and its impact on soil quality. Poorly managed pastures have the potential to be detrimental to the environment, aside from being aesthetically unappealing to neighbors and communities. Common concerns about soil quality in pasture include soil compaction, leading to problems with plant growth, and threats to water supplies from run-off containing high concentrations of nutrients and pathogens (Drewry, 2006; McDowell et al., 2004; Teague et al., 2011).

Preserving soil quality is vital to ensure future generations' ability to farm and feed themselves. As the world's population increases and the consumption of animals and their products rises (Delgado, 2003), agricultural resources in New England become more valuable and, without healthy soil, food cannot be grown to meet the needs of animals or humans. It is therefore increasingly important to focus local efforts to identify and implement agricultural systems that can raise livestock and feed people sustainably. To identify sustainable systems to feed our communities, we must know which types of livestock and management practices are beneficial, or least likely to negatively impact soil and environmental quality. This knowledge can help us make sound decisions about how to utilize land – without destroying or compromising natural resources, like the soil or ground and surface water.

I conducted a study to assess whether different types of livestock had differential impacts on soil quality in pasture, using hayed pastures as a control. I collected data and soil samples from 12 Rhode Island pastures: 3 hayed pastures and 3 pastures for each of three types of livestock: beef cattle, horses and sheep. Pasture soil quality was assessed by evaluating physical (e.g. penetration resistance, bulk density, percent organic matter), chemical (e.g. pH, electrical conductivity, extractable nutrients) and biological (e.g. soil respiration, earthworm abundance, active carbon) soil properties, with reference to general agricultural soil recommendations (Gugino et al., 2009). Data were analyzed using a one-way ANOVA on ranks to determine whether significant differences exist in soil quality parameters among pastures grazed by different types of livestock and hayed pastures.

Background

Soil quality

Soil is an essential part of agriculture: it is the substrate for plant growth and functions to filter and buffer threats to our water supply, such as high concentrations of nutrients or pathogens. Evaluation of soil quality is a useful assessment tool to quantify various aspects of soil health, based on rating physical, chemical and biological indicators (Gugino et al., 2009).

Soil quality is defined as “the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation” (Karlen et al., 1997). Unlike traditional soil classification and interpretation, soil quality assesses a variety of indicators, which can either can be inherent – those used to create soil surveys, classification and recommended land use based on a 2-m deep soil profile – or dynamic, describing the condition of the top 20-30 cm of soil due to recent land management (Karlen et al., 2003; Wienhold et al., 2004). Dynamic indicators are used to determine soil health in relation to soil use and management decisions (Wienhold et al., 2004), and can provide valuable insights into soil function when paired with traditional soil classifications (Karlen et al., 2003). Since the introduction of the concept of soil quality in 1977 by Warkentin and Fletcher, soil quality has been accepted by the international scientific community as a tool to assess and understand soil resources, and to educate others about their utilization and management (Karlen et al., 2003). Research has shown that this is a valuable, reasonably objective assessment tool both for evaluating current management practices and for comparing alternative practices (Wienhold et al., 2004).

The role of soil in crop production and environmental quality has been extensively investigated (Gil-Sotres et al., 2005). Soil is a critical component of land management because of its critical role in nutrient and water cycling, decomposition of plant residues, and filtering and buffering contaminants to our water supply (Karlen et al., 2003). Although physical soil properties are related to soil type, properties like bulk density and infiltration rates are affected by management practices (Bharati et al., 2002). Chemical soil properties are also affected by management practices, such as fertilization and/or manure application (Bhogal et al., 2011; Franzluebbers and Stuedemann, 2009). The chemical properties of the soil are important in determining plant health and, by extension, the health of the grazing animals (Gugino et al., 2009). Biological soil properties affect plant health and soil structure, and are largely determined by land management (Franzluebbers and Stuedemann, 2009; Franzluebbers et al., 2000a). Soil biological and chemical properties, such as microbial respiration and biomass, soil pH, and organic matter content, are affected by land use practices to a greater extent than are soil physical properties, such as bulk density or soil texture (Schipper and Sparling, 2000). Land use related effects on biological and chemical soil properties are consistent across different soil types in different geographic locations (Schipper and Sparling, 2000). Soil properties are therefore useful indicators of soil quality or health, because they reflect the effects of different management and land use practices.

Soil Quality in Pasture

The effects of grazing on pasture soils have been studied across the world. New Zealand soils under pasture grazed by sheep and cattle have been found to have greater total C and N, microbial biomass, respiration and mineralizable N, lower bulk density, greater porosity and higher water availability than arable or mixed cropping soils (Haynes and Williams, 1999; Schipper and Sparling, 2000; Sparling et al., 2004). When compared to 60-year-old continuously cropped fields used for vegetable production, pasture soils contain twice the amount of soil organic carbon (Haynes and

Williams, 1999). For the purposes of this study, pastures are considered a type of grassland.

Pasture soils tend to have moderate compaction relative to forest soils (Drewry and Paton, 2005; Sparling et al., 2004). Studies in Colombia have shown that bulk density is higher in grasslands grazed by beef cattle than in forest soils, and increases with pasture age (Martínez and Zinck, 2004). Cattle trampling impairs surface drainage, increases bulk density and penetration resistance, and decreases porosity and infiltration rates (Martínez and Zinck, 2004). When compaction increases, soil pore spaces hold less air and water, increasing the bulk density of the soil. The resulting decreased oxygen content and airflow through the soil, and decreased nutrient and water content and availability, affect microbial activity negatively (Martínez and Zinck, 2004). The upper soil horizons are most affected by cattle grazing, where soil structure tends to become platy with increasing pasture age (Martínez and Zinck, 2004). Fenceline pacing of deer in Australia has also been documented to decrease macroporosity, and to increase phosphorus and *E. coli* concentrations in overland flow (McDowell et al., 2004). Animal grazing can also result in significant accumulation of N and high levels of available P in soils under pastures, sparking concerns that these conditions increase the potential for eutrophication of receiving waters (Sparling et al., 2004).

Compaction decreases infiltration and increases runoff, and thus livestock grazing can pose a risk to both soil quality and ground and surface water quality. Proffitt et al. (1995) describe two soil processes that lead to deteriorating soil quality when sheep trample soil: (i) compaction by hooves, which decreases the volume of large pores

(Warren et al., 1986), and (ii) remolding of soil as rainwater is incorporated into the soil and disturbs interactions between particles (Mullins and Fraser, 1980, as cited by Proffitt et al., 1995). Proffitt et al. (1995) point out that this is a “self-perpetuating process”, since higher compaction leads to decreased infiltration, which increases free water on the soil surface, which can heighten the potential for soil damage by trampling. Prevention of livestock traffic when soil is wet is key to preventing compaction and maintaining soil health. In fact, several studies in New Zealand have indicated that damage caused by sheep and cattle in pasture in wet/winter seasons is ameliorated to some extent in warmer, drier spring/summer/fall seasons (Drewry and Paton, 2000; Drewry and Paton, 2005). Other research has found that removing sheep for brief periods from pasture after significant rainfall can help mitigate soil deterioration by the trampling action of hooves (Proffitt et al., 1995).

In the southern Piedmont area of the United States, researchers have found that properly grazed pastures could potentially significantly improve soil properties, by restoring natural soil fertility, sequestering soil organic C and N, and increasing biological activity (Franzluebbers et al., 2000a). Pasture soil has lower surface residue and particulate organic C-to-N ratios, and greater organic C content than conservation-tilled cropland, which may be attributed to ruminant processing of forage and deposition of manure and urine (Haynes and Williams, 1999). It seems that livestock improve pasture soil quality by increasing organic matter inputs, which are decomposed more rapidly in the lower C-to-N ratio environment (Franzluebbers et al., 2000a). The same study concluded that localized soil compaction caused by animals may have less impact on soil properties (e.g. bulk density) than machine traffic (e.g.

tractors, haying equipment), although the organic C content of pasture soil probably contributes to ameliorating negative effects of cattle trampling (Franzluebbers et al., 2000a).

Little research has been conducted on soils under pastures grazed by horses. Research by Landsberg et al. (2001) on the impacts of horses on trails and nature preserves suggests that horses have a significant potential to damage soils and vegetation: as horse traffic increases, bulk density increases, as do areas of bare ground. Areas most susceptible to damage include steep, wet and poorly drained terrain (Landsberg et al., 2001). Thus, many of the concerns for soil quality in cattle and sheep pasture are presumably similar for horse pastures. Other research indicates that stocking density of horses is often greater than would be ideal, leading to poor pasture performance (Newsome et al., 2008; Singer et al., 2002). Since pasture provides both exercise and nutrition to horses, many paddocks are occupied year-round, increasing the amount of manure deposited, leading to an excess of P in pasture soils (Singer et al., 2001). Pastures with low equine stocking densities have better values for pH, P and K, whereas organic matter content seems unaffected by stocking density (Singer et al., 2001).

Much of the northeastern United States was deforested and used for pasture in the 1800s (Compton and Boone, 2000). Soil N and P levels are greater in formerly pastured soil, relative to woodlots, and pasture sites have higher C:N ratios than cultivated soils (Compton and Boone, 2000). Some scientists suggest that conversion of forest to pasture can result in an 8% increase in soil organic carbon, since grassland have high productivity and turnover rates that add organic matter to the soil (Guo and Gifford, 2002).

Livestock

Most Americans consider livestock to be animals raised directly for labor or for their products, e.g. milk, fiber, and/or meat. Both cattle and sheep fit into this definition, since the first is a primary source for red meat and the latter provide meat and fleece in the US. These ruminants evolved eating grasses, which are digested through a complex interaction of microbes and the four chambers of their rumen, an analog of the human stomach. This ability to gain nutrition from plant leaves and stems makes ruminants both unique and easy to feed – they can be raised exclusively on pasture and hay, whereas non-ruminants require supplemental nutrition, and are generally not raised on pasture.

Before the 1900s, many Americans would have included horses under the livestock umbrella: horses were historically kept as labor animals before the invention of tractors and automobiles. Today, horses occupy a strange position between pet and livestock; few farmers still plow their fields using horses, though horses are popularly kept for recreational use across the US (Newsome et al., 2008). Logistically, horses can hardly be considered a pet, since they are quite large, require expensive veterinary care, consume a significant greater volume of feedstuffs than the average dog, cat or hamster, produce more manure, and require vastly more space to exercise and graze than the average suburban backyard.

Pasture Vegetation

Pasture vegetation has important and beneficial impacts on soil quality (Betteridge et al., 1994; Proffitt et al., 1995; Teague et al., 2011), and its effective management is therefore important. According to the USDA Natural Resource Conservation Service (NRCS) (USDA NRCS, 2003), the balance of the plant energy produced from sunlight, animal harvesting of plant energy, and conversion of plants to marketable animal products can be maintained through carefully managed grazing. The USDA NRCS (2003) recommends rotational grazing to allow livestock continuous access to young vegetative plants that are more palatable than more mature plants, without destroying the plant community in the pasture. Different rotational management techniques exist, though an intensive rotational grazing regimen has been shown to be the most effective: pastures composed of native species are significantly more productive, and annually yield more foliage to be consumed by animals, if grazed at high intensity for short periods of time between long periods during which the pasture vegetation is rested completely (USDA NRCS, 2003). Research on grazing intensity has led to the conclusion that moderate grazing, and grazing fertilized pasture consisting of non-native grasses, are both management practices that sustain, rather than destroy, soil quality (Wienhold et al., 2004). Proper grazing management can improve the health of both plant communities and the soil (Teague et al., 2011). Healthy plants are essential, since they increase water infiltration, and evaporation and temperature changes are decreased by plant litter and cover, resulting in longer soil moisture retention, when compared to bare soil (USDA NRCS, 2003). Increased, consistent soil moisture enhances soil microbial activity, promoting and maintaining aggregate stability, plant nutrient availability and growth conditions, ultimately increasing soil organic matter content (Teague et al., 2011). By carefully managing the health of the plant community in pastures, soil quality can be substantially increased.

Interestingly, research by Franzluebbers et al. (2000a) indicates that soil bulk density is unaffected by vegetation management (e.g. grazing versus haying), suggesting that the potentially negative long-term impacts of animal hooves are matched by those caused by machine traffic during haying. However, when pasture is grazed, more than two thirds of ingested nutrients are returned to the pasture during excretion, whereas when vegetation is cut for hay, there is a net loss of nutrients, since the amount of decomposable substrates added to soil is reduced. As a result, organic carbon accumulates at more than twice the rate in grazed tall fescue pasture than in hayed bermudagrass pasture (Franzluebbers et al., 2000a). It seems that pasture species composition may also affect soil properties (Franzluebbers et al., 2000a). Franzluebbers et al. (2000) conclude that in the long-term, managed grass systems have nearly equivalent potential to store soil organic carbon as forest land.

Summary

There are both positive and negative outcomes of grazing livestock, depending on livestock management and dedication to soil quality maintenance. However, much of the research suggests that with proper management, including rotational grazing, moisture management, and preventing both traffic in wet conditions and excessive herbivory, negative effects can be minimized or even prevented. Some research indicates that pasture improves soil quality measurably.

Regardless of livestock type, certain soils are likely to be more at risk for damage by livestock trampling. Moist soils, like those found on northern-facing slopes or in lower parts of the landscape, are likely to turn into mud when trampled, and are therefore significantly at risk for compaction. Furthermore, soils with fine texture (higher proportion of small particles) are more easily compacted than sandy or gravelly soils. Poorly developed structure, and low aggregate stability can also make a soil more susceptible to compaction, as does a lack of vegetation (USDA NRCS, 2001a). Vegetation is important because it cushions impacts from hooves and contributes soil organic matter, increasing infiltration and preventing water-erosion and run-off during precipitation events (USDA NRCS, 2001b).

Study Rationale and Justification

I chose to study a range of livestock because different types are likely to have different effects on soil quality. Pastures grazed by different livestock species were compared to hayed pastures, which served as a control, since they represent vegetation removal without the effects of livestock trampling and excretory inputs. Pasture grazed by sheep, beef cattle and horses were examined in this study, because each requires pasture (for direct grazing or for hay). Other animals raised as livestock, such as hogs, goats, dairy cattle, chickens and exotic animals were excluded from this study, since their abundance in RI is limited or management practices generally don't involve pasture. The livestock selected in this study specifically require pasture – either for direct grazing or indirectly for hay production. The beef cattle in this study were mainly fed hay and grass, rather than corn.

Livestock are hypothesized to have different effects on pasture due to differences in: (1) animal size and weight, (2) stocking densities, (3) manure composition, (4) traffic patterns, (5) browsing behavior and (6) vegetation removal. For example, cattle are significantly larger and heavier than sheep, and represent a potentially greater impact of localized soil compaction because of the large bodyweight to soil contact area ratio. Sheep are lighter, and thus may have smaller individual impacts on soil compaction; however, sheep can be grazed at greater densities than cattle, potentially affecting soil compaction and plant growth. Horses are similar in size to cattle, though the shape of the hoof differs vastly, potentially increasing localized pressure on soil (Figure 1.1).

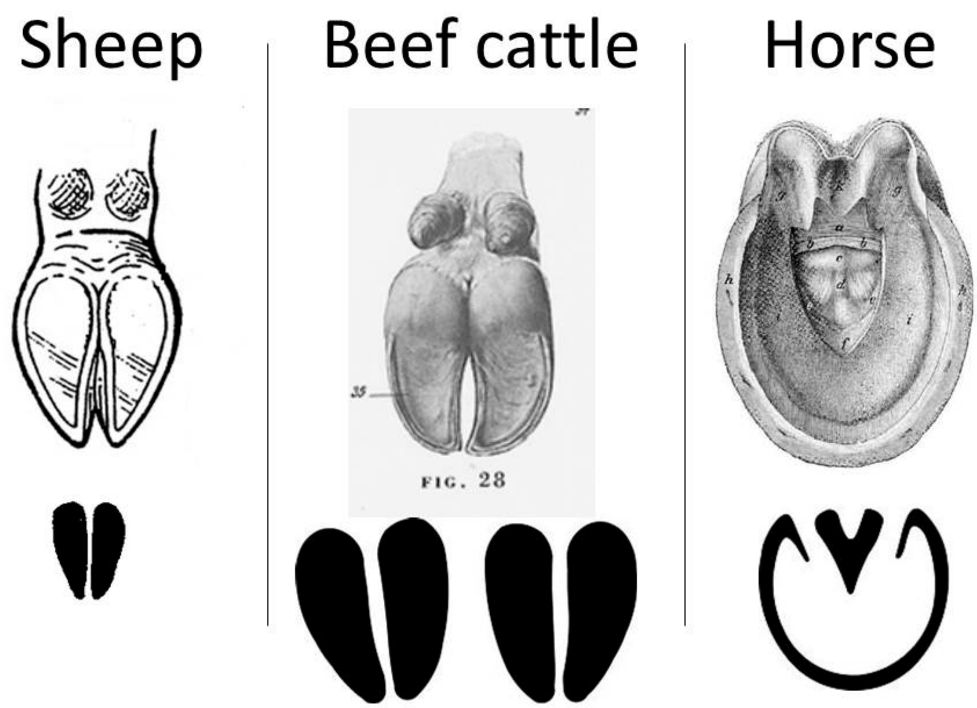


Figure 1.1. Livestock hooves. Upper image under livestock type is a plantar view of hoof anatomy. Lower image represents hoof prints made by hooves in soil, but are not to scale (Image Sources, 2013).

Furthermore, horses are generally moved to their paddock daily, whereas sheep and cattle tend to remain on pasture full-time. These traffic patterns – the amount, directionality and frequency of pressure transferred to soil during hoof trampling – are potentially quite varied and may have very different effects on soil quality. There are also differences among livestock excretions. For example, manure composition varies between ruminants and horses: horses are hind-gut fermenters with manure containing a high percentage of undigested organic matter, whereas cattle (true ruminants with 4-chambered stomachs) manure contains much less undigested organic matter content (Westover, 1926), which may affect organic matter and nutrient content of the soil. Finally, sheep, horses and beef cattle also have different browsing behaviors. Sheep have smaller mouths than cattle, allowing them to graze pasture closer to the ground. Horses selectively clip vegetation with their teeth (Singer et al., 2001), and sheep both bite and tear vegetation, whereas cattle wrap their tongues around the grass and pull. Differences in grazing can potentially affect plant growth, and by extension soil properties. Differential spatial patterns in pasture consumption (e.g. cattle are known to avoid grazing near feces) and plant preferences may also affect localized soil quality.

I conducted my study on farms situated on ablation till. This land was historically grazed by livestock, since pasture represents an efficient use of land that can support plant growth, but is impractical to plow (Compton and Boone, 2000). Ablation, or loose, till was deposited by melting glaciers, and includes materials ranging in size from boulders to sand, as well as smaller particles (Rector, 1981). While soils formed in this parent material do not generally have problems with water infiltration, the large number of rock fragments often present substantial problems for farming crops (Donkor et al., 2002). Today, land situated on ablation till is available for development, since drainage properties do not present obstacles to construction, like installation of septic systems, as might be present in other soil types (Donkor et al., 2002). In times of economic distress, farmers may feel pressured by high taxes and other economic factors to sell their land to developers, since agricultural land is often taxed at the same rate as land supporting houses (Rogers, 2009). However, open green fields preserved in historically pastoral areas are more aesthetically pleasing than suburban developments. In addition, pastures can provide many important ecosystem services: maintain fertile soils, promote nutrient cycling, sequester carbon, prevent run-off and soil erosion, prevent nutrients and pathogens from entering watersheds, and provide nesting sites for birds and other wildlife (Björklund et al., 1999; Hubbard et al., 2004; Milchunas et al., 1998). Agricultural land also provides tax benefits to the town without incurring infrastructure costs, since farm land does not require services such as schooling, municipal water or snow plowing (Rogers, 2009).

As the beneficial health effects of grass-fed protein are extolled (Daley et al., 2010), and consumer interest in these products rises (McCluskey et al., 2005), it is important to consider the effects these animals have on the environment. Pasture reserved for horse use and livestock grazing increases the aesthetic appeal of an area (as evidenced by RI legislation (RI Department of Environmental Management, 2003)), in terms of sustainable land use. Well-managed pasture can increase the quality of the soil, improving pasture yield, and requiring the farmer to purchase less feed for his animals (USDA NRCS, 2003). Pasture, therefore, provides both intangible aesthetic and real monetary value, especially if the farmer's land is productive enough to enable hay production in addition to grazing. Healthy pasture also functions to buffer threats to water supplies, reducing some of the environmental risks associated with agriculture, such as pathogen contamination or eutrophication of downstream waters. As such, the results of this study could have important management implications for sustainable land use decisions and recommended grazing animals and regimens in parts of Rhode Island that are currently under farm or recreational use, helping to preserve the rural quality of the area.

The data from this study are intended to provide an objective evaluation of current soil quality in pastures throughout Rhode Island as a function of livestock type and management. Livestock management practices (herd size and age structure, grazing frequency and duration) and agronomic factors (plant community structure, soil fertility management, manure management) were documented to provide a better context in which to interpret the data. These data may facilitate a discussion of the implications of this agricultural land use for long-term maintenance of soil health.

As land conservation efforts in Rhode Island continue to preserve small farms and pastures, questions arise about how best to use the land without diminishing soil or water quality. The results of this study may help farmers, planners, landscape managers, the general public and the scientific community establish which type of livestock can be raised healthily and profitably, without degrading soil quality, or perhaps whether recreational space (e.g. horse pasture) is less detrimental to soils than other land uses.

Study Overview

This study was designed to examine the current soil quality conditions in Rhode Island pastures, and assess whether there are differences in soil quality parameters among pastures grazed by different types of livestock (beef cattle, horses and sheep), with reference to general agricultural soil recommendations (Gugino et al., 2009). I chose farms on soils formed from ablation till that raise cattle, sheep or horses in Rhode Island, and sampled their pasture to assess soil quality. Three control sites, in which pasture was hayed, but not grazed, were included as well. Soil quality parameters were measured three times during the growing season in 2012 and included: physical (aggregate stability, bulk density, infiltration, texture and penetration resistance); chemical (pH, electrical conductivity, extractable P and N); and biological (soil organic matter, active carbon, earthworm number, soil respiration, and standing plant biomass).

Statistical analysis was conducted on means of values obtained from each pasture during each sampling month, since this represents a composite soil sample taken in each pasture during each season, which is the recommended soil sampling protocol in Gugino et al. (2009). Comparisons were made among pasture types and sampling months to determine if statistically significant differences ($P < 0.05$) existed. In addition, Pearson product-moment correlation coefficients were calculated to determine which soil quality parameters were correlated. Finally, individual soil quality parameter values for each pasture type were converted to scores (%) after Gugino et al. (2009). Scores for each parameter were averaged to a single overall score for each pasture type, to determine which had the highest soil quality.

CHAPTER 2

METHODOLOGY

Farm Selection

Names and addresses of farms raising sheep, beef cattle or horses were collected from various online sources, including the Rhode Island Raised Livestock Association (RIRLA, 2010-2013), Rhode Island Sheep Cooperative (Cooperative, 2008-2013), Rhode Island Horseman's Association (Association, 2005-2013) and the Rhode Island Department of Environmental Management Farm directory (RI Department of Environmental Management, 2011). Farm locations were plotted in ArcGIS (ArcMap^{TM} version 10.0) on an aerial photograph. An intersect function was used to identify farms within 100 m of ablation till. Farm locations that intersected with ablation till soils were visually inspected to determine whether aerial photos of fields or pastures coincided with appropriate soils and parent materials. Those farms with fields on ablation till were organized into a list, and the owners or managers were contacted by email and by phone to enroll in the study. Of the 18 farms on the list, 9 agreed to participate in the study (some farms had both livestock and hayed pastures). Each pasture in the study was assigned a unique identifier that consisted of a letter (B for beef, E for horse, H for hay and S for sheep) followed by a number (1-3) for organizational purposes, and to maintain confidentiality.

Farmers or farm managers were initially briefed on the purpose of study and data collection methods. If amenable to being a study participant, they were given a consent form to sign (Appendix A), as mandated by the University of Rhode Island

Institutional Review Board. Participants were given a copy of the form to keep for future reference (Appendix A), and interviewed about farm management practices (Appendix B).

Sampling

Soils and vegetation. Sampling locations were determined in consultation with farmers, who were asked to point out preferred pastures to sample. At each sampling location, a 10 m × 10 m square was marked by flags, and 10 sampling points were laid out in a "W" shape (Figure 2.1; (Gugino et al., 2009)). The squares were established away from fence lines and feeding areas to exclude excessive traffic bias. Samples and data were collected from each pasture in May, August and October of 2012.

Additional squares (0.5 m × 0.5 m) were marked with flags next to sampling points 1, 4 and 9, and the vegetation cut to 1 cm above the soil surface to determine plant biomass. Vegetation was identified based on pasture vegetation keys, using Martinson (2008) to identify grass species, and Bosworth (2010), Meade (2012), and Spearman et al. (2009) to identify herbaceous or weedy species. Vegetation samples were placed in plastic bags and stored in a cooler for transport to the laboratory. Soil and vegetation samples were stored in a 1°C walk-in refrigerator.

Vegetation samples were processed in order of collection. Samples were cut into 2-5 cm lengths, and dried at 60°C in brown paper bags. When all moisture had evaporated (after ≥ 2 days) samples were removed from the oven and weighed.

To collect soil samples, cylindrical aluminum soil cores (15 cm tall, 5 cm i.d.) were pounded into the ground so that they were flush with the soil surface. The cores were dug up using a spade, wiped on off the outside and excess soil removed so the bottom of the core was flush with the aluminum cylinder. Each core was placed in a labeled sealable plastic bag and stored in a cooler for transport to the laboratory.

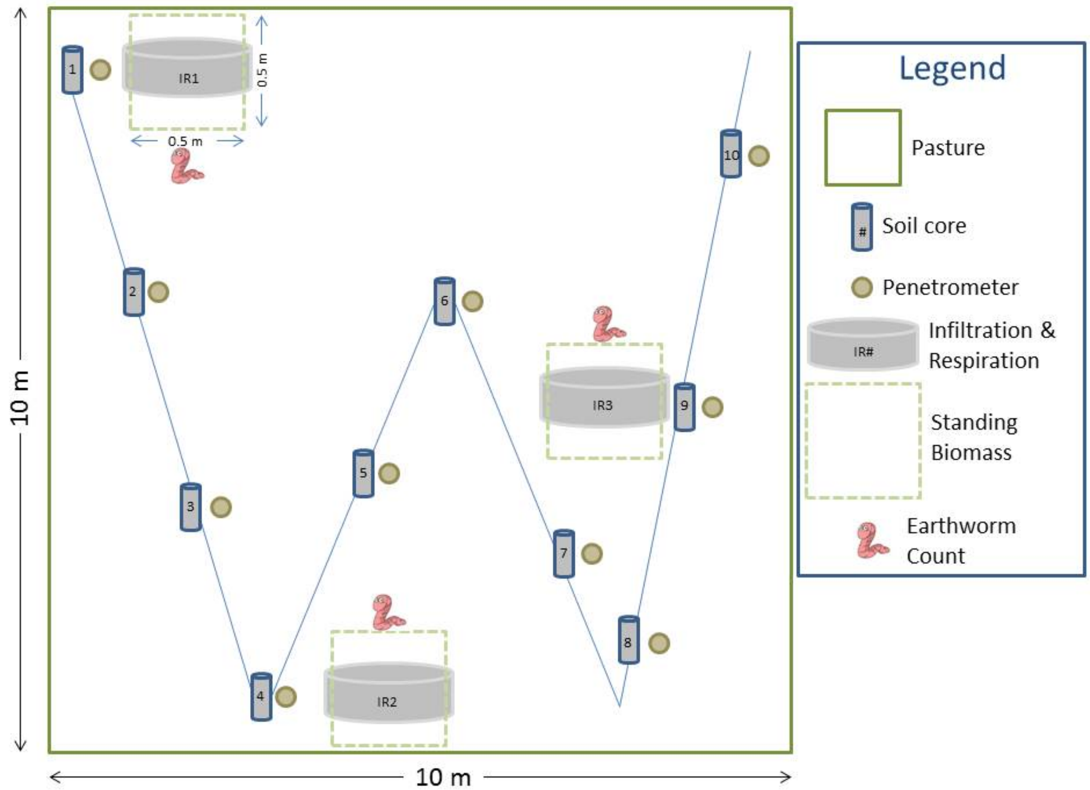


Figure 2.1. Soil and plant biomass sampling scheme for pastures.

Soil profile description. A soil profile description was made at each pasture site near sampling point 4 in August 2012. Soil was excavated to 50 cm, and the soil horizons were described following Soil Survey Division Staff (1993) standards. The depth, horizon designation, Munsell color, texture, rock fragment contents, redoximorphic features, boundaries, and structure of each horizon were recorded (Appendix D).

Penetration resistance. Penetration resistance was measured at all sampling points, using a model S/N 17039 penetrometer (Spectrum Technologies, Inc., Elysburg, PA), from 0-10 cm and 10-25 cm depths. The highest value was recorded while pushing the probe from 0-10 cm, and again from 10-25 cm.

Soil respiration. To measure soil respiration, PVC collars (11.5 cm tall, 30 cm i.d.) were pounded into the ground in the squares cleared of vegetation (Figure 2.1), so that the internal distance from the ground to the top rim of the collar was 8.9 cm. Soil respiration was measured with a Li-Cor 6262 infrared analyzer (Li-Cor, Lincoln, NE). The soil temperature and initial air temperature were measured using a digital thermometer with a metal probe (Fisher Scientific, Pittsburg, PA). Once the background CO_2 concentration was constant, the atmospheric pressure was recorded along with background levels of CO_2. A dome attached to the gas analyzer was placed over the collar and pressed down to make a good seal. The CO_2 concentration of the air in the chamber was recorded every 10 s for 5 min, after which the dome was removed and the final air temperature inside the collar was recorded. The instrument was moved to the next collar, allowed to equilibrate, and the process described above repeated.

Infiltration rate. After respiration measurements were made, a plastic bag was placed over each collar, and 1228 mL (equivalent of 2.5 cm depth) of water were placed on top. The time was recorded following the plastic removal until the water had infiltrated into the unmoistened soil and the surface was still moist and slightly shiny. If infiltration took less than 40 min, this process was repeated once more. Infiltration rates were averaged (when applicable) to yield the final infiltration rate.

Earthworm population density. To quantify earthworm populations, a 30 cm × 30 cm × 30 cm hole was dug near sampling point 1 in May, point 4 in August, and point 9 in October. Excavated soil was placed on a plastic cloth, sorted and earthworms found in the soil were set aside and counted, as were any earthworms found in the hole after the excavation was complete.

Analysis

Soil respiration. The Ideal Gas Law was used to calculate the CO_2 concentration inside the chamber, using the following equation:

$$n = (PV) / (RT),$$

where:

n = moles of CO_2 per mole of air

P = pressure (atm)

V = volume of gas (L)

R = universal gas constant (0.0821 L atm / mol K)

T = temperature (K)

The volume of the respiration chamber was 12.62 L, and the cross-sectional area of the chamber was 520.5 cm^2. Respiration data (CO_2 concentrations) were plotted against time, and the slope of the line when respiration data were increasing linearly (Davidson et al., 2002) was used to calculate the number of moles of CO_2 evolved per mol of air per second in the respiration chamber. These values were converted to kg CO_2-C/ha/d.

Bulk density. Within 2 days of sample collection, soil was removed from the aluminum cores, and weighed to determine bulk density. Subsamples (~20 g fresh weight) of each soil core were passed through a 2-mm-mesh sieve, placed into weighed crucibles, and dried at 105°C (except samples from points 1, 4, or 9, of which

~150 g were dried). These samples were weighed again immediately after removal from the oven. Bulk density was calculated by determining the moisture content (based on the 20-g subsample) and subtracting the total moisture content from the initial core weight. The extrapolated oven-dried core weight was divided by the core volume (118 cm^3) to determine soil bulk density. Core bulk density was not corrected for rock fragments.

Organic matter analysis. Oven-dried soil samples were weighed and combusted in a muffle furnace at 550°C for 5 h to determine organic matter content. Combusted samples were returned to a 105°C oven for at least 5 h, then weighed again immediately after removal from the oven. Soil organic matter was calculated by determining the percent of organic matter content of the oven-dried subsample using the equation:

%OM = 100*(dried soil wt – combusted soil wt)/(dried soil wt)

Particle size distribution. Combusted soil samples from sampling points 1, 4 and 9 were used for particle size distribution analysis using the hydrometer method (Palmer and Troeh, 1995).

Water-stable aggregates. The stability of aggregates >250 µm in diameter was determined using a modification of the procedure described in Schoenau and Karamanos (1993). Air-dried soil aggregates (1-2 mm) were weighed (W1) onto a 250-µm-mesh sieve. The sieve was placed in a shallow water bath for 5 min, allowing capillary action to wet aggregates. The sieve was attached to a pneumatic pump that raised and lowered the sieve ~60 times/min for 5 min, during which time the surface of the sieve remained submerged. The sieve travelled 3 cm vertically with each stroke.

After 5 min, the sieve was removed and aggregates remaining were washed into a tared, 125-mL Erlenmeyer flask and dried at 105°C. Samples were weighed again (W2), then 50 mL of a 0.5% Calgon (sodium hexametaphosphate) solution was added to the flask. Flasks were sealed and shaken for 45 min at low speed, and the resulting suspension poured onto a 250-μm-mesh sieve. After gentle washing, the material remaining on the sieve was returned to the Erlenmeyer flask, dried at 105°C, and weighed again (W3). The fraction of water-stable aggregates (WSA) was calculated using the equation:

$$\%WSA = 100(W2-W3)/[(W1/(1+WC))-W3]$$

Electrical conductivity and pH. To measure soil electrical conductivity and pH, fresh soil (~4 g) from each core was placed into a 50-mL plastic centrifuge tube. Deionized, distilled water (20 mL) was added, the tubes capped, shaken on a reciprocal shaker for 30 min, and allowed to rest for 1 h. Electrical conductivity (HI 9835 waterproof EC/TDS/NaCl/°C Meter, Hanna Instruments, Smithfield, RI) and pH (Accument pH ATC combination electrode with silver/silver chloride reference pH, Fisher Scientific, Fairlawn, NJ) were measured and recorded.

Extractable NH_4^+ and NO_3^-. To extract inorganic nitrogen (NH_4^+ and NO_3^-), 1 g of fresh soil (sieved to 2 mm) from each soil core was placed in a tared, 15-mL plastic centrifuge tube, 10 mL of 2 M KCl added, and the tube capped and vortexed to suspend soil particles. Tubes were shaken on a reciprocal shaker at low speed for 30 min, and the contents centrifuged at 2700 rpm for 7 min. A portion (1.8 mL) of the supernatant solution was stored in a 2-mL plastic microcentrifuge tube and frozen.

For analysis of NO_3^-, a modification of the method of Larios (2008) was used. Samples were thawed and 100 µL of extract were pipetted in triplicate into a 96-well plate containing blanks and standards. Saturated vanadium (III) chloride solution (100 µL; 0.175 g vanadium (III) chloride in 25 mL 1N HCl) was added to each well, and the contents mixed. After incubating at room temperature for 5 h, absorbance at 540 nm was determined using a microplate reader (BIO-TEK PowerWave 340, Winooski, VT). To measure ammonium concentrations, 40µL of thawed extract were pipetted in triplicate into a 96-well plate along with process blanks and standards. 6% NaOH solution (80 µL; containing 2% bleach) and 80 µL sodium salicylate solution (6.8 g sodium salicylate, 5 g sodium citrate, 5 g sodium potassium tartrate, and 0.025 g sodium nitroprusside in 100 mL deionized, distilled water) were added to each well and the contents mixed by gently tapping the corner of the plate. After incubating at room temperature for 50 min, the absorbance at 650 nm was determined using a microplate reader.

Extractable PO_4^{3-}. To extract phosphate, 1.5 g of fresh soil sample was placed into a 15-mL plastic centrifuge tube. 0.5M $NaHCO_3$ (15 mL; adjusted to pH 8.5) was added, the tube vortexed, placed on a reciprocal shaker at low speed for 30 min, followed by centrifugation at 2700 rpm for 7 min. The supernatant solution was decanted into clean, labeled 20-mL plastic scintillation vials, capped and stored frozen. For phosphate analysis (Schoenau and Karamanos, 1993), samples were thawed, shaken, and 1.5 mL of extract was transferred to a 2-mL plastic microcentrifuge tube. Samples were acidified to a pH of 3 with concentrated sulfuric acid. To determine PO_4^{3-} concentration, 32 µL of Murphy-Riley solution (2.5 M sulfuric acid, ammonium molybdate (2 g in 50 mL deionized, distilled water), ascorbic acid (2.64 g L-ascorbic acid in 50 mL deionized, distilled water), antimony potassium tartrate (0.1454 g in 50 mL deionized, distilled water) was added to 200 µL of each sample (in triplicate), blanks and standards in a 96-well microplate. After incubation for 15 min at room temperature, the absorbance at 712 nm was determined using a microplate reader.

Active carbon. To determine active C levels, soil samples were air-dried for 48-72 h and gently sieved to 2 mm. Sieved soil samples were ground to a fine powder using a mortar and pestle, and 2 g weighed into 15-mL propylene centrifuge tubes. The remaining air-dry soil was weighed, dried at 105°C and weighed again to determine moisture content. $KMnO_4$ solution (0.02 M, 8 mL) was added to the tubes, and the tubes vortexed and shaken by hand to suspend soil particles. The tubes were then shaken on a reciprocal shaker on high for 2 min (Weil et al., 2003) and centrifuged at 2700 rpm for 7 min. To account for sample changes due to processing, 3 process blanks per batch of samples were included by adding 8 mL $KMnO_4$ solution to clean, empty centrifuge tubes, and processed like the experimental samples. To analyze $KMnO_4$ absorbance (indicative of the amount of C reacted in a sample), 20 µL of sample was pipetted immediately after centrifugation into a 96-well microplate in triplicate, at a 1:10 dilution. Absorbance at 550 nm was determined using a microplate reader. The active C fraction was calculated by determining the fraction of the 0.02 M potassium permanganate that had reacted with active C in the sample using the equation (Weil et al., 2003):

$$\text{mol } KMnO_4 \text{ reacted} = \text{mol active C} = (0.02\text{M} - \text{sample conc.}) / \text{soil wt (kg)}$$

Moles of active C were converted to mg C using atomic weight to describe active C content in mg C/kg soil.

Soil quality score conversion. Values for individual soil quality indicators were converted to % values after Gugino et al. (2009). Graphs in Gugino et al. (2009) were used to determine the score (%) of a particular value for a given soil quality indicator. For indicators not included in Gugino et al. (2009) (the Cornell Soil Health Assessment Training Manual), values given in USDA (2001) (bulk density, respiration rate, electrical conductivity, infiltration rate, and earthworm density), Marx et al. (1999) (nitrate), Heckman (2003) (ammonium, nitrate), and Campbell and Stafford Smith (2000) (above-ground biomass) were used to estimate score percentage conversions (Appendix C). Final scores were calculated by averaging individual soil quality indicator scores after Gugino et al. (2009). All indicators were weighed equally in the final score determination.

Statistical analyses. Data from each farm at each sampling date for each soil quality parameter were compiled and combined according to farm type in SigmaPlot Version 11.0. This data set was used to generate descriptive statistical values and to create box plot graphs. For each pasture, means were calculated for each sampling month for each soil quality indicator, since mean values represent a bulk sample taken from the pasture, as suggested by Gugino et al. (2009) in their sampling protocol. Means for each month in each pasture were compiled by pasture type (n=9), as well as by month (n=12). Means were analyzed using a one-way ANOVA on ranks, since the data were not normally distributed (using the Shapiro-Wilk test). The ANOVA on ranks test is useful in determining whether three or more independent groups are similar or different in some variable, when ordinal data or an interval or ratio level of data is known, or when data are not normally distributed (Chan and Walmsley, 1997). ANOVA on ranks were run to determine whether values for each pasture type for each indicator differed significantly from one another. The same test was run on the data from each sampling month, to determine whether values from different months were significantly different from one another. Differences were considered significant for $P < 0.05$.

Mean values for sampling events in each pasture were also used to determine the Pearson product-moment correlation coefficient for each soil quality indicator. Correlations were considered significant if $P<0.05$.

CHAPTER 3

RESULTS & DISCUSSION

Site Characteristics

Farms. The results from the farmer questionnaire are presented in Table 3.2. Few farmers shared specific fertilization and liming information (e.g. application rates, types of fertilizer), some farmers provided a few details, and others were unwilling or unable to supply this information. Information from farmers was not particularly detailed or complete. Many farmers either were not comfortable sharing information with me or did not know things about their pastures.

Pasture size varied among farms, total area in pasture ranged from 0.4 ha to 16.4 ha (Table 3.1). Farms had a wide range of herd sizes, and had been in operation for a wide range of years. Some farmers reported rotating animals in pastures or paddocks, though this was observed only in a few pastures (B1, E1, S2; Table 3.2). Estimated stocking density varied from 5.4 to 53.8 animals/ha, but estimated stocking densities for each livestock type were within an order of magnitude of each other (Table 3.1). Pasture vegetation type was only well-known to farmers who managed or owned hay pastures; in general, knowledge of plant species in livestock pastures was limited. Half of the pastures in the study were amended with fertilizer and/or lime, though only one farmer shared specific information on application rates. Only 4 pasture soils had been previously tested, though farmers did not share results with me. Only one farmer had concerns about the pasture, which was to keep out poisonous plants. In general, farmers reported drainage to be fairly good, stating that pastures did not stay muddy for long. Horses were kept inside during rain, but it is unclear whether or not they were turned out on pasture if the rain has ceased but the pasture soil was still wet. Only one farmer knew anything about soil quality, which was a result of an NRCS manure management plan. Despite having expressed interest in a seminar presenting the results of the study, no farmers contacted me after receiving their soil quality test results regarding the seminar.

Table 3.1. Pasture area, total numbers of animals, and estimated stocking density in beef, horse, hay and sheep pastures. Pasture area was estimated using the “Measure” tool in ArcGIS (ArcMap™ version 10.0) on aerial photographs (Bing-generated). Animal numbers were those reported by farmers (Table 3.2). N/A indicates not applicable.

Farm	Pasture area (Ha)	Total # animals	Stocking density (animals / ha)
B1	7.1	50	7.0
B2	5.3	19	3.6
B3	1.8	12	6.7
E1	3.3	20	6.1
E2	5.6	30	5.4
E3	1.1	12	10.9
H1	3.4	N/A	N/A
H2	16.4	N/A	N/A
H3	12	N/A	N/A
S1	1.3	70	53.8
S2	2	45	22.5
S3	0.4	10	25.0

Soils. Soil profile descriptions (Appendix B) for all pastures were consistent with official descriptions of Charlton and Canton soil series (Soil Survey Division Staff, 1993), which are deep, well drained loamy soils formed in ablation till whose parent materials are very low in iron sulfides. These soils are found on nearly level to steeply sloping landscapes, and have moderately high saturated hydraulic conductivity. All pastures in this study had slopes of 0-3%, except for E2 and S3, which had slopes of

Table 3.2. Farm manager/owner answers to farmer questionnaire (Appendix B). N/A = no answer or “don’t know”.

	Beef			Horse			Hay			Sheep		
Question	B1	B2	B3	E1	E2	E3	H1	H2	H3	S1	S2	S3
Breeds, farm age, avg herd age	Polled Herefords; 10+ yrs	Polled Herefords; ~90 yrs	Angus cross; 5-10 yrs?	Horses; 20+ yrs; 15 yr avg	Horses	Horses; 11 yrs	60+ yrs	~40 yrs	~30 yrs	Sheep (variety); 30 yrs; 2yr avg age	Sheep (variety); 60+ yrs; 5 yr avg age	Sheep (variety); ~15 yrs
Number animals	50	19	12	Not sure – 20?	30?	12	N/A	N/A	N/A	70	45	10
Grazing management	Rotational – move when grass 2-3” tall	Continuous	Rotate depending on grass/rain	Semi-rotation – some paddocks rested 2 months	Rotate every few days	Rotational	N/A	N/A	N/A	Continuous	Rotational; graze ~2 wks	Continuous
Plant species in pasture	Orchard grass, timothy, fescue, wild oats	N/A	N/A	N/A	N/A	N/A	Timothy, white clover; problem with black swallowwort	Orchard grass, timothy, fescue, wild oats	35% orchard grass, 35% timothy, 15% brome, 15% other	Nettle, grass	Timothy, white clover; problem with black swallowwort	N/A
Lime, fertilizer	N/A	No	Spray chicken manure	Lime & fertilizer last year	N/A	No	10-10-10 fertilizer yearly	N/A	Milorganite fert. (3 ton/ ac), lime (1 ton/ac)	Lime, fertilizer some years	10-10-10 fertilizer yearly	No
Soil testing	No	No	Yes – NRCS	No	No	No	Yes – for fertilizer	N/A	Yes – every year	No	Yes – for fertilizer	No
Concerns about pasture	No	No	No	No	No	No	No	No	No	No	No	Keep out poisonous plants
Drainage	Good; cattle stay on pasture	Good; muddy 1 day; cattle stay on pasture	Good; rarely muddy; cattle stay on pasture	Good; muddy for few days; horses inside	Good; muddy for 1 day; horses inside	Good; muddy <1 day; horses inside	OK; muddy for a few days	Good	Good; muddy for 1 day	OK; muddy for few days; sheep stay on pasture	OK; muddy for a few days; sheep stay on pasture	Good; muddy 1 day; sheep stay on pasture
Soil quality knowledge	N/A	N/A	NRCS Manure management plan	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Interest in seminar	Yes; how to improve (specific)	Yes; how to improve inexpensively	N/A	N/A	N/A	N/A	Yes; how to improve	Yes; how to improve (specific)	N/A	N/A	Yes; how to improve	N/A
Last grazed	N/A	Current	Current	N/A	Current	Current	N/A	N/A	N/A	Current	N/A	Current

Table 3.3. Soil particle size distribution and textural class for pastures under beef, horse, hay and sheep pastures. Values are means of three soil samples from the upper 15 cm of the soil profile.

Pasture	Particle size distribution (%)			Textural class
	Sand	Silt	Clay	
B1	66.7	23.6	9.7	Sandy loam
B2	61.5	31.0	7.5	Sandy loam
B3	65.2	26.2	8.5	Sandy loam
E1	72.1	19.4	8.4	Gravelly sandy loam
E2	63.8	28.1	8.0	Sandy loam
E3	70.6	20.4	9.0	Gravelly sandy loam
H1	68.1	25.0	6.9	Sandy loam
H2	70.7	21.1	8.1	Sandy loam
H3	68.3	21.8	9.9	Sandy loam
S1	70.9	18.3	10.8	Sandy loam
S2	59.6	30.5	9.8	Sandy loam
S3	82.2	12.2	5.6	Loamy sand

Table 3.4. Aboveground plant biomass collected from pastures under beef, horse, hay and sheep (g dry weight/m^2).

Month	Beef			Horse			Hay			Sheep		
	B1	B2	B3	E1	E2	E3	H1	H2	H3	S1	S2	S3
May	106.1	269.4	57.3	131.8	64.1	0	391.7	389.1	282.3	20.3	363.4	94.3
Aug	159.5	128.3	149.5	83.8	215.7	0	147.9	0.0	48.4	64.3	166.9	37.4
Oct	0	141.0	0	0	0	0	294.4	102.9	81.6	0	154.9	0
Total	265.6	538.7	206.8	215.6	279.8	0	834	492	412.3	84.6	685.2	131.7
Total Mean		337.0			165.1			579.4			300.5	

3-8%. Stones and boulders are often prevalent at the soil surface. Charlton and Canton soils are extremely to medium acid, and have medium risk for runoff (Rector, 1981). The textural class for all farms, except for E1, E3 and S3, was sandy loam (Table 3.3). At S3, the prevailing textural class was loamy sand. Soil texture results were consistent with field soil profile descriptions, as well as Charlton and Canton soil series descriptions.

Vegetation. Plant species observed in pastures included grasses and forbs (Appendix C). Temperate pastures can produce anywhere from 400 (but generally from 800) to 1600 g vegetation/m^2 vegetation over the course of a year, from spring to fall (Campbell and Stafford Smith, 2000; Newton et al., 1995; Saggar and Hedley, 2001). Only one hay pasture (H1) was within the expected range for total plant biomass production (834 g/m^2; Table 3.3). The mean hay pasture plant biomass production from May to October was 579 g/m^2 (Table 3.4), within normal pasture production ranges. Despite being grazed, pastures B2 and S2 had biomass production rates approaching that of H1 (Table 3.4).

Although grazing has been shown to increase above-ground net primary productivity, or pasture growth (Guo and Gifford, 2002; Milchunas and Lauenroth, 1993), most grazed pastures in this study showed evidence of poor pasture production, potentially indicating overgrazing, especially in October (Table 3.4). From my observations during sampling, none of the pastures were subdivided for rotational grazing, which has been shown to be beneficial for plant growth, desirable pasture species establishment, and improved soil quality (Manley et al., 1995; Teague et al., 2011).

Physical Indicators

Bulk density. The median value for bulk density (g/cm^3) for horse pastures was highest across all seasons (1.26), followed by beef pastures (1.16), sheep (1.15) and hay pastures (1.08) (Figure 3.1). Bulk density values for surface soils in the Charlton soil series are around 1.0 g/cm^3 (Rourke and Beek, 1969), and values for cultivated sandy loams can range from 1.2 to 1.7 g/cm^3 (Brady and Weil, 2008). The values from the pastures studied are well within these ranges. None of the bulk density values exceeded the 1.60-1.75 g/cm^3 threshold, at which point roots are restricted from growing in sandy loam (Brady and Weil, 2008; Gugino et al., 2009). No pasture type appears to be in danger of problematic effects related to undesirably high bulk density values.

Bulk density values in hay and sheep pastures were more tightly clustered (CV = 6.85%), with fewer outliers than values in beef and horse pastures, suggesting a more uniform distribution of bulk density in these farms (Figure 3.1). Significantly higher bulk densities were observed in beef and horse pastures than in hay or sheep pastures (Figure 3.1). This is likely due to trampling – horses' hooves have smaller contact area with soil than cattle or sheep hooves (Figure 1.1), so this may lead to localized increased compaction. Cattle and beef are larger than sheep and their hooves have greater impacts with each individual step than sheep do (Di et al., 2001; Horn et al., 2004; Parés-Casanova and Oosterlinck, 2012). In addition, horse paddocks in our study tended to be smaller than other pasture types, and thus effective stocking density was likely higher in horse than in beef or sheep pastures. On average, horse pastures had higher stocking densities than beef pastures (Table 3.1). Furthermore, horse pastures had the lowest aboveground plant biomass production (Table 3.4), which could lead to lower organic matter content and thus greater values for bulk density. Higher above-ground plant biomass production (Table 3.4) may have led to lower bulk density values in hay pastures because of higher organic matter inputs.

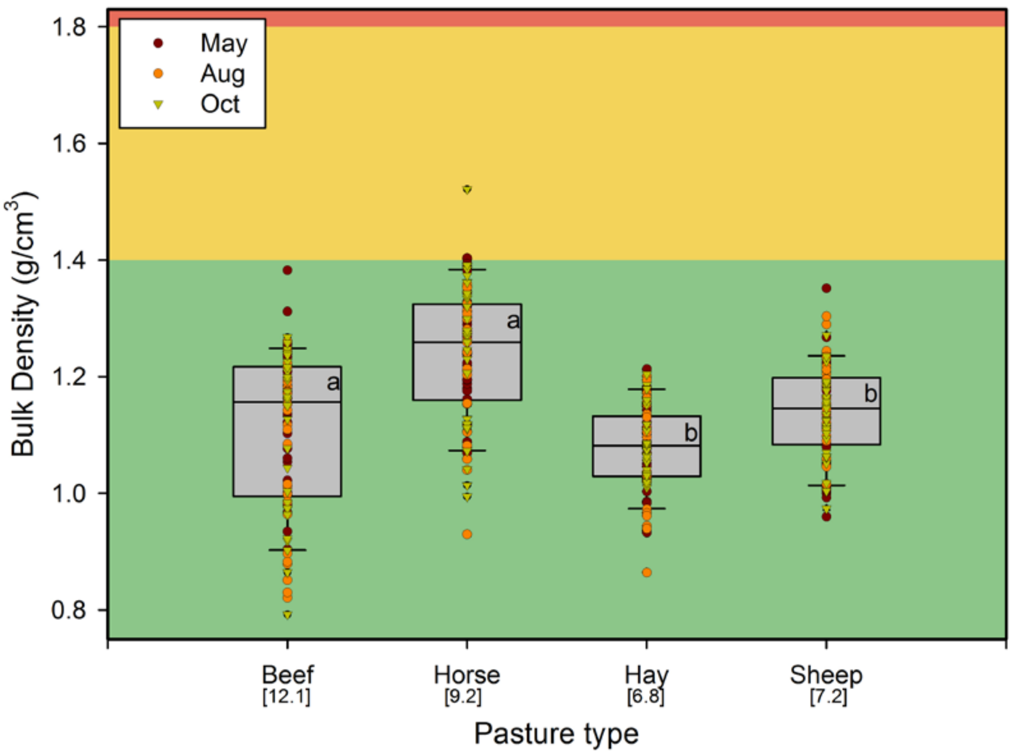


Figure 3.1. Bulk density of the upper 15 cm. Background colors in this and all the following figures indicate ideal (green), acceptable (yellow) and problematic (red) value ranges, according to Gugino et al. (2009). Boxes represent middle quartiles (25 to 75%), lines dividing boxes represent median value, and whiskers represent 5th and 95th percentiles. Circles and triangles represent individual data points, color-coded by sampling month. Pasture types with the same letter were not significantly different. Values in brackets below pasture types are the coefficient of variation (CV, %).

Bulk density is affected by organic matter content, aggregate stability, top-soil depth, and biological activity (Arshad and Martin, 2002). In our study, bulk density values was negatively correlated with aggregate stability, organic matter, active carbon content, nitrate concentration, electrical conductivity, moisture and above-ground biomass (Table 3.5). Low bulk density values indicate good soil quality, since lower bulk density facilitates water infiltration, aerobic soil conditions and good root growth, while reducing run-off (USDA NRCS, 2001a).

Penetration resistance. Penetration resistance values (PSI; 1 PSI = 6.89 kPa) for the upper 10 cm of the soil profile ranged from 43 for sheep pastures in May, to 295 for horse pasture in October (Figure 3.2). Median values for penetration resistance of the surface soils in beef, horse, hay and sheep pastures were 200, 175, 100 and 100 PSI, respectively (Figure 3.2). Penetration resistance for the upper 10 cm in beef and horse pasture were not significantly different from each other, but were significantly greater than values for sheep and hay pastures (Figure 3.2). Penetration resistance in the upper 10 cm did not vary significantly among sampling months.

Median values for penetration resistance (PSI) at 10-25 cm were highest for horse (250), followed by beef (235), hay (175) and sheep pastures (125 PSI) (Figure 3.2). Penetration resistance in the 10-25 cm soil depth was significantly higher in horse pastures than in sheep or hay pastures. There were no significant differences between beef and horse pastures, beef and hay pastures, or hay and sheep pastures.

Field penetration resistance provides an indication of soil compaction; it measures the amount of pressure required to push a probe through the soil. Roots cannot penetrate soils with resistance values above 300 PSI (Gugino et al., 2009), which would detrimentally affect pasture production. Values greater than 200 PSI in surface soils (0-10cm) indicate potential problematic conditions, since penetration resistance

Table 3.5. Pearson product-moment correlation coefficients for soil quality properties under study. Bold values are significant.

Property	Penet. 0-10	Penet. 10-25	Bulk dens.	Aggr. stabil.	Org. matter	Active C	NH_4^+	NO_3^-	PO_4^{3-}	EC	pH	Respiration	Infiltration	Earthworms	Moist.	Temp.	Biomass
Penet. 0-10		**0.900**	0.266	**-0.438**	-0.058	-0.332	0.180	0.099	-0.240	-0.058	-0.318	-0.133	-0.174	**-0.432**	-0.272	0.012	**-0.471**
Penet. 10-25			0.247	-0.291	-0.132	-0.151	0.229	-0.045	**-0.398**	-0.102	-0.131	-0.011	-0.040	**-0.405**	-0.201	-0.003	-0.262
Bulk dens.				**-0.337**	**-0.587**	**-0.680**	-0.050	**-0.352**	0.167	**-0.340**	-0.203	-0.198	-0.135	-0.103	**-0.486**	0.105	**-0.458**
Aggr. stabil.					0.183	0.253	-0.107	**-0.335**	-0.141	-0.316	0.076	0.105	0.175	**0.335**	0.137	0.023	**0.601**
Org. matter						**0.470**	0.070	0.295	-0.062	0.276	0.242	0.244	-0.122	-0.171	**0.423**	-0.060	0.106
Active C							0.250	0.162	-0.203	0.319	**0.667**	0.202	0.120	0.137	**0.521**	-0.179	**0.401**
NH_4^+								0.142	-0.108	0.079	**0.476**	0.079	-0.253	-0.166	0.230	0.0116	-0.062
NO_3^-									0.164	**0.824**	-0.016	0.173	-0.253	-0.156	0.150	0.001	-0.135
PO_4^{3-}										0.211	-0.105	-0.061	0.044	0.080	-0.073	-0.050	-0.064
EC											0.179	0.077	0.000	-0.082	0.161	-0.064	0.070
pH												0.109	-0.207	0.0383	**0.440**	-0.070	0.161
Respiration													-0.187	**-0.382**	0.068	**0.695**	0.161
Infiltration														0.050	-0.216	-0.302	0.090
Earthworms															**0.362**	**-0.497**	**0.462**
Moist.																**-0.424**	**0.394**
Temp.																	-0.042

values less than 125 PSI in surface soils are desirable for plant growth and good soil structure (Gugino et al., 2009; Magdoff and van Es, 2000). For subsurface (10-25 cm) penetration resistance, values greater than 350 PSI are problematic, whereas values less than 250 PSI indicate good soil quality with little risk of soil compaction (Gugino et al., 2009).

Horse and beef pasture penetration resistance in the surface soils were mainly in the acceptable and problematic ranges, indicating that there may be problems with soil compaction in these pastures (Figure 3.2). However, most farms were within the ideal range in terms of subsurface penetration resistance.

The exact mechanism of penetration resistance are somewhat unclear, though water content, bulk density, the susceptibility to decrease in bulk volume when subjected to a load, and soil structure can influence penetration resistance (Landsberg et al., 2003). In this study, penetration resistance values at different depths were positively correlated with one another, but negatively correlated with aggregate stability, earthworm counts and above-ground biomass for surface penetration resistance, and extractable phosphate and earthworm counts for sub-surface penetration resistance (Table 3.5). Magdoff and van Es (2000) suggest making repeated penetration resistant measurements over the growing season to account for variations in soil moisture. Penetration resistance has been shown to increase in pastures that are grazed during the dormant season in addition to the growing season (Stavi et al., 2011). However, in this study, penetration resistance did not vary significantly with sampling month for any pasture type (data not shown). Though October had the largest penetration resistance values across farm types, differences were not significant, and soil moisture

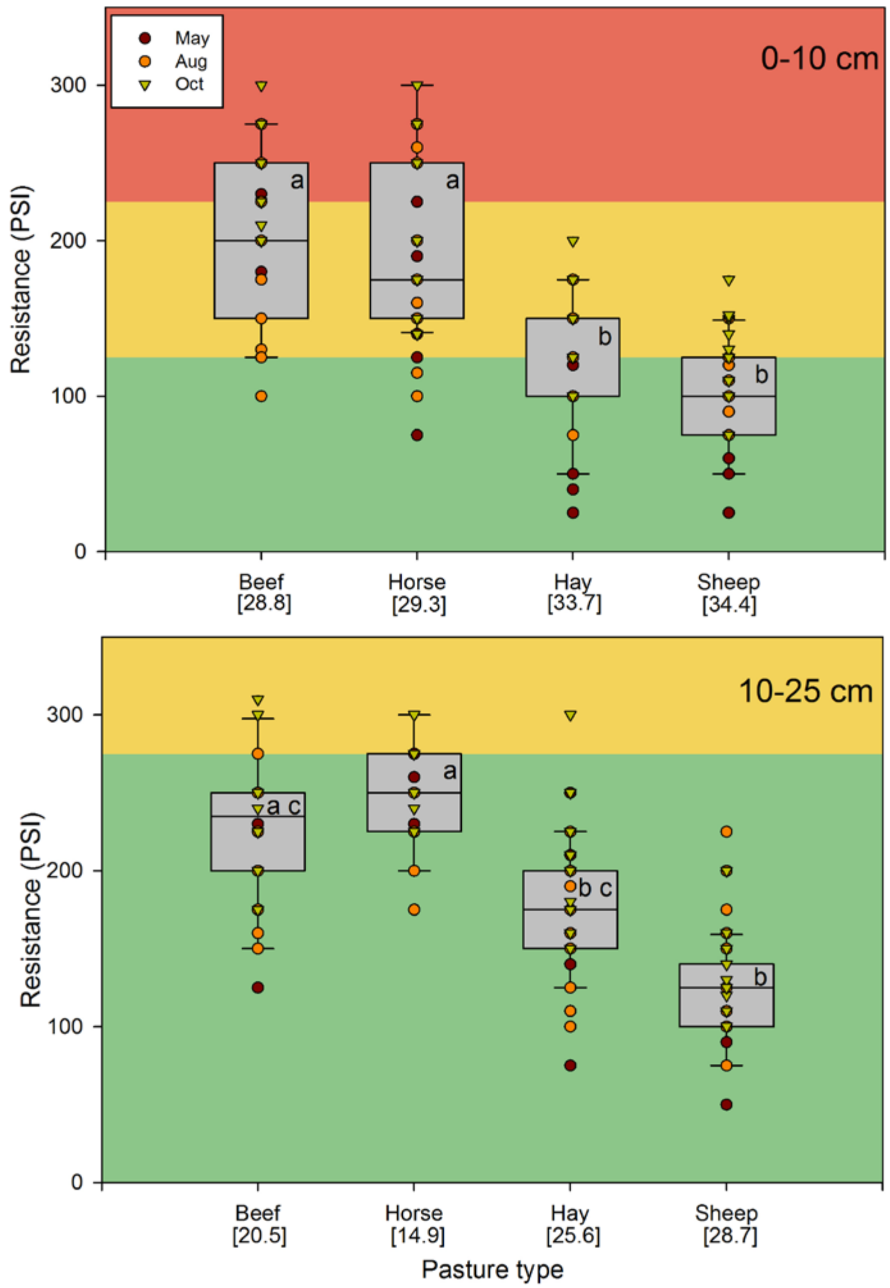


Figure 3.2. Soil penetration resistance of 0-10 and 10-25 cm (1 PSI = 6.895 kPa) in beef, horse, hay and sheep pastures. Boxes represent middle quartiles (25 to 75%), lines dividing boxes represent median values, and whiskers represent 5th and 95th percentiles. Circles and triangles represent individual data points, color-coded by sampling month. Pasture types with the same letter were not significantly different. Values in brackets below pasture types are the coefficient of variation (CV, %).

was not significantly correlated with penetration resistance, indicating that recommendations for repeat soil testing made by Magdoff and van Es (2000) and Landsberg et al. (2003) may not be valid for southern New England.

Penetration resistance and bulk density values appear to provide conflicting evidence regarding soil compaction concerns: while penetration resistance data suggest that beef and horse farms are at risk for surface compaction, bulk density values do not indicate problematic soil compaction in surface soil (Figure 3.1;Figure 3.2). Bulk density and penetration resistance were not significantly correlated (Table 3.4) Therefore, it seems important to take penetration resistance, soil moisture, infiltration rate and bulk density values into account to determine whether soil compaction is a real concern in pastures.

Infiltration rate. Median values for infiltration rates (cm/hr) were 33.9, 21.5, 12.8 and 8.1 for hay, sheep, beef and horse pastures, respectively (Figure 3.3). Infiltration rates in our study were higher than reported for well-drained soils, which range from 1 to 2 cm/hr for sandy and silty soils (Soil Survey Division Staff, 1993; USDA, 2001). Infiltration rates for hay pastures were more tightly clustered (CV = 68.6%) than for any other type of pasture (Figure 3.3). Infiltration rates were not significantly different among pasture types or seasons (Figure 3.3).

Higher infiltration rates in hay pastures are consistent with previous studies suggesting that ungrazed pastures have greater infiltration rates than grazed pastures (Bharati et al., 2002). Infiltration rates are reduced by soil compaction, high bulk density, low aggregate stability and organic matter content, management practices and the absence of deep-rooted plants (Bharati et al., 2002; Gugino et al., 2009). In this study, infiltration rates were not significantly correlated with any of the soil quality parameters measured (Table 3.5). Infiltration rates are known to decrease in pastures over the course of the grazing season under high stocking rates (Abdel-Magid et al., 1987; Radke and Berry, 1993), conditions observed in the horse pastures in our study, but also in other pasture types. Other studies have found that compaction caused by farm implements and grazing animals increases bulk density values and decreases infiltration rates (Bharati et al., 2002).

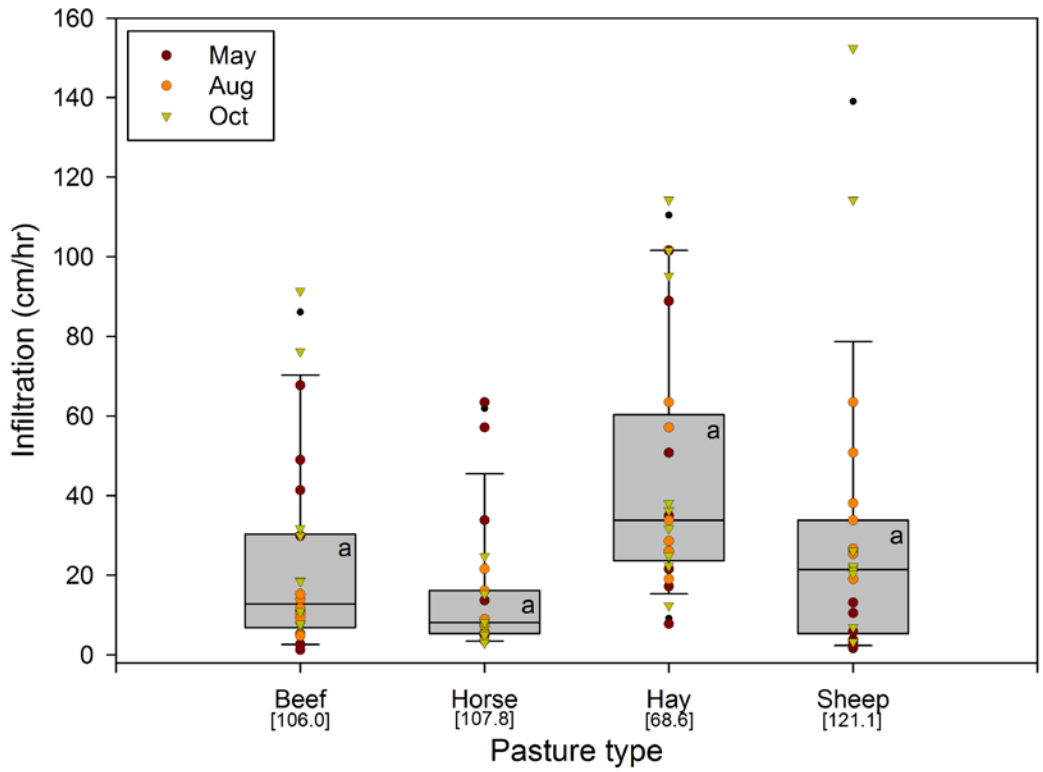


Figure 3.3. Water infiltration rates in beef, horse, hay and sheep pastures. Boxes represent middle quartiles (25 to 75%), lines dividing boxes represent median values, and whiskers represent 5th and 95th percentiles. Circles and triangles represent individual data points, color-coded by sampling month. Pasture types with the same letter were not significantly different. Values in brackets below pasture types are the coefficient of variation (CV, %).

Soil organic matter. Across seasons, hay pastures had a median organic matter content of 6.8%, beef 6.6%, sheep 6.2%, and horse 4.9% (Figure 3.4). Values for hay pastures were the least variable (CV = 15.0%) and had the fewest outliers (Figure 3.4). There were significant differences in soil organic matter content between beef and horse pastures, and between horse and hay pastures (Figure 3.4). Only horse and sheep pastures had values that fell outside the ideal range for organic matter content (Figure 3.4) for agricultural soils, indicating that current management practices are not negatively affecting organic matter content of the soil. Horse pastures had the lowest organic matter content, and the lowest plant biomass (Figure 3.4; Table 3.4), suggesting that the two indicators are strongly linked. However, there was no significant correlation in this study between organic matter content and above-ground plant biomass (Table 3.5). In the southeastern US, Franzluebbers et al. (2000a) and Franzluebbers and Stuedemann (2009) have shown that organic matter content is higher under grazed pastures, when compared to hayed pastures, which is not the case in this study. Animal trampling could potentially incorporate vegetation and excretions into the soil, increasing organic matter content in pastures that had adequate quantities of vegetation. Since horse pastures were noticeably over-grazed (Table 3.4), this might account for the lower soil organic matter content.

Soil organic matter affects physical, chemical and biological soil properties, by contributing to aggregate stability, improving water infiltration rates, retaining and providing nutrients and energy to plants and microbes (Gugino et al., 2009). As soil organic C decreases, microbial biomass and respiration, earthworm numbers, aggregate stability and overall porosity also decrease (Haynes and Williams, 1999).

However, significant correlations between soil organic matter content only existed between bulk density, active C content and soil moisture (Table 3.5).

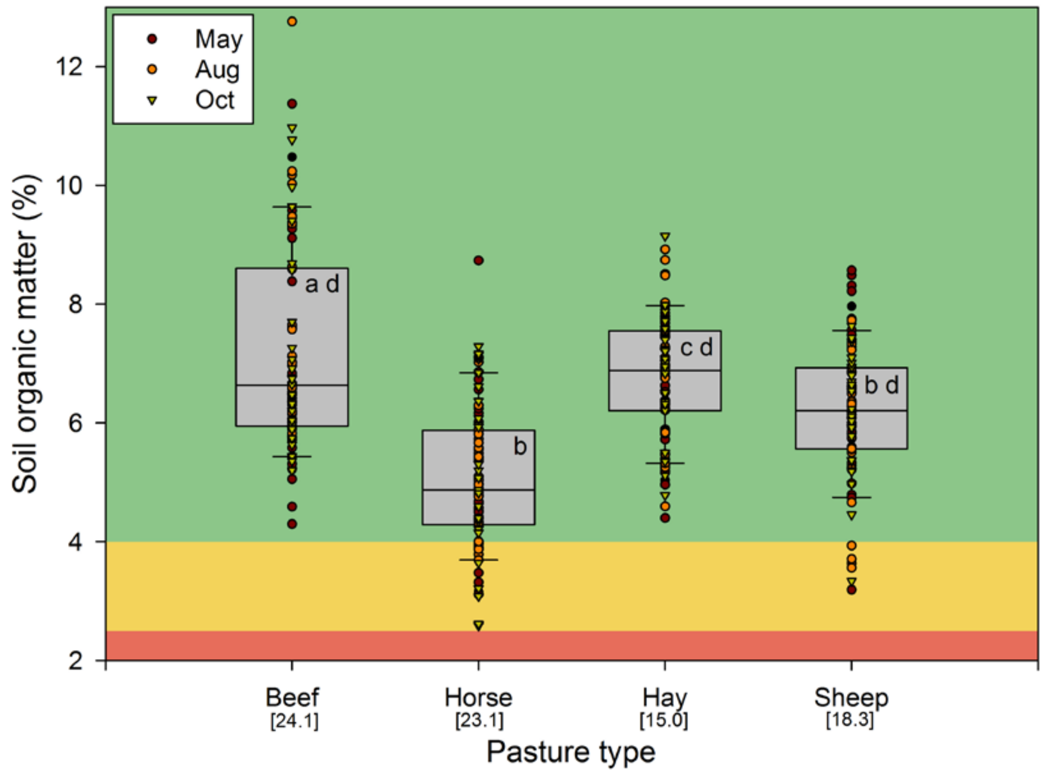


Figure 3.4. Soil organic matter content in beef, horse, hay and sheep pastures. Boxes represent middle quartiles (25 to 75%), lines dividing boxes represent median values, and whiskers represent 5^{th} and 95^{th} percentiles. Circles and triangles represent individual data points, color-coded by sampling month. Pasture types with the same letter were not significantly different. Values in brackets below pasture types are the coefficient of variation (CV, %).

Aggregate stability. The median percentage of water-stable aggregates (>250 μm) across seasons was 81 for hay pastures, 76 for sheep, 70 for beef, and 63 for horse pastures (Figure 3.5). Hay pastures had a significantly higher fraction of water-stable aggregates than beef or sheep pastures, and no other pairwise comparisons yielded statistically significant differences. Values were more tightly clustered in hay than in other pasture types (CV = 12.3%; Figure 3.5).

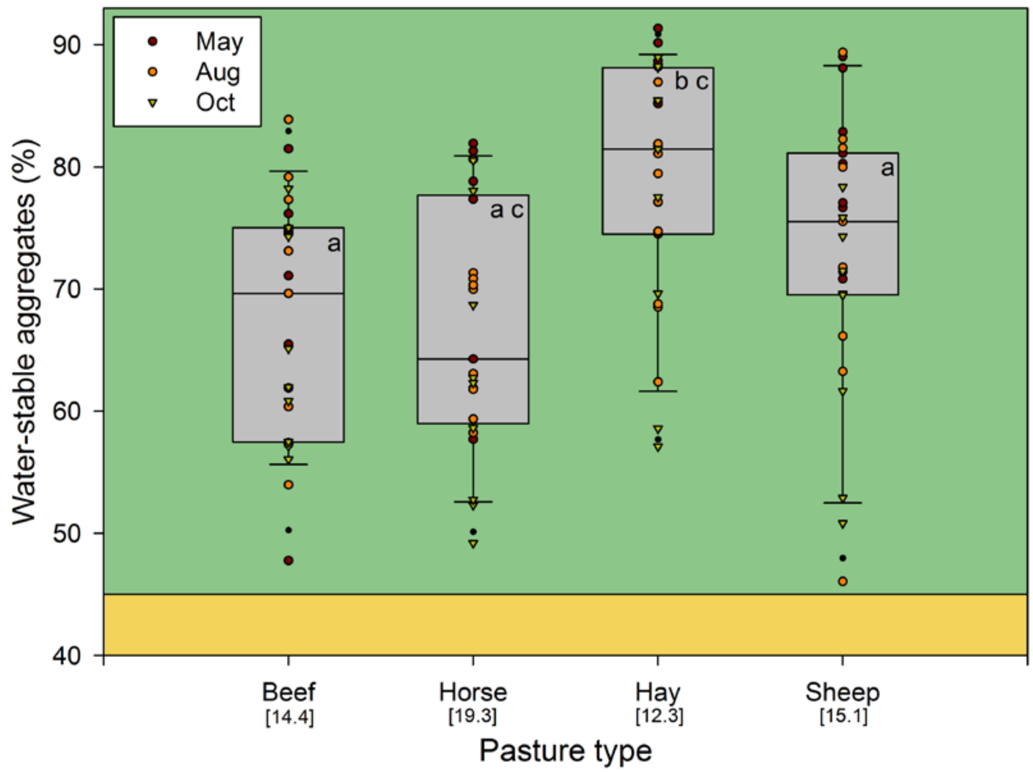


Figure 3.5. Percent water-stable soil aggregates in beef, horse, hay and sheep pastures. Boxes represent middle quartiles (25 to 75%), lines dividing boxes represent median values, and whiskers represent 5^{th} and 95^{th} percentiles. Circles and triangles represent individual data points, color-coded by sampling month. Pasture types with the same letter were not significantly different. Values in brackets below pasture types are the coefficient of variation (CV, %).

Aggregate stability is a measure of how resistant a soil is to slaking (Chan et al., 2001), and is interrelated with organic matter, microbial activity, and soil texture (Arshad and Martin, 2002). According to Chan et al. (2001), large macroaggregates (>250 µm) are stabilized mainly by transient forms of organic carbon such as root fragments, fungal hyphae, and polysaccharides, whereas smaller microaggregates

(<250 μm – not measured in this study) are stabilized by more persistent forms of organic carbon such as humified organic carbon. As a result, management practices strongly influence macroaggregate stability. Aggregate stability has also been found to increase near the surface of moist soils during freeze-thaw cycles (Lehrsch, 1998). Stabilization of macroaggregates occurs most optimally under extensive root systems of perennial grasses (Bharati et al., 2002; Chan et al., 2001; Oades, 1984), as might be found in pastures. Aggregate stability decreases markedly at soil C levels below 45 g C / kg soil, equivalent to 1.8% soil organic matter (Bharati et al., 2002). However, in this study, no pastures had an organic matter content lower than approximately 2%, so aggregate stability should not have been affected by lower organic matter content in the soils under study (Figure 3.4; Figure 3.5). In fact, there was no significant correlation between aggregate stability and organic matter content (Table 3.5). In this study, aggregate stability was significantly positively correlated with above-ground plant biomass and earthworm counts (Table 3.5).

Hay pastures are expected to have greater aggregate stability than grazed pastures, since livestock trampling has been hypothesized to break down soil aggregates and force smaller particles into existing soil pores (Cattle and Southorn, 2010; Stavi et al., 2011). Ungrazed pastures have greater aggregate stability and macroporosity than grazed pastures (Cattle and Southorn, 2010; Drewry, 2006; Drewry and Paton, 2000). In addition, aggregate stability can be increased by adding organic matter, and by allowing grass root systems to recover between vegetation removals (Oades, 1984), as is the case for hay harvesting. This is supported by research published by Cattle and Southorn (2010), who observed better soil structure (defined by good macroporosity and macropore surface area, which are related to aggregate stability) in pastures with regular defoliation without hoof pressure. They hypothesized that a “combination of consolidation, aggregate disruption, and repacking at the soil surface, caused by the presence, absence, and duration of livestock hoof pressure, and macropore construction by flora and fauna” is likely to affect soil structure (Cattle and Southorn, 2010), and by extension, aggregate stability. Data from this study support this: aggregate stability was negatively correlated with penetration resistance and bulk density, and positively correlated with earthworm counts (Table 3.5). Hayed pastures do not have continuous livestock hoof pressure coupled with defoliation, though other studies suggest that machinery traffic from haying equipment can be as detrimental as, or have greater impacts than livestock grazing (Franzluebbers et al., 2000b).

Chemical Indicators

Soil pH. Median values for hay, horse, beef and sheep pastures were 5.5, 5.5, 5.4 and 5.1, respectively (Figure 3.6). Soil pH values did not differ significantly among pasture types or sampling months (Figure 3.6). pH values for hay pastures were more tightly clustered (CV = 7.3%) and had fewer outliers than other pastures, especially when compared to sheep pasture (Figure 3.6).

Most pH values were below the ideal for high quality pasture plant growth of 6.1-7.5 (Gugino et al., 2009), and most values were in the problematic pH range (<6.5 (Gugino et al., 2009)) for all pasture types (Figure 3.6). This suggests that current management practices are not addressing soil acidity adequately. Charlton and Canton soils are naturally moderately to extremely acid, with pH values ranging from 4 to 6

(Rector, 1981; USDA, 2001). Thus, it is unclear whether management practices are the cause of lower pH, or whether it is the result of native soil conditions.

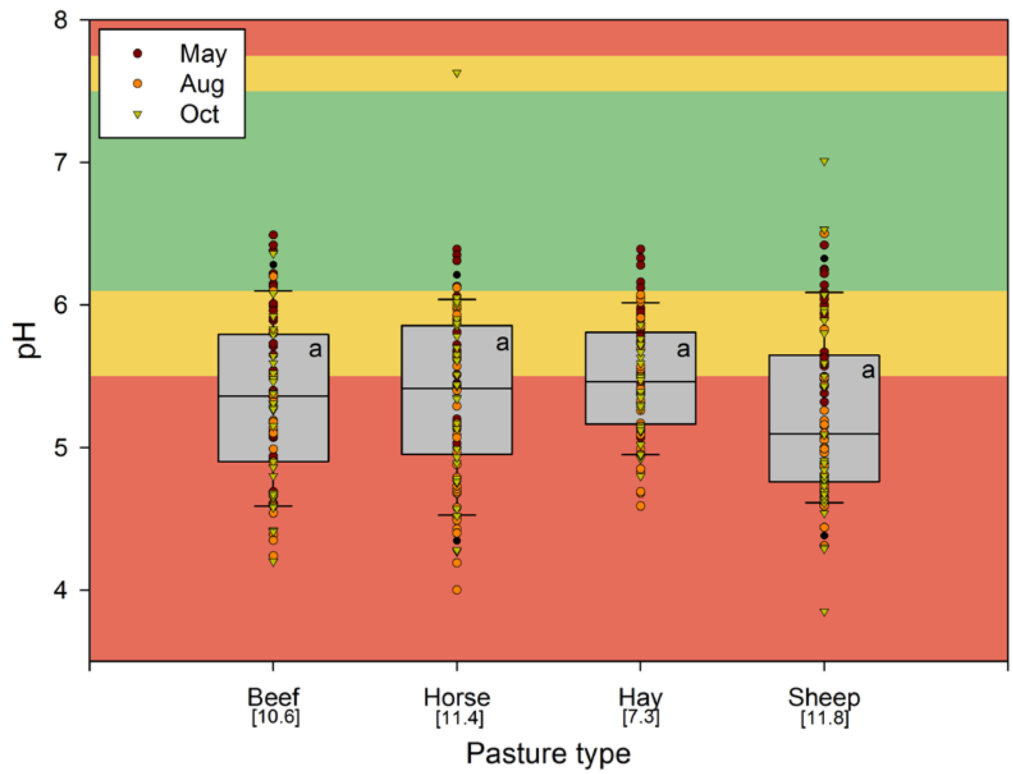


Figure 3.6. Soil pH values in beef, horse, hay and sheep pastures. Boxes represent middle quartiles (25 to 75%), lines dividing boxes represent median values, and whiskers represent 5th and 95th percentiles. Circles and triangles represent individual data points, color-coded by sampling month. Pasture types with the same letter were not significantly different. Values in brackets below pasture types are the coefficient of variation (CV, %).

Electrical conductivity. Electrical conductivity (EC; µS/cm) varied considerably, even within pastures, with individual values ranging from 32.5 to 1335. Median EC values (µS/cm) were highest for hay pastures (216.5), followed by beef (190.3), sheep (148.2) and horse pastures (106.3) (Figure 3.7). These values are lower than those reported by Guretzky et al. (2004) in pasture soils in Iowa, where electrical conductivity ranged from 189 to 604 µS/cm. Wienhold et al. (2001) found mean electrical conductivities of the upper 15 cm of soil in the northern great plains to range from 190 to 340 µS/cm – slightly higher than the range of means in this study.

Electrical conductivity in horse pastures was significantly lower than in other pasture types (Figure 3.7). Values of EC in horse pastures were more tightly clustered (CV = 70.97%) than sheep pasture values, which were more tightly clustered and had fewer outliers than hay or beef pasture values (Figure 3.7). However, there were no significant differences in EC among other pastures types or seasons. Only two localized samples had EC values greater than 1200 µS/cm, the point at which some pasture species (e.g. *Lolium perenne* (annual rye grass)) may be negatively affected by salt stress (Gugino et al., 2009; Venables and Wilkins, 1978). These elevated EC values are most likely due to animal excretions. Due to high nutrient and salt content, manure and urine have high electrical conductivities. For example, EC values for horse manure range from 350-1360 µS/cm, cow manure from 176-606 µS/cm, and sheep manure from 370-1180 µS/cm (Moreno-Caselles et al., 2002). Localized excretions, therefore, raise the electrical conductivity of the soil they land on. However, the variability in electrical conductivity in hay fields cannot be explained by localized livestock excretions. In this case, they could result from uneven fertilizer application, although two of the hay fields were not fertilized regularly. Alternatively, excretion inputs from wildlife (birds, deer or other animals) may have led to localized increases in electrical conductivity.

In horse pastures, 95% of values for electrical conductivity fell below 200 µS/cm, in the "problematic" range (Gugino et al., 2009), as did nearly 75% of values for sheep pastures (Figure 3.7). In addition, approximately half of EC values for beef pastures

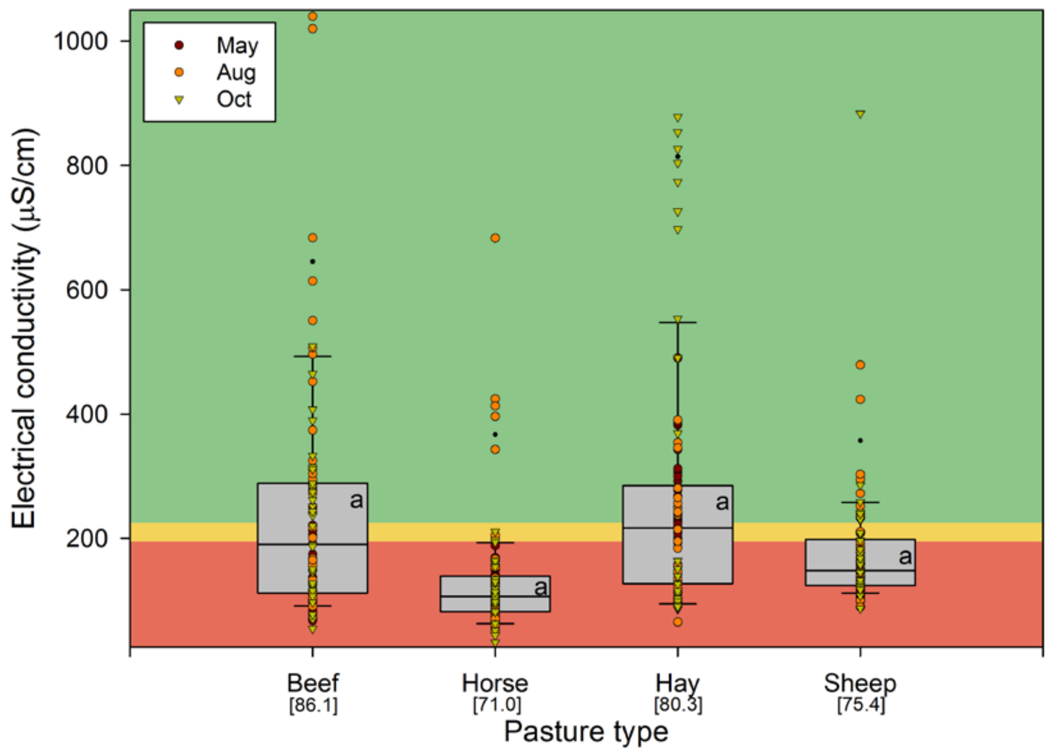


Figure 3.7. Soil electrical conductivity in beef, horse, hay and sheep pastures. Boxes represent middle quartiles (25 to 75%), lines dividing boxes represent median values, and whiskers represent 5th and 95th percentiles. Circles and triangles represent individual data points, color-coded by sampling month. Pasture types with the same letter were not significantly different. Values in brackets below pasture types are the coefficient of variation (CV, %).

were also in the problematic range. For hay pastures, approximately half of the values were in the acceptable or problematic ranges (Figure 3.7). Horse pastures also showed low values for extractable phosphate and nitrate, but relatively high values for extractable ammonium (Figure 3.8; Figure 3.9). In hay pastures, which had the highest median EC (Figure 3.7), ammonium concentration was relatively low, while nitrate and phosphorus values were intermediate, relative to other pasture types (Figure 3.8; Figure 3.9). Correlation analysis shows that, in this study, EC was only positively correlated with extractable nitrate (Table 3.5). Other extractable nutrients were not significantly correlated with electrical conductivity, even though electrical conductivity is a measure of solutes present in the soil, and thus should be affected by all mineral nutrient species (Mapfumo et al., 2000). However, I did not analyze soil samples for potassium or other ions which also contribute to soil electrical conductivity.

Wienhold et al. (2001) found EC to decrease with increasing stock density, which appears counterintuitive, but may explain lower EC in horse pastures. Horse pastures were smaller than other pastures in our study, and two of the pastures were continuously occupied by at least one horse (Table 3.2). However, a study by Mapfumo et al. (2000) found EC in surface soils increased after 3 years of heavy grazing.

Inorganic nitrogen. Medians NH_4^+ levels for each pasture type over all the seasons were 1.9, 0.7, 0.3, and 0.5 µg N/g soil for horse, beef, sheep and hay pastures, respectively (Figure 3.8). Ammonium concentrations were most consistent (CV = 190%) with fewer outliers in hay than in all other pasture types. There were no significant differences in ammonium concentration among pasture types (Figure 3.8). Although concentrations for ammonium were higher in May than in other sampling months for all pastures, there were no significant differences among sampling months for any pasture type (Table 3.6).

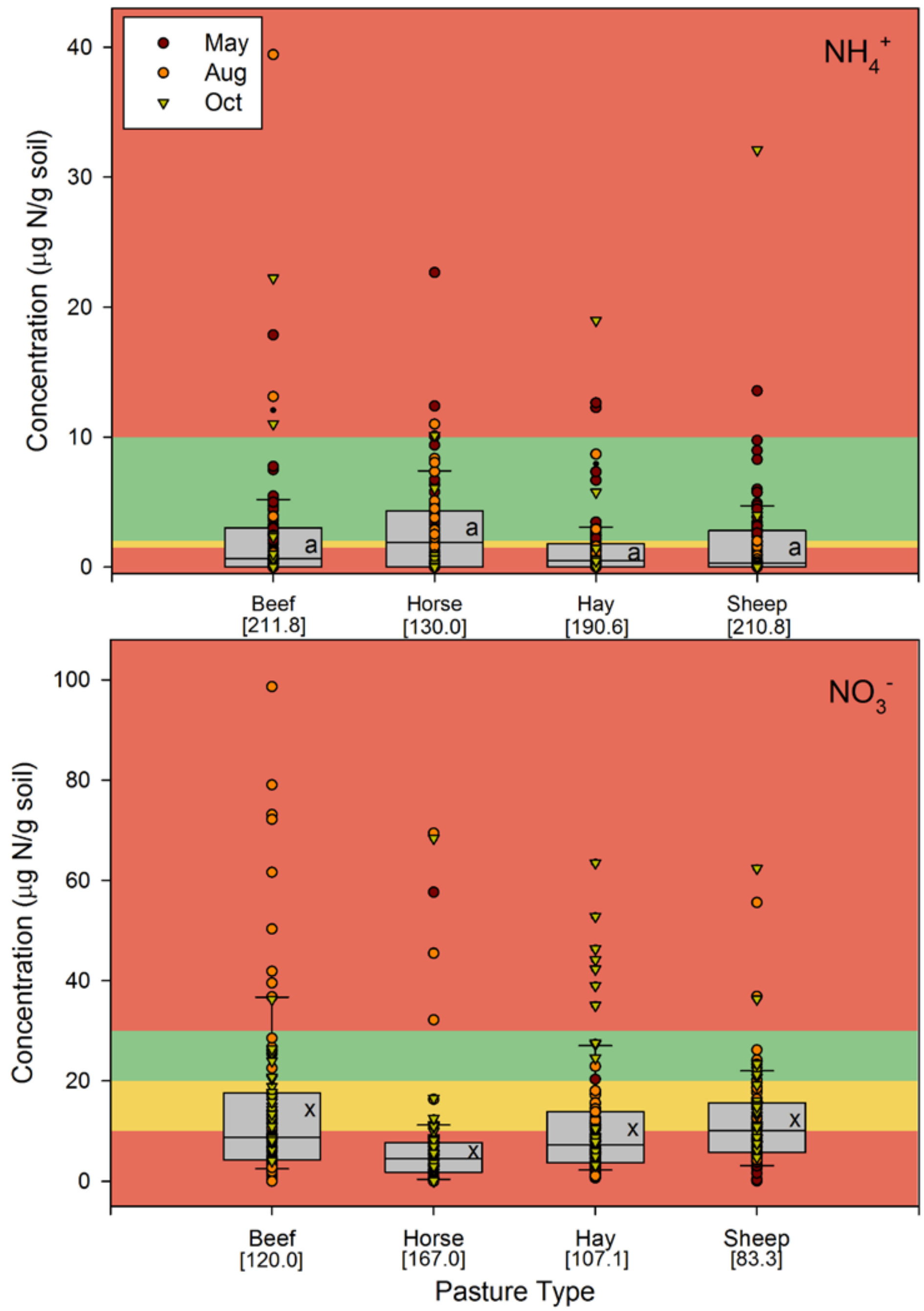


Figure 3.8. Extractable soil ammonium and nitrate concentrations in beef, horse, hay and sheep pastures. Boxes represent middle quartiles (25 to 75%), lines dividing boxes represent median values, and whiskers represent 5th and 95th percentiles. Circles and triangles represent individual data points, color-coded by sampling month. Pasture types with the same letter were not significantly different. Values in brackets below pasture types are the coefficient of variation (CV, %).

Table 3.6. Comparison of mean NH_4^+ and NO_3^- concentrations across seasons for each pasture type. There were no significant differences among sampling months (P<0.05).

Pasture type	Con. of inorganic N species (μg N/g soil)					
	May		Aug		Oct	
	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-
Beef	3.93	5.27	4.92	26.43	1.44	14.04
Horse	5.11	2.08	2.56	8.88	7.43	9.28
Hay	2.96	5.71	0.74	9.87	1.00	18.14
Sheep	4.19	4.81	0.37	16.93	1.22	14.70

Beef pastures had median NO_3^- levels (μg N/g soil) over all seasons of 8.8, sheep had 10.1, hay had 7.3, and horse pastures had 4.5 (Figure 3.8). Nitrate concentration values in sheep pasture were more tightly clustered (CV = 83.3%) than other pasture types. There were no significant differences in nitrate levels among pasture types (Figure 3.8). Although NO_3^- concentrations were lower in May for all pasture types, there were no significant differences among sampling months (Table 3.6). In our study, hay pastures did not have significantly lower inorganic nitrogen species concentrations than grazed pastures, despite research that shows ungrazed pastures to have lower soil organic nitrogen in surface soils (Manley et al., 1995).

Only 6 pastures in the study were fertilized: B3, E1, H1, H3, S1 and S2 (Table 3.2). However, except for H3, application rate and frequency are unknown, making it difficult to draw conclusions about the effect of fertilizers on inorganic nitrogen species in these pastures. Different fertilization rates may account for the large variation in both ammonium and nitrate values observed in pastures (Figure 3.8). However, mean concentrations of ammonium in May were predominantly in the normal range of 2-10 μg N/g soil (Table 3.6), indicating that most pastures do not have problems with ammonium in the spring (Marx et al., 1999). However, during the summer and fall, mean ammonium concentrations in most pasture types were below 2 μg N/g soil, suggesting that pastures are either deficient or, more probably, that ammonium is rapidly being oxidized to nitrate, leading to the high nitrate values observed in Table 3.6.

For nitrate, values below 10 or above 30 μg N/g soil are considered problematic, and 20-24 μg N/g soil is considered ideal for most plant species (Heckman, 2003). In our study, 95% of nitrate concentrations were below the 30 μg N/g soil threshold for every pasture type except beef (Figure 3.8). In soil with values above this point, nitrate leaching to groundwater becomes a real concern (Heckman, 2003). In August and October, all pasture types had several sampling points with nitrate concentrations well above this threshold (Figure 3.8), though it is likely that these are a result of livestock or wildlife excretions, leading to localized enrichment of nitrogen species. Urine patches are the main contributor to nitrate leaching from livestock pastures (Di and Cameron, 2002; Di and Cameron, 2004): cattle urine contains 0.5 to 16.6 g N/L, and sheep has 0.9 to 17.8 g N/L (Hoogendoorn et al., 2010), which may explain elevated overall values for pastures under these livestock types. Urine patches in pastures can leach up to 120 mg N/L, though nitrate leaching in sheep pastures is generally less than in cattle pastures, since sheep urinate smaller volumes more often than cattle (Di and Cameron, 2002).

Extractable phosphate. Median soil phosphate levels (μg P/g soil) for sheep pastures across season were 42.2, 32.0 for beef, 22.3 for hay, and 5.7 for horse pastures (Figure 3.9). There were significant differences among pasture types in soil phosphate concentrations: Beef and sheep pastures were significantly higher than horse and hay pastures, though they did not differ significantly from one another

(Figure 3.9). Values for extractable phosphate in horse and hay pastures were not significantly different. Unfertilized pasture in Massachusetts was reported to contain 18.6 µg PO_4^{3-}-P/g soil (Bolan et al., 1996). In New Zealand, extractable phosphate values range from 7-24 µg P/g soil (Sinclair et al., 1997), while values in other studies range from 25 to nearly 50 µg P/g soil (Hooda et al., 1999). The values in our study, therefore fall within previously reported values for extractable soil PO_4^{3-} under pastures.

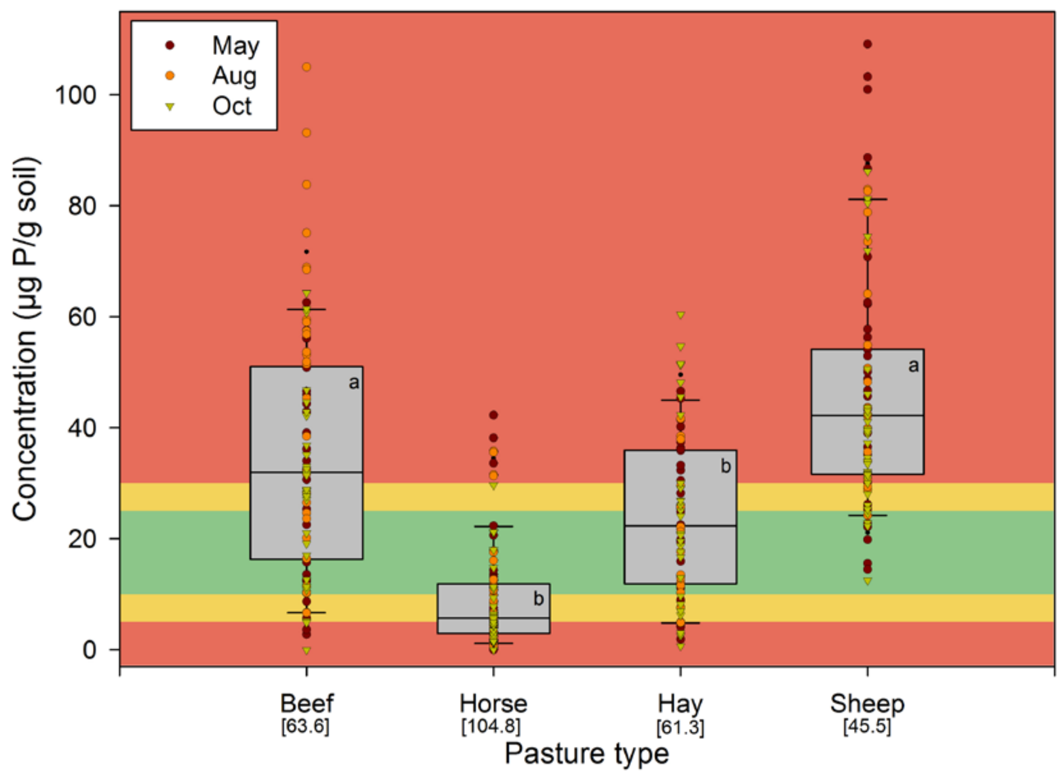


Figure 3.9. Extractable soil phosphate concentration in beef, horse, hay and sheep pastures. Boxes represent middle quartiles (25 to 75%), lines dividing boxes represent median values, and whiskers represent 5th and 95th percentiles. Circles and triangles represent individual data points, color-coded by sampling month. Pasture types with the same letter were not significantly different. Values in brackets below pasture types are the coefficient of variation (CV, %).

Research in the southern US has shown that increasing grazing intensity can increase soil P concentrations (Franzluebbers et al., 2002). Sheep manure contains less water than other types of manure, resulting in more concentrated excretions, which could affect localized phosphate concentrations (Moreno-Caselles et al., 2002), and may explain elevated soil P values in sheep pastures (Figure 3.9). Furthermore, the 25-75th percentile of sheep phosphate concentrations are within the problematic range for phosphate concentrations (Figure 3.9; Gugino et al. (2009)), as are the upper 50% of beef pasture phosphate values. Hay pastures have comparatively better ranges of phosphate concentrations.

Excess phosphate has serious implications for eutrophication of fresh waters if carried overland in run-off into surface waters. However, in acidic soil, phosphate binds to iron and aluminum oxides and becomes fairly insoluble (Hubbard et al., 2004; Sylvia et al., 2005). It is possible for soil-bound phosphorous to be eroded with soil particles and carried in overland-flow into surface waters. Thus high soil P values still pose a threat to water quality, even in acidic soils. In addition, excessively high soil phosphate concentrations can also affect plant growth by blocking plant uptake of micronutrients like iron and zinc (Provin and Pitt, 2002).

Biological Properties

Soil respiration. Across seasons, the median respiration rate (kg CO_2-C/ha/d) for beef pastures was 59.0, 48.6 for horse, 39.5 for sheep, and 43.6 for hay pastures (Figure 3.10). No significant differences in respiration rates were detected among pasture types. For hay and sheep pastures, respiration rates were significantly higher in

August than in October (data not shown). Respiration rates in temperate pasture soils range from 9.4 to 30.7 kg CO_2-C/ha/d (Raich and Tufekciogul, 2000), with values ranging up to 41.1 kg CO_2-C/ha/d in Brazil (Davidson et al., 2000). Respiration rates in our study were higher than values previously reported, for both temperate and sub-tropical climates, likely due to differences in soil temperature and moisture at time of measurement (Davidson et al., 2000).

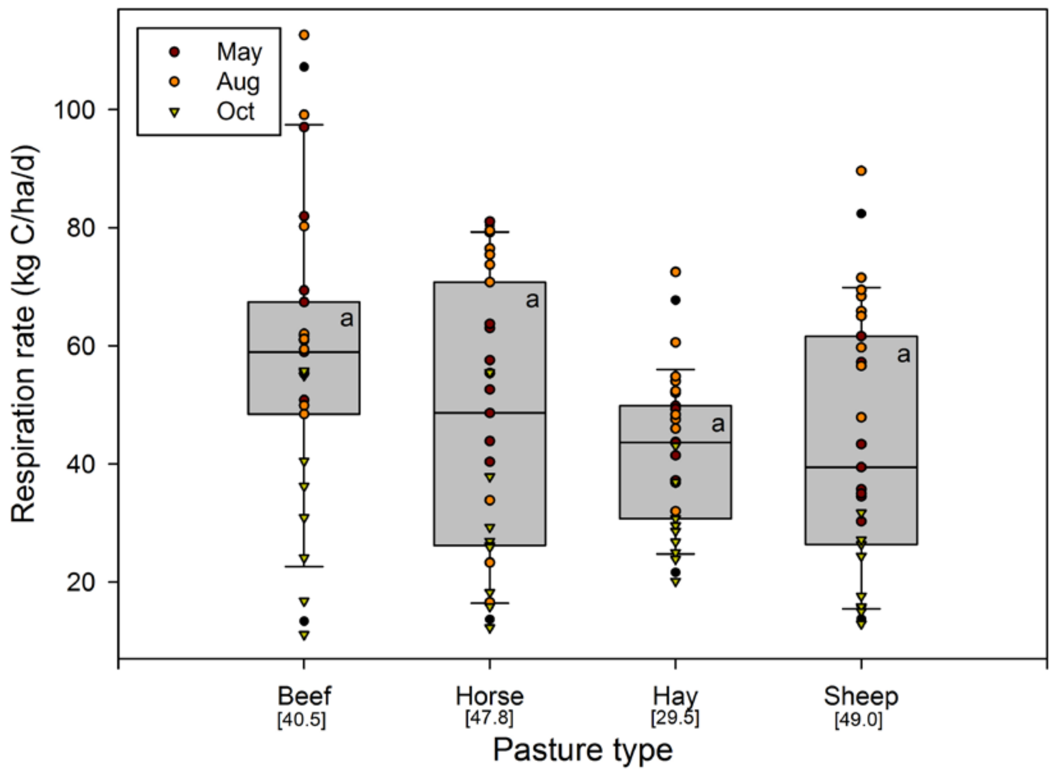


Figure 3.10. Respiration rates in beef, horse, hay and sheep pastures. Boxes represent middle quartiles (25 to 75%), lines dividing boxes represent median values, and whiskers represent 5th and 95th percentiles. Circles and triangles represent individual data points, color-coded by sampling month. Pasture types with the same letter were not significantly different. Values in brackets below pasture types are the coefficient of variation (CV, %).

Soil respiration represents the sum of all biological activity in the soil: faunal, microbial and plant root respiration. Respiration rates depend on organic matter content, aggregate stability, bulk density, soil moisture, pH and texture (Arshad and Martin, 2002). In this study, respiration rates were significantly positively correlated with soil temperature and negatively correlated with earthworm counts (Table 3.5). Higher rates of soil respiration are generally associated with higher soil quality; however, excessively high rates can indicate an unstable system (USDA, 2001).

Soil active carbon. Hay pastures had the highest median active carbon concentrations (µg C/g) across seasons (772), followed by beef (670), sheep (638), and horse (557) pastures. In addition, hay pastures had more tightly clustered values (CV = 16.9%) and fewer outliers than other pasture types (Figure 3.11). There were no significant differences in active carbon concentration among pasture types or sampling months (Figure 3.11).

Active carbon provides a measure of the fraction of soil organic matter that is readily degraded by the microbial community as a source of energy. It responds more quickly to changes in soil management than organic matter content (Gugino et al., 2009). In general, active carbon is positively correlated with organic matter content, aggregate stability and soil respiration (Gugino et al., 2009). However, only values for hay fell mostly in the ideal active carbon ranges (Figure 3.11). This is surprising, considering hay pastures did not have the highest organic matter content or respiration rates (Figure 3.4; Figure 3.10). Horse pastures did have lower respiration rates, organic matter content and active carbon content than other pastures (Figure 3.4; Figure 3.11). Active carbon levels tend to be higher under grazed than hayed pastures

(Franzluebbers and Stuedemann, 2003), which may be due to return of feces to soil. Other research suggests that C in accumulated manure has the greatest influence on soil properties, indicating that grazing may have beneficial impacts on biological soil quality (Bhogal et al., 2011). However, this was not observed in our study; perhaps the manure and urine nutrient inputs increased microbial C mineralization in the pasture soils, decreasing the active carbon content of the soils.

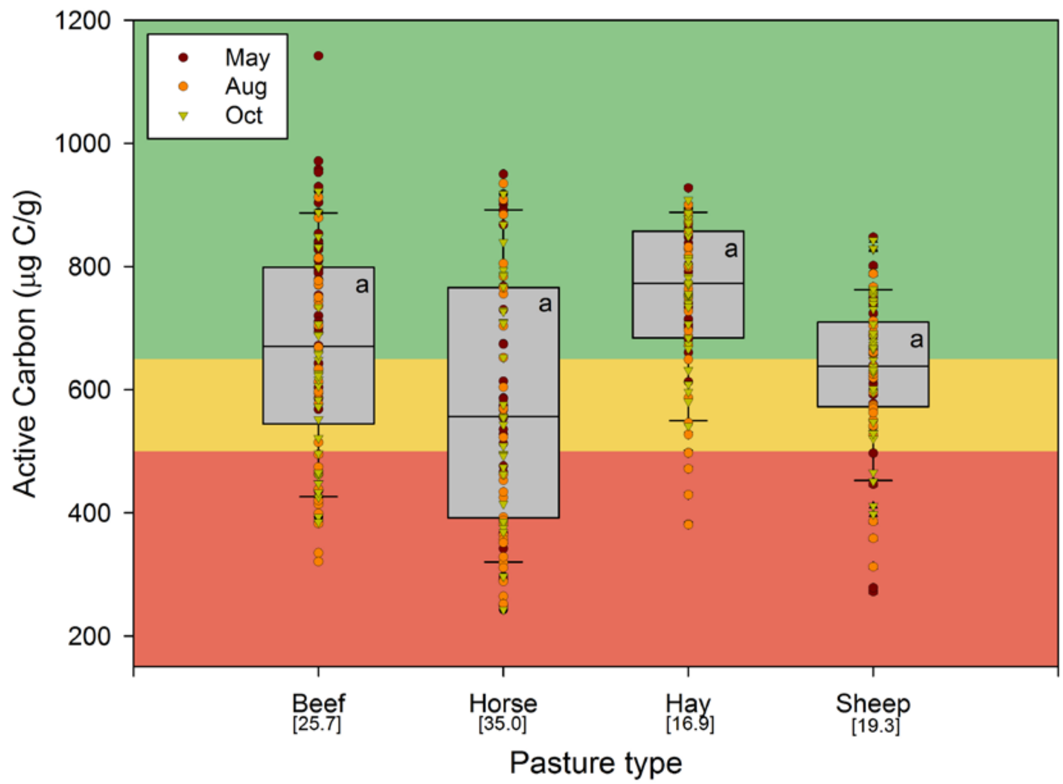


Figure 3.11. Soil active carbon concentration in beef, horse, hay and sheep pastures. Boxes represent middle quartiles (25 to 75%), lines dividing boxes represent median values, and whiskers represent 5th and 95th percentiles. Circles and triangles represent individual data points, color-coded by sampling month. Pasture types with the same letter were not significantly different. Values in brackets below pasture types are the coefficient of variation (CV, %).

In this study, active carbon levels were positively correlated with organic matter content, pH, soil moisture and above-ground plant biomass, and negatively correlated with bulk density (Table 3.5). Active C is a fraction of the total organic matter (Weil et al., 2003), so it is not surprising that organic matter and active C are correlated. Since above-ground biomass can be the source of organic matter in soil, the correlation between active C and plant biomass also seems logical. In this study, and others, organic matter and bulk density are inversely correlated (Cattle and Southorn, 2010; Franzluebbers and Stuedemann, 2008; Oades, 1984; Reeves, 1997), so the active C results of this study seem reasonable.

Earthworm population density. Median earthworm population density to a depth of 30 cm (no. per m^2) across seasons was lowest in horse pastures (56), followed by sheep (78), beef (89), and hay pastures (100) (Figure 3.12). Earthworm counts did not differ significantly among pasture types. Mean population densities in October were higher than in August for all pasture types, however population densities did not differ significantly for individual pasture types among sampling months (Table 3.7). Pastures in the northeastern US have earthworm population densities that range from 0 to 589 earthworms per m^2, with mean earthworm population density of 133 earthworms (Byers and Barker, 2000). Thus the size of earthworm populations in this study is comparable to, if slightly lower than, other earthworm communities in pastures in the northeastern US.

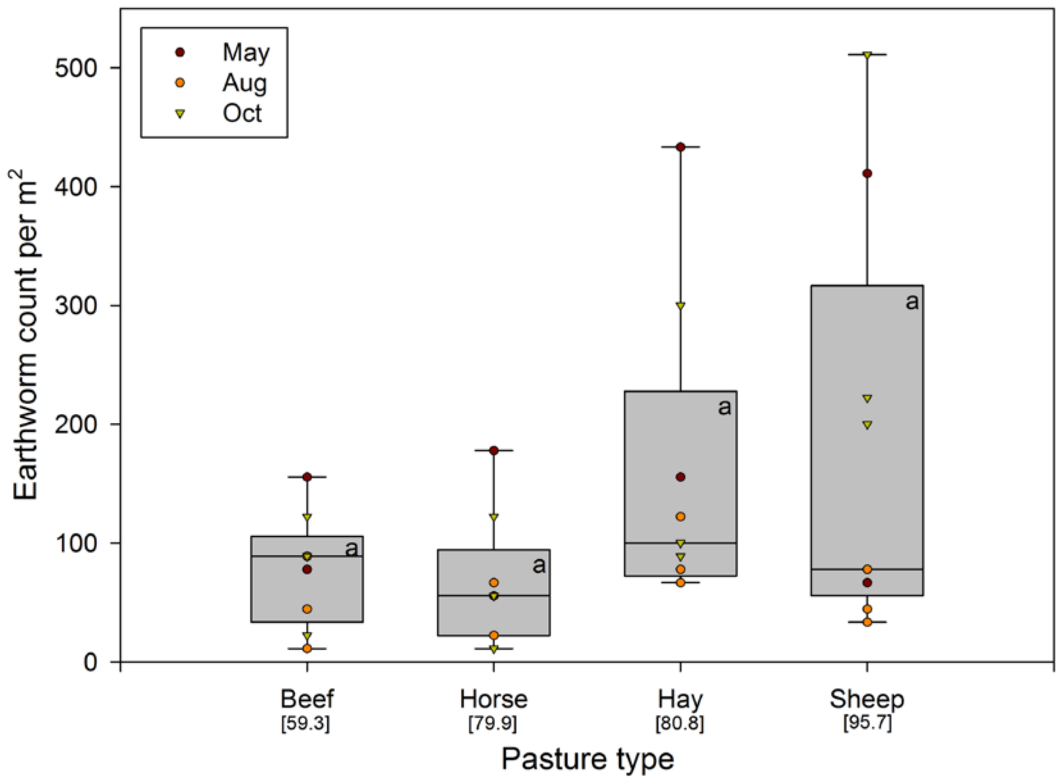


Figure 3.12. Earthworm population density per m^2 to a depth of 30 cm in beef, horse, hay and sheep pastures. Boxes represent middle quartiles (25 to 75%), lines dividing boxes represent median values, and whiskers represent 5^{th} and 95^{th} percentiles. Circles and triangles represent individual data points, color-coded by sampling month. Pasture types with the same letter were not significantly different. Values in brackets below pasture types are the coefficient of variation (CV, %).

Table 3.7. Mean earthworm population density (no. per m^2) to a depth of 30 cm in beef, horse, hay and sheep pastures. Values followed by the same letter within a row are not significantly different.

Pasture type	May	August	October	Mean
Beef	107a	48a	78a	78a
Horse	100a	37a	63a	67a
Hay	218a	89a	163a	157a
Sheep	181a	52a	311a	181a
Mean	152ab	56a	154b	121

Earthworms populations are highly variable in space and time, and are known to vary with soil characteristics, food availability, and season (USDA, 2001). Spring and fall tend to have higher earthworm populations than summer (Hendrix et al., 1992). Earthworms survive best in soils that have more than 40 g organic C/kg (1.6% organic matter content), and can respond very rapidly to changes in soil management (Haynes and Williams, 1999). In this study, no pastures had organic matter content values below this threshold (Figure 3.4). Overall, horse pastures had the lowest organic matter content and aggregate stability, along with the lowest number of earthworms, compared to other pasture types (Figure 3.4; Figure 3.5). Earthworms improve soil quality by increasing nutrient availability, accelerating organic matter decomposition, improving soil aggregation and porosity and enhancing beneficial microorganisms (USDA, 2001). Earthworms are also known to be closely related to pastoral vegetation production (Fraser et al., 1994). Data from our study support these findings: positive significant correlations were found between earthworm population density, aggregate stability and above-ground biomass, whereas penetration resistance, respiration rate and temperature were negatively correlated with earthworm population density (Table 3.5). However, extractable nutrient concentrations were not significantly correlated with earthworm population sizes (Table 3.5).

Overall Soil Quality Scores

Overall mean soil quality scores were 78% for hay pastures, 74% for sheep, 70% for beef and 69% for horse pastures (Table 3.8). Scores are calculated following guidelines in Gugino et al. (2009), where scores less than 40% are considered very low, 40-55% low, 55-70% medium, 70-85% high and greater than 85% is regarded as very high soil quality. The pastures in our study, therefore are in the medium to high range for overall soil quality. Our data suggest that, from a soil quality perspective, hay pastures are a better land use for open space than grazed pastures, and sheep pastures are less detrimental than beef or horse pastures. Hay pastures had better scores for penetration resistance, soil organic matter, active carbon, aggregate

Table 3.8. Overall soil quality scores (%) for beef, horse, hay and sheep pastures. Individual soil quality indicator values were converted to % after Gugino et al. (2009). The overall score represents the mean of scores for individual soil quality parameters. For nitrate and phosphate values, I indicates Ideal, A indicates Acceptable and P indicates problematic, with regards to different problems.

	Pasture type			
Soil Quality indicator	Beef	Horse	Hay	Sheep
Penetration resistance				
• 0-10 cm	45	45	80	90
• 10-25 cm	80	80	90	97
Bulk density[1]	100	100	100	100
pH	0	0	0	0
Electrical conductivity[1]	100	100	100	100
Ammonium[2]	100	100	70	90
Nitrate[2,3]	52	0	8	20
soil fertility	A	P	P	P
pollution risk	I	I	I	I
Phosphate	20	100	50	10
soil fertility	I	I	I	I
pollution risk	P	I	A	P
Organic matter	99	90	97	95
Active carbon	60	50	80	60
Aggregate stability	95	95	99	97
Respiration rate[1]	100	100	100	100
Infiltration rate[1]	100	100	100	100
Above-ground biomass[4]	36	20	96	45
Earthworms[1]	70	60	100	100
OVERALL SCORE	70	69	78	74

USDA (2001) [1], Marx et al. (1999)[2], Heckman (2003)[3], Campbell and Stafford Smith (2000)[4] stability, above-ground plant biomass production and earthworm counts, compared to beef and horse pastures (Table 3.8). However, hay pastures had lower scores than other pasture types for extractable nitrate and phosphate concentrations, potentially indicating that these nutrients were absorbed by plants. Horse pastures had lower scores in penetration resistance (especially in the surface soil), extractable nitrate, organic matter, active carbon, aggregate stability, above-ground plant biomass and earthworm counts (Table 3.8). In some cases, however, beef pastures had equally poor scores as horse pastures (e.g. penetration resistance, aggregate stability).

Horse pastures may have lower overall soil quality due to slightly higher mean stocking densities than beef pastures (Table 3.1). Most horse pastures were roughly 50 m × 50 m and had more or less continuous equine occupation, since stable owners can earn money by “pasturing” and housing horses. Horse pastures are not necessarily managed for soil or vegetation quality, but rather are considered as an area where horses may exercise and engage in normal behaviors. Horse hoof shape (Figure 1.1) likely exacerbates localized compaction, since the surface area of the hoof in contact with soil is quite small. Beef cattle pasture results are similar to horse pasture results, potentially due to similarly large localized soil compaction due to the animals’ large size and relatively small hooves. Beef cattle hooves exert 130 to 250 kPa of pressure to soil with each step (Di et al., 2001),whereas horses can exert up to a maximum of 300 kPa on soil per step (Horn et al., 2004).

Sheep pastures may have had better soil quality as a result of less individual compaction caused by hooves, since sheep weigh significantly less than beef cattle or horses. Therefore, each sheep hoof print may have less pressure exerted than a hoof print made by beef cattle. This hypothesis is borne out by research that shows that goats exert much less pressure per average hoof print (0.59 kg/cm^2 = 57.9 kPa) than horses (0.73 = 71.6 kPa) or cows (1.61 = 157.9 kPa), though these values can be higher when animals are moving quickly (Parés-Casanova and Oosterlinck, 2012). Since goats are fairly similar in size to sheep, sheep presumably exert similar hoof pressures on the soil. It would be interesting to assess quality in pastures grazed by goats, since they are similar in size to sheep, but have different feeding behaviors: if soil quality in goat pastures was similar to soil quality in sheep pastures and better than in pastures grazed by larger animals, it might indicate that smaller animals are less detrimental to soil quality.

It is important to note that the overall score may not accurately weigh comparatively more important soil quality indicators (e.g. organic matter or active C content (Chan et al., 2001)), since this score is a mean of all the individual soil quality parameters, rather than a weighted average. Focusing on individual soil quality parameters is likely more useful as a management tool for farmers to improve soil quality in their pastures.

Suggestions for Improvement of Soil Quality

The soil quality in all of the grazed pastures could be improved through careful livestock and grazing management to prevent overgrazing and damage to soil properties during wet conditions. For example, cattle grazing during the dormant season in a humid temperate climate negatively affects soil's physical quality (Stavi et al., 2011). Livestock trampling in moist conditions results in soil compaction, decreasing porosity and infiltration rates (Proffitt et al., 1995; Stavi et al., 2011). In contrast, haying machinery is unlikely to be used during the dormant season, as there is little or no hay to harvest in the winter. Absence of traffic on hayed pastures during wet winter conditions may lead to higher overall soil quality, despite findings by Franzluebbers et al. (2000a) that machinery traffic is as detrimental to soil quality as livestock trampling.

Many physical and biological soil quality indicators can be improved by maintaining adequate plant cover. Preventing overgrazing and patches of bare soil increases soil organic matter, aggregate stability, earthworm numbers, infiltration rates, and improves bulk density (Bellows, 2001). In addition, preventing and avoiding animal and machinery traffic on wet soils reduces negative effects on soil physical properties like bulk density, aggregate stability and infiltration rates (Abdel-Magid et al., 1987; USDA NRCS, 2001a). Lowered rates of infiltration can lead to increased surface run-off, which can erode soil and contaminate waterways with pathogens and nutrients (Bharati et al., 2002; USDA NRCS, 2001b), whereas higher infiltration rates reduce these risks. Management practices that lower bulk density and increase organic matter content and aggregate stability, as well as restricting grazing so that vegetation provides adequate soil surface cover, can improve infiltration rates, and reduce the risk of soil erosion and surface water contamination. Farmers in this study generally did not observe these practices, likely due to practicality or time constraints, or perhaps out of ignorance: farmers or managers may not have been aware of the damage sustained by wet soils or the detrimental effects of over-grazing their pastures.

Nutrient availability in soil is affected by organic matter content, pH, top-soil depth, texture and microbial activity (Arshad and Martin, 2002). Manure additions to pasture over 11 years have been shown to increase organic matter content, CEC, pH, P, K and total pore space in soils, when compared to pasture without manure additions, though the extent of increase depends on the quantity of manure applied (Magdoff and van Es, 2000). In this study, manure additions do not appear to be the driving factor of above soil quality indicators, since soil quality indicators for hay were often better than, or were near those for grazed livestock pastures.

Applying nitrification inhibitors can both decrease nitrate leaching and increase pasture productivity (Di and Cameron, 2004), making it a potentially attractive option for nitrogen management in pastures near surface water bodies. However, the cost of the inhibitor, and time and machinery required to apply it, may make this a cost-prohibitive for most small farmers. Another option might be to fertilize hay pastures with slow-release fertilizers, so that nitrification and subsequent leaching might be reduced.

Finally, regardless of whether the soil's acidity is natural to the soil series or a result of poor pH management, addition of agricultural lime to the soil would increase the pH, improve nutrient availability to both plants and microorganisms, and reduce the risk of aluminum and iron toxicity, ultimately leading to better pasture performance (Gugino et al., 2009; Spargo et al., 2012; Sparks, 2003).

In summary, to improve overall soil quality, farmers could implement a few simple management strategies that would affect a broad range of soil characteristics. These include:

1. Manage livestock grazing so that adequate vegetation remains on pasture (e.g. subdivide pastures for rotational grazing, where animals are removed from pasture sections when vegetation height is reduced below 7-12 cm).
2. Keep animals and machinery off pasture during wet conditions (may require a "sacrifice" pasture, which animals occupy when soil conditions are not ideal).
3. Regularly move watering, feed, and shade or shelter locations when possible to minimize animal congregation, which results in localized concentration of excretions.
4. Apply lime to pastures to bring pH values to more desirable ranges and improve chemical soil properties, nutrient availability and pasture biomass production (Bellows, 2001).

These strategies address physical and chemical properties of soils (e.g. organic matter and nutrient additions to pasture, pH improvement, decreasing compaction) resulting in more productive pastures and enhanced soil quality in the long term. Biological properties would also benefit from increased soil organic matter content, likely increasing active C values and earthworm numbers in pastures.

CHAPTER 4

CONCLUSIONS

Our results indicate that hay pastures have the highest soil quality relative to pastures grazed by sheep, beef cattle or horses. Pastures grazed by sheep have the next highest soil quality, while horse pastures have the lowest soil quality for farms in this study. Generally, livestock and hay pastures in this study did not have problems with bulk density, aggregate stability, organic matter content, electrical conductivity, soil respiration or infiltration rates, as indicated by fairly high score for these properties for all pasture types. Livestock pastures generally had good scores for extractable ammonium. All pasture types had problematic pH values, which ought to be addressed to improve pasture productivity and soil quality. In addition, penetration resistance and earthworm counts (especially in beef and horse pastures), nitrate concentrations, active carbon, and above-ground plant biomass (except in hay pastures) had poor scores in this study.

Due to the small sample size used in our study, these results may not be representative of sheep, horse, beef cattle or hay pastures in this region. Quantifying soil quality in additional pastures across New England, particularly in different soil series, may provide a more accurate picture of how livestock affect soil quality in New England soils, particularly whether sheep and hay pastures do support better soil quality than horse or beef cattle pastures. For example, different soil types or textures may be more easily damaged or more resistant to damage by livestock than others, and might be better used as hay fields.

Future studies might focus on a subset of the soil quality parameters measured in this study, especially if financial or temporal considerations are of concern. Data from this study suggest that bulk density, organic matter content, aggregate stability, respiration and infiltration rates, and earthworm counts were generally good in pastures, and therefore are good candidates to be excluded from future studies on the same soil type. Parameters like above-ground biomass, penetration resistance, pH, electrical conductivity, extractable nutrients, and active carbon should continue to be measured, since they have important implications for pasture (and animal) productivity. In addition, data for these parameters are both easy and fairly inexpensive to obtain.

In addition, future studies might re-evaluate the scoring system for pasture, since the scoring charts provided in Gugino et al. (2009) were developed for agricultural soils in general, rather than specifically for pasture. With a larger data set, it may be possible to establish better criteria and adjust scoring functions, so that pastures can specifically be evaluated – especially parameters like soil organic matter content, respiration and infiltration rates, and above-ground biomass yields.

Most pastures in our study would benefit from more attentive management. If farmers subdivided pastures into smaller paddocks, and managed pasture by vegetation height and soil moisture, many soil properties (e.g. organic matter content, infiltration and respiration rates, aggregate stability, bulk density, penetration resistance) could be improved. Liming soils to improve pH in pastures would also increase pasture productivity. These management practices are likely more time-consuming than current practices, but would increase pasture productivity and quality in the long run, eventually reducing the amount of supplemental feed farmers would have to provide to livestock, providing potential cost-savings over the long-term. Despite these recommendations, overall pasture soil quality scores were fair, indicating that they are a good land use, especially for soils that have large rock fragments that preclude other agricultural land uses. In general, pasture and forest soils have been found to have better soil quality that arable cropland, and some research suggests that grasslands may be better carbon sinks than forest soils (Compton and Boone, 2000; Franzluebbers and Stuedemann, 2003; Franzluebbers et al., 2002; Guo and Gifford, 2002; Reeves, 1997).

Investigating the effects other livestock (e.g. goats, alpaca, swine or poultry), co-grazing of different livestock types, or multi-species livestock rotations have on soil quality may also help elucidate best management practices to prevent deterioration of soil quality in pastures. In general, additional research is required to determine the most effective way to pasture animals with the least detriment to pasture productivity, soil or water quality, especially if consumer demand for “grass-fed” proteins continues to increase and become more main-stream. More productive pastures with fewer negative environmental effects can increase public support of pastured animals, as well as provide significant monetary benefits to farmers, by reducing feed costs and potentially increasing price premiums for their animals by marketing them a grass-fed.

APPENDICES

Appendix A. Consent form signed by farmer owners or managers who participated in the study.

Informed Consent Form

Dear Participant,

You have been invited to take part in the research project described below. If you have any questions, please feel free to call Alissa Becker (401-368-6026) or Dr. Jose Amador (401-874-2902), the people mainly responsible for this study.

The purpose of this study is to compare soil quality in pastures that are grazed by different types of livestock. To do this, I need to collect three sets of soil samples (once in May, once in August, and again in October 2012) from your pasture. I will need to collect some pasture vegetation, as well, on my first visit. In addition, I will need to do a few short in-field measurements of soil properties, like infiltration, compaction and soil respiration. I will not disclose any results from the tests I perform on your pasture's soil in a way that could identify your farm's identity or location. Before I start my measurements and sample collection, I will also need to ask you a few questions about the way you manage your pasture. Responses to these questions will be kept confidential, meaning no person other than myself or Dr. Amador will have access to the information you provide.

If you decide to take part in this study, your participation will involve answering a few questions pertaining to the way you manage your pasture (fertilization, animal occupation / movement, etc.), and permitting me to collect vegetation and soil samples from your pasture. Once I have analyzed my data, you will receive the results of your pasture's soil tests.

The possible risks or discomforts of the study are minimal.

Although there are no direct benefits of the study, your answers will help increase the knowledge regarding the impact different types of livestock have on pasture soils in Rhode Island.

Your part in this study is confidential. That means that your answers to all questions are private. No one else can know if you participated in this study and no one else can find out what your answers were. Scientific reports will be based on group data and will not identify you or any individual as being in this project.

The decision to participate in this research project is up to you. You do not have to participate and you can refuse to answer any question. You may also choose to stop participating in my study at any point in time. Please feel free to contact me with any questions you might have, whenever they arise.

Participation in this study is not expected to be harmful or injurious to you. However, if this study causes you any injury, you should write or call Alissa Becker or Dr. Jose Amador at the University of Rhode Island at (401-874-2902).

If you have other concerns about this study or if you have questions about your rights as a research participant, you may contact the University of Rhode Island's Vice President for Research, 70 Lower College Road, Suite 2, URI, Kingston, RI, (401) 874-4328.

You are at least 18 years old. You have read the consent form and your questions have been answered to your satisfaction. Your signature on this sheet implies your consent to participate in this study.

Thank you,

Alissa Becker
Master's Candidate

I, ________________________________, hereby declare myself as a willing participant of this study, and give Alissa Becker permission to collect soil and vegetation samples, as well as make measurements of soil properties in my pasture. I understand that my participation in this study is voluntary, and that I may choose to stop participating at any point in time.

Signature:____ Date:______________

Appendix B. Institutional Review Board-approved sample farmer questionnaire discussed during the first farm visit.

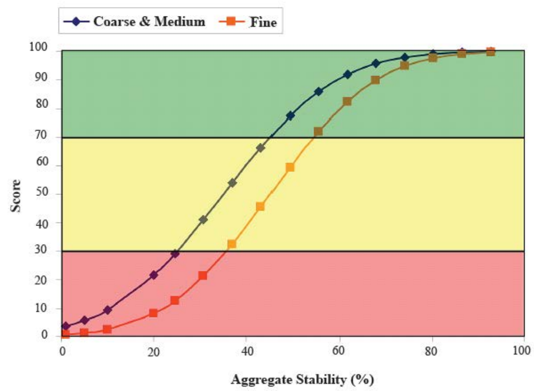
Questions for the Farmer

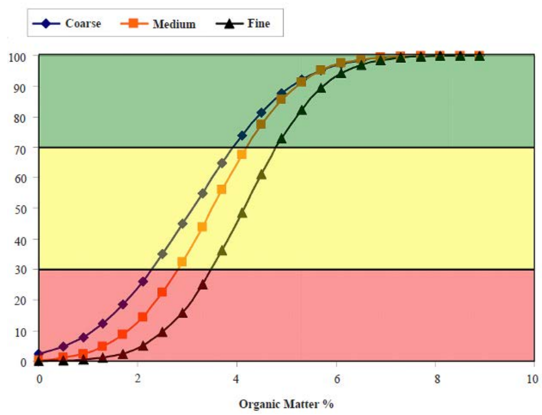
1. What type of livestock (breeds) do you raise? How long have you been raising each breed? How old is the average member of your herd?
2. How many animals on your farm?
3. What is your grazing management style: Continuous grazing, rotational grazing, or management intensive grazing? Do you have a grazing plan? How often do animals move in and out of paddocks? How long do your animals graze each paddock? How long have animals been grazing this paddock (years)?
4. What plant species grow in your pasture? Are you managing the species composition? If so, how?
5. Do you fertilize your pasture? How?
6. Have you had your pasture soils tested? What were the results? How often do you re-test?
7. Are you aware of any problems with your pasture (erosion, standing water, poor plant growth)?
8. What is drainage like in the pasture? Have/do you observe run-off during rainfall? How long does it take for pasture to stop being muddy? Are your animals removed from the pasture when soil is muddy/easily deformed?
9. What do you know about soil quality? Do you currently have any concerns about the health of your pasture's soil? Are you currently doing anything to improve it / prevent its deterioration? How and why?
10. Would you be interested in attending a seminar/workshop in January 2013 to see my overall results, so you can have some context for your own results? What sort of information would you like to take from such an event? Would you be interested in a follow-up from the NRCS or future research?
11. When was the last time animals grazed in the pasture I do my sampling/testing in? Is there anything I should know about that pasture / the animals in the pasture while I do my work?

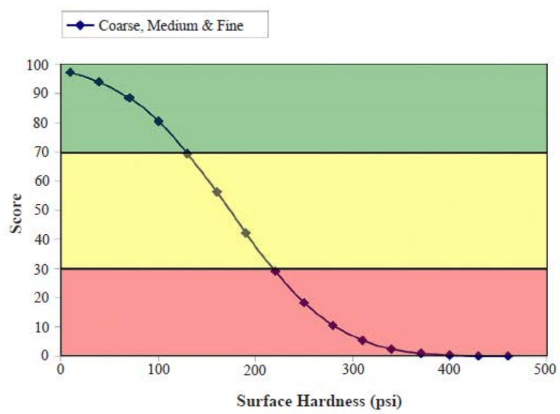
Do you have any questions for me?

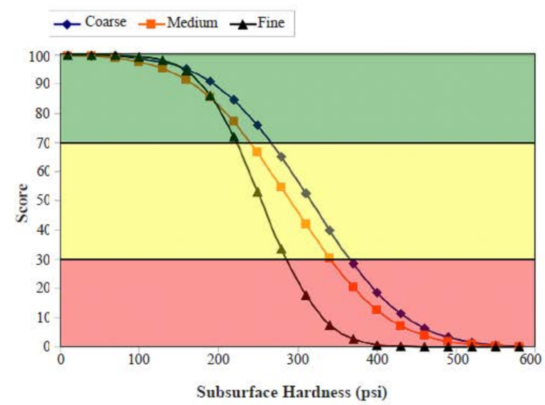
What’s the best way to contact you?

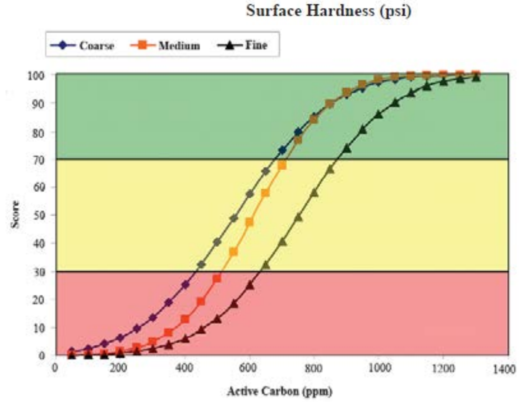
Appendix C. Soil Quality score conversion charts used to calculate scores for each livestock type. Graphs for aggregate stability, organic matter, penetration resistance (surface & subsurface hardness), active C, pH, and phosphorus are copied from Gugino et al. (2009). Data from Marx et al. (1999) and Heckman (2003) were used to generate nitrogen graphs, while data from Campbell and Stafford Smith (2000) were used to generate the vegetation graph.

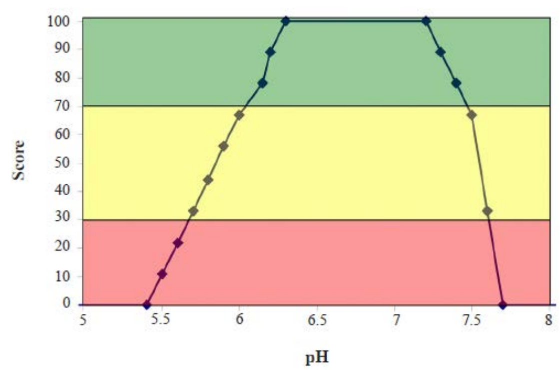


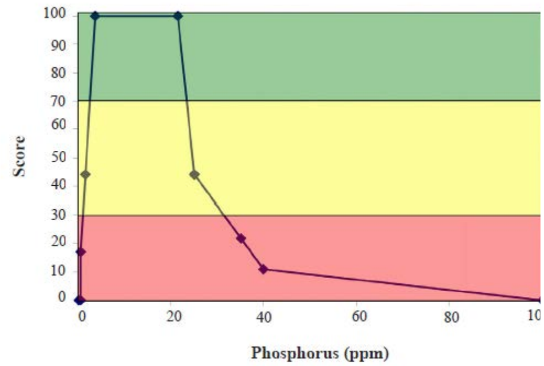


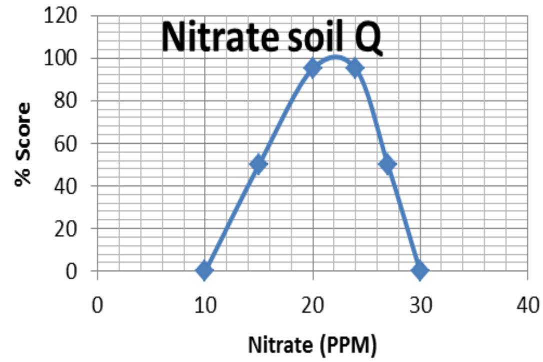


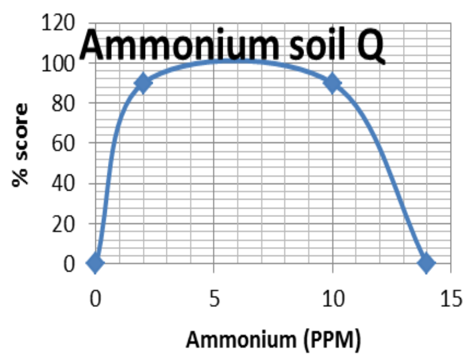


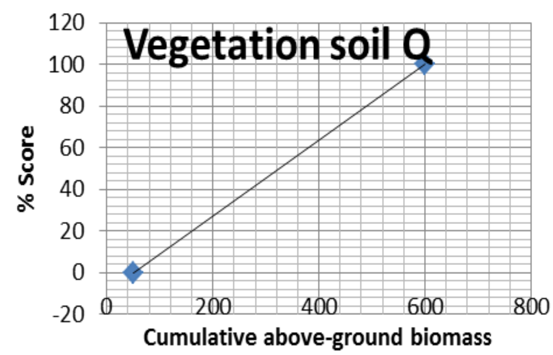





Score
Phosphorus (ppm)


Nitrate soil Q
% Score
Nitrate (PPM)


Ammonium soil Q
% score
Ammonium (PPM)


Vegetation soil Q
% Score
Cumulative above-ground biomass

Appendix D. Soil profile descriptions for beef, horse, hay and sheep pastures to 50 cm depth. Descriptions made in August at sampling point #4 (**Figure 2.1**).

Farm	Horizon	Description
B1	Ap	**0 to 23 cm;** dark brown (10YR 3/3) sandy loam; weak fine to medium granular structure; friable; smooth abrupt boundary.
	Bw1	**23 to 43 cm;** yellowish brown (10YR 5/6) sandy loam; weak mediumg subangular blocky structure; friable; smooth clear boundary.
	Bw2	**40 to 50+ cm;** yellow (10YR 7/6) sandy loam; weak medium subangular blocky structure; friable.
B2	Ap	**0 to 19 cm;** very dark grayish (10YR 3/1) fine sandy loam; many fine distinct strong brown (7.5YR 5/6) iron masses/pore linings; weak medium subangular blocky structure; friable to firm; smooth abrupt boundary.
	E	**19 to 24 cm;** dark grayish brown (2.5Y 4/2) fine sandy loam; many fine distinct strong brown (7.5YR 5/6) iron masses; weak medium subangular blocky structure; friable; wavy abrupt boundary.
	Bw1	**24 to 41 cm;** dark grayish brown (2.5Y 4/2) gravelly fine sandy loam; weak medium subangular blocky structure; friable; 30% rock fragments; smooth clear boundary.
	Bw2	**41 to 50+ cm;** light olive brown (2.5Y 5/3) gravelly sandy loam; common medium prominent strong brown (7.5YR 5/6) iron masses; weak medium subangular blocky structure; friable; 35% rock fragments.
B3	Ap1	**0 to 16 cm;** dark brown (10YR 3/3) sandy loam; weak medium subangular blocky structure; friable; smooth abrupt boundary.
	Ap2	**16 to 27 cm;** dark yellowish brown (10YR 3/4) gravelly sandy loam; weak medium subangular blocky structure; friable; 25% rock fragments (gravel and cobbles), smooth abrupt boundary.
	Bw	**27 to 50+ cm;** yellowish brown (10YR 5/6) gravelly sandy loam; weak medium subangular blocky structure; friable; 30% rock fragments (gravel and cobbles).
E1	Ap	**0 to 18 cm;** brown (10YR 3/2) gravelly sandy loam; weak medium subangular blocky structure; very friable; 15% rock fragments; smooth abrupt boundary.
	Bw	**18 to 40 cm;** dark yellowish brown (10YR 4/6) very gravelly sandy loam; weak small to meduim subangular blocky structure; very friable; 40% rock fragments (gravel and cobbles); smooth clear boundary.
	C	**40 to 50+ cm;** pale yellow (2.5Y 8/2) very gravelly sandy loam; structreless single grain; loose; 40% rock fragments (gravel and cobbles).
E2	Ap	**0 to 19 cm;** brown (10YR 4/3) coarse sandy loam; weak medium to coarse granular structure; friable; smooth abrupt boundary.
	Bw1	**19 to 36 cm;** brownish yellow (10YR 6/6) gravelly sandy loam; weak medium subangular blocky structure; friable; 25% rock fragments (gravel and cobbles); smooth clear boundary.
	Bw2	**36 to 50+ cm;** light olive brown (2.5Y 5/6) gravelly sandy loam; weak medium subangular blocky structure; friable; 35% rock fragments (gravel and cobbles).
E3	Ap	**0 to 13 cm;** dark brown (10YR 3/3) gravelly sandy loam; weak medium subangular blocky structure; friable; 15% subangular rock fragments; abrupt smooth boundary.
	Bw1	**13 to 33 cm;** dark yellowish brown (10YR 4/4) gravelly sandy loam; many medium distinct reddish brown (10YR 3/2) masses, weak medium subangular blocky structure; friable; 15% angular to subangular rock fragments; clear smooth boundary.
	Bw2	**33 to 50+ cm;** yellowish brown (10YR 5/6) gravelly sandy loam; weak medium subangular blocky structure, very friable; 15% angular to rounded rock fragments.

Farm	Horizon	Description
H1	Ap	**0 to 25 cm;** brown (10YR 4/3) sandy loam; weak medium subangular blocky structure; friable; abrupt smooth boundary.
	Bw	**25 to 35 cm;** yellowish brown (10YR 5/6) gravelly sandy loam; weak medium subangular blocky structure; very friable to friable; 20% rock fragments (some cobbles and flagstones); clear smooth boundary.
	C	**35 to 50+ cm;** light olive brown (2.5 Y 5/6) very gravelly to cobbly loamy sand; structureless single grain; loose; 50% rock fragments.
H2	Ap	**0 to 18 cm;** brown (10YR 3/2) sandy loam; weak medium subangular blocky structure; friable; smooth to irregular abrupt boundary.
	Bw	**18 to 38+ cm;** yellowish brown (10YR 5/8) extremely gravelly sandy loam; common medium prominent brown (10YR 3/2) pore linings; weak medium subangular blocky structure; friable; 45% rock fragments (gravel to cobbles).
H3	Ap	**0 to 21 cm;** dark yellowish brown (10YR 3/4) sandy loam; weak medium to coarse granular structure; friable; smooth abrupt boundary.
	Bw1	**21 to 40 cm;** yellowish brown (10YR 5/6) gravelly coarse sandy loam; weak medium subangular blocky structure; friable; 20% rock fragments; smooth clear boundary.
	Bw2	**40 to 50+ cm;** brownish yellow (10YR 6/6) gravelly coarse sandy loam; weak medium subangular blocky structure; friable; 20% rock fragments.
S1	Ap	**0 to 19 cm;** dark brown (10YR 3/3) sandy loam; weak medium subangular blocky structure; very friable; smooth abrupt boundary.
	Bw1	**19 to 34 cm;** yellowish brown (10YR 5/6) gravelly sandy loam; weak medium subangular blocky structure; friable; 30% rock fragments; smooth clear boundary.
	Bw2	**34 to 50+ cm;** yellowish brown (10YR 5/8) very gravelly coarse sandy loam; weak medium subangular blocky to structureless single grain; friable to loose; 50% rock fragments.
S2	Ap	**0 to 15 cm;** brown (10YR 3/2) sandy loam; weak medium subangular blocky structure; friable; clear smooth boundary.
	Bw	**15 to 27 cm;** brown (10YR 4/3) gravelly sandy loam; common medium prominent masses (10YR 5/6); weak small to medium subangular blocky structure; friable; 25% angular to subrounded rock fragments; wavy clear boundary.
	BC	**27 to 40 cm;** yellowish brown (10YR 5/6) very gravelly loamy sand; structureless single grain; loose; 45% rock fragments; smooth clear boundary.
	C	**40 to 50+ cm;** light olive brown (2.5Y 5/6) very gravelly loamy sand; structureless single grain; loose; 50+% rock fragments (gravel to cobbles).
S3	Ap	**0 to 27 cm;** brown (10YR 3/2) loamy sand; weak medium subangular blocky structure; very friable; smooth abrupt boundary.
	AB	**27 to 31 cm;** dark yellowish brown (10YR 3/4) loamy sand; weak medium subangular blocky structure; friable; smooth abrupt boundary.
	Bw	**31 to 50+ cm;** yellowish brown (10YR 5/6) loamy sand; weak medium subangular blocky structure; friable.

Appendix E. Vegetation types found in 10 m × 10 m sampling quadrats in beef, horse, hay and sheep pastures (Figure 2.1). Observations recorded in August 2012. Underlined species are perennials, species in bold are nitrogen-fixing plants.

Farm	Vegetation
B1	Broad leaf plantain (*Plantago major*), chickory (*Cichorium intybus*), dandelion (*Taraxacum officinalis*), orchardgrass (*Dactylis glomerata*), **red clover (*Trifolium pratense*)**, smartweed (*Polygonum spp.*), smooth bromegrass (*Bromus inermis*)
B2	Annual bluegrass (*Poa annua*), broad leaf plantain (*Plantago major*), buckhorn plantain (*Plantago lanceolata*), canada thistle (*Cirsium sp.*), fall dandelion (*Leontodon autumnalis*), horse nettle (*Solanum carolinense*), nutesedge (*Cyperus esculentus*), orchardgrass (*Dactylis glomerata*), pokeweed (*Phytolacca americana*), smartweed (*Polygonum spp.*), smooth crabgrass (*Digitaria ischaemum*), **white clover (*Trifolium repens*)**
B3	Broad leaf plantain (*Plantago major*), pepperweed (*Lepidium spp.*), red root pigweed (*Amaranthus retroflexus*), smartweed (*Polygonum spp.*), smooth crabgrass (*Digitaria ischaemum*), **white clover (*Trifolium repens*)**
E1	Annual bluegrass (*Poa annua*), buckhorn plantain (*Plantago lanceolata*), orchardgrass (*Dactylis glomerata*), Queen Anne's lace (*Daucus carota*), **red clover (*Trifolium pratense*)**, smooth bromegrass (*Bromus inermis*), **white clover (*Trifolium repens*)**
E2	Annual bluegrass (*Poa annua*), buckhorn plantain (*Plantago lanceolata*), daisies (*Aster spp.*), horseweed (*Conyza canadensis*), orchardgrass (*Dactylis glomerata*), perennial ryegrass (*Lolium perenne*), potentilla (*Potentilla spp.*), Queen Anne's lace (*Daucus carota*), ragweed (*Ambrosia artemisiifolia*), **red clover (*Trifolium pratense*)**, red root pigweed (*Amaranthus retroflexus*), smooth crabgrass (*Digitaria ischaemum*), **white clover (*Trifolium repens*)**
E3	Annual bluegrass (*Poa annua*), black swallowwort (*Vincetoxicum nigrum*), buckhorn plantain (*Plantago lanceolata*), horse nettle (*Solanum carolinense*), potentilla (*Potentilla spp.*), prostrate spurge (*Euphorbia supina*), Queen Anne's lace (*Daucus carota)*, smooth crabgrass (*Digitaria ischaemum*), **white clover (*Trifolium repens*)**
H1	Black swallowwort (*Vincetoxicum nirgum*), orchardgrass (*Dactylis glomerata*), perennial ryegrass (*Lolium perenne*), **red clover (*Trifolium pratense*)**, reed canary grass (*Phalaris arundinacea*), timothy (*Phleum pratense*), **vetch (*Vicia spp.*)**
H2	Dandelion (*Taraxacum officinalis*), garlic mustard (*Alliaria petiolata*), henbit (*Lamium amplixicuale*), milkweed (*Asclepias syriaca*), orchardgrass (*Dactylis glomerata*), perennial ryegrass (*Lolium perenne*), **red clover (*Trifolium pratense*)**, timothy (*Phleum pratense*), **vetch (*Vicia spp.*)**
H3	Buckhorn plantain (*Plantago lanceolata*), fall panicum (*Panicum dichotomiflorum*), orchardgrass (*Dactylis glomerata*), perennial ryegrass (*Lolium perenne*), red root pigweed (*Amaranthus retroflexus*), smooth bromegrass (*Bromus inermis*), smooth crabgrass (*Digitaria ischaemum*), **white clover (*Trifolium repens*)**
S1	Annual bluegrass (*Poa annua*), horseweed (*Conyza canadensis*), pokeweed (*Phytolacca americana*), red root pigweed (*Amaranthus retroflexus*), smooth crabgrass (*Digitaria ischaemum*), stinging nettle (*Urtica dioica*), white campion (*Silene alba*), **white clover (*Trifolium repens*)**
S2	Black swallowwort (*Vincetoxicum nigrum*), perennial ryegrass (*Lolium perenne*), **red clover (*Trifolium pratense*)**, smooth bromegrass (*Bromus inermis*), timothy (*Phleum pratense*), **white clover (*Trifolium repens*)**
S3	Horse nettle (*Solanum carolinense*), red root pigweed (*Amaranthus retroflexus*), smooth crabgrass (*Digitaria ischaemum*), stinging nettle (*Urtica dioica*), **white clover (*Trifolium repens*)**

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