EFFECTS OF TRAMPLING AND COVER ON BULK DENSITIES AND RECRUITMENT OF GRASSES ON RESEEDED PASTURELANDS OVER TIME

By

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A Thesis Submitted in Partial Fulfillment

of the Requirements for the Degree

MASTER OF SCIENCE

Major Subject: Plant, Soil, and Environmental Science

West Texas A&M University

Canyon, Texas

May, 2018

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ABSTRACT

A field study was conducted to determine how soil bulk density and plant foliar cover change over time in response to deferment following a high density, high intensity, short-term grazing/trampling event. The research site was in the Texas High Plains on the West Texas A&M University Nance Ranch, in Randall County, USA. Average annual precipitation is 50 cm, annual high temperature is 21°C, and annual low temperature is 6.5°C (NRCS- WCC, 2017). Green Sprangletop (*Leptocloa dubia* Kunth.) and Kleingrass (*Panicum coloratum* L.) were broadcasted at approximately 4.5 kg ha^{-1} pure live seed (PLS) on former cropland that had a partial stand of WW-Spar Bluestem (*Bothriochloa ischaemum* L.) prior to treatments. Four 0.10 ha plots were grazed and trampled following a 4.3 cm rainfall by twenty four 408 kg yearling heifers (*Bos taurus*, 97,920 kg ha^{-1}) to enhance soil-seed contact, compact the soil, and put standing plant material in contact with the soil. Four adjacent 0.10 ha control plots were left untrampled. There were no differences in mean soil bulk density among treatments before trampling. Six Daubenmire frames were placed randomly in each plot to determine canopy, basal, litter, and total cover of the plants, and a 5.08 x 7.62 cm core was collected from the center of each Daubenmire frame to determine bulk density. Forage consumption goal was to remove 50% of total canopy. Actual canopy removal was about 70% as a result of the trampling/grazing treatment. We then deferred grazing to measure the rate of soil bulk density change over time. Sorghum-Sudangrass (*Sorghum bicolor* L.) hay was spread in strips on the untrampled and trampled treatment plots 195 days post-trampling to achieve 100% soil surface cover to determine if the amount of litter cover affects seedling establishment and total vegetative canopy cover in trampled and untrampled areas. After precipitation events of > 0.254 cm, canopy, basal, litter, total canopy cover, and soil bulk density measures were collected as previously described after soils had time to drain. Trampled treatments had 20% less vegetative cover ($P<0.01$) and average soil bulk density was 0.20 g cm^{-3} higher ($P<0.01$) than untrampled plots immediately after trampling. Bulk density decreased sporadically with deferral until bulk density was no longer significantly different between treatments on day 240 after trampling. Freeze/thaw cycles, and root growth likely mitigated compaction from trampling. Significant recruitment of Green Sprangletop and/or Kleingrass did not occur. However, WW-spar basal cover increased in grazed and ungrazed treatments, but no differences were noted between treatments for basal cover or seedling recruitment between trampled and untrampled plots. Canopy cover of warm season perennial grasses in grazed treatments surpassed that of the ungrazed treatments during the early growing season of 2016 ($P<0.01$), but was no different after mid-June. Regression analysis indicated that for every hoof print per 0.1 m^{-2}, bulk density increased 0.018 g cm^{-3} ($P<0.0001$), and for every 1% increase in the soil surface that was trampled, bulk density increased 0.0026 g cm^{-3} ($P<0.001$). Trampling at high stocking densities did not affect grass recruitment or establishment, and appeared to enhance growth rate in the early growing season. Bulk

density and hydrologic function can be maintained with high stock density grazing by providing adequate deferment to re-establish sufficient cover and allow natural processes to restore porosity.

ACKNOWLEDGEMENTS

I would like to thank and acknowledge my major professor, Dr. Tim Steffens. I appreciate the opportunities he has given me over the last few years here at West Texas A&M University. I not only learned about how to conduct research, think critically, or delve into the world of range ecology, but I also learned about life and mistakes he has made over the years and how to overcome obstacles I will face in my lifetime. Those life lessons and his determination to push me past my limits have molded me into the person I am today and continue to become, and for that I will be forever grateful. Kim Peters was instrumental in helping me get the lab and pre study layout for my research completed. She was one of my most trustworthy confidants and will continue to be one of my greatest friends throughout life. I had no previous experience working in a lab or conducting research before I began my masters study, and her patience and willingness to help me has impacted the way I look at other students who may be struggling like I was as well. It has carried over into my desire to reach out to new master's students beginning their graduate school journey at Texas Tech University as I begin my own studies as a PhD candidate at Texas Tech University. Landon Canterbury, Matthew Ham, and Luis Franco all helped me do any heavy lifting, fence building, spread litter, and move cattle through the pastures throughout the entirety of the research. They all did a great job and really went above and beyond their call of duty numerous times. I would also like to thank the various WTAMU grad students who helped me understand classwork, study for exams, supported, and helped me assimilate into life in Canyon. Eric Bailey was not only one of my advisors and teachers, but one of my greatest friends here. Thank you for believing in me, being a wonderful resource, and most importantly being patient with me throughout this process. You are one of my greatest blessings. To the rest of the “awesome crew”/committee members, thank you. There were times I would get frustrated with the writing process and you always talked me off the ledge and believed in me. The diversity on my committee was by far the most eye opening of experiences. Not one advisor came from the same background, whether that is range ecology, animal science, environmental science, or agronomy. The beauty of a diverse committee was seeing the bigger picture of the entire research project, learning different ways to do the same task, learning about scientific writing preferences, and looking at the same thing from a different angle. The diversity made me realize how well rounded of a scientist I want to become as I continue my education at TTU. Often times it seems as if most PhD’s focus on one area of study during their entire scientific career and do not explore new areas they are unfamiliar with, or listen to different ideas. Having a diverse committee was challenging, but one of the best things that ever happened to me. Finally, I would like to thank my family, my mom, dad, and little brother. I have missed them while I have been away at school and I want to thank them for their love and support throughout the entire process. Thank you to my loving companions, for wiping away tears when times got tough and ‘sticking it out’ with me.

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Basic Concepts Of Soil Functions

Understanding soil function and how livestock impact biological processes above and below ground can facilitate management decisions that maintain or improve soil productivity, integrity, and fertility. Understanding these impacts begins with understanding soil-water relationships and how soil physical and chemical attributes relate to water movement and retention in the soil.

Water is the essential medium of biogeochemical processes and essential to survival of all living organisms on earth (Smith, 1974). Precipitation that reaches the soil may run off, evaporate, be stored in surface depressions, or infiltrate, then percolate throughout the soil profile. Infiltration rate is the rate at which water passes through the soil surface (Allan and Castillo, 2007; Thurow, 1991; Winter, 1998). Low infiltration rates often indicate poor soil structure (Ehlers, 1975; Franzluebbers, 2002).

Surface detention is the water in temporary storage as a thin sheet over the soil surface during the occurrence of overland flow. Where the water settles is a function of slope, microrelief, soil structure, texture, and depth (Hillel, 1980). Water that is ponded on the surface is typically lost via evaporation or it infiltrates the soil through the soil pores. Runoff tends to increase with increasing slope, clay content, and the greater proportion of bare ground (Schoonover and Crim, 2015), and decreases with increasing soil porosity, plant, and litter cover (Sharpley, 1985). Sharpley (1985), found that when slope increased from a 4% slope to an 8% slope, runoff increased from 2.94 mm hour^{-1} to 4.19 mm hour $^{-1}$ and decreased from 7 mm per hour to 3 mm per hour when 5.0 Mg ha^{-1} of straw was incorporated on 8% slopes.

Pore size will determine the rate at which water will move into the soil (Schoonover and Crim, 2015). Porosity describes the void space in the soil matrix, and is a function of soil texture, and the degree to which that particular soil is aggregated (Hillel, 1980). In a “perfect” soil, 50% of the matrix is the soil solids, 25% gas, and 25% liquid (Brady and Weil, 1999).

Soil texture is the first basic determinant of porosity. Soil texture is determined by the proportions of sand, silt and clay. The coarsest fraction is sand, which is subdivided into sub-fractions that include coarse, medium, and fine sand (Hillel, 1980). Clay is the smallest fraction, with the silt component being intermediate in size between clay and very fine sand. Clay has the most influence on soil mechanics because it has a greater surface area per unit mass. Clay particles will absorb water, causing the shrinking (drying) and swelling (wetting) action of the soil (Hillel, 1980). Sandier soils are referred to as “light” soils because they are well-drained, loose, and well aerated, though the term “light” says nothing about the proportion of the matrix that is composed of pores, nor anything about the bulk density. Clayey soils tend to retain water and become plastic and sticky when wet, and cohesive when dry, so they are referred to as “heavy” (Hillel, 1980).

The arrangement of the soil particles is known as the soil structure (Brady, 1974). The way soil particles are held together determines the structural characteristics of the soil aggregates (Hillel, 1980). The shape, size and stability of structural aggregates control movement of water, air, roots, and organisms through the matrix, and thus are a good indicator of soil health and productivity (Oades, 1984). Larger pores, that are larger than 50 nm in diameter, known as macropores, are associated with improved structure and result in higher infiltration rates (Allison, 1973). Wetting and drying, freezing and thawing, the physical activity of roots, burrowing animals, and soil churning by hooves or farm implements affect the formation of soil aggregates by mixing, compacting, and/or pulverizing the soil and changing decomposition rates of plant material, thus changing the size, shape and stability of soils aggregates (Thurow, 1991).

Roots, byproducts of organic matter, and microbial synthesis help this aggregation and can be changed by management (Bot and Benites, 2005). Humus forms chemical bonds between soil particles that bind them together (Brady, 1974), creating aggregate stability, which is the measure of the degree to which soil particles are bound together when the soil is wetted (Thurow, 1991). The aggregates must maintain their structural integrity when wet so that infiltration through the soil pores will occur (Oades, 1984). If aggregates lack structural integrity, the water will break the aggregates apart, dispersing them, possibly lodging in the remaining pores, or sealing the pores off completely (Lynch and Bragg, 1985). Compaction breaks down the aggregate structural integrity of the soil, thereby reducing water and air infiltration into the soil, as well as reducing the pore space available for root exploration (Tisdale et al., 1985), and increasing soil losses to erosion.

Compaction can be measured with bulk density (Schoonover and Crim, 2015). Bulk density refers to the weight of the soil solids in a given volume of an intact portion of the *in situ* soil matrix. As bulk density increases, the proportion of voids in the soil matrix decreases. The particle density of a rock and a clay particle are both assumed to be about 2.65 g cm^{-3}. In the "perfect" soil ratio of soil solids to porosity components (50% soil solids and 50% gas and air, or pore space), the dry bulk density should be 1.325 g cm^{-3} (Hillel, 1980). Bulk densities higher than a 1.65 g cm^{-3} tend to restrict root and shoot growth in silty clay loams (USDA-NRCS, 1999). Eavis (1972) found that root elongation in pea (*Pisum sativum* L.) decreased from 5.5 cm to 4 cm with an increase in bulk density from a 1.4 g cm^{-3} to 1.6 g cm^{-3}.

Accelerated erosion is defined as an increase in soil erosion associated with human activities that change vegetative cover and/or the physical properties of the soil (Lal, 2003). The erosion process develops in three phases: detachment, transportation, and deposition (Hillel, 1980). Erosion is a function of the energy of the water or wind acting on the soil, the soil's detachment factor and physical characteristics, topography, type of land use, and type of vegetation (Smith and Wischmeier, 1957). Different soils exhibit different responses to each of these phases; sand, for example, is more easily detached than clay, but clay particles are more easily transported (Hillel, 1980). The rate of erosion must be equal to or less than the rate of soil formation to maintain sustained, long-term productivity.

Interrill erosion combines the detachment of soil by raindrop splash and its transport by a thin flow of water across the surface, which is highly turbulent with a high erosive capacity (Meyer, 1981). Vegetative cover can slow overland flow, reducing the kinetic energy of runoff. This results in decreased sediment transport capacity (Thurow, 1991). Gutierrez and Hernandez (1996) found that sediment concentration in the runoff had mean values of 2.10, 2.52, 1.58, 1.41 and 1.22 g cm^{-3} in the 0–10, 20–30, 40–50, 60–70 and > 80% grass cover classes indicating that as cover increased, sediment production decreased.

Runoff and sediment production are typically related to the amount of cover, while interrill erosion is more strongly related to vegetation type (Gutierrez and Hernandez, 1996; Thurow, 1991). Interrill erosion is less when equal cover is provided in bunchgrass vegetation types than sodgrass types, because the bunch growth form and the accumulated litter at the base of the bunch grasses effectively obstruct overland flow (Thurow, 1991). Annuals, on the other hand, tend to have diffuse basal characteristics, and therefore generally do not effectively catch and hold sediment. Therefore, perennial bunchgrasses are important in plant communities to help keep sediment production low (Thurow, 1991). Extreme interrill erosion is evident when soil pedestals are formed where a resistant material such as rock or a plant with roots holds the soil in place (Thurow, 1991).

Because of the close association of runoff with water erosion, any practice that reduces runoff, reduces water erosion (Blackburn, 1983; Pimentel et al., 1995; Seta et al., 1993; Thurow, 1991). Therefore, practices that increase infiltration rate and surface detention, tend to reduce sediment loss. Managing disturbances such as livestock grazing and trampling in ways that maintain living or dead plant cover and rooting depth for longer periods, helps to optimize porosity, aggregate formation and stability, and infiltration so that plant and animal productivity and sustainability are enhanced at a landscape scale.

Reseeding Cropland

Reseeding old cropland to native or improved grassland pastures is becoming more common due to the declining crop prices and increasing production costs. According to the 2012 Census of Agriculture, from 2007 to 2012 the amount of cropland in the continental United states decreased from 406.4 million acres to 389.7 million acres, and the amount of permanent pasture increased from 408.8 million acres to 415.3 million acres (United States Congress, 2014). Successfully establishing grasses in formerly cultivated acres has been a challenge due to environmental conditions of most semiarid rangelands (Li et al., 1999). Water availability is the most limiting factor in grassland production in semiarid environments (Laurenroth et al., 1978), therefore the lack of rainfall can reduce the probability of establishment of grasses in semiarid regions. Continuous cultivation can also affect establishment because cultivation can degrade the soils and deplete soil nutrients, especially where nutrient cycling and soil carbon content outputs exceed the inputs (Lal, 2004).

The Texas high plains belongs to the dry semiarid steppe (Leemans and Cramer, 1991), with the average mean temperatures ranging from 10 degrees centigrade in January to 30 degrees centigrade in July (UDSA- FS, 2004). The average annual precipitation is around 375 to 550 mm per year and fluctuates from year to year (USDA, 1981). Soils in the Texas high plains are fine to coarsely textured, well drained, and soil moisture is limited for most warm season grasses during the most important growing months (USDA-FS, 2004).

The Southern High Plains is home to between 25,000 and 30,000 playa lakes (Haukos and Smith, 1992). Playas are shallow, circular basins averaging about 6 ha in surface area, and the floor has a platy soil structure (Haukos and Smith, 1992). Soils in the playa floor are predominantly slow draining clays and fill from precipitation or irrigation water runoff (Haukos and Smith, 1992). Establishment of vegetation in playa lakes depends on the existing soil moisture (Haukos and Smith, 1992). For example if the playa is dry, vegetation resembles upland vegetation, and if it is moist resembles wetland vegetation (Haukos and Smith, 1992).

Often replanting species that existed on the land prior to the conversion to row crops is not as common as improved forages (Li et al., 1999). Grasses such as Old World Bluestems (*Bothriochloa ischaemum* L.) are common in Texas in improved pastures due to their drought tolerance (Dewald et al., 1995), and high production values. There are many adaptable varieties to choose from (Dewald et al., 1995; Eck and Sims, 1984), and determining the right species of forage to plant in these improved pasturelands can be difficult. Perennial bunch grasses that are drought tolerant and high in crude protein during the summer months are the most desirable species for producers, especially in the Texas High Plains (Redfearn, 2013).

Old World Bluestems are perennial bunchgrasses that can grow up to 125 cm tall and are primarily used for grazing and hay production (Darlymple, 2001). These grasses tend to do well in areas with low rainfall and can grow in various soil types as long as soil moisture at time of establishment is not limiting (Darlymple, 2001), with an optimum soil pH of about 8.0. The growth of most bluestems begins in late April and is more responsive to late-summer and fall precipitation than native grasses. Bluestems also allow for substantial regrowth to occur in August and September when moisture is available, even when there is early summer grazing or haying (McCoy et al., 1992; Redfearn, 2013).

Old World Bluestems, especially the WW-SPAR (*Bothrichloa ischaemum* L.) and WW-B. Dahl (*Bothriochloa blahdii* [Retz.] S.T. Blake) varieties are common in Texas improved pastures that were planted to renovate deteriorated native rangelands or marginal croplands (Londono et al., 1981). B Dahl is most known for its late maturity and stand production, however, it is not a cold tolerant species (Redfearn, 2013). SPAR is winter hardy, and the most drought tolerant variety. In Randall county, WW-SPAR would seem to be more appealing due to its tolerance to freezing temperatures that are sometimes encountered in this particular area during the winter months (Redfearn, 2013).

A popular seeding technique to establish Old World bluestems is drilling at 2.2 kg pls ha^{-1} in the spring directly into wheat at a shallow depth of 0.635 cm (Berg et al., 1996; McCoy et al., 1992). Pre grazing the wheat can offer a firm seedbed, while the wheat residue can provide some site protection for the seedlings (Berg et al., 1996), as well as aid in controlling the growth of some weeds (McCoy et al., 1992). Good seed-to-soil contact is essential to maintain adequate moisture near the seeds, and is necessary for germination (Berg et al., 1996). However, if water is limiting, these firm seed beds have been shown to decrease the seedling establishment rate (Berg et al., 1996) more than 1.2 kg pls ha^{-1} (Rollins and Ahring, 1987). Although grazing wheat prior to planting is most widely used, it has negative effects on soil water, due to the decrease in water infiltration associated with compaction, therefore depleting soil water at the time that soil water is most crucial for the grass seed to germinate (Rollins and Ahring, 1987).

The most frequent cause of seeding failure that causes slow establishment of warm- and cool-season grasses other than drought, is poor weed control. Grass seedlings grow slowly and will compete poorly with weedy species (Allen, 1995). This is why grazing wheat prior to drilling seed can be beneficial. New grass seedlings, especially warm-season grass seedlings, lack sufficient vigor to recover rapidly from grazing or clipping, therefore it is essential to wait a year or until maturity before grazing or haying to allow for stand establishment (Redfearn, 2013).

Starting fertilizer should be applied according to soil test recommendations (Redfearn, 2013) and will help with the establishment and productivity of Bluestems. Fertilizing bluestems with 60 lbs N per acre can almost double its annual forage production (Sims and Dewald, 1982), and can improve crude protein content by 2-5% (Darlymple, 2001). However, fertilizer is not often applied, especially if there are native grasses present. Native grasses do well with sufficient soil organic matter and proper management. Fertilizers can also encourage the growth of undesirable competition like annual forbs and grasses (Warnes and Newell, 1969). Therefore, if maximum production of Old World Bluestems is not critical, fertilization is unnecessary once the grasses establish.

Once grasses begin to establish, grazing can maintain pasture vigor. Summer grazing begins in June when plants develop the leaves to support photosynthesis, and ends in early September to permit plants to enter the reproductive stage, and grasses complete the growth cycle (Redfearn, 2013). Stocking rates should permit 600 lbs of live weight per acre over a grazing season in "normal" years in the panhandle region but should be lowered if there is a dry spring and summer (Redfearn, 2013). Continuous grazing offers good animal performance, but tends to promote uneven spot grazing that results in deterioration of the stand, while rotational grazing promotes better distribution and forage utilization (Redfearn, 2013). Rotational grazing can also increase plant vigor and increase grass production (Redfearn, 2013). Volesky (1990) and Volesky et al., (1994) also demonstrated that rotational stocking increased utilization and production efficiencies and provided a means of maintaining root biomass, as well as a high proportion of live leaf and utilization efficiency. Better soil fertility management and rotational stocking can improve the utilization and productive efficiency of pastures (Teague et al., 1996).

Vegetative Interactions With Soil

Grasslands provide ecological services, including carbon sequestration (Follett and Reed, 2010), water infiltration (Franszluebbers, 2002), and soil and nutrient retention (Tilman et al., 1996). Soil is a living, dynamic ecosystem that, if healthy, is brimming with organisms that perform many functions, including converting dead and decaying matter as well as minerals to plant nutrients (Doran and Safley, 1997). Organic matter includes any plant or animal material that returns to the soil and goes through the decomposition process (Bot and Benites, 2005). Therefore, vegetation has an impact on the soil structure, organic matter, soil biota communities, and affects the quantity and quality of water coming into and running off of the soil surface (Bilotta et al., 2007).

Importance of Foliar Cover

The intensity with which raindrops strike the surface is important, since a greater proportion of gentle rainfall is able to adhere to the surface compared to an intense driving storm, which puddles or runs off (Miller, 1977; Thurow, 1991). When live vegetation, dead vegetation, and/or litter intercepts rainfall, the kinetic energy is dissipated and redistributed before it strikes the soil, thereby protecting aggregate structure (Callaway, 2007; Corbet and Crouse, 1968; McMillan and Burgy, 1960). However, some rainfall intercepted by foliage may evaporate because it never reaches the soil surface- referred to as interception loss.

In the Edwards Plateau the estimated annual interception loss – that is, the proportion of precipitation that never reaches mineral soil – for a given site dominated by stoloniferous grass was 10.8% of annual precipitation, while a bunchgrass dominated site had an annual interception loss of 18.1%. Oak trees and the litter beneath the trees intercepted about 46% of annual precipitation (Thurow et al., 1987). This indicated that shifts in the kind or amount of vegetation affect interception.

Vegetation mosaics in arid regions are created due to the different infiltration capacities of various soils and vegetation types, where areas under some species infiltrate more water from a precipitation event than others with lower infiltration capacities (Thompson et al., 2010). Mean infiltration capacity was 20% greater in the hardwood forest, where the mean infiltration rate was 15.15 mm per hour compared to that of the grass field which had an infiltration rate of 11.6 mm per hour. Infiltration rate and, therefore, runoff differ with the amount and type of vegetative cover. For example, the rate of infiltration is usually greatest under trees and shrubs, followed by bunchgrasses, short grasses, and lastly bare ground (Blackburn, 1975; Knight et al., 1984; Thurow et al., 1986). Infiltration rates were greatest during the first five minutes of rainfall for each vegetation type, and then declined subsequently until reaching a terminal infiltration rate (Thurow et al., 1986). Moreover, infiltration rates vary seasonally because of variation in growth dynamics (Thurow et al., 1988).

Another important difference between vegetation types relative to their effect on infiltration rate is related to the amount of litter (Thurow, 1991). Soil organic matter is dependent on humus and the microbial decomposition of litter (Cotrufo et al., 2013). Bunchgrasses and shrubs tend to produce greater amounts of foliage than annuals and short grasses. The foliage that falls then accumulates as litter and can increase the soil organic matter by creating a more consistent temperature and moisture microenvironment that favors microorganism activity (Thurow, 1991).

Importance of Roots for Soil Ecological Communities and Formation of Organic Matter

The root system serves primarily to anchor the plant in the soil and take up water and nutrients necessary for plant growth (Miller and Jastrow, 1990). The growth and metabolism of the plant root system is supported by the process of photosynthesis occurring in the leaves (Neales and Incoll, 1968). There are two types of root systems. The tap root system that has a thick main root from which smaller branch roots emerge, an important adaptation for searching for water (Miller and Jastrow, 1990) that can also help penetrate compacted soil layers. Fibrous root systems have a mass of dense but diffuse, similarly-sized, roots that are excellent for erosion control, because the mass of roots cling to soil particles, and aid in soil aggregation (Miller and Jastrow, 1990).

Processes occurring during plant growth affect the properties of the soil in close vicinity to plant roots through the action of rhizosphere biota, and many of these processes are interwoven. The magnitude of the effects of roots on the properties of soil varies with soil type, plant species present, and the feedback response of the rhizosphere microorganisms that are present (Angers and Caron, 1998). The physiological state of the plant characterizes the rhizosphere habitat, and is also modified by spatial and temporal variations of the soil properties along the root (Brimecombe et al., 2000). For example, bacterial: fungal ratios are higher in agricultural or grassland soils compared to forest soils (Bossuyt et al., 2001). Changes in temperature, moisture (Rasche et al., 2011; Tourna et al., 2008) and resource availability due to seasonal variation (Rasche et al., 2011) can affect soil communities.

Roots release sugars, amino acids, organic acids, mucilage, root border cells, and dead root cap cells, that are then used as carbon sources by soil microorganisms (Philippot et al., 2013). Mucilage, consisting of polysaccharides, is secreted by root cells as the root grows through the soil (Czarnes et al., 2000), as well as by rhizosphere microbes. Mucilage forms a gel which binds soil particles and microbes together with the root to form a ‘rhizosheath’ (Morgan et al., 2005). Since it binds the soil and root together, the gel ensures that gaps do not form as the soil shrinks and swells, thereby maintaining hydrologic integrity (Morgan et al., 2005).

Soil organisms are attracted to root exudates as a source of food. Therefore the abundance of soil organisms also increases closer to the surface of the roots (Newman and Watson, 1977). The density of organisms can be about 500 times greater in the rhizosphere than in the rest of the soil (Rouatt et al., 1960). Roots and the organic residues of forages create soil macro-pores that reduce soil compaction and increase infiltration rate (Russell and Bisinger, 2015).

Some soil organisms increase root growth by producing compounds that function as root growth hormones (Valencia-Cantero et al., 2007), while other organisms may decrease root growth by creating a significant drain on carbon reserves in the plant (Livne-Luzon et al., 2015), which in turn, can alter root growth and the formation of organic matter in the rhizosphere (Kuzyakov, 2002; Bertin et al., 2003). If root growth decreases, mitigation of compaction from root growth in the spring may be decreased, taking the soil longer to recover from any type of compaction.

Organic matter in soils is important because plants obtain nutrients from two sources, organic matter and minerals (Weil and Brady, 2017). Soil organic matter affects the chemical and physical properties of the soil and its overall health. Its composition and breakdown rate affect soil structure and stability, porosity, infiltration rate, and water holding capacity, plant diversity, and plant nutrient availability (Bronick and Lal, 2005). Land use and management practices affect soil organic matter. Decreased aboveground biomass results in a decrease in root biomass, and therefore, less organic matter incorporated into the soil (Cao et al., 2004; Grier et al., 1981).

Importance of Soil pH

Soil pH is an important driver of soil microbial communities (Bru et al., 2011; Fierer and Jackson, 2006), and changes the absorption of ions from the soil by roots (Philippot et al., 2013). Jensen (2010) determined that most plant nutrients are optimally available in a pH range between 6.5 to 7.5, which is also the range of pH generally most compatible to plant root growth. Many factors affect soil pH, such as climate, mineral content and soil texture. Temperature and rainfall control leaching intensity and soil mineral weathering (Bridges, 1978). In humid and warm environments, the soil pH decreases over time, due to leaching from high amounts of rainfall (McCauley et al., 2017). In dry climates, however, soil leaching is less intense, and pH can be neutral or alkaline (McCauley et al., 2017). Soils with high clay and organic matter content have a greater buffering capacity and are more able to resist changes in pH than sandy soils (McCauley et al., 2017).

Changes in pH are caused by a loss of organic matter, erosion of the surface layer, and effects of nitrogen and sulfur fertilizers (McCauley et al., 2017). Legumes can acidify their rooting zone through nitrogen-fixation (Wortman et al., 2015). The acidifying potential of annual legumes is lower than that of perennial legumes (Flynn and Idowu, 2015).

Improper land management, improper pH, poor fertility, fire, compaction, and drought, can increase mortality of native grasses, and create niches and bare areas for other species to germinate and establish (Adair and Groves, 1998). Deep-rooted plants, such as sunflower use water and nitrogen that may escape shallow rooted crops (Jones and Olson- Rutz, 2011), thereby reducing soil acidification and nitrogen loss from the system (McCauley et al., 2017). Annual sunflowers grow in places with compaction issues and bare ground that make the site inhospitable to perennial plants. Forbs that grow in these inhospitable areas can possibly mitigate some soil compaction, keeping the soil in place, thereby reducing run off and erosion so less bare ground is present (Heiser, 1969). With proper management of these forbs and the surrounding grasses, the desirable species can possibly outcompete the forbs and regain dominance.

Based on the foregoing information in this section, managers of grasslands for livestock forage must also adequately consider environmental quality and ecological services to maintain ecological function and productivity sustainably. To do so, livestock must be managed in time and space in ways that capitalize on the positive effects they may have in redistributing and cycling nutrients, dispersing seeds, and managing plant community structure and competitive relationships among plants while mitigating negative consequences such as defoliation and trampling.

Basic Concepts Of Cattle Grazing

The single most important aspect of understanding plant and animal interactions is the firm understanding of the foraging processes of grazing ungulates (Crawley, 1983). A proper perspective of the plant/animal interface requires a dual focus on balancing both short and long term production goals (Huston and Pinchak, 1991). Practices that promote maximum production of average daily gains and plant quality will eventually reduce long term production of the plants, by decreasing the stability of the forage resource in the plant community (Huston and Pinchak, 1991). Both the animals' needs and consequences that result when these needs are adequately, marginally, or even inadequately met, determine the proper balance between short term and long term productivity (Huston and Pinchak, 1991).

When an animal grazes a plant, behavioral actions and hierarchies of responses are used that lead to the prehension and consumption of forages (McNaughton, 1987; Senft et al., 1987; Senft, 1989). Range animals rely on vegetation for the nutrients needed to support their basal metabolic rate and tend to select forages based on quality (Moore and Jung, 2001). Quality is used to describe the worth of the digestible components of diet and the chemical composition of the plants selected for consumption by grazing ungulates (Huston and Pinchak, 1991). For instance, any forage species containing 20% protein is considered of higher quality than that of a similar forage species containing only 10% protein (Huston and Pinchak, 1991). However, both may be desirable to an animal having a relatively low protein requirement to sustain their basal metabolic rate.

Palatability refers to inherent plant physical or chemical factors that elicit a selective response by the animal (Baumont, 1996) and is, therefore, related to quality. Livestock tend to avoid grazing plants with high proportions of structural carbohydrates and low content of elemental constituents (Moore and Jung, 2001), so the grazing pressure on palatable plants is much higher than on unpalatable plants. Preference involves the proportional choice of one plant species from among two or more species, and the preference status of a particular plant species is largely dependent upon its inherent abundance, its morphological and/or phenological characteristics, the array of species within the plant community, and the species of animal consuming the forage (Stuth, 1991).

The type of ruminant, plant species, and morphological parts of plants will cause the ruminant to exhibit "preferences" in the materials selected for consumption (Hofmann, 1989) that vary with time and among the species of animal. Preference constantly changes as season and weather conditions alter the nature of the plants in the plant community (Allison, 1985). Therefore, some species are selected only under specific conditions or at certain times of the year. For example, in the dormant season, shrubs with higher crude protein content such as four wing saltbush (Cordova and Wallace, 1975) could improve the intake of grasses in circumstances where grasses contain marginal amounts of protein.

Range herbivores have been variously classified into three classes (Langer, 1984) by morphological differences in their digestive systems, including salivary glands, rumen size, and rumen papillae (Hofmann, 1989), and are associated generally with different feeding habits. All domesticated ruminants belong to grazers or to the intermediate type. The first of these are bulk/roughage grazers (cattle, bison), who are able to digest low quality roughage, particularly different kinds of grass. The second kind are concentrate selectors (white-tail deer, mule deer), who only forage for plants and plant parts high in energy. The third type of ruminant is the intermediate feeders (red deer, goats), who, in contrast, select leaves and young plants with high energy content, if available (Hofmann, 1989), but can make better use of low quality plants (Hofmann, 1989) than concentrate selectors. Grazers of low quality forage possess a larger rumen and a smaller omasal orifice than intermediate types and concentrate selectors (Hofmann, 1989). The two latter groups can use their reticular groove to bypass the forestomach and to lead the food directly into the abomasum (Hofmann, 1989), increasing the efficiency of digestion and reducing the retention time.

Generally, nutrients are utilized and metabolized in the hierarchical order of maintenance, lactation, reproduction, and storage (Duncan and Gordon, 1999; Radunz, 2012). However, reproduction and lactation can occur when the diet does not provide the required levels for these functions, provided that the animal has sufficient energy reserves in the form of fat, though body condition suffers (Comerford, 2017).

Cattle typically will not travel further than 1.6 km from water for forage needs (Valentine, 1947). Thus grazing is often concentrated around water points. However, during drought, the foraging distance from water is increased as forage supply diminishes (Gerrish and Davis, 1999; Smith, 1988; Squires, 1982; Walker et al., 1987). If windmills, trees, or other visual cues are prominent near water sources, the strength of the water's attraction is increased (Stuth, 1991). Rough terrain, steep slopes and/or rocky outcrops restrict animal movements, even when water sources are within acceptable distances (Stuth, 1991).

Cattle prefer to use established trails, roads, or cleared paths rather than attempt to penetrate thick brushy areas or difficult terrain (Roath and Krueger, 1982). Spatial-use patterns of livestock can be regulated by mixing experienced animals with inexperienced animals (Roath and Krueger, 1982). This matriarchal system of experience training can be a vital means for reducing the learning curve of replacement animals in a herd so that if extended drought occurs, experienced animals can show others those sites which improve the chances of survival for new cattle (Roath and Krueger, 1982).

Foraging animals first harvest food, then move to bedding sites to ruminate and digest the food ingested in a previous grazing bout (Stuth, 1991). Animals will reduce daily grazing time as digestibility of available forage declines and retention time of ingesta increases (Allison, 1985; Demment and Van Soest, 1985). When observing grazing strategies, palatable green leaves are highly selected due to the minimal amounts of structural carbon such as lignin and cellulose (McNaughton 1985; Stuth, 1991). During periods of dormancy, however, the animal's selection of sites may be based more on the abundance of plant material, regardless of greenness (Stuth, 1991).

Basic selection of grazing areas and plants within those areas, as well as the timing of grazing, are also modified by ambient conditions that affect animal comfort. When daytime temperatures are within the thermal neutral zone of cattle, most grazing, (about 90%) takes place during daylight hours (Walker and Heitschmidt, 1989). During hot periods, cattle reduce afternoon grazing and increase evening or night grazing (Walker and Heitschmidt, 1989), due to the fermentation process of the rumen increasing body temperature. When winter temperatures are below the thermal neutral zone of cattle, they limit evening grazing, but will increase afternoon grazing (Walker and Heitschmidt, 1989), to increase body temperature.

Stocking rate is the relationship between the forage source and the livestock consuming the forage, and is the number of animals on a grazing unit over a specified amount of time (Vallentine, 2000). Carrying capacity of a given pasture is how many animals the pasture can support for a season. Stocking density is how many animals are in a given area at a given moment and increases as the number of animals increase or the size of paddock decreases (Vallentine, 2000). Grazing intensity is how much leaf matter from a particular plant the livestock are consuming (Vallentine, 2000).

An animal's feeding station is established when it stops walking, lowers its head and bites a plant (Lyons, 2000). The pattern of feeding stations is strongly related to the distribution and profitability of patches in a community, the size of the community, and the geographical relationship of the community to the animal’s grazing path (Novellie, 1978). When the animal has oriented itself in a habitat, it must decide when to lower its head and establish a feeding station along its grazing path (Bailey et al., 1996). Within the feeding station, the animal then selects from among the plant species available. The animal will then decide which plant parts will be consumed (Stuth, 1991). Therefore, the diet selection process has two distinguishing levels, spatial choice and species choice. The animals appear to select fewer plant species and focus their selection on plant species which offer the maximum amount of green forage per bite within the primary food group (Duncan and Gordon, 1999). Therefore, animals may cause severe defoliation on smaller spatial scales across a landscape when allowed access for too long, as a result of their forage preferences and distribution within a pasture that can detrimentally affect the defoliated plants, even when average stocking rates are low or moderate. By increasing the number of pastures (paddocks) on a landscape, animals can be more evenly distributed in time and space. Though stocking density may be higher, many of these problems can be avoided because grazing may be more equitably distributed and plants have a chance to recover between defoliations.

Grazing Impacts On Vegetation

Negative effects of grazing may include loss of plant biodiversity and destruction of native vegetation (Brown and Ewel, 1988; Thurow et al., 1988), reduction in seedling emergence and establishment (Blom, 1977), reduced litter (Johnston, 1963), and reduced soil aggregate stability (Beckmann and Smith, 1974; Knoll and Hopkins, 1959; Warren et al., 1986b). In some cases, however, properly managed grazing livestock may encourage plant growth (Frank et al., 1998), create a mulch that can reduce erosion and increase soil water (Heitschmidt et al., 1987), distribute seeds (Couvreur et al., 2004; Fischer et al., 1996; Pakeman 2001), improve seed-soil contact (Graff, 1983), increase carbon sequestration (Franzluebbers et al., 2000), and decrease fire fuel loads (DiTomaso and Johnson, 2006).

Basic Understanding of Grass Responses to Herbivory

Individual grass plants consist of roots and shoots. The shoot refers to the stem and leaves, and is comprised of several phytomers (Dahl, 1995). A phytomer consists of a leaf, an internode, an axillary bud, and a node (Dahl and Hyder, 1977; Hyder, 1974). At the tip, or apex, of each stem and root is an apical meristem. The cell division at the apical meristem contributes to the lengthening of the tiller. This lengthening is termed primary growth, and it takes place in tender, young tissues. The axillary bud is a grouping of meristematic tissue that develops into tillers (Dahl, 1995). Roots grow from the nodes that are on or below the ground (Dahl, 1995).

Plants grow and respond to grazing as members of a population and community, and their response is reflected in the number of plants per unit area and the number of tillers per plant (Thurow, 1991). Many bunchgrass species are palatable and high in nutritional value. If they are too intensely grazed, the apical meristems can be damaged (Sims et al., 1982), and lose apical dominance- the suppression of meristems in basal buds caused by hormones produced in the apical meristem. The loss of apical dominance then triggers growth of additional tillers from buds at the base of the plant if growing conditions permit (Briske, 1991). Viable perennial grass seed in rangeland soils are surprisingly low (Reece et al., 2007). Therefore, the production and survival of vegetative buds are critical to maintenance of a species in the community from year to year (Reece et al., 2007).

Effects of Grazing on Plant Canopies & Roots

Some plant species are tolerant to grazing, while others have morphological or physiological characteristics such as low growth habits, secondary compounds, or thorns that minimize the probability of defoliation (Archer and Tieszen, 1980; Briske, 1986). Moderate defoliation can stimulate above ground production in some species (Heitschmidt et al., 1982; McNaughton, 1979; Provenza et al,. 1983), while excessive herbivory can set back plant growth (Oesterheld et al., 1992). The functional differences in the ability of a grass species to maintain root mass and activity following grazing is an important component of grazing tolerance (Caldwell and Caldwell, 1987).

A potential mechanism that aids in a plant’s tolerance to herbivory is the increase in the rate of leaf biomass regrowth post defoliation (Suwa and Maherali, 2008), or compensatory growth (McNaughton et al., 1983) that has been measured in certain circumstances. Grazing alters the age structure of leaves within plant canopies, reducing total leaf area, which has direct consequences for the photosynthetic capacity of plants (Caldwell, 1984). Grazing can increase light penetration to lower canopy leaves through defoliation of the upper canopy. Leaves generally exhibit maximum photosynthetic rates during the time of early growth stages and full leaf expansion, and subsequently decline (Caldwell, 1984). Therefore, leaves of defoliated plants may display greater rates of photosynthesis than non-defoliated leaves because many of the leaves are chronologically younger and more efficient photosynthetically (Briske, 1991). This is generally seen in turf-grasses where net production per unit area may be stimulated by frequent clipping at a moderate height (Mortimer and Ahlgren, 1936).

Carbohydrate production shifts after defoliation because the plant has more roots than shoot area. When defoliation occurs, there is more root area than necessary to supply nutrient requirements of the resulting smaller residual leaf area (Crossett et al., 1975). Therefore the plant response is to shed the root or build new leaves to balance the surplus from the respiring roots (Crossett et al., 1975). Richards (1984) found that severe defoliation caused a 50% reduction in root length. Increased rates of photosynthesis following defoliation are relative to similar aged leaves of non-defoliated plants (Nowak and Caldwell, 1984). After severe defoliation, however, little leaf growth occurs (Crawley, 1983), and the shedding of roots is more likely to occur.

When the leaf area index (amount of leaves covering any point over an area of soil) is high, grazing may remove transpiring leaf tissue and reduce canopy interception losses of precipitation, thereby enhancing soil moisture and enabling plants to sustain growth over longer periods (Archer and Smeins, 1991; Laurenroth et al., 1985). Defoliation may also increase the water potential of remaining plant parts and contribute to increased rates of leaf expansion (Hodgkinson, 1976; Wolf and Perry, 1982).

Cessation of root growth following a grazing bout has been observed within hours of defoliation (Davidson and Milthorpe, 1966; Hodgkinson and Baas Becking, 1977). Grazing affects both vertical and lateral development of root systems (Schuster, 1964; Smoliak et al., 1972), reduces root initiation, diameter, branching and total production (Biswell and Weaver, 1933; Carman and Briske, 1982; Evans, 1973; Jameson, 1963), as well as a reduction of the absorptive surfaces of the roots themselves. This also reduces the soil volume that is explored for water and nutrients by the roots (Briske, 1991). Root elongation and respiration rate, as well as phosphorus absorption, remained suppressed for eight days following defoliation of orchard-grass to a height of 2.5 cm (Davidson and Milthorpe, 1966). Responses of defoliation on root functions originate from the processes of energy production in plant photosynthesis (Caldwell and Caldwell, 1987).

Defoliation and changes in root growth can also affect water available to the plants. Defoliation may conserve water by decreasing root depth or root density (Archer and Detling, 1984; Svejcar and Christiansen, 1987), because rooting density and rooting depth decrease in response to defoliation (Crider, 1955; Cook et al., 1958; Shariff et al., 1994; Stroud et al., 1985), especially during the growing season (Ganskopp 1988; Engel et al., 1998). However, heavy grazing may also cause increased evaporation by taking away above ground biomass, causing an increase in bare soil exposed. Zhao (2010) found in semi-arid Mongolian grasslands that with increasing grazing intensity, soil temperature increased, particularly in the topsoil, due to sparser vegetation coverage and drier soil surface moisture in the grazed versus ungrazed sites. They also noticed that sites that had been ungrazed since 1979, 1999, and moderately grazed since 1979 and 1999 all had a mean soil water content of 0.572 cm^3 cm^{-3} in the top 4-8 cm of the soil while the heavily grazed treatment had 0.523 cm^3 cm^{-3} of soil water in the top 4-8 cm (Zhao, 2010). The soils in the grazed sites also warmed up or cooled down quicker than in the ungrazed ones, indicating reduced vegetation in the heavily grazed and moderately grazed areas resulted in more evaporation losses compared to the ungrazed areas (Zhao, 2010). Heavily grazed sites also showed a shallower root distribution, which led to a reduction of the exploitable soil volume, thereby significantly reducing the amount of plant available water and thus a decreasing plant growth (Zhao, 2010). Consequently, the heavily grazed site was more susceptible to drought, and prone to soil degradation.

Crider (1955) defoliated eight different grass species at different frequencies and intensities over a period of 6-18 days. A single defoliation removing 50% or more of the shoot volume retarded root growth for 6 - 18 days in seven of the eight perennial grasses investigated, while a single defoliation removing 80 or 90% of the shoot volume stopped root growth for 12 and 17 days, respectively. The initial removal of 70% of the shoot volume followed by three subsequent defoliations per week stopped root growth for the entire 33 day investigation in species subjected to multiple defoliations. Based on these results, Crider concluded that multiple defoliations detrimentally influenced root growth to a greater extent than single defoliations, and root mortality increased following very severe defoliation (Hodgkinson and Baas Becking, 1977; Troughton, 1981; Weaver and Zink, 1946).

In a global synthesis of the literature, Diaz et al., (2007) found that the abundance of annual plants generally responded positively to grazing, and perennial plants responded negatively under all combinations of precipitation and herbivory (Diaz et al., 2007). Short plants frequently responded positively and tall plants responded negatively in all systems except in dry systems with short evolutionary history of grazing (Australian sites), where effects of herbivory on short and tall plants did not differ (Diaz et al., 2007). They also found plants with rosettes and that were stoloniferous responded positively to grazing but tussock graminoids responded negatively.

Forbs and woody species showed neutral responses to grazing, whereas graminoids had predominantly neutral or negative responses to grazing (Diaz et al., 2007). They most frequently detected an increase in unpalatable plants in grazed ecosystems, with the effect being stronger in dry systems than in humid systems (Diaz et al., 2007). The most common response to grazing was no change in the richness of both native and exotic species with grazing, but in the cases of abundance, there was a weak trend for a positive response of exotic plants and a negative response of native plants to grazing (Diaz et al., 2007).

Effects of Grazing on Litter

Thus, detrimental effects ensue because soil degradation is usually associated with excessive herbivory, excessive trampling, extended drought, and fire (Herrick, 2000; Herrick and Jones, 2002), that result in increased bare ground (Naeth et al., 1991). Reduced litter with more bare ground has been shown to increase short-lived perennials and annuals, and shift the community into less productive grasses (Grime, 2006). Litter and plant cover enhance infiltration, aggregation and aggregate stability, decrease raindrop impacts, runoff, erosion, and soil temperature, and therefore, decrease soil surface evaporation (Bardgett, 2005; Thurow, 1991;Tomanek, 1969). Decreased evaporation will retain precipitation and moisture in the ground longer, and thereby enhance soil microbial activity, which promotes soil aggregate stability and sustains plant nutrient status (Bardgett, 2005; Thurow, 1991). However, greater interception associated with excessive levels of dead vegetative cover sometimes more than offsets the benefits of reduced evaporation (Lull, 1964).

Overgrazing typically reduces litter mass, with the lowest values under very heavy grazing (Coupland et al., 1960; Johnston, 1962), leaving more open areas that are bare. Grazing may, therefore, affect soil water by removing excessive amounts of litter and vegetative cover that intercept precipitation, exposing the soil to the sun and heat and maintain a survivable microclimate at the soil surface (Bremer et al., 2001; Whitman, 1971; Wraith et al., 1987), and can significantly change the content of water in the soil (Bremer et al., 2001). Bremmer et al. (2001), found that at day 190 and 210, soil temperatures at 0.05 m averaged 3.8^{o}C higher on the grazed site (30.7^{o}C) than on the ungrazed site (26.9^{o}C). Soil temperature remained higher on the grazed site throughout the remainder of the study.

Hotter soil decreases microbial activity, accelerates loss of organic matter, and increases erosion risks (Bardgett, 2005; Blackburn, 1975, Blackburn et al., 1986). Excessive litter removal over a large region also reduces the population of the bacteria *Pseudomonas syringae*, which are important sources of nuclei for the formation of raindrops in clouds (Vali et al., 1976). Such reduction in the quantity of these raindrop nuclei may lead to reduced precipitation (Vali et al., 1976). Excessive removal of cover and litter, without allowing sufficient regrowth also increases surface reflectivity, or albedo, (Otterman, 1977), reducing the amount of heat absorbed and retained by the land surface.

Bare ground cools quickly at night, reducing the opportunity for the convective activity to promote precipitation events (Charney et al., 1975). Soil covered by vegetation has less albedo than soil uncovered by vegetation. Desert regions reflect more solar radiation to space than their surroundings (Charney et al., 1975). Idso et al., (1975) have shown that albedo of bare soil is linearly related to water content on the uppermost layers of the soil, with values ranging from about 0.14 if the soil is saturated and about 0.30 if the soil is dry. The value of 0.14 for the albedo represents an average for a vegetatively covered continent. The increase of albedo from 0.14 to 0.35 decreased mean rainfall by 46% and cumulus cloud cover by 7% (Charney et al., 1975).

Cold advections will result in a region that becomes cooler. As air moves from the regions of high pressure to the local region of lower pressure, air is pushed downward from above, which is the sinking motion that is caused by cold advection. Soil moisture content may, therefore, affect atmospheric conditions directly by influencing evaporation, and hence, the proportion of net radiation available as latent heat.

Thus, grazing management may have significant effects, not only on the efficiency of water use by plants on the landscape, but also on the amount of precipitation that falls, and the amount retained in the soil through its effects on vegetative and litter cover. If trampling reduces litter particle size and increases litter- soil contact, it may promote plant establishment, and protection of seedlings from frost, full sun, or excessive water loss (Evans and Young, 1972; Loydi et al., 2013; McCalla, 1943; Rotundo and Aguiar, 2005), as well as rapid decomposition by soil microorganisms (Bardgett et al., 1998; Hobbs, 1996; Olofsson and Oksanen, 2002).

Effects of Grazing on Seed and Seedling Emergence

Grazing at flowering and seed set can influence subsequent seedling recruitment by reducing the number and size of seeds produced (Crawley, 1983; Frank et al., 2013; Jameson, 1963; Maun and Cavers, 1971). Grazing animals can also decrease flower and seed production directly by consuming reproductive structures, or indirectly by removing meristematic tissue, as stated previously. Stressing the plant will reduce the energy available for the plant to develop seeds (Kozlowski, 1972). These effects increase as grazing intensity increases (Xie et al., 2016).

Generally there is a direct relationship between seed size and seedling performance (Harper and Harper, 1977). Large seeded taxa, have greater seedling growth rates, and may improve establishment even in the face of herbivory, competition, and abiotic stress (Kitajima and Fenner, 2000). Therefore, avoiding grazing at seed filling times and decreasing the frequency of grazing through the season could improve reproductive success for palatable plants.

Wulf (1986) found in North Carolina that seedlings generated from large seeds of *Desmodium paniculatum*, had a 35% greater dry weight than those from smaller seeds when grown under low-nutrient conditions, but a 63% higher dry weight when grown under high-nutrient conditions. They also found that the same ratios held for leaf-area comparisons. However, seedlings from smaller seeds maintained higher photosynthetic rates at full soil water saturation than those from larger seeds, if grown under low irradiance, though seedlings from large seeds still had greater biomass (245 mg vs 130 mg) and leaf area (63.4 cm^2 vs 34.3 cm^2) compared to those from small seeds under those conditions.

Grazing during early stages of seedling establishment can cause death of that plant (Limb et al., 2011; Teague et al., 2008; Thompson, 1982). Seedlings and juveniles have low nutrient energy reserves, shallow roots, and typically low density root systems (Thompson, 1982). Because plants are relatively sensitive to defoliation early in their life cycle, deferment of grazing at that time is often helpful, if not necessary, to ensure that seedlings can establish (Archer and Pyke, 1992). At maturity, defoliation has little effect on the current year's production and no effect on plant vigor (Blaisdell and Pechanec, 1949). Herbage removal is most injurious when apical meristems are removed after the date when substantial regrowth is unlikely (Blaisdell and Pechanec, 1949).

Disturbances by livestock at the right time of the year can help with seed germination (Silverton, 1980). Disturbance of the soil surface results in good seed-soil contact (Leffler et al., 2016). Soil firming has shown an improvement of soil hydraulic conductivity to the seed by reducing soil surface area and soil macro porosity, allowing easier water flow to the pore in which the seed is located in (Hyder and Sneva, 1956; McGinnies, 1962). Adequate deferment from grazing following disturbance, can reduce seedling mortality (Fenner, 1978; Limb et al, 2011) and promote seedling establishment (Gross, 1984; Keeley, 1987; Miles, 1972).

Grazing Impacts On The Soil

Livestock trampling alone, without the removal of any vegetation, has increased soil compaction (Alderfer and Robinson, 1947; Betteridge et al., 1999; Hamza and Anderson, 2005; Kako and Toyoda, 1981; Lull, 1959; Van Haveren, 1983, Warren et al., 1986c, 1986d ; Willat and Pullar, 1984), reduced infiltration (Gifford and Hawkins, 1978; Van Haveren, 1983; Warren et al., 1986a, 1986b;), increased run off (Thurow et al., 1986, 1988; Warren et al., 1986a, 1986d), increased evaporation losses (Knoll & Hopkins, 1959; Whitman, 1971; Wraith et al., 1987), and destroyed biological soil crusts (Belsky & Gelbard, 2000; Brotherson and Rushforth, 1983; Fleischner, 1994; Kleiner and Harper, 1972; Loope and Gifford, 1972) in regions where these crusts are essential to hydrologic and soil stability. Temporary or long term negative effects of trampling at a site depend on soil texture (Van Haveren, 1983), climatic conditions (Warren et al., 1986a), soil water content (Robinson and Alderfer, 1952), and intensity and frequency of grazing (Thurow, 1991).

Grazing Effects on Bulk Density and Infiltration

Infiltration rates are highly correlated with soil bulk density (Warren et al., 1986a). Bulk densities indicate the amount of pore space available in a given volume, so increased bulk densities indicate increasing compaction. Soil pores are occupied by water or air that exist between soil particles and within a given soil aggregate. Macropores are large soil pores that are greater than 50 nm in diameter (Brady, 1974), that allow the easy movement of water and air through the soil matrix. Therefore, the structure of the soil and macropores are vital to water and air exchange, plant root exploration, and habitat for soil micro-organisms, because they drain freely by gravity.

Soil structure is a good indication of compaction. For example, granular structure typically has loosely packed, crumbly soil aggregates, separated by macropores, which allow for rapid infiltration and promote biological productivity. Platy structure however, is an indication of soil compaction (Brady, 1974). Platy structure looks flat and “plate-like,” and impedes the downward movement of water and roots through the soil (Brady, 1974). The macro-pore volume of compacted soil has been shown to be half that of uncompacted soil (Douglas and Crawford, 1993).

Bulk densities are a quick and objective way to measure soil hydrological function, and reflect the soil’s ability to function for structural support, water and solute movement, and soil aeration (Gifford and Hawkins, 1978). The hydrologic condition of rangelands is the result of complex interrelationships of soil, vegetation, topography, and climate (Thurow, 1991). Impacts of grazing on hydrologic functions differ from region to region and are different through seasons of the year and across years (Knight, 1980; McCalla et al., 1984; Thurow, 1985; Thurow, 1991; Warren et al., 1986a). The degree of compaction is dependent on soil texture (Orr, 1960; Van Haveren, 1983), soil moisture content when grazing (Assouline and Mualem, 1997; Nawaz et al., 2013), soil microbiological content (Assouline and Mualem, 1997; Coder, 2000), and frequency and intensity of grazing (Belsky and Blumethal, 1997; Warren et al., 1986a). Compaction can indirectly reduce the pH of the soil (Assouline and Mualem, 1997), reduce soil organic matter, restrict root growth (Shierlaw and Alston, 1984), decrease seedling emergence (Van Haveren, 1983), reduce aggregate stability (Blackburn et al., 1986), decrease infiltration (Van Haveren 1983), and reduce nutrient uptake (Duiker, 2004). High intensity hoof action associated with higher stocking density has decreased biomass, increased compaction and resulted in less infiltration, and more run off (Warren et al., 1986a, b, c, d). Variables influencing infiltration rates include aggregate stability, organic matter content, mulch, standing crop, bulk density, initial soil moisture content, ground cover, perennial grass cover, and total grass cover (Wood and Blackburn, 1981).

It is harder to compact sandier soils when grazed, but finer textured soils with higher clay content show an increase in bulk density with grazing pressure (Daum, 2002; Van Haveren, 1983). For instance, on coarse textured soils, soil bulk density means were not significantly different between light, moderate, or heavy grazing intensity (Van Haveren, 1983), but on fine textured soils, average bulk density of heavily grazed pastures were 11.8% to 13.4% higher than moderate and lightly grazed pastures. Other studies have shown that regardless of texture, when grazing pressure is heavy, there are significantly higher bulk densities (Reed and Peterson, 1961). Infiltration rate and sediment production on a silty clay soil, were affected less due to intensive and repeated grazing during the growing season than during periods of winter or drought induced dormancy (Warren et al., 1986a).

The degree to which grazing intensities affect compaction in grasslands depends on the soil and moisture conditions at the time of trampling, because they remain in the plastic state for extended periods. As the soil dries, it may be less difficult to avoid soil compaction (Daum, 2002), since more force is needed to compact a dry soil than a wet soil (Lull, 1959). In northeastern Utah, Laycock and Conrad (1967) found no measurable compaction due to grazing on loam and clay loam soils and concluded that conflicting results from bulk density studies are due to varying soil moisture conditions.

Studies on grazing and soil compaction generally find that exposure to livestock grazing compacts soil, and the degree of compaction is increased with higher grazing intensity (Fleischner, 1994; Kauffman and Kreuger, 1984; Warren et al., 1986b; Willatt and Pullar, 1984). With proper grazing management, however, infiltration rates can be suststained when adequate ground cover is maintained (Russell and Bisinger, 2015). Cattle tend to create radial paths that lead to water. These compacted trails may increase as the number of pastures increases with rotational grazing systems (Andrew, 1988; Walker and Heitschmidt, 1986). If deferral periods are too short, it takes longer for the soils to recover between grazing periods. Low porosity decreases the infiltration in these trails, thereby creating gullies (Wilson, 1995).

Changes in soil physical properties often also influence soil chemical properties (Arévalo-Gardini et al., 2015). As pore space is reduced by compaction, water and oxygen flow through the soil is decreased (Nawaz et al., 2013; Whalley et al., 1998), nutrient uptake is decreased (Duiker, 2004), and evaporation losses can increase (Harivandi, 2002; Sosebee, 1976). This decreased macropore size that slows percolation of water in compacted soils may also cause prolonged periods of saturation in soils (Duiker, 2004). In the anaerobic state (DeJong-Hughes et al., 2001), certain soil organisms use nitrate instead of oxygen for respiration (Kozlowski, 1999), resulting in denitrification, an increase in N_2O emissions, less mineralization of organic nitrogen, nitrate losses by leaching, loss of organic nitrogen, and slower diffusion of nitrate to the plant (Duiker, 2004). Douglas and Crawford (1993) found that nitrogen mineralization was reduced 33 percent, denitrification rate increased 20 percent, and nitrogen fertilization rates had to be more than doubled on the compacted soil to achieve the same dry matter yield (Douglas and Crawford, 1993).

Nutrient losses are influenced by nutrient solubility, soil morphology and chemistry, climate, and topography (Schoonover and Crim, 2015). Nutrient losses associated with removal of vegetation by livestock are minimized by the limited productivity of many grasslands and the digestive physiology of herbivores (Floate, 1981). Availability of nutrients is frequently limited by low aboveground productivity containing nitrogen concentrations of 1.5 - 2.0% in live vegetation and less than 1.0% nitrogen in dead grassland vegetation (Wilkinson and Lowrey, 1973). In addition, nutrients ingested by livestock are voided as urine or feces, thus leaving only a relatively small proportion to be removed as animal products (Wilkinson and Lowrey, 1973).

Soil contains micro-, meso-, and macro-fauna (Duiker, 2004) that are affected by soil compaction. Nematodes (*Nematoda spp.*) and earthworms (*Lumbricina spp.*), are likely to be reduced in number by soil compaction because of the reduction in pore space and aeration (Duiker, 2004). Earthworm tunnel creation is reduced in soils with high bulk density, indicating reduced earthworm activity (Rushton, 1986). Non-burrowing animals such as mites (*Acarina spp.*), springtails (*Collembola spp.*), and fly larvae (*Diptera spp*.) will have an especially difficult time living in compacted soil. In a study in Australia, compaction of wet soil with a 10-ton axle load decreased earthworms from 166,000 to 8,000 per acre due to severe compaction of 1.65 g cm^{-3} (Radford et al., 2001), while, compaction of dry soil with 10-ton axle load had no effect on macro-fauna. Infiltration of water in compacted soil is often increased by earthworm burrows, and elimination of these earthworms has shown decreases in water infiltration rates by almost 93% (Clements, 1982), showing the importance of earthworms and other fauna in the grazed ecosystems. Water infiltration has been shown to increase soil infiltration capacity 4 – 10 times more in soils containing earthworms than in soils without them (Edwards and Bohlen, 1996).

Soil compaction resulting from grazing may reduce subsurface microbial biomass (Duiker, 2004), often decreasing rate of decomposition of organic matter. Bacteria and fungi that live on organic matter or on living plants perform useful functions such as the decomposition of plant residues, release of nutrients, and formation of aggregates (Duiker, 2004). Some bacteria, such as rhizobia, provide nitrogen to plants, while others facilitate the uptake of immobile nutrients such as phosphorus and potassium (Duiker, 2004). The smallest organisms such as bacteria, fungi, and even protozoa can live in pores that are not easily compacted (Duiker, 2004) and are not likely to be affected directly by compaction, but may be affected by the associated anaerobic conditions.

Soil compaction destroys soil structure, creating a soil structure with fewer natural voids (Kooistra and Boersma, 1994). Increases in bulk density and reduced pore size for plants restrict root growth (Nawaz et al., 2013), which can cause soil to crack because the shallower roots absorb water only from the upper part of the soil (Batey, 2009). Penetration resistance is a better indicator of the effects of soil compaction on root growth than bulk density because results can be interpreted independent of soil texture. Research on completely disturbed soil packed to different densities has shown that root growth decreases linearly with penetration resistance starting at 100 psi until root growth completely stops at 300 psi (Taylor et al., 1966). In many cases, cracks and fissures will be available for roots to grow through, so a total lack of root growth is not likely (Duiker, 2004). Instead, roots will concentrate in areas above or beside compacted zones in the soil (Duiker, 2004). Aside from the effect of penetration resistance, roots also suffer from increased anaerobic conditions in compacted soils (Duiker, 2004) as discussed earlier.

Drought stress caused by poor infiltration has been a major problem limiting production in the western U.S. (Boyle et al., 1989). In addition, when stressed by lack of water, the vegetation is less capable of coping with the animal-related stresses (McNaughton et al., 1982, 1988). Deep and thick root systems are helpful for extracting water from considerable depths during drought (Kavar et al., 2007), but herbivory will reduce root biomass in the upper soil profile (Johnson, 1956). Therefore, the long-term success of a grazing strategy depends, at least in part, on how well it maintains aggregate stability. If water is applied to soil faster than it infiltrates into the soil, the excess runs off, resulting in decreased water availability later in the season (Daum, 2002).

During soil compaction, soil aggregates are compressed into dense, unstable clods (Beckmann and Smith, 1974; Blackburn et al., 1986). Water infiltration rates are consistently less at increased stocking rates and it can be reduced by treading damage for as little as 40 minutes (Russell et al., 2001). The greater sensitivity of water infiltration to grazing intensity is likely related to factors like vegetative cover, plant community composition, ambient soil moisture, soil surface roughness, and slope that affect water infiltration beyond the loss of macropores. Water infiltration is also more responsive to grazing management than soil compaction (Warren et al., 1986a).

Soil compaction severely limits infiltration of rain and, therefore, recruitment of desirable perennial grasses (Blackburn, 1975; Gifford and Hawkins, 1978; Thurow et al., 1986; Van Haveren, 1983). Infiltration through a soil profile supporting tall grasses is greater than that of a profile supporting short/ sod-forming grasses (Blackburn et al., 1986). Therefore, recruitment of bunch grasses is necessary for maintaining soil health and hydrologic function (Gamougoun et al., 1984; Thurow et al., 1988; Wood and Blackburn, 1981). Wood and Blackburn (1981) measured no difference in infiltration rates between high intensity low frequency grazing or continuous grazing under moderate or heavy stocking when bunch grasses were present. Infiltration rate under deferred-rotation grazing was higher than that of the recently grazed high intensity low frequency pastures, but not in the deferred high intensity low frequency pastures in mid grass, short grass interspaces or under the shrub canopy.

Topsoil compaction and high bulk densities are considered partly reversible (Schäffer et al., 2008). Subsoil compaction, however, is regarded as the major problem, because it can be permanent, meaning the pores cannot be restored after deterioration (Hakansson and Reeder, 1994), and compaction has persisted for more than four years (Lowery and Schuler, 1991). Subsoil compaction is not alleviated by freeze-thaw and wetting-drying cycles (Daum, 2002; Hakansson and Reeder, 1994), meaning that alleviation of compaction at these depths would have to be either by tap roots penetrating the subsoil compaction layer, by plowing deep into the subsoil layer, or by weathering processes, either chemical or physical, if top soil erodes away.

Trampling alone, however, normally does not alter bulk density much beyond a depth of 20 cm (Alderfer and Robinson, 1947; Ferrero, 1991), unlike that of tractor tire compaction. In Piedmont Italy, Ferrero (1991) found that when the silt loam soil was compacted with a pneumatic compactor (76 kg) the soil bulk density increased in the top

10 cm of the soil from 1.22 to 1.33 g cm^{-3}. In the next layer (top 11-20 cm of the soil) the bulk density increased from a 1.26 to 1.30 g cm^{-3} but there was no difference in the third layer (top 21-30 cm of the soil profile). When it was compacted again within a season, bulk density in the top layer increased from 1.33 to 1.40 g cm^{-3}. The second layer bulk density increased again from 1.30 to 1.36 g cm^{-3}, and there was no difference in the third layer of the soil profile, indicating that the probability of subsoil compaction by cattle is slim, unless the areas are frequently used, or trampled at high densities or intensities that cause erosion that exposes subsoil.

Bulk densities typically increase with soil depth, since subsurface layers are more compacted and have less organic matter, less aggregation, and less root penetration compared to surface layers (Cresswell and Hamilton, 2002). Any disturbance that causes the degradation of grasses can, in turn, cause erosion that exposes the subsurface layers. Compacted, poorly aggregated exposed subsoils may take years to improve and establish grasses because when pore space shrinks, there is less air and moisture in the soil, a condition that negatively influences seed germination, seedling emergence, root growth, and nutrient uptake (Daum, 2002). Freeze/thaw, burrowing of meso, micro, and macro fauna, and root growth likely mitigate the effects of compaction and aid in the recovery of the compacted soils over time (Jabro et al., 2012; Kozlowski, 1999).

Effects of Grazing on Soil Crusts

Cryptogamic crusts are symbiotic communities of moss, algae, and lichens that play an important role in very arid environments by stabilizing soils that are highly susceptible to wind erosion (Belnap, 2001). They reduce water infiltration, slow runoff and evaporation, which leads to a net soil water benefit (Johansen, 1986). Some crust species fix nitrogen, and resist seed germination and recruitment of weedy species (Johansen, 1986). Cryptogamic crusts are prone to deterioration resulting from trampling or air pollution (Hawksworth, 1971), and take longer to recover from damage than vascular plants. In Utah, Kleiner and Harper (1972) found that the surface area of biotic crusts were about seven times bigger in the ungrazed areas, with approximately three times as many crust species versus the grazed areas (Kleiner and Harper, 1972). The relative ratios of species within the biotic community, particularly the number of individual lichen members, were higher in the ungrazed areas than in the adjacent grazed areas (Kleiner and Harper, 1972).

In crust communities with higher proportions of mosses, grazing at certain times of the year can be more detrimental than others. Memmott et al (1998) measured cryptogamic cover in southeastern Idaho on crested wheatgrass pastures interseeded with shrubs. Mosses were the principal component of the cryptogam cover. No significant reduction of cryptogam cover was associated with winter grazing (27.4% cover versus 27.6% cover for controls). However, summer grazing pastures had 14.4% cover and spring grazed pastures had 10.6% cryptogam cover. The authors concluded that "controlled winter grazing has minimal impact on the total cryptogamic plant cover that protects soil surfaces on cold desert range ecosystems."

Physical soil crusts are formed by the clogging of the surface pores by disaggregated soil particles, because of low organic matter content and low aggregate stability (Blackburn, 1975). Physical soil crusting is a problem that livestock grazing management can address, at least temporarily, if poor aggregate stability is present.

Livestock grazing strategies that increase plant and litter cover as well as organic matter reduce the effects of physical soil crusts (Blackburn, 1983). Trampling with livestock disrupts the crusts by hoof action (Office of Technology Assessment, 1982), breaking them into smaller aggregates. However, the benefits from breaking up soil crusts will be short-lived if there is no vegetation cover because the subsequent impact of falling raindrops will seal the soil surface in the presence of an intense rainstorm and cause more crusting (Thurow and Hester, 1997).

Grazing Effects on Erosion

Wind erosion is more likely to occur in arid environments, where dry soil and periods of strong winds are often associated with large land masses (Sterk et al., 1996). Wind erosion is a self-generating process that becomes increasingly difficult to stop as it develops. The process starts as fine soil particles detach and strike other particles with enough energy to detach them, exposing the remaining larger particles, and making it easier for them to also be detached (Thurow, 1991). The suspended particles may contain over 3 times as much organic matter and nitrogen as the parent material left behind (Bennett, 1939). Once larger particles have begun the process of movement of soil particles with a diameter of 0.05 mm to 0.5 mm by bouncing or being lifted off the soil for short distances, reestablishment of plant seedlings is difficult because of the abrasion associated with the soil movement (Bennett, 1939).

Satterlund (1972) developed the critical point of deterioration concept to explain what happens if erosion is not controlled. Biological potential can be restored during recovery if the critical point has not been passed. Beyond the critical point, erosion continues at an accelerated rate which cannot be reversed by the natural processes of revegetation and soil stabilization, even if the initial cause of disturbance is corrected. As runoff and soil erosion increase, less water and fewer nutrients are retained to support the level of plant growth needed for surface soil protection (Pimentel et al., 1987). The microclimate deteriorates, leading to less microorganism activity that is needed for soil aggregate formation and a harsher environment for germination (Pointing and Benlap, 2012; Thurow, 1991). These factors contribute to even more soil exposed to raindrop impact, further accelerating surface runoff and erosion. This spiraling pattern of deterioration eventually results in desertification.

Management intervention on most grazing lands is usually not economically viable once the critical point has been passed. Therefore, it is vital that management of the resource be sensitive to the hydrologic relationships of the site so that the desertification process is never initiated. Land use practices and the concern for soil and water conservation may vary, depending on whether the management time horizon is focused on short-term economic gain or long-term sustained yield (Thurow, 2000). Loss of soil fertility and water-holding capacity associated with erosion also reduce productive potential of vegetation, and therefore, the magnitude of future benefits that could be gained through introduction of improved livestock breeds or better husbandry techniques.

When disturbance has been too disruptive and erosion has developed beyond the critical point, resource deterioration continues, regardless of whether the destructive land use continues, resulting in a "death spiral" towards desertification (Peters et al, 2013). Soil loss cannot be effectively restored through management, since topsoil formation occurs at the rate of 2.54 cm formed every 300-1000 years (Fresco and Kroonenberg, 1992). Therefore, the first priority of grazing land management should be to maintain the soil resource and hydrologic condition of the site. Length of deferment, rather than intensity of livestock activity, appears to be the key to soil hydrologic stability (Warren et al. 1986a).

Grazing Impacts On Ecosystems

Tracy and Sanderson (2000) found that ungrazed or poorly managed grasslands become dominated by few grass species, invasive weeds and woody plants while grasslands exposed to periodic disturbances such as grazing maintain a more diverse plant community than ungrazed systems (Rook and Tallowin, 2003). Many of the world's rangelands evolved in the presence of grazing ungulates that moved periodically in large herds under the influence of predators (Bailey and Provenza, 2008; Frank et al., 1998; Hartnett et al. 1997; Provenza, 2003). After the animals had selectively decreased the availability of forage based on quality and availability, they left the area, leaving mulch in the areas from which they had just moved (Social, 1997). Animal droppings also tend to cause animals to avoid places that have been fouled, while urine tends to cause only an initial aversion (Lyons, 2000; McNaughton et al., 1989). This aversion can last from a few days to several months (Lyons, 2000). Many grasses deteriorate in the absence of disturbances like fire, mowing, or infrequent grazing, while they thrive and remain competitive under infrequent defoliation (Hulbert, 1988; Knapp, 1985; Old, 1969).

Many rangelands were historically dominated by perennial grasses (Xianglin, 2009). These grasses maintain ground cover throughout the year, have extensive root systems, are quite productive, and also are often very palatable to cattle (Beard and

Green, 1994; Hashemi, N.D.). Species richness, or number of species, the evenness with which they occur, and their life forms – whether forbs, grasses, shrubs, or trees – determine the diversity of a plant community (Robertson et al., 1988).

When growing conditions are favorable, and plants are not overgrazed, perennial grasses produce new buds every year and supply energy needed to maintain the preceding year's cohorts of dormant buds (Reece et al., 2007). Overgrazing occurs when individual plants are subjected to multiple severe defoliations without sufficient physiological recovery between events (Roshier and Nicol, 1998). With chronic excessive herbivory, a degradation spiral is initiated (Ash and Smith, 1996).

The impacts of grazing on different parts of ecosystems are dependent on six things; 1) location; 2) timing; 3) duration; 4) intensity; and 5) frequency of grazing (Council for Agricultural Science and Technology, 2002); as well as 6) soil water before, during, and after a grazing event or events (Archer and Smeins, 1991; Briske, 1991). Trampling and overgrazing can injure individual perennial plants and communities, by reducing their competitive and reproductive capacities (Huntly, 1991), decreasing species diversity and increasing density of annual plants.

Location of Grazing

The hydrologic condition of rangelands is the result of interactions among soil, vegetation, topography, and climate (Thurow, 1991). Therefore, the impacts of grazing on hydrologic function will differ from region to region as well as during different times of the year (Thurow, 1991). Grass seed production and species diversity on semiarid rangeland is limited by timing or quantity of precipitation in most years (Reece et al., 2007). Initiation of vegetative growth for perennials varies with species as well as local environmental factors like precipitation (McMillan, 1957; Trlica, 1977), photoperiod and temperature (Dahl, 1995).

The way cattle disperse in a pasture is also important to understanding their effects on ecosystems. Since animals often prefer some areas over others, plants there may be severely and repeatedly defoliated, resulting in degradation at that location (Odum, 1979). These areas may then become focal points of further degradation of adjacent areas (Ash and Smith, 1996). Combinations of factors will cause cattle to concentrate in different areas of a pasture. Roath and Krueger (1982) found that the most common places of concentration were riparian zones early in the growing season, due to the green forage available in these areas, while areas with steep slopes saw less cattle activity throughout the season.

Degradation can occur in riparian areas heavily utilized by livestock, (Odum, 1979) as a direct result of trampling stream-side vegetation and compacting soils (Lyons et al., 2000; Moseley et al., 1998). Many wildlife species need nitrogen-rich green forage for good digestion, because they are concentrate selectors, which is most abundant in riparian areas (Odum, 1979). Therefore, if livestock overgraze and degrade riparian zones, other animals will also suffer the consequences.

Favorable long-term climatic conditions are necessary for more productive and palatable grasses to recover from defoliation, thus more arid rangelands require longer recovery periods (Heitschmidt and Stuth, 1991). The length of deferral required for adequate plant recovery may range from weeks to years in these areas (Bradford, 1998; Trlica et al., 1977).

Timing of Grazing

Plant responses to herbivory depend on season of tissue removal, stage of life cycle and temperature (Archer and Smeins, 1991; Briske, 1991). Soil responses to herbivory and their hydrologic functions fluctuate at different times of the year as well (Knight, 1980; McCalla et al., 1984; Thurow, 1985; Warren et al., 1986a), since soil moisture and temperature are more favorable for plant growth (Warren et al., 1986a) during the growing season.

Warren et al., 1986a found soil aggregate stability and soil organic matter were significantly higher and soil bulk density was significantly lower during the growing season, creating a more stable soil hydrologic condition. Mean infiltration rate was also significantly lower and sediment production significantly higher (about 500 kg per ha) during the dormant season than the growing season (Knight, 1980; McCalla et al., 1984; Thurow, 1985; Warren et al., 1986a). Aggregate stability and soil organic matter were significantly higher during the growing season in warm season perennial grasslands, as a result of the disruptive action of roots in the soil, as well as the production of organic compounds that help soil particles adhere together and enhance aggregate stability, resulting in lower soil bulk density (Warren et al., 1986a).

Infiltration rate and sediment production responses to an intensive rotational grazing system on a silty clay soil were higher during the growing season than during winter or drought induced dormancy (Warren et al., 1986a). The ability of a watershed to recover from livestock impacts is related to the condition of the watershed at the time of the impact. During the growing season, above and below ground plant growth, bulk density, soil moisture status, microbial activity, and soil aggregate stability are near or at optimum levels (Warren et al., 1986a). During the growing season the potential for the forage resource to recover following the removal of livestock is also much higher (Warren et al., 1986a).

Protective cover in riparian areas (Morgan, 2009) is important where large seasonal runoff events are more likely to occur. These areas filter sediment and slow the rate of overland flow (Naiman and Decamps, 1997; Thurow, 1991). Riparian vegetation growth, especially during the growing season, can also stabilize banks that are susceptible to erosion by peak flows (Roath and Krueger, 1982). Therefore, riparian management strategies to improve ecological functions, sustainability, and productivity that include adequate growing season deferment, changing the season of use, and reducing stocking rate or grazing period to match forage availability to forage demand, can lead to improvements in condition and function in riparian areas (National Research Council, 2002).

Time required for adequate recovery during winter dormancy would be longer, since there is no or very slow regrowth at that time to mitigate the impacts of compaction and defoliation. Therefore, to improve hydrologic stability, land managers should implement moderate levels of defoliation and/ or longer grazing deferment if the dormant season occurs during the deferment period. Maintenance or improvement of hydrologic condition and soil retention on the entire landscape, not just in riparian areas, are critical determinants of long-term sustained productivity. It is possible to interpret and anticipate livestock effects on hydrology by understanding how livestock use of grazing lands impacts the soil and vegetation.

Duration of Grazing

Continuous grazing use with no time to recover between defoliations results in degradation (Odum, 1979; Teague et al., 2013). When cattle congregate in riparian areas for example, and the duration of trampling is too long, soils are compacted (Lyons et al., 2000; Moseley et al., 1998), and vegetation declines. Changes in vegetation and stream channel morphology can then lower the water table, and the streams may become silty from erosion and possibly eutrophied (Beegle et al., 1998; Belsky et al., 1999; Leonard et al., 1997; Sovell et al., 2000).

Migratory defoliation patterns of wild ungulates that select high protein concentration in forages can result in intense grazing at a particular site, especially if that forage is sparse, but such grazing usually doesn't last long. Defoliated plants are afforded time before the ungulates revisit them, and allow for suitable conditions to regrow (McNaughton et al., 1989). Nomadic pastoral systems that mimic such natural grazing patterns seem to have fewer detrimental effects on vegetation than continuously grazed strategies (Danckwerts et al., 1993), indicating that duration of grazing affects responses of vegetation to defoliation.

Intensity of Grazing

Heavy stocking rates, regardless of grazing system, have decreased infiltration and increased sediment production (Blackburn, 1983 Pluhar, 1984; Thurow et al., 1987; Warren et al., 1986a). Low infiltration rates, and high sediment production have been attributed to the removal of standing vegetation (Pluhar, 1984; Weltz, 1983). Where vegetation was sparse or absent, the effect of grazing must be attributed to changes in soil physical properties (Warren et al., 1986b), since they also found that trampling when the soil was moist versus dry significantly decreased infiltration rates and increased sediment production. Repeated high intensity trampling increases bulk density, which in turn, reduces infiltration rates and increases surface runoff (Blackburn, 1983; Gifford and Hawkins, 1978; McCalla et al., 1984; Orr, 1975; Warren et al., 1986b), which can then cause soil water deficits, sheet erosion and gully formation (Cole, 1982; Jim 1987a, b; Kramer and Boyer, 1995; Wood et al., 1989), decrease the quantity and quality of water that infiltrates a soil (Bilotta et al., 2007), and thereby, plant productivity (Archer and Smeins, 1991; Briske, 1991). Water infiltration rates have shown decreases of 25% in areas of light to moderate grazing, and as much as 50% reduction where grazing was heavy (Gifford and Hawkins, 1978).

Frequency of Grazing

When grasses are not given sufficient time to reestablish photosynthetic capacity following defoliation, the reduction of regrowth and insufficient recuperation causes a decline in available forage, decreased competitive ability relative to ungrazed neighbors, and even death of some plants (Briske, 1991; Ferraro and Oesterheld, 2002). High intensity grazing bouts aren’t always detrimental if given longer recovery time (Reardon and Merrill, 1976). However, if both the intensity and frequency of defoliation are high, growth rates and tiller recruitment are reduced (D’Angelo et al., 2005), and the accumulation of herbage mass is hindered (Bryan et al., 2000; Garcia et al., 2003).

Soil Water at Time of Grazing

The amount, duration, form, intensity, and spatial distribution of precipitation are beyond human control, so examining how management of the livestock in time and space affects the hydrologic cycle can help managers to make better decisions to improve productivity and resilience of ecosystems (Thurow, 1991). Modification of soil hydrologic properties by grazing also regulate plant responses to defoliation, community composition, and productivity (Archer and Smeins, 1991), since plant responses to herbivory depend on available soil moisture (Archer and Smeins, 1991; Briske, 1991). Typically, arid environments are less productive, providing less plant cover to protect the soil surface from rainfall impact and runoff, thereby increasing evaporative losses and decreasing infiltration (Warren et al., 1986 a, b).

Microbial activity may also be limited by high temperatures, due to no cover on the soil, and low soil moisture conditions (Warren et al., 1986 a, b). With high levels of soil moisture at the time of grazing, compaction is also more severe because more force is needed to compact a dry soil than the same soil when wet (Lull, 1959).

Management Implications

Grazing by large ungulates is an important part of most ecosystems, and the co-evolution of ungulates and plants under highly variable and changing environmental conditions has resulted in resilient grazed ecosystems that support more animal biomass and sustain high levels of herbivory (Teague et al., 2013; Stuart Hill and Mentis, 1982; Frank et al., 1998).

The replacement of free ranging herbivores with livestock has restricted movements and removed the key stabilizing element of periodic use and recovery (Teague et al., 2011). Breaking land up into pastures and grazing livestock continuously has altered their natural movements across landscapes, and so potentially altered the botanical composition and cover (Ellison, 1960) as well as soil physical properties (Klemmedson, 1956; Reed and Peterson, 1961). Since fire and grazing regimes can be manipulated directly, they are potentially important management tools to maintain ecosystem function and the provision of ecosystem services (Biondini et al., 1989; Frost et al., 1986; Liedloff et al., 2001; Petraitis et al., 1989). If the rotational movement of livestock through paddocks does not change defoliation patterns enough to maintain the existing plants and enable recruitment of new desirable plants, the rate of degradation may be slow, but the outcome will be undesirable (Steffens et al., 2013).

Resiliency

In order to make the plant community more resilient, goal-oriented, adaptive land managers must; (1) change the timing, frequency, and distribution of defoliation compared to continuous stocking on landscapes; (2) allow recovery of defoliated plants to maintain or increase their proportional representation on the landscape through vegetative reproduction or seedling recruitment; (3) change management strategies based on physiological responses of preferred and heavily defoliated plants; (4) adapt to changes in animal behavior and weather (Steffens et al., 2013); (5) stock flexibly to match forage availability and animal numbers in wet and dry years or have buffer areas that can be grazed; and possibly, (6) use multiple livestock species when applicable to reduce costs, improve work efficiency, enhance profitability and achieve environmental goals (Teague et al., 2008). These actions cannot be executed with continuous, season-long grazing in environments that receive enough moisture to have growing periods of more than a few days (Teague et al., 2008). Following are considerations for successfully applying these guidelines.

Goals

The first step in successful ranching is developing clear goals and objectives, with the grazing program being a part of the overall management strategy (Provenza et al., 2013). Perennial plant communities tend to have greater root mass that support more diverse communities of soil organisms and often have greater inherent resilience and productivity than communities of annual plant monocultures (Milne and Haynes, 2004). Therefore, management and production goals should support heterogeneous perennial plant communities.

Grazing management involves human regulation and manipulation of the consumptive process of ruminants to meet specific production goals (Briske and Heitschmidt, 1991), and managers should apply grazing prescriptively to achieve goals in their pastures.

The most common form of grazing management is continuous grazing (Teague et al., 2013). However, even with low stocking rates, grazing pressure on palatable plant species can be high in preferred areas across a landscape (Teague et al., 2008), often with no recovery period for those plants to recuperate from an intense grazing bout. The fencing of land into smaller continuously grazed pastures, without the sufficient adjustment of forage demand in times of drought, has led to severe degradation of rangelands (Dregne, 1978; Teague et al., 2013), that has diminished overall health of ungulates and decreased the nutritional quality of the plants (Provenza, 2008).

Extensive management may not be sufficient for positive results in a given managed rangeland pasture. To achieve goals set by a manager, intensive managerial strategies may rely on the direct incorporation of energy inputs into a system. Examples include fertilization, introducing improved forage species into a pasture, as well as aeration and control of woody species. Rotating grazing among pastures using electric fence to move animals to portions of pastures they don't normally utilize, incorporating more water points, using salt and mineral licks to change distributions are more intensive grazing strategies (Klopatek and Risser, 1982; Pimentel et al., 1980). These strategies do not overcome the ecological constraints limiting energy flow efficiencies that have been discussed previously (Klopatek and Risser, 1982). However, more intensive, adaptive management of the grazing process may provide a means to achieve goals without large and expensive energy inputs.

Both the grazing process and efforts to manage it are influenced by a common set of biological, biogeochemical, and ecological concepts discussed previously. Overstocking and understocking are two concepts that address both managerial and economic goals and that add to the complexity of the ecological processes associated with grazing (Crawley, 1983). Overstocking is associated with improper management decisions that reduce palatable species in a given area. When palatable species decline, increases in bare ground and/ or unpalatable species become apparent, and decreased livestock production per unit land area results (Briske and Heitschmidt, 1991).

Understocking, on the other hand, is associated with inappropriate managerial decisions where livestock do not fully utilize all the species within an area of land, and production of livestock is not optimized per unit land area (Briske and Heitschmidt, 1991).

Prescription grazing is the application of livestock grazing at a specified season, duration, intensity, and frequency to accomplish specific vegetation management goals, (Frost and Launchbaugh, 2003). By using different types of ruminants within a management plan, and carefully managing the duration, intensity, and frequency of grazing to accomplish specific vegetation management goals, altering the community composition in favor of native and desired species is possible (Frost and Launchbaugh, 2003).

Adaptive, Goal-oriented Management

To achieve goals, successful managers should view stocking rates as variables applied adaptively to meet a variety of objectives under constantly changing circumstances (Teague et al., 2009). Such adaptive management is based on plant and animal ecophysiology. When adaptive management is applied correctly, multiple paddocks per herd can be used to provide adequate recovery between graze periods based on growing conditions and the physiology of the plants to achieve possible increases in animal productivity, as well as improved productivity of desired plant species (Teague et al., 2013).

The scientific community continues to debate the effects of different grazing management strategies on plant communities, watershed function, and soils (Briske et al., 2013, 2014; Cibilis and Fernandez, 2014; Grissom, 2014; Teague, 2014). A recent review of the literature suggests that multi-paddock rotational grazing does not improve vegetation productivity or livestock performance compared to continuous grazing (Briske et al., 2008). Briske et al., (2013) suggested that adaptive management is the most promising future for rangelands. Yet, most research cited by Briske et al., (2008; 2011; 2013) has been short-term, and has not included the critical adaptive management strategies outlined previously to achieve any positive results such as resource improvement, increased animal production, or socioeconomic goals under the varying conditions inherent to rangelands (Teague et al., 2013). Moreover, management decisions and their outcomes are often neglected due to a simplistic, narrowly focused formula recipe for rangeland improvements (Bundy et al., 2008). Therefore, grazing management that involves the manipulation of grazing intensity, timing, duration, frequency, and distribution in time and space may maximize livestock production per unit land area on a sustainable basis (Teague et al., 2013).

Knowledge of the effects of grazing on plant growth and hydrologic functions at different temporal and spatial scales, which in turn change plant population dynamics, structure, and function of heterogeneous perennial plant communities, soils and ecosystems, is necessary to evaluate the influence of grazing on system integrity, sustainable production, and overall ecological health (Teague et al., 2013). In terms of hydrologic stability, land managers should consider moderate stocking rates, or moderate levels of defoliation and/ or longer deferment periods to provide adequate recovery for defoliated plants (Warren et al., 1986a). Maintenance and even improvement of hydrologic condition of soils are critical for long-term sustained production.

A common hypothesis is that intense trampling activity associated with high stock densities ("herd effect") can enhance infiltration (Office of Technology Assessment, 1982; Savory, 1978a, b; Walter, 1984). This herd effect has even been hypothesized to enhance infiltration at doubled or even tripled conventional stocking rates (Goodloe, 1969; Savory and Parsons, 1980). Research conducted to date does not support the hypothesis that an increase in the magnitude of trampling can result in a hydrologic benefit, at least in the short term (Thurow, 1991; Warren et al., 1986 a,b,c,d). However, none of these studies have investigated whether differences in the frequency of trampling can mitigate the short-term detrimental effects of trampling, and how much deferment after trampling is required to mitigate the detrimental effects of compaction.

A study conducted at the High Plains Grasslands Research Station, in Cheyenne, Wyoming found that infiltration rate was higher in the continuously grazed treatment than the rotational deferment treatment but no different than for the short duration treatment in the first year. But in the second year, the highest equilibrium infiltration rate was in the short duration treatment, while the continuous grazing treatment had the lowest (Adbel-Magid et al., 1987). Average infiltration rates were significantly less in the fall (dormant) season than the spring (Adbel-Magid et al., 1987). They concluded that no significant differences were detected for infiltration among varying grazing strategies, attributing the action of freeze- thaw each winter to the mitigation of any detrimental soil compaction, which had previously reduced infiltration.

Adaptive Management

“The biggest problem for me is that I can never come up with a grazing plan that I can stay with- I am continually changing grazing rotations, time and stock numbers… But that is one of the reasons that his program works. It is not a system, it is a continually changing program that moves with the weather, livestock, and markets” - Frank Price (personal communication cited in Kothmann, 2009). Adaptive management and intensive management are both approaches that should be based on a full cycle of planning, constant monitoring of the effects of management strategies, interpretation of the results from your management approach, and revision of management in response to monitoring information to reach desired goals (Williams and Brown, 2012).

An effective adaptive management framework should facilitate learning and adjustments through the detection of change in response variables. Land managers should document information and outcomes, testing alternative strategies, and consistently adapt and manage based on the complex interactions in rangelands (Briske et al., 2011; Grissom and Steffens, 2013; Holling, 1978; Teague et al., 2011, 2013).

Outcomes of management practices should be monitored to evaluate their effectiveness (Briske et al., 2011) and revise management practices from year to year to make rangeland improvements. Monitoring rainfall, forage quality, animal nutrient requirements, and body condition can be used to identify changes in pasture and cattle conditions, and make timely decisions to increase the flexibility of the grazing program in order to increase the grazing capacity and profitability of the ranch, even during drought (Ortega et al., 2013).

Adaptive Management at Work

A case study by Grissom and Steffens (2013) showed an improvement in rangelands at Rancho Largo in eastern Colorado by changing the management strategy. In the early years (1996-1999) a method-driven grazing system was used. High stocking rates and short recovery periods resulted in poor animal performance, low gross margin per head, negative returns on assets, low residual herbage, litter, and plant diversity (Grissom and Steffens, 2013). Ongoing ecological and financial monitoring facilitated the adaptation process to form questions, make observations, and set goals. In the later years (2004-2012), Rancho Largo diversified their cattle business to gain flexibility in stocking rates, which caused economic improvement. By changing grazing protocols to season-long recovery periods, Rancho Largo saw changes in recruitment of mid grasses and some forbs, which increased forage production, carrying capacity, residual cover, litter, and improved the water cycle (Grissom and Steffens, 2013).

Outcomes and Recommendations For Management

Managers should implement grazing deferment for individual pastures to mitigate bulk density and compaction issues (Bisinger, 2014). There is evidence that strategies providing short grazing periods and/or long deferral periods may reduce soil compaction. A single grazing event at a high stocking density-short duration (5 to 9 hours) resulted in lower soil bulk density and penetration resistance measurements over the next three years than a single grazing event at a moderate stocking density-moderate duration for 24 hours (Bisinger, 2014). Similarly, soil penetration resistance at the soil surface and at depths greater than 5 inches from the soil surface were lower in strip-stocked paddocks which had rest periods > 90 days than pastures grazed continuously (Bisinger, 2014). Therefore, adequate recovery for plants to produce roots and soil organisms, loosen soils, and allow freeze-thaw cycles to have an impact will likely mitigate compaction effects.

The intensity with which managers allow cattle to defoliate plants drives outcomes, regardless of stocking rates or density in several studies. When grazing continuously or rotationally, in mid grass to tall grass pastures, Haan et al., (2006) found that a residual plant height of 2 inches reduced water infiltration and increased phosphorus transport in rainfall simulations. However, grazing by rotational stocking to a residual plant height of 4 inches resulted in no greater water runoff or phosphorus transport in simulated precipitation runoff than from non-grazed exclosures. Therefore, they concluded that maintaining a minimum sward height of 4 inches in both upland and riparian areas seemed most valuable in minimizing the risk of decreased infiltration and non-point water pollution. Thus, defoliation intensity and subsequent deferment, rather than stocking density had more effect on water infiltration. The results from Haan et al., (2006) corroborate that of other studies that show that with adequate deferment, plant species composition and production have improved, under moderate (Teague et al., 2013) and even heavy grazing intensities (Reardon and Merrill, 1976).

Recovery seems to be one of the most important aspects of many of these studies. Teague et al., (2013) measured higher proportions of desirable tall grasses and lower proportions of less desirable short grasses with higher standing crops when multiple paddocks per herd were used in rotation, than in lightly stocked or heavily stocked continuously grazed pastures. By allowing proper recovery periods for regrowth, both the livestock, and ecosystems benefitted in this study.

CHAPTER II :

INTRODUCTION

In the Texas Southern High Plains (SHP), primary sources of agricultural producer income are grain crops, beef cattle (*Bos spp.*), and cotton (*Gossypium hirsutum* L.). Decreases in grain crop prices and increases in cattle prices have stimulated interest in converting cropland to grass pastures (Volesky and Berger, 2010). Many plant Old World Bluestem (OWB) varieties on portions of irrigated and dry land to maximize profits by including stocker cattle or hay production enterprises in their production models. Others completely convert old dry land cultivated lands into pastureland to specialize in livestock grazing. However, it can be difficult to establish grasses when converting cropland to pasture in these dry land systems.

Lack of water, phosphorus, soil organic matter, planting the seed too deep, competition with weeds, herbicide residues, and poor soil aggregation are a few of the reasons these grasses do not establish well in land that has been continuously farmed for years (Clark, 2001; Nation, 1995). Producers, therefore, often gradually convert cropland into pastureland rather than all at once (Nation, 1995). In cases where the grass doesn't establish quickly, grazing is often deferred in an effort to enhance grass establishment. Light grazing followed by adequate recovery time can encourage the new grass stand to thicken (Winkel and Roundy, 1991). On previously tilled cropland, using smaller grazers, such as sheep, may be best for grazing the new grass stand, due to their lighter body weight and preference for forbs over grasses.

In the 1980's, a Rhodesian named Allan Savory began educating producers about a management theory known as holistic management. He claimed that throughout the world there are "brittle environments" that are used for livestock production (Savory, 1983). As they deteriorate, they become desert-like at different rates, decreasing carrying capacity each year (Savory, 1983). He said that livestock behavior should mimic wild grazing ungulates moving in dense herds across landscapes in response to predation. This movement of animals and their consumption patterns under such management supposedly facilitates nutrient cycling by digestion of the forages they graze and putting dead vegetation in close contact with the soil where it will enhance infiltration, protect soils from erosion, and increase rate of plant material decomposition. Limiting the movement from one area to the next has been postulated as a reason for degraded pasturelands (Provenza et al., 2013, Savory, 1988).

Savory used a systems approach, along with the incorporation of goal setting, structural decision making, and financial planning to elucidate a management and decision-making strategy that has been valuable to some ranching families (Briske et al., 2011; Teague et al., 2013). However, his views on high density and high intensity grazing management strategies were and are still very controversial (Briske et al., 2013, Grissom, 2014).

In Sonora Texas, in the 1980's, a group of scientists began to look at high density grazing effects on soil-water functions (Thurow et al., 1986; Warren et al.,1986a, b, c, d). One of these studies (Warren et al., 1986a) measured the effects of increasing grazing densities on infiltration. They trampled every 30 days at different densities, removing all living, and dead vegetation between trampling events. They looked at pre-trampling infiltration and post trampling infiltration in dry and pre-wetted plots. The three stocking rates were 8.1 ha AU^{-1} yr^{-1}, 4.1 ha AU^{-1} yr^{-1}, 2.7 ha AU^{-1} yr^{-1}, and a control that received no trampling. They found that with increasing stocking densities, infiltration into the soil decreased and runoff and sedimentation increased. When trampled moist, less force was needed to compact the soil and decrease infiltration rates than when the soil was dry (Warren et al., 1986a). However, they failed to note that there was a non-significant but arithmetic increase in infiltration between trampling events, indicating that even in the absence of plant growth, the soil still showed signs of recovery. Interestingly, it seems that after these studies were conducted, no studies to our knowledge looked at the length of time required for the soil to fully recover after a heavily stocked grazing bout.

We know that cattle will compact the soil (Warren et al., 1986 a,b,c), especially if it is wet prior to trampling and has little to no plant growth, as seen in the previous study by Warren et al., (1986a). Degraded pastures or pastures with little stand establishment would have low root densities keeping the soil in place, and would be prone to compaction, especially if trampled when wet at high densities, if they had sufficiently high clay content.

The former cropland field where the study was conducted was reseeded to WW-SPAR (SPAR) Old World Bluestem (*Bothriocloa ischaemum* L) in 2010 and 2011. The portion seeded in 2010 established well. However, the 2011 portion did not establish a full stand due to drought and competition with various perennial and annual weedy species, even in the year of record rainfall in 2015. The site had been ungrazed for years, in an unsuccessful attempt to increase recruitment of the seeded species. The portion that had established was predominantly SPAR and buffalo grass, while the portion that didn't establish well had a mixture of natives and the seeded SPAR.

Therefore, the objectives of this study were to: 1) quantify the effect of cattle trampling at high stocking density on soil bulk densities; 2) quantify the length of deferment required for the bulk densities to attain pre-trampled values; 3) quantify the effects of standing plant cover and/or litter on soil bulk density over time; and 4) determine if disturbances by cattle and/or litter cover can be a tool for grass recruitment on a degraded pasture.

CHAPTER III :

METHODS

Study Area

We conducted a field study on the West Texas A & M University's Nance Ranch, 11.27 km east of the city of Canyon in Randall County, Texas USA from August 2015 until June, 2016. The site has a semi-arid climate, with an average annual precipitation of 50 cm, an average annual high temperature of 21^{o}C, and an average annual low temperature of 6.5^{o}C (Natural Resource Conservation Service, 2017). Research plots were located on an old crop field (0-1% slopes), seeded to WW- SPAR Old World Bluestem (*Bothriocloa ischaemum* L.) (SPAR) on an Olton clay loam in 2011 that failed to achieve a fall stand due to drought. This soil is a Fine, mixed, superactive, thermic Aridic Paleustoll. This soil is classified as a Deep Hardland ecological site by USDA-NRCS Soil Survey Staff (1999), and was cultivated for many years prior to initiation of the study. Prior to this study, there had been no cattle grazed on these sites from the time of the initial seeding until our research was conducted. The potential total forage production for native rangeland on this site can average 2,578 kg ha^{-1} on a favorable year, 1,793 kg ha-$^{-1}$ on a normal year, and about 1,009 kg ha^{-1} on an unfavorable year (USDA-NRCS, 1999).

There are three alternate stable states, for the Deep Hardland ecological site. A shortgrass dominant community, degraded shortgrass communities, and a broom snakeweed/ annual forb dominant community. The historic climax plant community for this site is a Shortgrass/Blue grama (*Chondrosum gracile* Willd.) dominant community with low densities of mid-grasses, and a small number of moisture dependent forbs. Very few woody plants are normally found, but include prickly pear (*Opuntia engelmanni* Salm-Dyck. and *Opuntia phaecantha* Engelm.), broom snakeweed (*Gutierrezia sarothrae* Pursh.) and yucca (*Yucca glauca* Nutt.) in small quantities.

Blue grama (*Chondrosum gracile* Willd.), buffalograss (Buchloe dactyloides Nutt.), side oats grama (*Bouteloua curtipendula* Michx.), western wheatgrass (*Pascopyrum smithii* Rydb.), sand dropseed (*Sporobolus cryptandrus* Hitchc.), silver bluestem (*Bothriochloa laguroides* D.C.), and vine mesquite (*Hopia obtusa* Kunth.) are also present.

The major annual forbs are mares-tail (*Conyza canadensis* L.), and major perennial forbs are scarlet globemallow (*Sphaeralcea coccinea* Rydb.), prairie coneflower (*Ratibida columnifera* Nutt.), chocolate daisy (*Berlandiera lyrata* Benth.), slimleaf scurfpea (*Pediomelum linearifolium* Torr and A. Gray.), western ragweed (*Ambrosia psilostachya* DC.), silver leaf nightshade (*Solanum eleagnifolium* Cav.) and Heath aster (*Aster ericoides* L.). In open places, increasing native species such as sandbur (*Cenchrus longispinus* Hack.), tumble windmill grass (*Chloris verticillata* Nutt.), and perennial threeawn (*Aristida purpurea* Nutt.) can be found. Non-native species that have become naturalized include cheatgrass (*Bromus tectorum* L.), rescue grass (*Ceratochloa cathartica* Vahl.), and bindweed (*Convolvulus arvensis* L.) and various annuals, especially Kochia (*Kochia scoparia* L.)and Prickly Russian thistle (*Salsola kali* L.).

Each of these species provided low to moderate amounts of foliar cover in the plant community during the study. Mares-tail was the dominant annual forb in 2015, and bindweed was the dominant perennial forb throughout 2015 and 2016. In addition, alfalfa

(*Medicago sativa* L.), yellow (*Melilotus officinalis* L.) and white sweetclover (*Melilotus alba* L.), and johnsongrass (*Sorghum halepense* L.) have become part of the species mix either as a deliberate or unintentional addition to the original planting mix or introduced naturalized plants from roadsides in the region. Common species identified within the research plots by functional group are presented in Table 1. All grass names follow Shaw (2011), and all forb and woody species names follow Weber (1967).

Experimental Design

We selected four 0.20 ha plots based on similar plant species composition, soil type, and topography (Illustration 1). We determined soil texture using graduated shake sieves with one core from each treatment, to confirm constant soil textures throughout the treatments. The top three inches of our profile were all silty clay loam. Silty clay loam is not a part of the Olton Clay loam series, and is most likely Aeolian deposits accumulated during the years of cultivation from the area surrounding the study sites. Plots were then split in half and randomly allocated in July 2015 to either trampled or untrampled treatments (Illustration 1).

Before trampling we broadcasted green sprangletop (*Leptocloa dubia* Kunth.) and kleingrass (*Panicum coloratum* L.) at a rate of 4.5 kg ha^{-1} pure live seed (PLS) into both the control and the trampled treatment areas to provide a means of determining if germination and recruitment of desirable species differed among treatments, since green sprangletop and kleingrass were not endemic to the site or part of the seed mix that had been previously seeded.

We randomly located and collected six soil cores in each trampled or control plot prior to application of the trampling treatment to calculate baseline bulk densities before trampling. To collect the cores, we placed a block of wood approximately 35 cm long over a round aluminum core sleeve 5.08 cm in diameter x 7.62 cm deep, beveled edge down. Then, using a rubber mallet, we drove the sleeve into the ground flush with the soil surface, dug around the sleeve with a trowel and carefully lifted it out to prevent any loss of soil. We removed excess soil from the sample with a knife, making sure the soil was even and flat with the bottom edge of the core sleeve. We then labeled the core and wrapped it with plastic wrap, until it was weighed to determine moist weight (in the core sleeve), and placed in an oven at 105°C. After drying for 48 hours, we weighed the dry core (in the core sleeve), removed the core from the sleeve, weighed the sleeve, and subtracted the weight of the sleeve. Bulk densities were calculated by dividing the weight of the dry soil core, by the volume of the soil core sleeve and were recorded in g cm^{-3}.

On 18 to 22 August 2015, beginning one day after a 4.3 cm rainfall event (Table 2), 24 heifers with an average weight of 408 kg each, grazed each 0.10 ha plot allotted to the TNC treatment. These heifers stayed in each trampled treatment for about 9-12 hours, while we moved them evenly throughout each plot until we estimated that they had consumed 50% of the standing vegetation. Between treatment applications, the heifers were held adjacent to the treatment plots in a pen with long stem hay and ad libitum water. Day zero of deferment started as soon as the heifers were removed from the fourth treatment plot on August 22, 2015.

After the grazing/trampling was accomplished, we randomly placed six Daubenmire frames in each plot (Illustration 2) to estimate canopy and basal cover classes by functional group (Coulludon et al., 1999; Daubenmire, 1959). The Daubenmire technique involves visually designating a cover class (Illustration 3) to each species in each quadrat (Bureau of Land Management, 1996; Coulludon et al., 1999). Sections of the quadrat frame are delineated into various sizes (Illustration 3), to provide a visual guide that would represent 5, 25, 50, 75, 95 and 100% of the frame (Bureau of Land Management, 1996). This method recognizes the difficulty in accurately assigning an exact percent cover value to each functional group in a quadrat with a visual estimation. Therefore, assigning broader cover classes with a range of cover percentages provides a more repeatable measure (Bureau of Land Management, 1996

To estimate canopy cover, an imaginary line connects each outside leaf tip of a plant or group of plants of the same species (ignoring inflorescence). The estimation of the canopy is the polygon that is projected onto the ground from above the quadrat. Each species within the quadrat can be assessed separately; however we grouped the species together by functional group due to the low frequency of many species. Basal cover refers to the proportion of the quadrat that is covered with each plant base at the ground surface. Functional groups were designated as warm season perennial grasses, cool season perennial grasses, warm season perennial forbs, cool season perennial forbs, warm season annual grasses, cool season annual grasses, warm season annual forbs, and cool season annual forbs. We also visually estimated total litter and bare ground in the same way before supplemental litter was applied in March.

In the same quadrat used to estimate plant cover, we counted the number of complete hoof prints and visually estimated the percentage of the area inside the frame covered with hoof prints immediately after trampling. Partial hoof prints were not counted. Bulk density cores were also collected from the center of the same quadrat, and processed as described previously. As soon as roads were passable after each rainfall event >0.25 cm, we collected soil cores and foliar and basal cover data in the same way until termination of the project in June, 2016. On several occasions, we were unable to reach the plots because of the amount and/or frequency of rain or snow over several days. Therefore, data were collected on only eight dates.

Long-stem Sorghum-Sudan grass hay was spread in every treatment before the growing season for the warm season perennial grasses (March 2016) using a tractor driven hay processer, then spread with hand rakes in three strips that were about 90 cm wide to achieve 100% soil surface cover under the strips by either standing vegetation or hay mulch (Illustration 4). This allocation yielded four replicates of the following four treatments: 1) trampled with supplemental cover (TC), 2) trampled with no supplemental cover (TNC), 3) untrampled with supplemental cover (UC), and 4) untrampled with no supplemental cover (UNC) in a 2x2 factorial arrangement.

Data Analysis

Because we applied the cover treatment in March, we split the analysis into two parts. Bulk density, canopy cover, basal cover, and seedlings were analyzed in SAS using paired T-tests comparing TNC and UNC treatments within a given date from August until June. Bulk density was the independent variable and treatment was the dependent variable (SAS, 2013). Differences were determined at an alpha of 0.05.

We then used the PROC MIXED function in SAS for an analysis of variance (ANOVA) to test for statistical significances in all four treatments (TNC, TC, UNC, UC) from when the litter treatment was applied in March until the termination date in June (SAS, 2013). Bulk density, canopy, and basal cover were the dependent variables, while date and treatment were the independent variables. We used the Levene's test to check for homogeneity of variance. We used an alpha level of $P<0.05$ to determine statistical significance among treatments.

A simple regression and correlation was performed in SAS with bulk density being the dependent value and number of hoof prints and percentage of hoof prints being the independent variable (SAS, 2013).

CHAPTER IV:

RESULTS AND DISCUSSION

At a stock density of 240 hd ha^{-1} (97,920 kg ha^{-1}), for 10 hours per plot, soils were compacted to a mean bulk density of 1.57 g cm^{-3} (Figure 1, Table 3) in the TNC treatment. After cattle were removed from the treatments, mean bulk density in the TNC treatments decreased over time, with the most rapid decreases in bulk density occurring from days 100-130 and days 200-216 of deferment (Figure 1). The average temperature in November (100 days post trampling) was 8.3°C and 1.1°C in December (130 days post trampling) (Table 2). We received freezing rain and snow throughout the months of November and December with a total accumulated precipitation from day zero through day 130 of 22.36 cm (Table 2). Freeze/thaw associated with the heavy precipitation and low temperatures during this period likely contributed to decreasing bulk densities during this time frame. Soil bulk densities are a good indicator of infiltration capacity of the soil (Warren et al., 1986a).

Warren et al., 1986a found an arithmetic improvement in infiltration rate and sediment production between applications of trampling applied every 30 days, even though they removed all living and dead vegetation before and between treatment, decreasing the availability of the mechanisms needed for recovery. It is important to note that factors aiding in soil compaction recovery will depend on the region where the pastures are located, as well as soil texture (Warren et al. 1986a), and predominant vegetation types (Wood and Blackburn, 1991). For example, the studies in Sonora would not have seen any freeze/thaw processes that would have decreased soil compaction as our study did. Likewise, a study conducted on a sandy soil may see minimal soil compaction.

Between days 130 and 200, little recovery occurred in the TNC treatments (Table 3), likely due to low temperatures, precipitation, and plant dormancy that minimized plant growth during that 70 day period. Between days 200 and 216, however, bulk densities decreased from 1.44 g cm^{-3} in the TNC treatments to 1.39 g cm^{-3}, and continued to fluctuate between 1.39 g cm^{-3} and 1.37 g cm^{-3} through the remainder of the study. Around day 200-216 (March), growth of the warm season perennial grasses began, and the bulk densities in the TNC treatments by this date are no longer statistically different (Figure 1) from that of the UNC treatment, indicating that the soil compaction from the grazing event had recovered, probably as a result of root growth of the warm season grasses. Bulk density decreased significantly and rapidly over the 40 days represented by these two periods, accounting for 65% of the total decrease in bulk density over the course of the 295 day study.

Restricted root penetration and elongation reduces the amount of soil that can be exploited by a particular plant for water and essential plant nutrients, which in turn negatively affects plant growth. The degree of compaction is dependent on soil texture (Van Haveren, 1983), soil moisture at the time of grazing (Nawaz et al., 2013), grazing frequency, density, and intensity (Belsky and Blumethal, 1997; Warren et al., 1986a). The threshold bulk density at which root elongations is reduced depends on soil texture (O’Connell, 1975; Veihmeyer and Hendrickson, 1948). The ideal bulk density for plant growth for a silty clay loam is <1.40 g cm^{-3} (Table 4). Bulk density >1.65 g cm^{-3} restricts root growth (Figure 1; Table 4).

Immediately after livestock removal, soil bulk density was 1.57 g cm^{-3} in the TNC treatments (Figure 1), which likely decreased root growth compared to the UNC treatments. The soil never reached a critical bulk density of 1.65 g cm^{-3} that would have completely restricted root growth for the soil type in our plots (Figure 1). By the beginning of the growing season in March (day 200-yellow circle, Figure 1), the bulk density was 0.20 g cm^{-3} less than that at which root growth is restricted, indicated with the red line on figure 1.

Litter cover was added on day 195 (March 3, 2016) with 6.38 cm of rainfall five days later (Table 2). On day 200, bulk densities were about 1.40 g cm^{-3} ($P<0.01$) in the TC treatment compared to the TNC with a bulk density of 1.44 g cm^{-3} in the treatment (Figure 2, Table 3). On day 216 the bulk density in the UC was 1.33 g cm^{-3} compared to 1.39 g cm^{-3} in the TC and TNC treatments and 1.36 g cm^{-3} ($P <0.01$) in the UNC treatment (Table 2, Figure 2). We have no explanation why the bulk density was significantly lower in the UC treatment on day 216 other than the soil having been very saturated at the time of the data collection. No differences among the treatments were noted for bulk density after day 240 (Table 3). Had we added the litter cover treatment at the beginning of the study, we may have seen bulk density decreasing more rapidly. However, due to the tardiness of our application, we cannot say whether or not adding litter cover aided in faster soil recovery. Grazing deferral allowed the soil to recover from the compaction of the high intensity grazing.

We found both the percentage of hoof prints and the number of hoof prints within a Daubenmire frame were positively associated with bulk density. Bulk density was positively associated with the percentage of hoof prints within the frame (Figure 3) (P=0.0001 $R^2 = 0.5198$). For every 1% increase in soil surface that was trampled, bulk density increased 0.0026 g cm^{-3} (Figure 3). The trend was similar for regression when observing the number of individual hoof prints within the frame ($P < 0.0001$, R^2 0.7233). For every hoof print in a frame, bulk density increased 0.018 g cm^{-3} (Figure 4).

Willat and Pullar (1984) found that higher densities of foot prints, decreased total pore space (Willatt and Pullar, 1984), resulting in higher bulk densities, which in turn, decrease infiltration rates (Edmond, 1974; Warren et al., 1986a). However, Shaver et al., (2016), analyzing 20 years of data for fall grazing of corn residues in Nebraska, did not observe any decreases in corn yields and had no consistent effects on soil bulk density if given a full season of plant growth between grazing events (Shaver et al., 2016). They may also have seen freezing and thawing of the soil to help mitigate compaction issues, as well as some wetting and drying.

Animals do not graze uniformly across a landscape. Therefore, the effects of grazing can differ substantially (Milchunas and Laurenroth, 1989). In managed grazing strategies, the detrimental or beneficial effects of grazing are largely determined by when, how often, how long, how intensely, and where grazing occurs within the pasture. The negative impacts of livestock grazing that decrease grass production are often the result of misuse. At higher stocking densities, cattle may be less selective in their grazing and utilize more of the plant community more uniformly (Barnes et al., 2008). At high levels of utilization, the amount of animal production per acre increases, but may be at the expense of the plant communities if not managed correctly and given sufficient recovery time.

Crider (1955) showed that root growth diminished when >50% of the leaf area was removed from a grass plant. The intense defoliation in the TNC treatment, took more than half the leaf canopy of the tall grasses (Day 0; Figure 5). Therefore, the low residual canopy cover (10%) we left likely suppressed root growth for some time.

In March of 2016, the next growing season, between day 200 and 216 of deferral (Figure 5), the canopy cover rapidly increased from 20.13% to 42.55%, and the bulk density decreased rapidly from 1.44 g cm^{-3} to 1.39 g cm^{-3} (Figure 5) in the TNC treatment. The increases in canopy suggest that there are associations with the increases in canopy cover with recovery of soils from compaction. In this case, when canopy cover increased to levels similar to untrampled plant communities, bulk densities has also returned to similar values (Figure 5).

Though basal cover increased in both treatments with time, it was not significantly different between the TNC and UNC treatments at any time during the study. Since basal cover was no different between treatments at any sampling day since trampling, this suggests that trampling at a high stock density, and grazing at a high intensity did not have any detrimental effects on basal area of our warm season perennial grasses.

Thurow et al., (1987) found when interception of rainfall was higher under tallgrasses than short grasses, or bare ground. Tall grasses typically have deeper root structures (Weaver, 1930). Since the majority of the grasses in our study were tall- or mid-grasses, the root structure was likely deep in areas where grasses had established, resulting in higher infiltration and interception of rainfall in those areas, particularly in the dormant season, than those with short grasses or bare ground. Because temperatures were low, evaporative losses remained low, even in the grazed/ trampled treatments. Lull (1959) observed that cattle alter infiltration and run-off rates by reducing vegetative and litter cover (Lull, 1959). Therefore, leaving enough vegetation to enhance infiltration and decrease evaporation during months of heaviest rainfall events is important to optimize precipitation that falls.

Haan et al., (2006) also found when grazing by continuous or rotational stocking in mid-grass to tall-grass pastures, that a residual plant height of 2 inches reduced water infiltration. However, grazing by rotational stocking to a residual plant height of 4 inches resulted in no greater water runoff in simulated precipitation runoff than from non-grazed exclosures. Therefore, they concluded that maintaining a minimum sward height of 4 inches in both upland and riparian areas seemed most valuable in minimizing the risk of decreased infiltration and non-point water pollution. Thus, defoliation intensity and subsequent deferment, rather than stocking density had more effect on water infiltration. The results from Haan et al., (2006) corroborate those of other studies that show that plant species composition and production can improve under moderate (Teague et al., 2013) and even heavy grazing intensities (Reardon and Merrill, 1976), with adequate deferment.

Total canopy cover in the TNC treatment following the grazing period in late August was statistically lower of the dormant season, as expected (Figure 5), though basal area was not statistically significant on any date during the study. This suggests that a short period of grazing with deferment had no negative effects on basal area. On day

240 of deferment, the total canopy cover in the TNC treatment recovered to levels that were comparable to the UNC treatment (Figure 5). Note that the rate of canopy growth in the TNC treatment from 240-283 days of deferment was higher than that for the UNC treatment, perhaps as a result of compensatory growth attributable to more efficient photosynthesis in the plants with less old growth in the canopy to shade new leaves. McNaughton et al., (1983) also noted compensatory growth in grazed versus ungrazed swards.

Reduced ground litter has been shown to increase short-lived perennials and annuals, and shift the community into less productive grasses (Grime, 2006). Litter and plant cover enhance infiltration, decrease raindrop impacts, runoff, erosion, decrease soil temperature, increase aggregation and aggregate stability, thereby decreasing soil surface evaporation (Bardgett, 2005; Thurow, 1991;Tomanek, 1969), retaining precipitation and moisture in the ground longer. These conditions would enhance soil microbial activity, which promotes soil aggregate stability and sustains plant nutrient availability (Bardgett, 2005; Thurow, 1991).

Warm season perennial grass canopy (Figure 6) followed the same trend as total cover, which included annuals and forbs. The majority of established species in the treatments were warm season perennial grasses. On day 240, warm season perennial grass canopy cover in the TNC treatment surpasses that of the UNC treatment and is statistically higher on day 283 (Figure 6). On day 295, however the means of both the UNC and TNC treatments are not statistically significant. Grazing, even at high intensities does not always result in decreased plant establishment or decreased ability for the grasses to compete with other plants (Milchunas and Laurenroth, 1989). The capacity for regrowth following an intense grazing bout can increase with the availability of water, nutrients, and light to the remaining plant tissues (McNaughton, 1983; Sterner et al., 1986) when there is no further defoliation. When there is slower regrowth, more time for recovery is required.

Annual warm season grass canopy cover (Figure 7) was higher in the UNC treatment on day 0 and 100 compared to that of the TNC treatment (P-value <0.05), but was not different through the remainder of the study. Basal cover for annual warm season grasses (Figure 8) was significantly higher (P-value <0.05) on days 0, 100 and 216, in the UNC than the TNC treatment (Figure 8). There was no substantial stand of annual grasses at the beginning of the study, and there was no significant recruitment of annual grasses in either treatment at the end of the study. This suggests that warm season perennial grasses are continuing to out-compete the annuals, regardless of treatment.

The most predominant perennial forb in our plots was field bindweed, which causes more than $40 million in crop losses (Westbrooks, 1998), and can outcompete establishing grasses (Phillips, 1978). When fencing off plots, we were careful to make sure that the competition among the grasses with field bindweed was similar among treatment plots. On day 0, 130, and 216, canopy and basal cover for perennial warm season forbs were higher ($P \leq 0.001$) in the UNC treatments than that of the TNC treatments (Table 5, 6). Only on day 295 of deferment was canopy of warm season perennial forbs higher in the TNC treatment (Table 5). But there was no difference in basal area between TNC and UNC (Table 6). This indicated that the perennial grasses were successfully competing with the bindweed.

The amount of warm season perennial forbs never reached more than 3.5% of total canopy or basal area. The only plants that can out-compete field bind weed are perennial grasses (Phillips, 1978). With a low percentage of bindweed in the treatments, and the subsequent establishment of the grasses within the plot, we hypothesize that perennial grasses can successfully compete with bindweed if bindweed is also consumed and grasses are provided extended deferment following grazing that allows them to reestablish a full complement of leaves.

The TNC treatment had lower values for canopy and basal cover of annual warm season forbs on day zero and 216 of deferment, but greater canopy cover on day 240 than the UNC treatment (Tables 7, 8), with no significant differences between treatments at any other times during the study. The highest proportion of annual warm season forbs present in the study plots was marestail. We saw that the cattle trampled the majority of the marestail after the TNC treatment was applied. Weather conditions through the dormant season that put the annual forbs on the ground likely explain the similar values through the dormant season (through day 200). We anticipated that there would be a significant increase in annual warm season forbs in the TNC treatment due to the high density, high intensity grazing. However, we did not observe that response in weedy species, possibly due to the rapid increase in grass cover.

There was no difference between the TNC and UNC treatments or the TC and UC treatments for seedling recruitment, indicating that grazing followed by deferment as practiced in our study has no negative affect on seedling recruitment. We then compared cover or no cover without regard to the trampling treatment, to see if there were differences in seedling recruitment. Since cover was applied 195 days post trampling, we only ran the paired T-Tests from day 200-295 (Figure 9). Cover treatments had more seedlings than the uncovered treatments in three out of the five observation dates (Figure 9, days 200, 240, and 283 after grazing/trampling). We hypothesize that prolonged soil moisture, more stable soil temperatures, and lower evaporation losses created a favorable environment for seedling recruitment (Bardgett, 2005).

The most common form of grazing management is continuous grazing (Teague et al., 2011). However, this extensive management strategy may not be sufficient for positive results in a given managed rangeland pasture. Even with low stocking rates, grazing pressure on palatable plant species can be high across a landscape (Teague et al., 2009), with insufficient recovery provided for those defoliated plants to recuperate from an intense grazing bout. Fencing land into smaller, continuously grazed pastures, without sufficient adjustment of forage demand in times of drought or recovery of defoliated plants following defoliation has led to severe degradation of rangelands (Dregne, 1978; Teague et al., 2013), that has diminished overall health of ungulates and decreased the nutritional quality of the plants (Provenza, 2008).

Until now, there has been no research that we are aware of that has quantified the time required for recovery from trampling and defoliations, or that has studied the possible factors that mitigate soil compaction when it occurs. Understanding the deferment required to mitigate compaction and re-establish cover and vigor after grazing will help land managers improve watershed function and soil health. Periodic deferment using multiple paddocks per herd and higher stocking densities for shorter grazing periods has been associated with improved plant productivity and soil quality (Teague et al., 2013). By employing flexible stocking rates, shortening grazing periods, increasing stocking densities, and providing season long recovery periods, as we did in this study, Rancho Largo saw an increase in the proportion of desirable mid-grasses and forbs, improved forage production and quality, residual cover, litter, and economic performance (Grissom and Steffens, 2013). Therefore, grazing strategies that sustain vegetation productivity by conserving the water and soil resources are essential.

Schlinter et al. (1978) found that 20 year old grazing exclosures showed a decrease in species number, and species diversity compared to areas subjected to light or heavy grazing intensities. Similarly, Paulsen (1975) and Turner and Paulsen (1976) found that forbs and secondary grasses increase as palatable and desirable species decline with long-term grazing exclusion. Teague et al., (2013) found that managing consistently for moderate levels of defoliation during short grazing periods, with adequate deferral for defoliated plants to recover, resulted in improved hydrologic function and soil properties compared to continuous grazing, and similar soil properties to ungrazed controls on similar soils, in similar catenal positions. These results indicate that management for adequate deferment to allow for plant and soil recovery following grazing/trampling may help maintain the integrity of the soils, regardless of intensity of the trampling event. Length of deferral, rather than short-term intensity of livestock activity, appears to be the key to soil hydrologic stability (Warren et al., 1986 b).

When soil compaction is too severe, it limits infiltration of rain and, therefore, recruitment of desirable perennial grasses (Van Haveren, 1983; Gifford and Hawkins, 1978). The amount of vegetation cover influences hydrological functions of the soil (Blackburn, 1975; Thurow et al., 1986). Grazing influenced soil bulk densities in this study, but our results indicate that water infiltration rates can be sustained with proper grazing management practices that maintain adequate ground cover, and are corroborated by other studies (Russell and Bisinger, 2015).

Total expiring Conservation Reserve Program (CRP) acres will increase from 1.2 million acres in 2016 to 2.6 million acres in 2017 (Stubbs, 2014) with Texas having the most expiring acres nationwide. If the soil conservation and wildlife habitat benefits of these areas are to continue or improve once the CRP contracts expire, they should be grazed in a sustainable manner. We found that perennial warm season grass cover increased over the course of the study in both grazed and ungrazed treatments to similar levels as long as sufficient recovery was provided, even at intense levels of defoliation.

Effects of grazing management decisions such as grazing intensity, duration and periods of deferment for recovery of plants and soils may have important consequences for grassland community stability and resiliency of plant species and functional group diversity, which in turn, can influence long-term animal productivity and plant sustainability. The information gained from this study should be applicable to help land managers sustainably manage forage based livestock production systems, maintain proper watershed function, grassland vigor, and diversity. The factors affecting grassland responses to trampling and grazing, are dependent on the location, timing, frequency, and intensity of grazing, as well as soil moisture and soil texture. Grazing deferment during the growing season seems to be one of the biggest management components determining outcomes in grassland communities recovering from any type of herbivory. Optimum recovery period may be longer than that provided in many grazing management studies found in the literature. Having clear and concise goals and managing for those goals, are critical to sustainable management of resources.

CHAPTER V:

CONCLUSIONS

Bulk density increases with trampling intensity. Upon removal of livestock, bulk density decreases over time to similar values as untrampled areas. This study did not determine mechanisms, but possible mitigating factors are freeze/thaw cycles and root development and turnover. Bulk densities and hydrologic function can be maintained with high stock density grazing when adequate deferment is provided to re-establish sufficient cover and allow natural processes to restore porosity.

High intensity grazing will decrease the amount of canopy cover. Grazing may increase the presence of weedy species but may not affect perennial warm season grass production if annuals are not too dense. Short periods of intense trampling/grazing with subsequent deferment had no negative effects on desirable perennial grasses. Canopy growth of grazed plants compared to ungrazed plants in the same environment may be an indicator that soils, as well as the plants within the community, have recovered sufficiently from previous grazing, but we did not specifically test that hypothesis. It may be a subject worthy of further investigation.

CHAPTER VI:

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Illustration 1. Google Maps image where plots were located. The plots and treatments are depicted on the image. The "T" represents the "grazed and trampled" treatments. "U" represents the "ungrazed and untrampled" treatments. The green stripes represent where Sorghum-Sudan grass hay was spread in strips across the treatments for supplemental litter cover.

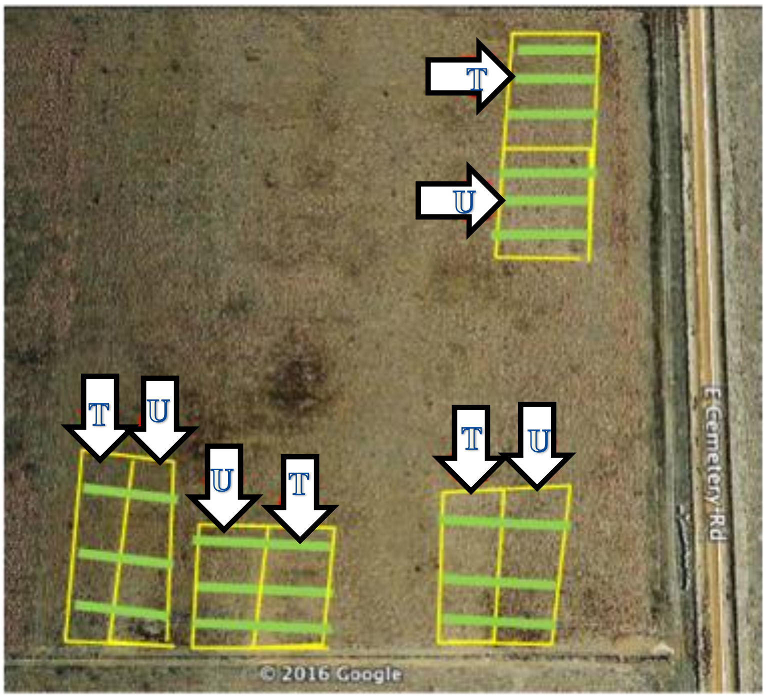


Illustration 2. Depiction of an example of how samples were randomly collected after a rainfall event of more than 0.254 cm prior to the application of supplemental cover that occurred on day 195 after grazing/trampling. Daubenmire frames were placed within trampled (TNC) and untrampled (UNC) treatments at random to estimate canopy and basal cover by functional group at six locations in a replicate. One soil core of 5.08 cm in diameter and 7.62 cm in length was then taken from the center of the Daubenmire frame.

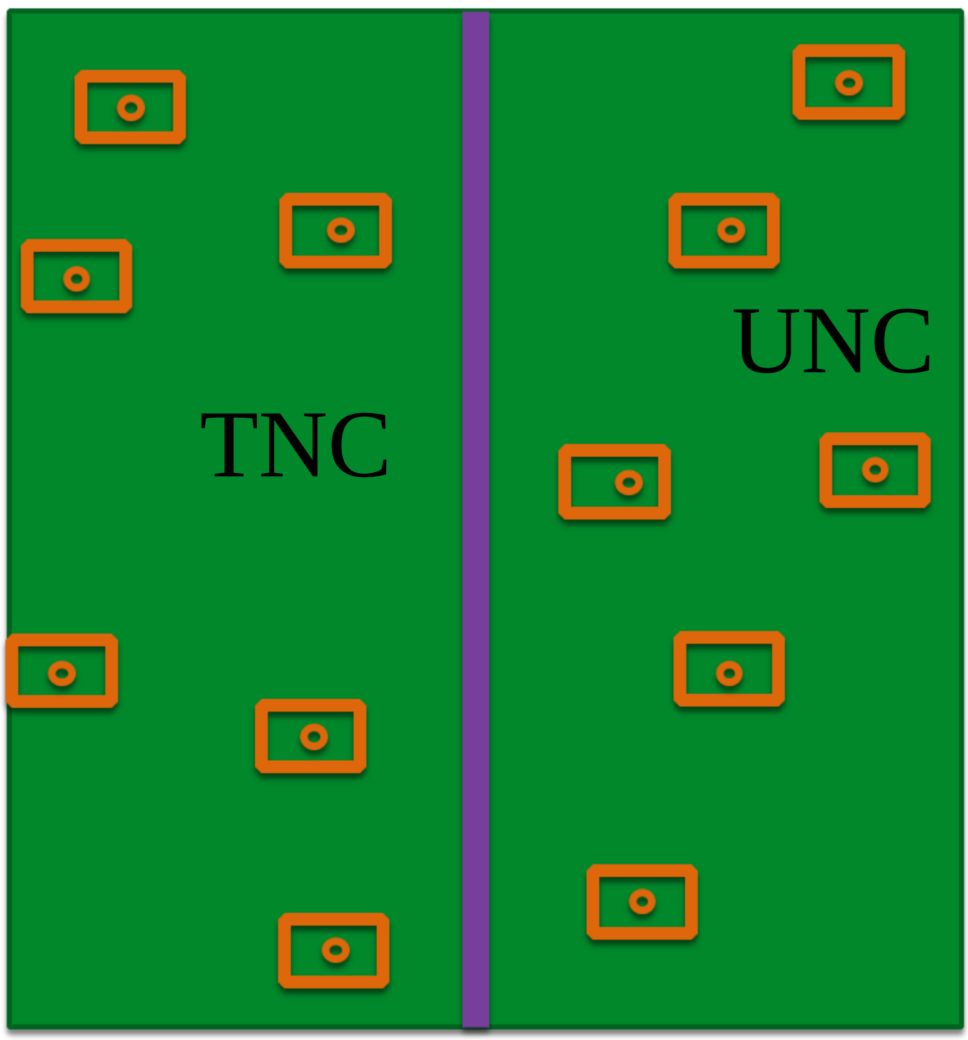
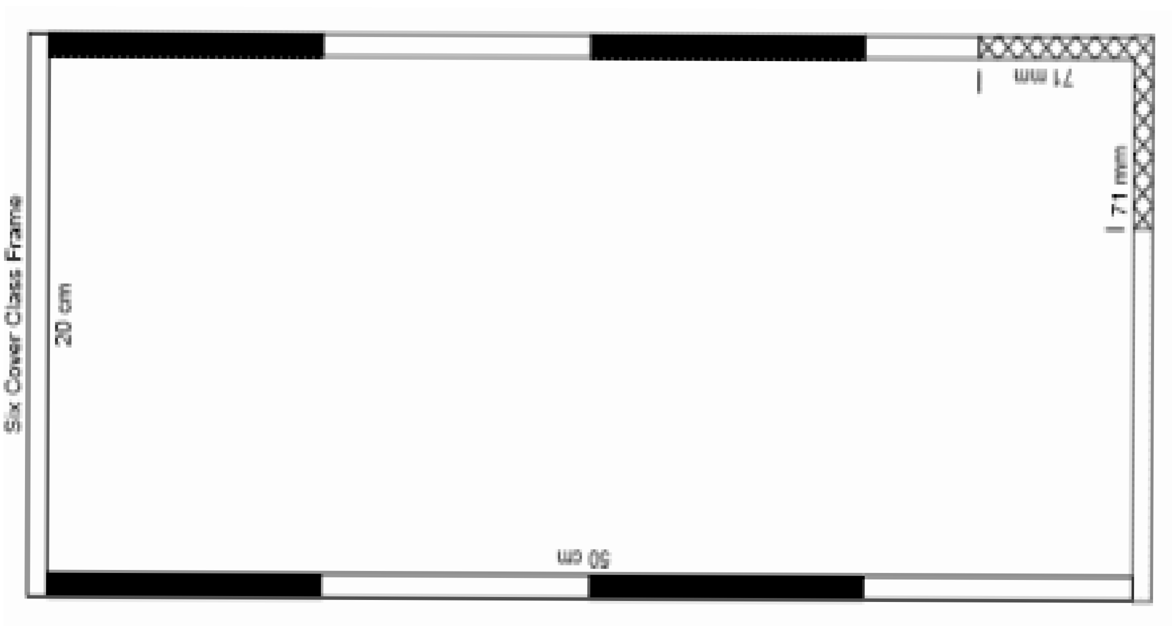


Illustration 3. Daubenmire frame and cover classing system. The percentage of the frame covered by plant canopy and the basal area of the 20 x 50 cm frame were estimated. The alternating white and black marks along the frame's edge represent 25% of the frame with all four sections equaling 100%. The 71mm cross-hatched portion of the frame represents 5% of the frame. Estimates of cover were recorded and placed into their respective cover classes. For data analysis, the "midpoint of range" value for each cover class was used. Mid point of range values are to decrease visual estimation biases and provide a repeatable measure.



Cover Class	Range of Coverage	Midpoint of Range
1	0 - 5%	2.5%
2	5 - 25%	15.0%
3	25 - 50%	37.5%
4	50 - 75%	62.5%
5	75 - 95%	85.0%
6	95 - 100%	97.5%

Illustration 4. Depiction of an example of how samples were randomly collected after a rainfall event of more than 0.254 cm including the cover treatments. Daubenmire frames were placed within trampled uncovered (TNC), untrampled uncovered (UNC), trampled covered (TC), and untrampled covered (UC) treatments in six locations in each treatment replicate at random to estimate canopy and basal cover by functional group. One soil core of 5.08 cm in diameter and 7.62 cm in length was then taken from the center of the Daubenmire frame.

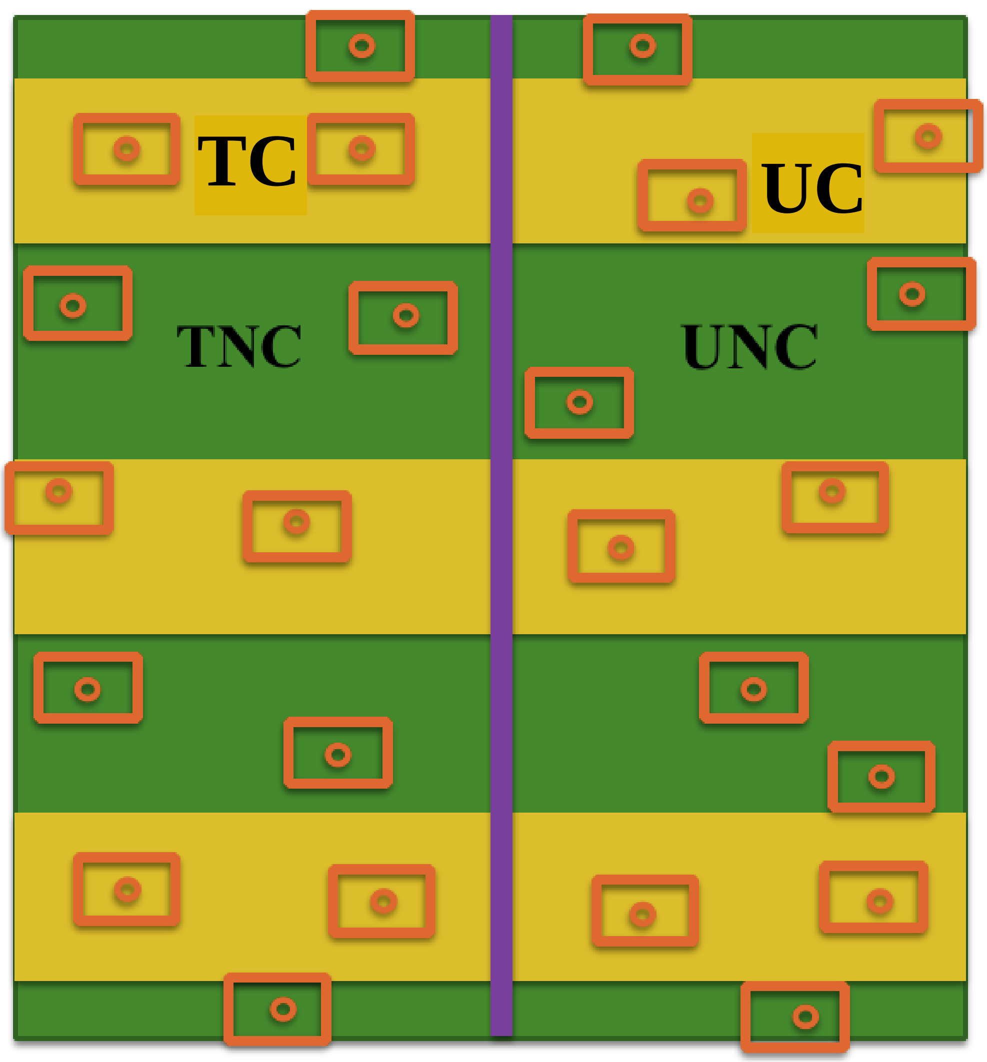


Table 1. Dominant Species in Cover Classes

WS Per. Grass	CS Per. Grass	WS Per. Forb	CS Per. Forb	WS Ann. Grass	CS Ann. Grass	WS Ann. Forb	CS Ann. Forb
Oldworld Bluestem WWSPAR (*Bothriocloa ischaemum* L.*)*	Western Wheatgrass (*Pascopyrum smithii* Rydb.)	Silver leaf nightshade (*Solanum eleagnifolium* Cav.)	Englemanndaisy *(Englemannia persitenia* Nutt.)	Sandbur (*Cenchrus longispinus Hack.)*	Cheatgrass (*Bromus tectorum* L.)	Marestail (*Conyza canadensis L.*.)	Musk Thistle (*Carduus nutans* L.)
Blue grama (*Chondrosum gracile* Willd.),	Squirreltail (*Elymus elymoides* Raf.)	Western Ragweed (*Ambrosia psilostachya* DC.)	Alfalfa *(Medicago sativa* L.)		Rescuegrass (*Ceratochola cathartica* Vahl.)	White sweetclover (*Melilotus alba* L.)	
Buffalograss (*Buchloe dactyloides* Nutt.),		Scarlet globemallow (*Sphaeralcea coccinea* Rydb.),				Yellow sweetclover (*Melilotus officinalis* L.)	
Side oats grama (*Bouteloua curtipendula* Michx.)		Prairie coneflower (*Ratibida columnifera* Nutt.),				Russian Thistle (*Salsola kali* L.)	
Sand dropseed (*Sporobolus cryptandrus* Hitchc.),		Slimleaf scurfpea (*Pediomelum linearifolium* Torr and A. Gray.),				Kochia (*Kochia scoparia* L.)	
Perennial threeawn (*Aristida purpurea* Nutt.)		Heath aster (*Aster ericoides* L).					
Tumblegrass (*Schedonorus arundinaceus* Schreb.)		Field bindweed (*Convolvulus arvensis L.)*					
Tumble windmill grass (*Chloris verticillata* Nutt.),							

Table 2. Average temperatures and monthly precipitation for Canyon, TX from August 2015- July 2016

Date	Temperature (ºC)	Precipitation (cm)
August, 2015	23.9	4.3
September, 2015	22.2	0.20
October, 2015	16.7	1.93
November, 2015	8.3	6.32
December, 2015	1.1	11.81
January, 2016	2.2	0.03
February, 2016	7.2	0
March, 2016	10	6.38
April, 2016	13.3	2.96
May, 2016	17.2	2.57
June, 2016	25.6	5.79

Table 3. Effect of high density, high intensity, short term trampling/grazing and subsequent deferment with and without supplemental litter cover applied on day 195 of deferment on soil bulk density (g cm^{-3}) on a silty clay loam soil showing cumulative rainfall since cattle were removed. (*) indicates a bulk density which is different ($P < 0.05$) among treatments on a given date. Blue Box indicates the paired T-Test analysis. The Red-dashed box indicates analysis of variance.

	Cover		No Cover		
Days of Deferment-Month	**Trampled**	**Untrampled**	**Trampled**	**Untrampled**	**Cumulative Precip. (cm)**
0- August			1.57*	1.37	1.63
100- November			1.53*	1.35	10.08
130- December			1.45*	1.36	21.89
200- March	1.40*	1.35	1.44*	1.35	28.3
216- March	1.39	1.33*	1.39*	1.36	31.26
240-April	1.36	1.35	1.37	1.36	33.83
283- June	1.36	1.37	1.39	1.37	36.37
295- June	1.36	1.37	1.37	1.36	39.62

Table 4. General relationship of soil bulk density and root growth based on soil texture. (USDA-NRCS, 1999). Blue box shows the values for an Olton clay loam. Red-dashed box indicates the values for a silty clay loam, as found in the top 7.62cm of the study

Soil Texture	Ideal bulk densities for plant growth (g cm^{-3})	Bulk densities at which root growth (g cm^{-3}) is detrimentally affected	Bulk densities that restrict root growth (g cm^{-3})
Sand, loamy sand	<1.60	1.69	>1.80
Sandy loam, loam	<1.40	1.63	>1.80
Sandy clay loam, clay loam	<1.40	1.60	>1.75
Silt, silt loam	<1.41	1.60	>1.75
Silty clay loam	<1.40	1.55	>1.65
Sandy clay, silty clay	<1.10	1.49	>1.58
Clay (>45% clay)	<1.10	1.39	>1.47

Table 5. Effect of deferment after a high intensity, high density, short term trampling/grazing on perennial warm season forb canopy cover over time. Day zero was the date cattle were removed on August 20, 2015. Comparisons are T-tests between treatments for a particular number of days of deferment. TNC= trampled with no supplemental cover, UNC= untrampled with no supplemental cover.

Day	Treatment	Mean canopy cover (%)	SEM	P- Value
0	TNC	1.35	0.26	0.0001
0	UNC	2.19	0.61	
100	TNC	1.35	0.28	0.66
100	UNC	1.77	0.24	
130	TNC	1.56	0.25	<0.0001
130	UNC	1.98	0.62	
200	TNC	0.63	0.23	0.95
200	UNC	0.83	0.24	
216	TNC	0.73	0.24	<0.0001
216	UNC	1.55	0.72	
240	TNC	3.86	1.21	0.37
240	UNC	2.6	1	
283	TNC	2.08	0.85	0.50
283	UNC	3.02	0.96	
295	TNC	4.32	0.53	0.01
295	UNC	2.03	0.35	

Table 6. Effect of deferment after a high intensity, high density, short term trampling/grazing on perennial warm season forb basal cover over time. Day zero was the date cattle were removed on August 20, 2015. Comparisons are T-tests between treatments for a particular number of days of deferment. TNC= trampled with no supplemental cover, UNC= untrampled with no supplemental cover.

Day	Treatment	Mean basal cover (%)	SEM	P- Value
0	TNC	1.35	0.26	0.01
0	UNC	2.19	0.61	
100	TNC	1.35	0.26	0.74
100	UNC	1.7	0.24	
130	TNC	1.56	0.25	<0.0001
130	UNC	1.98	0.62	
200	TNC	0.63	0.23	0.76
200	UNC	0.52	0.21	
216	TNC	0.73	0.24	<0.0001
216	UNC	1.55	0.64	
240	TNC	3.33	1.11	0.18
240	UNC	2.29	0.83	
283	TNC	2.08	0.85	0.50
283	UNC	3.02	0.96	
295	TNC	1.67	0.63	0.98
295	UNC	1.56	0.64	

Table 7. Effect of deferment after a high intensity, high density, short term trampling/grazing on annual warm season forb canopy cover over time. Day zero was the date cattle were removed on August 20, 2015. Comparisons are T-tests between treatments for a particular number of days of deferment. TNC= trampled with no supplemental cover, UNC= untrampled with no supplemental cover.

Day	Treatment	Mean canopy cover (%)	SEM	P- Value
0	TNC	2.10	0.84	0.02
0	UNC	7.70	1.4	
100	TNC	3.22	1.12	0.84
100	UNC	3.75	1.10	
130	TNC	1.51	0.64	0.93
130	UNC	1.92	0.63	
200	TNC	0.73	0.34	0.3
200	UNC	1.12	0.26	
216	TNC	0.63	0.23	0.04
216	UNC	1.41	0.26	
240	TNC	3.22	2.3	<0.0001
240	UNC	1.24	0.22	
283	TNC	2.10	1.03	0.39
283	UNC	1.77	0.86	
295	TNC	2.10	0.85	0.39
295	UNC	2.40	1.01	

Table 8. Effect of deferment after a high intensity, high density, short term trampling/grazing on annual warm season forb basal cover over time. Day zero was the date cattle were removed on August 20, 2015. Comparisons are T-tests between treatments for a particular number of days of deferment. TNC= trampled with no supplemental cover, UNC= untrampled with no supplemental cover.

Day	Treatment	Mean basal cover (%)	SEM	P- Value
0	TNC	2.08	0.84	0.02
0	UNC	7.70	1.40	
100	TNC	3.22	1.12	0.79
100	UNC	3.6	1.04	
130	TNC	1.46	0.64	0.93
130	UNC	1.88	0.63	
200	TNC	0.60	0.23	0.98
200	UNC	0.52	0.24	
216	TNC	0.63	0.23	<0.0001
216	UNC	1.25	0.64	
240	TNC	1.15	0.64	0.98
240	UNC	1.24	0.72	
283	TNC	1.56	0.88	0.15
283	UNC	1.15	0.64	
295	TNC	2.08	0.85	0.90
295	UNC	1.96	0.88	

Figure 1. The effect of days of deferment after a high density, high intensity trampling/grazing event and cumulative rainfall on soil bulk density. Day zero was the date cattle were removed on August 20, 2015. Bulk densities were obtained as soon as field conditions allowed data collection after every significant rainfall event (>0.254 cm). TNC= trampling with no supplemental cover, UNC= untrampled with no supplemental cover. Red line indicates bulk density where root growth is detrimentally affected. Yellow circle is the date at which new growth of the perennial warm season grasses was first noted.

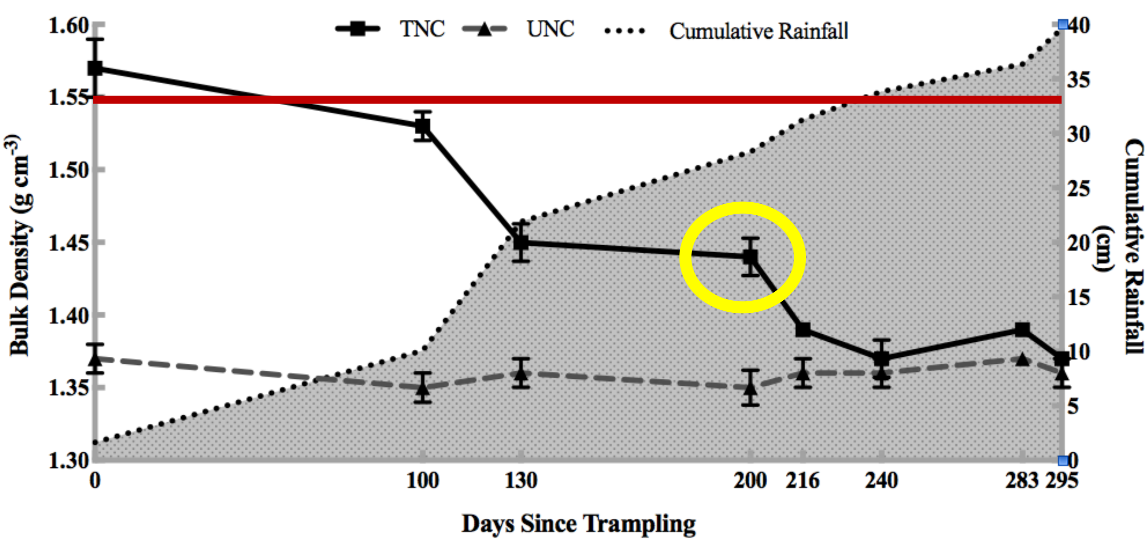


Figure 2. The effect of days of deferment and supplemental litter cover after a high density, high intensity trampling/grazing event and cumulative rainfall on soil bulk density over time. Day zero was the date cattle were removed on August 20, 2015. Bulk densities were obtained as soon as field conditions allowed data collection after every significant rainfall event (>0.254 cm). Litter cover was applied on day 195, and bulk density measurements obtained from day 200 to the day of termination on day 295. (*****) indicates significant differences among treatments on a given date within parameters $P < 0.05$. TNC= trampled with no supplemental cover, UNC= untrampled with no supplemental cover, TC= trampled with cover, UC= untrampled with cover.

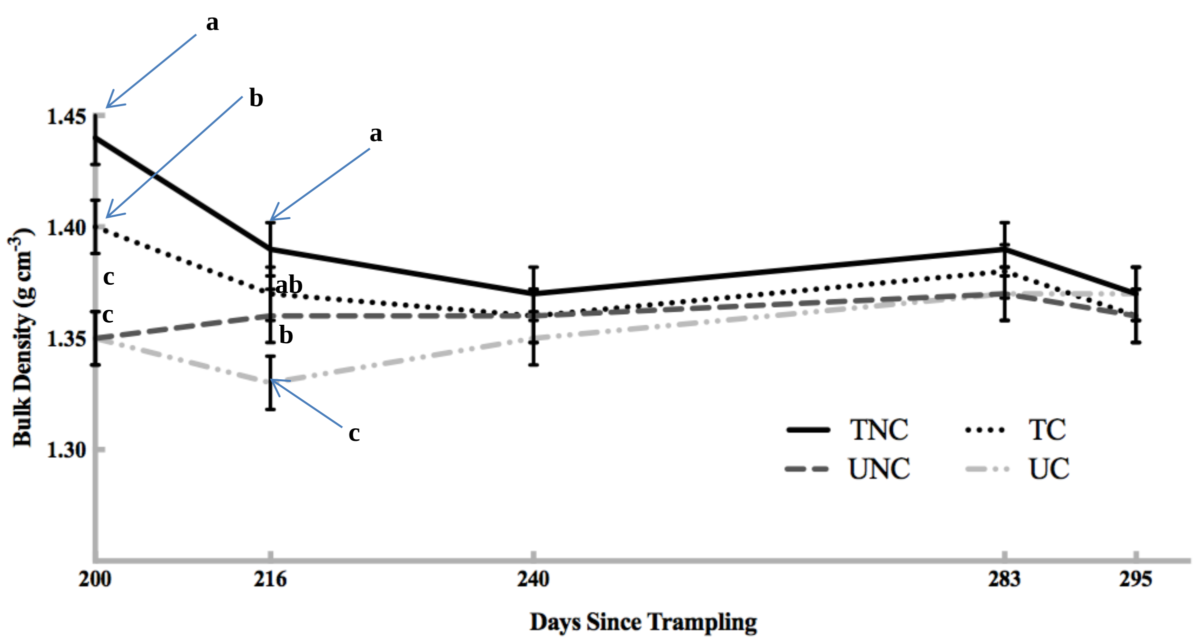


Figure 3. Regression of the percentage of hoof prints on soil bulk density. Initial bulk density samples were collected on day zero immediately after trampling. Daubenmire frames were placed randomly in TNC treatment and the percentage of area within a frame that was occupied by hoof prints was estimated, along with a canopy and basal cover estimate. A soil bulk density core was collected from the center of each Daubenmire frame.

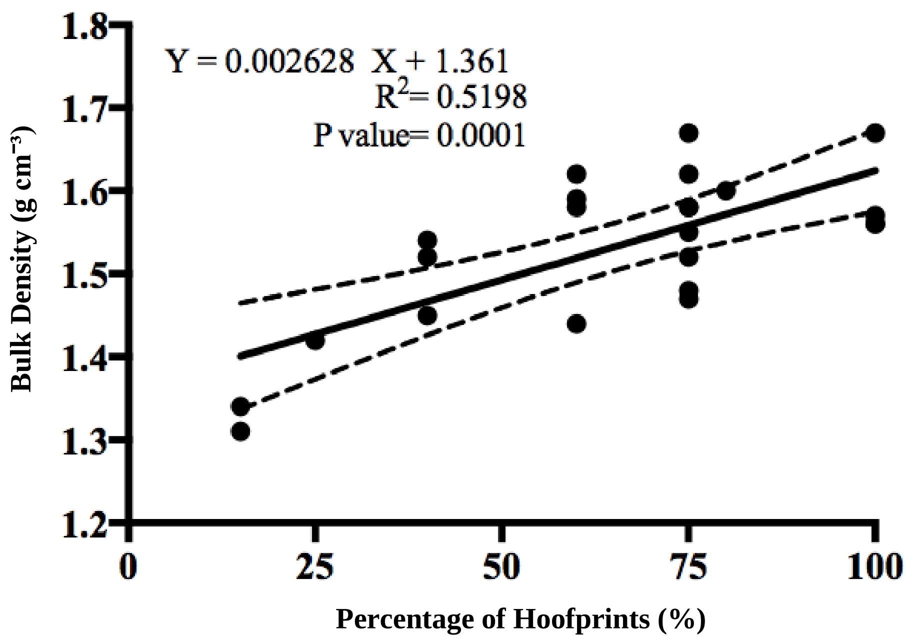


Figure 4. Regression of the number of hoof prints per quadrat on soil bulk density. Initial bulk density samples were taken on day zero immediately after trampling. Daubenmire frames were placed randomly in TNC treatment and the number of whole hoof prints within the frame was estimated, along with a canopy and basal cover estimate. A soil bulk density core was collected from the center of each Daubenmire frame.

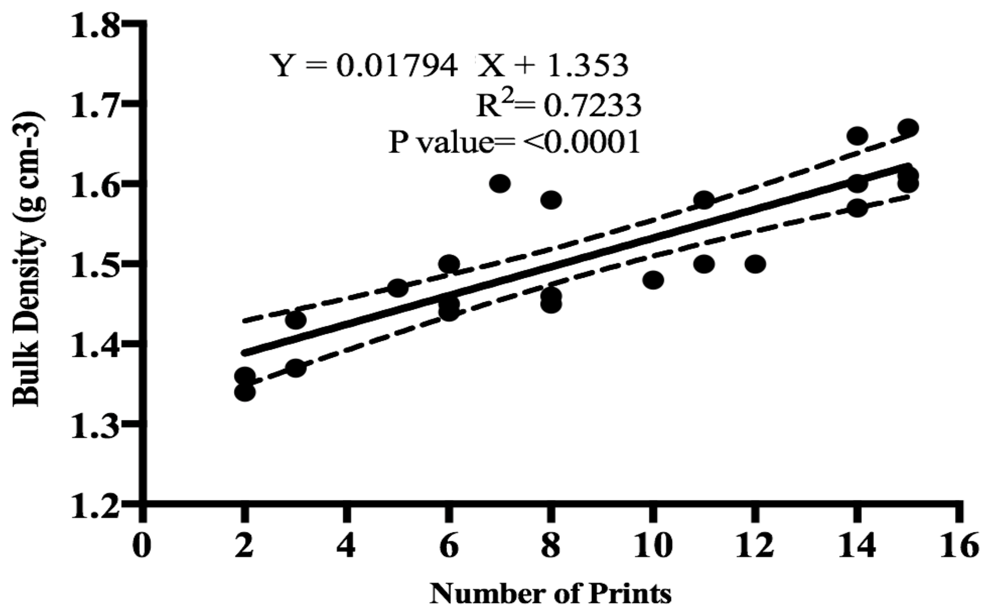


Figure 5. Changes in bulk density and total canopy cover over time under grazing deferment following a high density, high intensity trampling/grazing event. Day zero was the date cattle were removed on August 20, 2015. Bulk densities were obtained as soon as measurements could be collected after every significant rainfall event (>0.254 cm). Bulk density is on the primary y-axis, and total canopy cover is on the secondary y-axis. Graph depicts what is happening to bulk density as canopy cover increases. TNC= trampling with no supplemental cover, UNC= untrampled with no supplemental cover, BD= Bulk density, and CV=total canopy cover. The solid and dashed lines are the bulk density treatments, while the dotted and dotted/dashed line is the canopy cover over time.

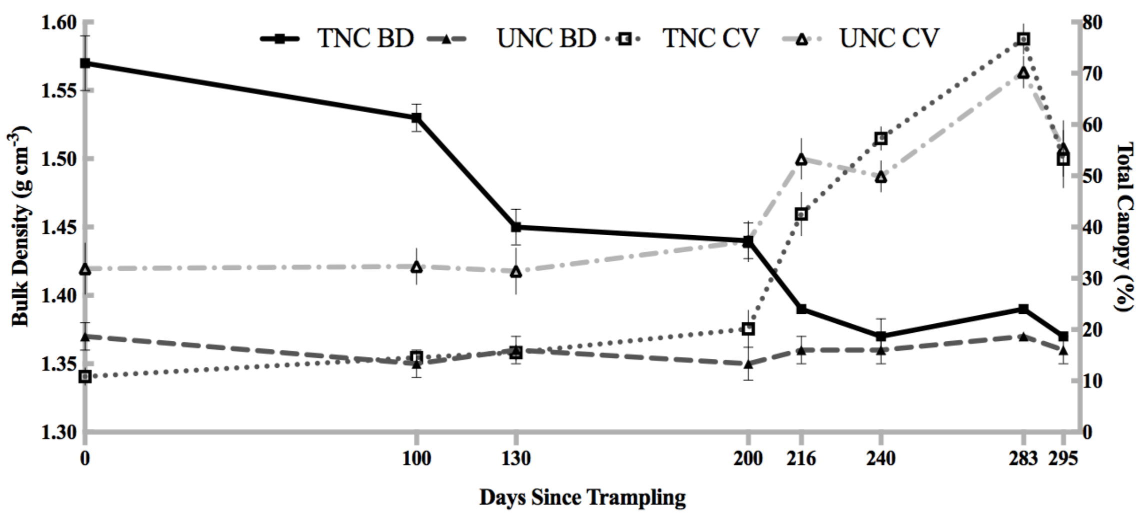


Figure 6. The effect of deferment following a high density, high intensity, short term grazing/ trampling event on warm-season perennial grass canopy cover over time. Cattle were removed on day zero. Canopy cover includes all plants rooted in the ground within the Daubenmire frame. Day zero was the date cattle were removed on August 20, 2015. Canopy was measured as soon as possible after a significant rainfall event (>0.254cm). TNC= trampling with no supplemental cover, UNC= untrampled with no supplemental cover.

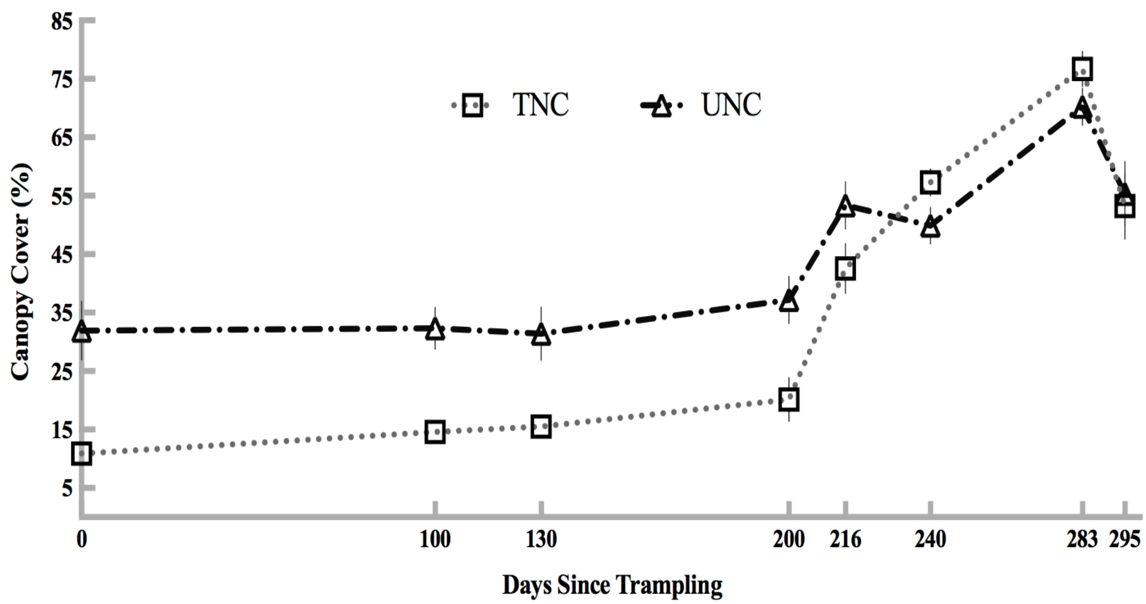


Figure 7. The effect of deferment following a high density, high intensity, short term trampling/grazing event on annual warm season grass canopy cover over time. Cattle were removed on day zero (August 20, 2015). Canopy cover includes all plants rooted in the ground within the Daubenmire frame. Canopy was measured as soon as possible after a significant rainfall event (>0.254cm). TNC= trampling with no supplemental cover, UNC= untrampled with no supplemental cover. (*****) indicates significant differences among treatments on a given date within parameters ($P < 0.05$).

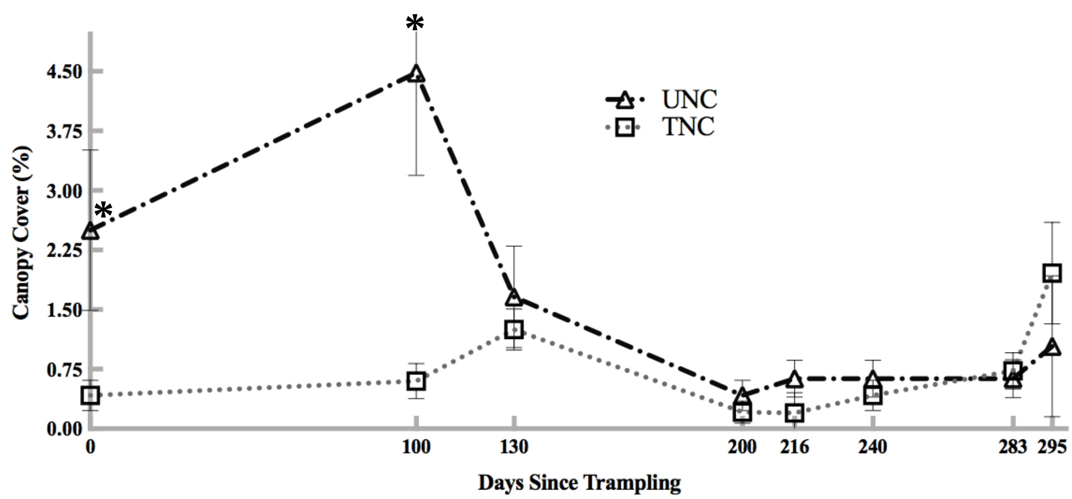


Figure 8. The effect of deferment following a high density, high intensity, short term trampling/grazing event on annual warm season grass basal cover over time. Cattle were removed on day zero (August 20, 2015). Canopy cover includes all plants rooted in the ground within the Daubenmire frame. Canopy was measured as soon as possible after a significant rainfall event (>0.254cm). TNC= trampling with no supplemental cover, UNC= untrampled with no supplemental cover. (*) indicates significant differences among treatments on a given date within parameters ($P < 0.05$).

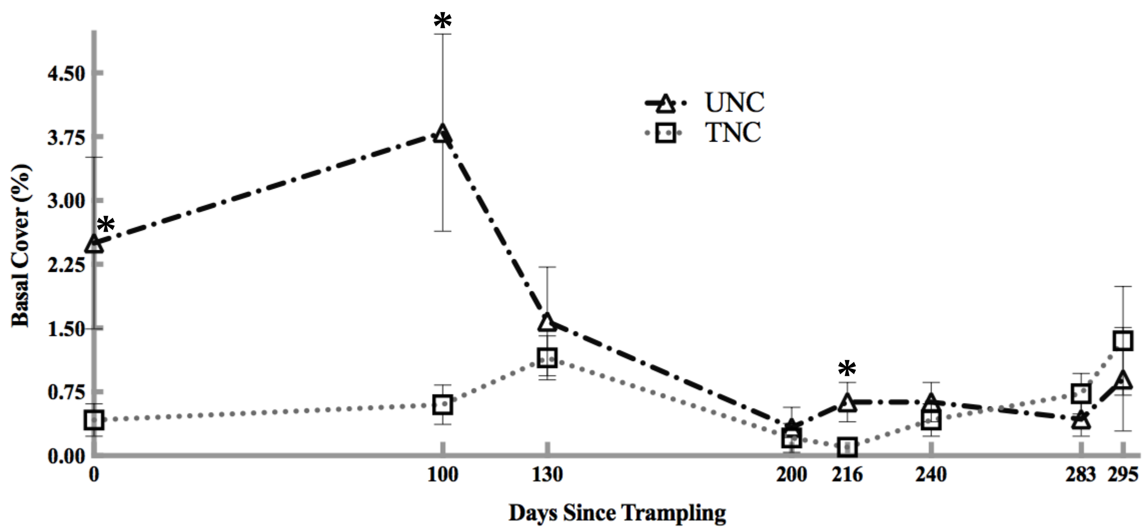


Figure 9. The effects of supplemental cover on mean number of seedlings over time. Seedlings were counted after litter cover was applied in March 11, 2016, 195 days after a high density, high intensity trampling/grazing event on August 20, 2015, using six randomly placed Daubenmire frames in each treatment replicate as soon as possible after a significant rainfall event (>0.254 cm). (*) treatments are significantly different within a date since trampling (P= 0.05).