QUANTIFYING THE EFFECTS OF SIMULATED MACHINERY TRAFFIC ON ALFALFA YIELD AND NUTRITIVE VALUE: A GREENHOUSE STUDY

by

RENEE ANDERSON

(Under the Direction of Nandita Gaur)

ABSTRACT

Machinery traffic can negatively impact alfalfa (*Medicago sativa L.*) yield and nutritive value. The objective of this research was to simulate machinery traffic through the effect of downforce on the alfalfa crowns and soil, and quantify its impact on alfalfa yield and nutritive value. Treatments evaluated include the impacts of compaction on 'Ameristand 435TQ RR' and 'Alfagraze 600 RR' when compacting 1) the crown of the plant (C), 2) the surrounding soil (S), 3) both the surrounding soil and crown of the plant (CS), and 4) neither as an untreated control (UC) with compaction occurring at 5 timings to mimic machinery traffic in the field during dry hay and silage production. Measurements included: yield, number of shoots per plant, damage to the roots, and nutritive value. Regardless of variety, yield gradually decreased throughout the season, and there was a threshold in which there was a significant difference between harvests 3 and 4 (5.69 g DM plant^{-1} and 3.14 g DM plant^{-1}) where compaction started to damage the plant significantly. Ameristand overall had greater crude protein (CP) values and lower NDF and ADF, which is desirable. CP was greater for no compaction controls for both varieties. The bulk density increased throughout the season but not to a level that restricted root growth. However, the S treatment had higher bulk density compared to other treatments. For the root evaluations,

Ameristand had more total root mass, but the controls of both varieties had the least amount of cracks and damages to the top 8 cm of roots.

INDEX WORDS: Alfalfa, *Medicago sativa,* forage mass, forage nutritive value, CP, NDF, ADF, soil compaction, machinery traffic, silage, hay

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CHAPTER 1

INTRODUCTION

Alfalfa (*Medicago sativa* L.) is a valuable perennial forage crop that is widely grown within the United States. It is a popular animal feed and forage due to its superiority in yield, protein content, and palatability (Simons et al., 1995). However, alfalfa harvests, whether for hay or silage, can involve up to four different pieces of machinery equipment that covers up to 70% of the field leading to a greater risk of impact of vehicular traffic on yield (Grimes et al., 1978; Williams, 2021). Like other agricultural production that is impacted by vehicle traffic in the field (Hefner et al., 2019), alfalfa's yield reflects the impact of traffic on the physiology of crowns, stems, and changes in soil characteristics (Rechel et al., 2012). With alfalfa playing an important role in the food supply chain as a feedstock for animals, specifically dairy cattle, beef cattle, and the equine market, optimization of inputs to alfalfa production could have a significant impact on yield and cost of production for producers.

1.1 Impact of Machinery Traffic

Alfalfa is a forage species that is most susceptible to mechanical damage caused by machinery wheel traffic (Glab, 2008). Subsurface compaction as a result of vehicular traffic has been found to be negatively correlated to a number of growth variables in alfalfa. As an example, dry matter yields have been found to be reduced as a function of tractor passes, especially in the second and third harvest, due to compacted soil (Glab, 2008). Machinery traffic within agricultural fields can be significant due to the number of vehicles that are involved. Transport vehicles alone have been found to have made 1,370 passes through alfalfa and corn forage

harvest (Harmon et al., 2018). This traffic causes compaction, which has a significant impact on soil health and crop production potential (Unger & Kaspar, 1994; Hamza & Anderson, 2005). With alfalfa harvest involving multiple pieces of machinery equipment, a large portion of the field will see at least one pass of compaction due to the machines, if not more. Kroulik et al. (2014) found that 64% of a grassland field used for silage was impacted by machinery passes in a single harvest.

Current management practices recommend using the smallest tractors possible, using common operating widths across tractors and implements, driving over the field as soon as possible after cutting, and avoiding unnecessary trips within a field (Undersander, 2010). Yield losses from traffic have been estimated at approximately 5% per day after mowing (Undersander, 2010). Rechel et al. (2012) simulated compaction due to field operations on various portions (0% - 83%) of plots in alfalfa grown in raised beds. Results showed that the simulated machinery traffic reduced yields in the second and third year of production within the treatment with 83% of the plot compacted with one tractor pass. The average yield reduction in this study was 7% over four years and was caused by soil compaction and damage to the crown of the plant (Rechel et al., 2012).

1.2 Motivation for the Experiment

There has been research focused on showing that machinery traffic within agricultural fields has a negative impact on alfalfa yield (Glab, 2008; Rechel et al., 2012; Harmon et al., 2018)However, few studies have focused on the impact of timing of the machinery traffic through the field. Furthermore, no studies have looked at compaction to the soil compared to compaction to the crown of alfalfa and its effect on yield and root development.

1.3 Research Objectives

The objectives of this study are to 1) quantify the effect of downforce on the alfalfa crowns and soil on alfalfa yield and nutritive values at different timings that simulate traffic for hay and silage harvests and, 2) determine the effects of compaction on soil bulk density and root development. This study provides information to alfalfa producers about the harmful effects of machinery traffic on the crop and has the potential to increase the adoption of controlled traffic farming.

1.4 Hypothesis

It is hypothesized that when alfalfa is compacted, the yield is affected over time. The number of times the plant is passed over with machinery traffic will be directly proportional to the damage that occurs to the crown. It is also hypothesized that the timings of application will affect the plant more if the plant has already started the re-growth process.

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CHAPTER 2

LITERATURE REVIEW

Alfalfa is a valuable, high-quality forage for the animal agriculture industry, specifically in dairy cattle, beef cattle, and equine operations. However, in modern crop production, agricultural vehicles tend to increase the number of passes and loads carried through the field resulting in a soil compaction hazard (Glab, 2011). Alfalfa yields reflect the impact of machinery traffic on the physiology of the crowns and stems and changes in soil characteristics (Rechel et al., 2012). Therefore, quantifying the impact of machinery traffic on alfalfa yields, nutritive values, and physiology of the crown and roots is important in the context of the future of harvesting alfalfa silage and hay.

2.1 Alfalfa

2.1.1 History:

Alfalfa, known as the queen of forages, was introduced in Georgia in the 1700's. However, alfalfa production has been mostly confined to California and the northern and intermountain regions of the United States. Prior to 1925, most alfalfa breeding efforts were directed toward selecting strains that were more winter hardy, mainly because of the use in northern regions of the United States (Barnes et al., 1988). After 1925, bacterial wilt was discovered as a new disease and an emphasis was placed on developing cultivars that combined winter hardiness with disease resistance (Barnes et al., 1988). Historically, soil fertility and yield data measurements were taken annually, but today's technology developments have provided the ability to collect data on the crop throughout the growing season allowing for input adjustments

to be made in real-time (Barnes et al., 1988). Improvement in alfalfa productivity, persistence, and nutritive value over time has come about through varietal development and agronomic advances (Monteros and Bouton, 2009). The development of cultivars adapted to conditions where they are grown has allowed alfalfa production to increase in the southern United States (Haby and Leonard, 2005). In the 2000s, genetic engineering technology contributed to the development of Roundup Ready alfalfa to facilitate weed control through the application of the herbicide of glyphosate (Sheaffer et al., 2007). It provided control for winter annuals and perennial weeds in established alfalfa without injuring alfalfa.

2.1.2 Harvesting Alfalfa:

Alfalfa is a unique crop that requires a variety of different machines to harvest either for silage or hay: mower, merger or rake, tedder, forage harvester or baler, and multiple types of transport vehicles. Harvest regimen can impact alfalfa stands; usually harvesting later in maturity can increase stand persistence and yield but will decrease nutritive value (Moyer et al., 1998). One study found that harvesting between early and late bloom stage will produce the most forage per hectare and have the highest productivity of stands (Gasser et al., 1969). Maximum quality of alfalfa is the highest prior to flowering, but the maximum yield is achieved at the stage of full flowering (Bacenetti et al., 2018). Physiological maturity stage is often expressed as an indication of the nutritive value of alfalfa and can be used to determine the appropriate cutting time. Harvesting can be completed on a fixed frequency (four or six-week intervals) or by morphological stage (i.e. bud, 10%, 30%, or 50% bloom). Harvesting at a mature stage can have a negative impact on nutritional value (Weir et al., 1960). Harvesting high-quality alfalfa hay depends on both the timing of the harvest and the harvest process. To achieve high-quality alfalfa hay, it is essential to avoid delayed harvests, but sometimes the weather gets in the way causing

tough decisions: harvest in wet conditions or let the stand mature (Bacenetti et al., 2018). Sheaffer and Marten (1990) found that older alfalfa stands respond differently to harvest regimens when compared to younger stands. Maintaining consistent yield is critical to remaining a competitive alfalfa producer that is able to produce enough forage to sell or feed livestock.

2.1.3 Forage Quality:

The quality of a forage like alfalfa has a direct impact on animal performance, forage value, and profits (Al-Gaadi, 2018). Many factors affect forage quality: forage species, leaf to stem ratio, stage of maturity at harvest, and storage methods (Ball et al., 2001). By increasing the maturity of alfalfa, digestibility declines due to an increase in stem concentration leading to higher lignin content (Sheaffer et al., 2000). The nutritional value of a growing forage also decreases with maturity meaning that there is a negative association between quality and maturity (Fick and Mueller, 1989). Sheaffer et al. (2000) found that a decrease in leaf concentration from 540 g kg^{-1} to 401 g kg^{-1} when harvesting at bud stage compared to late flower stage.

The growth stage at harvest also impacts the nutritional value of alfalfa. Kalu and Fick (1983) found that crude protein (CP) content increases as maturity increases and then plateaus at the early bud stage, eventually declining with later maturity. However, maximizing protein content at harvest at early maturity may lower yields and decrease seasonal protein yield (Weir et al., 1960).

Neutral detergent fiber (NDF) represents the total fiber fraction of the forage. Acid detergent fiber (ADF) is associated with decreased digestibility. Kallenbach et al. (2002) found that alfalfa that was harvested more frequently (up to six times) had lower NDF and ADF values

than those harvested less frequently. Increased leaf content and a lower maturity stage at harvest result in lower NDF and ADF values (Sheaffer et al., 2000).

2.1.4 Nutrient Requirements:

Alfalfa can rapidly deplete the phosphorus, potassium, and other nutrients in the soil (Kelling, 2000). Phosphorus and potassium fertilizer applications can significantly improve alfalfa yield, but the plants' morphology and physiology may be altered in ways that impact forage quality (Berg et al., 2005). Phosphorus and potassium are macronutrients which means that the plant requires them in relatively high amounts when compared to other nutrients. However, applications can cause shoots to grow taller and thicker, which reduces the amount of leaves relative to the amount of stem tissue (Lissbrant et al., 2009).

Plants require potassium (K) for a number of physiological processes: activation of enzymes, synthesis and degradation of carbohydrates, synthesis of protein, and the opening and closing of stomata (Lissbrant et al.,2009). Potassium fertilization can increase yield, growth, and nutritive value of alfalfa (Berg et al., 2007). Potassium fertilization has been shown to maintain alfalfa stand density and without it, complete stand loss had been reported after 5 years (Markus and Battle, 1965). Using greenhouse-grown alfalfa, Li et al. (1997) found that plants that received adequate K averaged twice as many shoots per plant when compared to plants deficient in K. Yield responses can be seen from increased potassium fertilization due to increased photosynthesis, but rates are dependent on soil types (Collins et al., 1986).

Phosphorus (P) is the second most essential macronutrient for plant growth and is a major yield-limiting nutrient in many agricultural systems (Hinsinger, 2001). It is the least mobile but is available to plants in most soil conditions. Plants require phosphorus for cellular constituents such as DNA, RNA, phospholipids, ATP, and other high energy compounds (Lissbrant et al.,

2009). Plant roots can secrete some amounts of phosphatase into the rhizosphere and allow mobilization and utilization of organic P in the soil.

Molybdenum is a critical micronutrient, meaning the plant requires it in relatively low amounts when compared to other nutrients, for nitrogen fixation in legumes and more specifically alfalfa (Adhikari and Missaoui, 2017). Alfalfa provides nitrogen to the soil and surrounding grasses through atmospheric N fixation in nodules. The process by which alfalfa fixes atmospheric nitrogen (N_2) is through a symbiotic relationship between the host and N-fixing bacteria (Rhizobia) (Groat and Vance, 1981). The symbiotic relationship between the legume and rhizobia can be affected by various stresses such as drought, low pH, alkalinity, heavy metals, and nutrient deficiency (Zahran, 1999). Molybdenum (Mo) containing enzymes are an essential component of biological N fixation, and low soil pH induces Mo deficiency which impacts N fixation (Kelling, 2000). Mo deficiency symptoms resemble those of N deficiency where plants turn pale green and are stunted (Kelling, 2000).

Boron (B) is another essential micronutrient for alfalfa flowering, seed set, and yield (Dordas, 2006). It also aids in carbohydrate metabolism, translocation of sugars, and root growth among other things (Howe, 1998). Since the B sufficiency is narrow for plant growth and development, both toxicity and deficiency can arise (Rahman et al., 1999). Boron is essential for nodule development in leguminous plants; therefore, boron deficient alfalfa can produce relatively low root biomass and root nodule numbers and size, reducing nitrogen-fixating ability (Bonilla et al., 2009). Boron deficiency can cause reduced plant growth as well as reduced quality of the crop. Because nutrient removal is high in alfalfa hay production, boron deficiency can eventually negatively affect alfalfa yield and quality if the nutrients are not replenished (Dordas, 2006).

2.1.5 Soil pH:

Soil pH affects nutrient availability, rhizobia effectiveness, and herbicide activity. Macronutrients are available within a pH range of 6.5 to 8, while the majority of micronutrients are available from a pH range of 5 to 7. In addition to the effects of pH on nutrient availability, individual plants and soil organisms also vary in their tolerance to alkaline and/or acid soils. El-Kherbawy et al. (1989) found that alfalfa growing in a soil with a pH between 4.3 and 5.3 failed to survive as a result of soil acidity and heavy metal toxicity. It is known that toxic levels of aluminum (Al) and manganese (Mn) which are present at a low soil pH are major causes of poor performance in plants (Moore, 1974). At a pH below 5.5, a toxic form of aluminum, Al^{3+}, is solubilized from aluminosilicate clay minerals into soil solutions (An et al., 2020). High concentrations of Al^{3+} in soils can damage plants by inhibiting cell elongation leading to poor plant growth (An et al., 2020).

2.2 Impact of Vehicular Traffic on Alfalfa

2.2.1 Machinery Traffic:

Because alfalfa harvests can involve up to four separate pieces of machinery in addition to a transport vehicle, the yield can be decreased due to harvest traffic covering up to 70% of the field (Grimes et al., 1978). Alfalfa yield is reduced when machinery passes over the plant damaging new shoots re-growing after cutting (Schmierer et al., 2004). Research has found that during a single season, transport vehicles alone made 1,370 passes through the field for alfalfa and corn harvest (Harmon et al., 2018). With multiple transport vehicles passing over the field throughout the season, soil compaction and damage to the plant can be significant. There has been found to be a subsequent reduction in root stored carbohydrates and reduced plant vigor due to machinery passes (Schmierer et al., 2004). Wheel traffic damage to the alfalfa crowns can

result in breaking or cracking of the crown and can lead to reduced production of shoots as well as a possibility of disease to enter (Schmierer et al., 2004). External mechanical stress on the soil caused by wheeling or tillage can cause deformation and reduction of the pore space, which affects water and solute transport, nutrient availability, aeration of the soil, and yield of the crop (Hamza and Anderson, 2005).

2.2.2 Effect on Alfalfa

Subsurface compaction has been found to be negatively correlated to a number of growth variables in alfalfa, including the number of tertiary branches (Mapfumo et al., 1998). With alfalfa being one of the most susceptible forage species to mechanical damage caused by machinery wheel traffic (Glab, 2008), this machinery traffic can not only cause soil compaction but can damage the crown allowing the plant to be more susceptible to crown rot (Samac et al., 2013). Grimes et al. (1978) reported on data from the third harvest of first-year alfalfa observed a 53.9% reduction in yield when comparing 0 with 100% trafficked alfalfa; whereas an average 22.6% reduction in yield from 100 % trafficked plots were observed from four harvests in first-year alfalfa (Undersander and Moutray, 2001). Dry matter yields have been found to be reduced as a function of tractor passes, especially in the second and third harvest due to compacted soil (Glab, 2008). However, it has been reported that yields of perennial plants were not always reduced by compaction and yields could be greater on compacted soils when compared to non-compacted soils (Frost, 1988).

The root system commonly responds to increased bulk density by decreasing the root length and concentrating the roots in the upper layer (Lipiec et al., 2003). Alfalfa roots can improve soil structure and decrease the effects of traffic overtime; decreases in bulk density overtime could be ascribed to biological activities such as earthworms and roots (Glab, 2008).

2.2.3 Nodulation:

The ability for nodules to stay functional after harvesting a shoot of a legume, such as alfalfa, may depend on nodule morphology, rate of shoot regrowth, nutrient availability, and competition between plants (Vance et al., 1979). It has been suggested that perennial legumes often lose their nodules after shoot harvest and new ones form during re-growth (Vance et al., 1979). Starch granules in nodules and root nonstructural carbohydrates are not readily available to sustain nodule activity in alfalfa (Vance et al., 1979). Harvesting alfalfa can cause a rapid increase in nodule protease activity that can be reflected by a decrease in nodule soluble protein concentration (Vance et al., 1979).

2.3 Soil Compaction

2.3.1 Soil Compaction:

Soil is composed of three components: mineral, air, and water. Soil compactibility depends on soil type, moisture content, and initial compactness (Hakansson et al., 1988) and is a major cause of inadequate rooting and poor yields in crops around the world (Correa et al., 2019). As a vehicle passes over the soil surface and soil compaction occurs, there is a reduced volume available for air and water as the mineral components are pressed closer together (Raper, 2005), and with the new inventions in mechanization, equipment size has increased. Harvesting alfalfa can involve multiple pieces of machinery of different weights and wheel alignments traveling over the field causing compaction (Rechel et al., 2012). A large amount of traffic occurs when forages are mowed and harvested for hay and silage, and in some cases, traffic intensities of forage crops have been reported to double that of arable row crops leading to compacted soils (Mapfumo et al., 1998). However, the estimated amount of compacted soil worldwide is estimated at 68 million hectares of land from vehicular traffic alone (Flowers and

Lal, 1998). Agricultural traffic due to harvesting can increase soil compaction which also increases soil bulk density and soil strength while decreasing water infiltration rates (Hakansson et al., 1988; Raper, 2005). Deep soil compaction is related to wheel axel weight, whereas soil compaction at surface level is related to contact weight (Undersander and Moutray, 2001). Soil compaction can occur in a wide range of soils and climates, and the effects can last for years and may not be reduced by tillage, freezing, or thawing. Soil moisture for the top 3 to 6 inches of soil that is near field capacity increases the potential for soil compaction as clay content and soil organic matter decreases (Wortmann & Jasa, 2003). Soil texture and soil particle size distribution determine the self-compactibility of a soil: a poorly graded soil with finer particle sizes will have less of an ability to compact as opposed to a well-graded soil with a uniform distribution of particle sizes over the entire range of diameter classes (Craul, 1994). Numerous experiments have been conducted with varying axle loads that completely covered a plot's area in order to assess the soil properties and crop reduction due to the load. One study conducted in Minnesota found that when loads of 9 and 18 Mg were applied to two types of soil, very little change occurred to the subsoil when the soil was dry; however, when the soil was wet, bulk density increased significantly (Voorhees et al., 1984). Using dual tires has been a method used to spread the load over the soil surface. Spreading the same weight over a larger contact area decreases the ground pressure (Hakansson et al., 1988). Dual tires traffic twice the width of vehicle track and may cause excessive surface compaction depending on the cropping system (Raper, 2005). Increasing tire size could offer a method to increase the area of a tire that comes in contact with the soil. On clay soils, mechanical loosening cannot immediately alleviate the effects of soil compaction (Hakansson et al., 1988).

Soil compaction can cause many problems: reduced water infiltration, loss of pore space, increased soil density, decreased water holding capacity, reduced aeration, increased mechanical impedance to root growth with a concomitant decrease in nutrient uptake ultimately leading to a decrease in crop yield (Craul, 1994; Hamza and Anderson, 2005; Batey and McKenzie, 2006; Chen and Weil, 2011; Lipiec et al., 2012).

Soil water infiltration rate can be used to monitor compaction status for topsoil (Hamza & Anderson, 2005). Drainage rates are limited by the hydraulic conductivity of subsoil layers that are affected by heavy traffic (Hakansson et al., 1988). There is an increased risk of runoff and soil erosion because water infiltration rates of compacted soils are severely reduced (Hakansson et al., 1988). Soil compaction affects soil hydraulic conductivity, which will affect the rate of water supply to the root cells because of the reduction of the number of large pores (Taylor and Brar, 1991). To encourage macropore formation in compacted soil, crop production system should be managed in a manner that promotes earthworm activity (Unger and Kaspar, 1994).

Quantifying the impact from the machinery is critical when trying to obtain maximum yields, which is also significant on soil health (Unger & Kaspar, 1994; Hamza & Anderson, 2005; Tullberg et al., 2007; Rechel et al., 2012). Traffic during cutting does not have the same harmful effects as that of later traffic does when comparing cutting to baling and bale removal (Schmierer et al., 2004). Normally, cutting equipment damage is a slight reduction in yield whereas moderate and heavy traffic patterns occur later in the harvesting process causing more damage (Schmierer et al., 2004). After five days, the shoots of alfalfa will have begun to regrow, and if they are broken by the wheel traffic, this will result in a reduction of yield (Undersander and Moutray, 2001). Breaking shoots that may have started to re-grow for the second time after cutting has a depleting effect on stored root carbohydrates (Schmierer et al., 2004). The depth of

compaction can vary widely from 10 to 60 cm (Flowers and Lal, 1998), but it is more visible on topsoil above 10 cm (Hamza and Anderson, 2005).

Two measures of soil compaction that are commonly used are soil bulk density and cone index. Soil bulk density is a measure of the mass of dry soil per unit of volume, and because of the relationship between soil compaction and its capacity to store and transport water or air, dry soil bulk density is the most frequently used parameter to characterize the state of soil compactness (Hamza & Anderson, 2005). Bulk density increases as soil compaction occurs due to constant mass and reduced volume (Raper, 2005). Bulk density values of clays, silt loams, and clay loams typically range from 1.00 to 1.60 g/cm^3 depending on their condition and history (NRCS), but compacted soils may exhibit values near 2.00 g/cm^3 if severely trafficked. Changes in bulk density in addition to penetration resistance with depth can determine overall compaction and the depth at which compaction occurs.

Penetration resistance is measured using a penetrometer that measures soil strength and is assumed to be equal to the resistance encountered by roots during growth (Bengough and McKenzie, 1994). Soil strength increases with increased soil bulk density or decreased soil matric potential (Taylor and Brar., 1991). Organic matter added to the soil can help reduce bulk density by binding soil particles together as aggregates, so they are not easily cracked, split, or compressed by tillage or wheel traffic (Wortmann and Jasa, 2003). Penetration resistance is the primary soil property that describes soil strength and regulates root growth and water accessibility. High levels of penetration resistance negatively affect root elongation rate (Colombi et al., 2018). Root growth for most crops is impacted when the soil penetration resistance is about 1500 kPa, while at 2500 kPa, the root growth of many plants completely stops

(Kees, 2005; Kuang et al., 2012). Soil water content and bulk density have the largest short-term impacts on penetrometer resistance (Souza et al., 2021).

2.3.2 Rooting Restrictions:

Machinery traffic reduces pore space and increases the bulk density of the soil (Raper, 2005). In order for roots to elongate, the pressure in which the roots generate must be greater than the soil resistance, and they must have an adequate supply of oxygen, water, and nutrients (Mapfumo et al., 1998). Roots penetrate through pores that have the same diameter or larger as their root tips, and therefore the root will penetrate a smaller pore only if the soil is loose and can make the pore larger (Craul, 1994). By forcing plant roots to grow in a compacted soil environment, the plant can suffer due to the increased mechanical impedance and decreased oxygen availability (Unger and Kaspar, 1994). Rooting depth in corn has been found to decrease from 90 cm in plots with no traffic to 37 cm in plots where 15 passes of vehicle traffic occurred with contact pressures of 62 kPa (Raghavan et al., 1979). Another study found that soil compaction caused by tractor passes caused alfalfa roots to have the highest proportion of roots in the upper 10 cm of soil but also resulted in decreased root length (Glab, 2008). Many researchers have reported that a response to increasing bulk density is a decrease in root length and root concentration in the upper soil (Lipiec et al., 2003; Glab, 2011). Reduction in oxygen levels around the elongation zone of the root caused by soil compaction reduces root growth pressure (Taylor and Brar, 1991). Ethylene gas accumulates under soil conditions where diffusion of oxygen is low causing an increase in the formation of root hairs and lateral roots (Taylor and Brar, 1991). However, changes in the appearance of the root system do not necessarily mean changes in above-ground growth or yield (Taylor and Brar, 1991).

2.4 Current Study

In this study, two varieties were chosen as representative varieties for those recommended and grown in Wisconsin (AmeriStand 435TQ RR) and Georgia (Alfagraze 600 RR). Each variety has a different fall dormancy rating, but both have been developed to be traffic tested and Roundup Ready. It is known that the depth of crown in alfalfa is inversely related to fall dormancy ratings, so these varieties exhibit differing crown locations in the soil profile.

2.4.1 Alfagraze 600 RR:

'Alfagraze 600 RR' (Alfagraze) was developed by Dr. Joe Bouton, Professor Emeritus at the University of Georgia. With a fall dormancy rating of 6 on a scale from 1 to 11 with 1 being the most dormant and 11 being the least dormant, 'Alfagraze 600 RR' is advantageous because of its high yielding potential, traffic tolerance, persistence, and high resistance to nematodes and *Fusarium* wilt. Fall dormancy is the ability of the alfalfa to grow tall in the fall with less fall dormancy leading to more fall growth and faster spring recovery. Alfagraze is a semi-erect, broad-crowned type of alfalfa that produces numerous crown buds (Bouton et al., 1991). Being a dual-purpose variety for hay or grazing, it combines improved yield potential with semi-dormancy and tolerance to Roundup herbicide for weed control. Alfagraze has been found to be morphologically different from other modern hay varieties, having many thin stems, and was selected under continuous grazing systems (Brummer and Bouton, 1991). Additionally, Alfagraze has been found to tolerate weekly harvests in a greenhouse setting (Brummer and Bouton, 1992).

2.4.2 Ameristand 435TQ RR:

'Ameristand 435TQ RR' is a traffic-tested, Roundup Ready alfalfa variety from America's Alfalfa. Selected for survival and persistence, this variety has a fall dormancy of 3.1 meaning

that it is a dormant variety. It is known for its outstanding leaf retention and stem quality for optimizing digestibility and forage quality potential.

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CHAPTER 3

THE SIMULATED EFFECT OF DOWNFORCE TREATMENT OF MACHINERY TRAFFIC DURING HARVESTS ON CROWN AND SURROUNDING SOIL OF ALFALFA YIELD, NUTRITIVE VALUE, AND ROOT DEVELOPMENT

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Abstract

Machinery traffic can negatively impact alfalfa (*Medicago sativa L.*) yield and nutritive value. The objective of this research was to simulate machinery traffic through the effect of downforce on the alfalfa crowns and soil, and quantify its impact on alfalfa yield and nutritive value. Treatments evaluated where the impacts of compaction on 'Ameristand 435TQ RR' and 'Alfagraze 600 RR' when compacting 1) the crown of the plant (C), 2) the surrounding soil (S), 3) both the surrounding soil and crown of the plant (CS), and 4) neither as an untreated control (UC) with compaction occurring at 5 timings to mimic machinery traffic in the field during dry hay and silage production. Measurements included: yield, number of shoots per plant, damage to the roots, and nutritive value. Regardless of variety, yield naturally decreased throughout the season, and there was a threshold in which there was a significant difference between harvests 3 and 4 (5.69 g DM plant^{-1} and 3.14 g DM plant^{-1}) where compaction started to damage the plant significantly. Ameristand overall had greater crude protein (CP) values and as expected lower NDF and ADF, which is desirable. CP was greater for no compaction controls for both varieties. The bulk density increased throughout the season but not to a level that restricted root growth. However, the S treatment had higher bulk density compared to other treatments. For the root evaluations, Ameristand had more total root mass, but the controls of both varieties had the least amount of cracks and damages to the top 8 cm of roots.

3.1 Introduction

With the development of larger machinery used to harvest silage and hay, issues arise due to decreases in alfalfa (*Medicago sativa* L.) stands and increases in soil compaction. Like other agricultural production that is impacted by vehicular traffic in the field (Hefner et al., 2019), alfalfa's yield reflects the impact of traffic on the physiology of the crowns and stems, as well as changes in soil characteristics (Rechel et al., 2012). Alfalfa harvests often involve more than four separate pieces of machinery with harvest traffic covering up to 70% of the field (Grimes et al., 1978; Williams, 2021), hence there is a greater risk of impact of vehicular traffic on yield. With alfalfa playing an important role in the food supply chain as a feed for livestock animals, specifically dairy and beef cattle and the equine market, optimization of inputs to alfalfa production could have a significant impact on yield and cost of production for producers.

Alfalfa is a forage species that is most susceptible to mechanical damage caused by machinery wheel traffic (Glab, 2008). When a tractor passes through an alfalfa field, the pressure from the tires can cause damage to the crown which can potentially cause a decrease in yield and increases the risk of pathogens entering the plant. Harmon et al. (2018) found that vehicles transporting the forage from a 50 ha field are responsible for 1370 passes during alfalfa and corn forage harvest alone. This traffic causes compaction, which has a significant impact on soil health and crop production potential (Unger & Kaspar, 1994; Hamza & Anderson, 2005). The negative effects of machinery traffic on water infiltration, soil aggregates, biological activity, and other factors that have the potential to reduce yields are well documented (e.g., Wolkowski, 1990; Tullberg et al., 2007; Antille et al., 2015). Subsurface compaction has been found to be negatively correlated to a number of growth variables in alfalfa. As an example, dry matter yields have been found to be reduced as a function of tractor passes, especially in the second and

third harvest, due to compacted soil (Glab, 2008). Yield losses from traffic have been estimated at approximately 5% per day after mowing (Undersander, 2010). Rechel et al. (2012) simulated compaction due to field operations on various portions (0% - 83%) of plots in alfalfa grown in raised beds. Results showed that the simulated machinery traffic reduced yields in the second and third year of production within the treatment with 83% of the plot compacted with one tractor pass. The average yield reduction in this study was 7% over four years (Rechel et al., 2012).

Current management practices recommend using the smallest tractors possible, using common operating widths across tractors and implements, driving over the field as soon as possible after cutting, and avoiding unnecessary trips within a field (Undersander, 2010). Adopting methods that reduce compaction within fields allows for a reduction or elimination of tillage operations which could lead to reductions in soil erosion and carbon loss (Montgomery, 2007). Therefore, the objective of this trial was to determine the impact of machinery traffic during silage and hay harvests on alfalfa yield and nutritive value as well as evaluate the impact on the crown, roots, and surrounding soil.

3.2 Materials and Methods

3.2.1 Study Location and Establishment

The experiment was conducted at the J. Phil Campbell, Sr. Research and Education Center (JPC-REC) in Watkinsville, GA (33°52'21.5"N 83°25'23.0'W; Watkinsville) in a hoop-style greenhouse. A split-split-plot experimental design was used with the main plot factor being the two varieties, 'AmeriStand 435TQ RR' and 'Alfagraze 600RR'. Both varieties are from America's Alfalfa (Forge Genetics International, LLC., Nampa, ID) and marketed as "Traffic Tested." The former has a fall dormancy rating of 3.1, while the latter has a fall dormancy rating of 6.0. These varieties were chosen as representative varieties for those recommended and grown in Wisconsin and Georgia, respectively. Moreover, it is known that the depth of crown in alfalfa is inversely related to fall dormancy ratings, so these varieties exhibit differing crown locations in the soil profile.

The two varieties of alfalfa were planted into trays containing a standard germination potting mix (Sun Gro®, Agawam, Massachusetts), and the plants were transplanted after 55 days into polyvinyl chloride (PVC) tubes that were 15.2 cm in diameter and 1.25 m in length. To obtain the soil media, three layers of Cecil sandy loam soil type were compacted into each tube. The bottom layer of soil (0.9144 m) was obtained from JPC-REC with an average pH of 5.9. The top 0.3048 m of soil was obtained from the University of Georgia's Iron Horse Farm (33°43'05.8"N 83°18'42.5'W; Watkinsville) due to the higher pH of the soil and to ensure the soil is a true representation of Georgia's top soil. Three soil tests were taken from each site. For Iron Horse farm, the soil test results showed an average pH of 5.9, low phosphorus (P) content with an average of 1.12 kg ha^{-1}, low to medium potassium (K) content with an average of 128.9 kg ha^{-1}, and an average lime buffering capacity of 225. For JPC-REC, the soil test results showed

an average pH of 5.45, medium P content with an average of 36.61 kg ha^{-1}, medium K content of 300.9 kg ha^{-1}, and an average lime buffering capacity of 221. Based on the soil test results and recommendations from the University of Georgia's Soil, Plant, and Water Laboratory the bottom 0.1524 m of the top 0.3048 m of soil was amended with phosphate (P_2O_5) at a rate of 252 kg ha^{-1}, potash (K_2O) at a rate of 280 kg ha^{-1}, and dolomitic lime at a rate of 4203 kg ha^{-1}, while the top 0.1524 m of soil was amended with dolomitic lime, potash, and phosphate at the same rate but also had organic humus. Compost was added to the topsoil such that it represented 1% of the dry weight of the soil to represent manure spread on the alfalfa field. The average starting bulk density for the study was 1.27 g/cm^3, which is an ideal bulk density for plant growth (Brady and Weir, 2008).

3.2.2 Plant and Machine Management

A split split-plot factor compared downforce treatments of (1) the top of the crown but not impacting the surrounding soil (**C**), (2) the surrounding soil but not the crown (**S**), and (3) the crown as well as the surrounding soil (**CS**) (Figure 3.1). The split-split plot factor applied 207 kPa of pressure with 5 timings of application and untreated control. The level of down force was chosen based on the availability of soil-tire interface pressure data (Mohsenimanesh & Ward, 2007; Roth, 2010) and to be representative of a mid-size tractor capable of completing most required field operations. The timing of down force application simulated machinery traffic within both silage and hay harvest systems for 1-pass, 3-pass, and 5-pass systems and described in detail in Table 3.1. Tubes were randomly assigned one of the treatment combinations of variety, downforce treatment, and timing. Each treatment was replicated four times.

For the C treatment, the footprint of the pneumatic press's plate was 13 cm^2 centered over the top of the crown. For the S down force treatment, a 15.2 cm diameter plate with a cut-out in the center (13 cm^2) was used to allow placement of the plate around the crown but without the uniformly applied force directly impacting the crown. For the CS treatment, a solid 15.2 cm diameter plate with no cutout was placed over the center of the tube and a uniformly applied force was applied to impact the crown and surrounding soil. The application of the different force treatments was achieved using a specially designed pneumatic press (Figures 3.2 and 3.3), which is described in detail in Williams (2021). Once the desired force was applied, the pressure was immediately released to simulate the momentary force of a wheel impacting the surface that would occur during field operations.

The 128 tubes were randomly organized in the greenhouse, and the plants were allowed to grow until the controls were in the late budstage of maturity before initiating the cutting and traffic simulations. On 3 December 2019, the plants were provided 41.4 g B $plant^{-1}$ using Borosol® (Loveland Products, INC., Greeley, CO) to ensure adequate B. On 11 February 2020, the plants received 13 g $plant^{-1}$ of 10% available phosphate (P_2O_5) and 10% soluble potash (K_2O) to ensure adequate nutrient supply. On 24 July 2020, the alfalfa plants showed some evidence of damage from fall armyworm (*Spodoptera frugiperda*), so gamma-cyhalothrin (Declare®, FMC Corporation, Philadelphia, PA) was sprayed at over the top of all tubes at a rate of 0.02 kg $hectare^{-1}$.

Each plant was irrigated via a NETAFIM drip irrigation system with a woodpecker pressure compensating dripper and received 0.61 L of water per week during the growing season. The plants were not watered 7 days prior to the first harvest to ensure that the moisture of the soil would not affect compaction. However, after the first harvest, the plants were very dry and

showed drought stress. Because of this, the plants were not watered 5 days prior to harvest 2-6. After each harvest, each tube received 0.85 g of 60% K_2O in order to meet the nutritional needs of the plant.

On 9 March 2020, 25 plants were dead or close to dead and were removed from the study. Three plants from both varieties were sent off to University of Georgia's Soil, Plant, and Water Laboratory for Plant analysis. From the results, we concluded that because of the extremely high amounts of aluminum, the plants were experiencing aluminum toxicity. The experiment continued despite unequal replication, but no treatment had lost more than one replicate.

3.2.3 Data Collection

Six harvests were completed between April and September 2020, occurring on 14 April 2020, 26 May 2020, 23 June 2020, 14 July 2020, 11 August 2020, and 15 September 2020. Response variables included non-destructive and destructive measures. After the application of the downforce, the number of damaged shoots per plant was counted. The mean stage of development was assessed once initial stages of bud development was observed, and each harvest was made at the late bud stage in the untreated controls (Kalu and Fick Stage 4; Kalu and Fick, 1981). The average growth stage for each harvest was as follows: 14 April 2020—4.55; 26 May 2020—4.60; 23 June 2020—4.81; 14 July 2020—3.89; 11 August 2020—3.93; and 15 September 2020—3.97. At each destructive harvest, the response variables measured were total forage (DM) herbage mass, shoots per plant, and damaged shoot number.

Before each harvest, growth stage, height of tallest shoot (inches), and moisture readings using a Theta Probe M3 of HH2 Hand Held Meter (Delta-T Devices Ltd, Cambridge, England)

were taken. Each plant was then cut with scissors, and the shoots per plant were counted and recorded. Each tube was placed into the pneumatic press at the hours indicated in Table 3.1, and then after the application of the appropriate compaction, the number of damaged shoots were counted (Appendix A). Moisture readings were taken at the beginning of the day for each compaction timing (Table 3.2).

After each harvest and compaction, the alfalfa plants were given ten days to re-grow, then a handheld multispectral sensor (Crop Circle, Holland Scientific) was used to take NDVI measurements. In order to do so, the surrounding plants were covered with a white sheet of paper so that they would not interfere with the reflectance. The NDVI machine was held 30 cm above the plant, and ten measurements were taken. The highest value was recorded (Appendix B).

After the sixth cutting in the year, a portable self-driven penetrometer (Dickey-John, Auburn, Illinois) was used to determine the penetration resistance with depth of the soil at a water content near field capacity for each tube. The penetrometer had a cone tip diameter of 1.91 cm. The depth at which the penetrometer resistance reached 1380 kPa was recorded. The cap was taken off and the tube was tapped to slide the soil column out of the tube. For one tube per rep, soil moisture was determined for the tube by weighing the entire tube, taking soil samples at the top, middle, and bottom of the soil column, and dried down in a forced air oven at 105°C for 48 hours. The bulk density was calculated as shown below.

$$\theta = \frac{(W_{soil,wet} - W_{soil,dry})_{top} + (W_{soil,wet} - W_{soil,dry})_{middle} + (W_{soil,wet} - W_{soil,dry})_{bottom}}{3} \quad (1.1)$$

$$W_{moisture,tube} = \theta x \left[\frac{W_{soil,tube}}{\frac{(W_{soil,wet})_{top} + (W_{soil,wet})_{middle} + (W_{soil,wet})_{bottom}}{3}} \right] \quad (1.2)$$

$$\rho_b = \frac{W_{soil,tube} - W_{moisture,tube}}{v} \quad (1.3)$$

where: $\theta = moisture\ in\ samples, g$

$w_{soil,wet} = weight\ of\ wet\ soil\ in\ the\ sample, g$

$w_{soil,dry} = weight\ of\ oven-dried\ soil\ in\ the\ sample, g$

$W_{moisture,tube} = total\ weight\ of\ moisture\ in\ tube, g$

$W_{soil,tube} = weight\ of\ wet\ soil\ in\ tube, g$

$\rho_b = Bulk\ density, g/cm^3$

This was used to determine the change in soil bulk density in each tube over the course of the season by changing the volume of the tube each time the soil level dropped due to compaction. The alfalfa plant and roots that were growing in the tube were lifted away from the soil column and washed. The crown and roots were examined. The length and total root and crown mass per plant were measured and recorded. The number of cracks and damage to the crown were counted and the top 8 cm (as measured from the soil surface) of the crown and roots were weighed. Each plant root system was photographed and evaluated in semi-automated Root Image Analysis (smRIA) (Appendix C) (Narisetti et al., 2019).

3.2.4 Forage Analysis

The samples were dried in a forced-air dryer at 60°C until the weight was within 0.1 grams of the last measurement and dry matter yield was then obtained. Then each sample was ground to pass a 2-mm screen using a Wiley® Mill (Thomas Scientific, Swedesboro, NJ) and then through a 1-mm screen, in a CT 293 Cyclotec™ Labtec™ Line (Foss, Hillerod, Denmark) for nutritive value analysis using the Alfalfa Hay calibration provided by the NIRS Forage and Feed Testing Consortium (NIRSC, 2019). Samples were shipped to the U.S. Department of Agriculture - Agricultural Research Service's U.S. Dairy Forage Research Center in Madison, WI to determine crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), and *in vitro* true dry matter digestibility at 48 hrs (IVTDMD48) by near-infrared reflectance spectroscopy using a model FOSS 6500 (FOSS NIRS system Inc., Laurel, Maryland)

spectrophotometer. Fit statistics calibration for the NIR equations were as follows: DM, SEC = 0.2378, 1-VR = 0.9569; CP, SEC = 0.6746, 1-VR = 0.9421; NDF, SEC = 1.7999, 1-VR = 0.9495; ADF, SEC = 1.5047, 1-VR = 0.9243; and IVTDMD48, SEC = 2.2264, 1-VR = 0.8607, where SEC = standard of error of calibration and 1-VR = 1-variance ratio is coefficient of determination in cross-validation.

3.2.5 Statistical Analysis

Data were analyzed in SAS v9.4 (Cary, NC) using PROC MIXED. Variety, compaction treatments, and timings of downforce were considered fixed effects, and replication was considered a random effect. For all data points except the root evaluations, all main factors and their interactions were evaluated per harvest, with and without control. When testing the three-way interaction between variety, compaction, and timing with the untreated controls included, a treatment column was created that combined compaction and timing so that it was possible to analyze the variety and treatment interaction. Tukey-Kramer test was applied in PROC PLM to compare multiple means of each effect at an alpha level of 0.05 with tendency levels being 0.01.

3.3 Results

3.3.1 Herbage Accumulation

There was no discernable trend in herbage accumulation over the course of the study. As the season progressed, herbage accumulation showed a steady decline (Figure 3.4). This decline is not unusual and is consistent with alfalfa production behavior (e.g., Bula and Massengale, 1972; Rechel et al., 1987). There was a difference between varieties for harvest 3 ($P = 0.009$) and 5 ($P<0.001$), and Alfagraze tended to yield less than AmeriStand across all harvests (Figure 3.4).

The effect of compaction treatment on herbage accumulation differed by variety in harvests 4 and 6 and tended to in harvest 5 ($P = 0.0016$, 0.0031, and 0.0971, respectively; Table 3.4). NDVI data followed a similar pattern (Appendix C). In general, the C and the CS compaction treatments resulted in a reduction ($P < 0.10$) in yield from Alfagraze in later harvest dates but had no significant effect on Ameristand.

3.3.2 Forage Nutritive Value

Some metrics on nutritive value were influenced by an interaction ($P < 0.001$) between the compaction treatment and variety within a harvest. Therefore, data are compared among compaction and variety by individual harvest periods for all metrics of forage nutritive value (Table 3.5).

<u>Crude Protein</u>

Crude protein concentrations were influenced by variety for each harvest period ($P < 0.05$) but were not affected by timing or compaction other than for harvest period 3 ($P = 0.0287$ for timing and $P = 0.0081$ for compaction). Ameristand had a greater ($P < 0.05$) CP concentration throughout the entire season when compared to Alfagraze. For harvest period 3, there was an

interaction between variety and compaction *(P* = 0.0081) in which the C compaction had a lower ($P < 0.05$) average CP when compared to the control in Alfagraze but not Ameristand. In harvest period 5, the S compaction resulted in lower ($P < 0.05$) average CP from the Ameristand variety compared to the no compaction control, but there were no differences among compaction treatments for Alfagraze in that harvest. The no compaction control resulted in higher CP levels similar to those reported by Kallenbach et al. (2002) for alfalfa harvested six times (4 yr mean of 250 g CP kg^{-1}). In general, all compaction treatments tended to result in lower CP values than the no compaction control.

Growth Stage

The plants were harvested when the mean stage count of the controls reached ca. 4 as described in Kalu and Fick (1983). There was a significant ($P < 0.05$) varietal difference for harvests 2 through 6, as Alfagraze was more mature than Ameristand at harvest (Figure 3.6). For all harvests after harvest 1, the controls of both varieties were the most mature when compared to other the other compaction treatments within varieties (6.33, 5.67, 6.00, 5.67, 6.00 and 5.67, respectively for Alfagraze; 4.33, 4.33, 5.33, 4.00, 4.33, and 3.67, respectively for Ameristand). This is consistent with the observations in alfalfa small plots in Wisconsin by Williams (2021) who found that similar compaction timing treatments reduced the maturation of alfalfa at harvest. No consistent trend was detected as to the impact of compaction type or timing on mean stage count at harvest, as they all seemed equally impactful relative to the control.

Fiber and True Dry Matter Digestibility

Concentrations of NDF and ADF, as well as IVTDMD48, were influenced by an interaction ($P < 0.05$) of variety and compaction type in harvests 2, 3, 4, and 6. This magnitudinal interaction was somewhat attributable to a substantial difference ($P < 0.05$) in NDF

and ADF concentration and IVTDMD48 between the two varieties, which was observed throughout the whole season. Alfagraze had higher NDF and ADF with concomitantly lower IVTDMD48 values than Ameristand throughout the trial. This seemed to be the result of the aforementioned varietal differences in mean stage count at harvest since the more mature growth stage of Alfagraze at harvest compared to Ameristand is consistent with these results and the known linkage between maturity and fiber concentration and digestibility.

For Alfagraze, the concentration of NDF and ADF was higher ($P < 0.05$) and IVTDMD48 values were lower ($P < 0.05$) for the C and S compaction treatments relative to the no compaction control in harvest 2 through 6. However, no such impacts of compaction treatment ($P > 0.10$) were observed in the Ameristand variety. Notably, the CS compaction treatment consistently had similar NDF, ADF, and IVTDMD48 values to the control for both varieties for all harvests.

3.3.3 Shoots Per Plant

Theoretically, the number of shoots per plant correlates positively with alfalfa yield, at least until the impacts of shoot number and size at the self-thinning boundary line (i.e., the -3/2 self-thinning rule) offset one another. If shoots per plant are reduced as a result of compaction or traffic patterns, and there is limited capacity for the size of individual shoots to grow larger to compensate, then yields will suffer. So, examining the impacts of compaction treatment on shoots per plant can be indicative of potential yield limitations, particularly in alfalfa stands which generally have progressively fewer plants per unit area each year.

At each harvest after compaction treatments were applied (i.e., harvest 2 through 6), the number of shoots per plant produced by Alfagraze and Ameristand was differentially affected ($P < 0.05$) by compaction treatment. When averaged over harvests 2 through 6, the C, S, and CS

treatments resulted in 34%, 25%, and 35% fewer ($P < 0.05$) shoots per plant, respectively, from Alfagraze compared to the no compaction control (Figure 3.5). In contrast, only the S treatment reduced ($P < 0.05$) shoots per plant from Ameristand.

After the stems are harvested, new shoot development continues and the number of shoots per plant is determined within the first 14 days of the new growth cycle (Weirsma et al., 2007). However, new shoot development begins to occur even before the current alfalfa plant's stems are cut (Undersander et al., 2011). Moreover, less dormant varieties tend to form new shoots earlier in that cycle than varieties with lower fall dormancy ratings. Alfagraze has a fall dormancy rating of 6 while Ameristand has a fall dormancy rating of 4. It is possible that Alfagraze produced more shoots at the crown buds prior to harvest and made it more susceptible to shoot loss from compaction than Ameristand, but further research would be needed to determine the reasons for the varietial differences.

3.3.4 Bulk Density

Soil bulk density at the beginning of the study prior to compaction ranged from 1.22 to 1.34 g/cm^3 with an average starting bulk density of 1.28 g/cm^3. Bulk densities across the length of the study varied from 1.23-1.42 g/cm^3 due to compaction (Figure 3.7). The NRCS states that for Cecil sandy loam soils, bulk densities less than 1.40 g/cm^3 are ideal for plant growth, and bulk densities greater than 1.63 g/cm^3 start to affect root growth (NRCS). In this study, the bulk density of soil in two of the experimental units increased above 1.40 g/cm^3, meaning that the majority of the tubes were not compacted above the point at which it started to affect plant growth. However, with this only being a one-year study, conclusions cannot be drawn about the cumulative effect of compaction on bulk density across multiple years.

When comparing the soil bulk densities of each compaction treatment, the S compaction treatment had a greater soil bulk density for the entire season followed by the CS treatment (1.32-S; 1.31-CS; 1.30-C; Table 3.6). The C treatment had the lowest soil bulk density for the study, which is reasonable given that the crown was primarily impacted and likely compressed, defraying some of the downforce from impacting the surrounding soil. Consequently, there was not a drastic change in bulk density of the soil in the treatment. The final bulk density after six harvests and the correlating average penetrometer resistance depth is displayed in Table 3.7.

The percent change in bulk density from the beginning of the study to the end of the study is displayed in Figure 3.8. For Alfagraze, S treatment created the most change in bulk density over the season. In contrast, the C treatment resulted in the most change for Ameristand.

In other response variables, there was a general lack of significant effect of traffic pattern even among those simulating 5 passes. The change in soil bulk density over the course of the season likewise demonstrates no effect of traffic pattern. These results contrast with results in Poland where soil bulk density increase with intensity of tractor traffic (Glab, 2013). However, they reported that soil bulk density did not significantly change in the second and third years of the study (Glab, 2013).

3.3.5 Penetration Resistance

For penetrometer resistance, there were no discernable trends. The resistance depth was recorded when the resistance reached 1380 kPa of pressure. However, some tubes did not reach 1380 kPa of resistance before breaking through the compacted layer, so therefore those depths were taken out of the average per treatment (Table 3.7). As mentioned before, Kaung et al. (2012) suggest that at 1500 kPa root growth becomes restrictive. Since none of the tubes reached that resistance level, this is likely why there were no discernable trends or effects in the root

system due to compaction. However, it would be beneficial to see the additive effects of compaction for three or four years to really determine rooting restrictions.

3.3.6 Top 8 cm Root and Crown Mass

The top 8 cm of roots and the crown of the plant were weighed. There was a significant ($P = 0.002$) varietal difference with Ameristand having more total mass (Figure 3.9). The interaction between variety and timing was significant ($P = 0.0243$). Both varieties had the highest mass for the 1 pass silage/hay timing. The Alfagraze 5 pass silage timing had the lowest average mass, whereas for Ameristand, 3 pass silage timing had the lowest average mass. However, there was not a significant ($P = 0.2594$) interaction between variety and compaction.

3.3.7 Top 8 cm Damage

There were no discernable trends in damage to the top 8 cm of damage to the root system (Table 3.7). When comparing the compaction types with the untreated control ($P = 0.0463$), the control had the least amount of damage, which was to be expected. However, the C treatment exhibited the most damage to the top 8 cm of roots. There was a significant ($P < 0.0001$) interaction between timing and compaction. Within the C treatment, 1 pass silage/hay timing had significantly more damage when compared to the 3 pass silage and 5 pass hay timings. For the S treatment, 5 pass hay timing had the most damage to the roots when compared to all other timings. There were no significant differences among the five timings in the CS treatment. This data suggests that when the crown of the plant is compacted, there can be more damage to the crown and root system rather than if the weight of the tire was evenly distributed across the crown and surrounding soil. This is conflicting to results where Glab (2013) found that the roots

of red clover in the 0-5 cm depth were not affected by soil compaction, though they did find that the 4 pass tractor system resulted in lower root dry weight in the 10-15 cm soil layer.

3.4 Discussion

Though there was not a discernable trend when looking at the impact of variety with compaction on herbage accumulation, the number of shoots per plant was significantly suppressed. From this, it is presumed that because this is a young stand of alfalfa, the plant was resilient enough to compensate for the damage by increasing the width of the shoots as well as the height of each shoot. Therefore, herbage accumulation was not noticeably affected even with fewer shoots because the plant had overall taller shoots that have growthier, bigger stems. However, the compaction is likely causing the stand to self-thin once it reaches a certain threshold, and in this study, the threshold was between harvest 3 and harvest 4. This suggests that there is a decline in overall plant vigor as shown in the decrease in the number of shoots per plant as the season progressed. One reason for this could be due to the fact that even though the crown of the plant is not being compacted, the compacted soil is having an effect on the basal buds causing decreased shoot growth. These results are similar to results found in a study where alfalfa yield was reduced by 17% in the repeated traffic treatment where the plot was trafficked 100% after each harvest (Meek et al., 1988). The reduction in herbage accumulation can be attributed to damage to the regrowth buds due to wheel traffic and compaction (Grimes et al., 1978). These larger stems lead to more fiber and less digestibility even though the plants were harvested at a younger growth stage when compared to the control. If this study were to be repeated on a stand for three to four years, the suppression of shoots per plant could have a significant effect on yield, leading to why many producers are moving away from producing alfalfa. Undersander (2010) found that the sooner the wheel traffic drives over the plants, the less damage there will likely be. For example, silage chopping 1 day after mowing may cause less yield reduction when compared to baling 4 or 5 days after mowing (Undersander, 2010). With

machinery equipment used for harvesting getting increasingly larger due to trying to get through the field as quickly as possible, the alfalfa yield and quality can be negatively impacted.

There was a trend in which the bulk density increased with each harvest compaction. Contrary to other studies changes in bulk density did not significantly impact yield (Glab, 2011). However, it should be noted that the bulk density values for any of our plants did not reach restricting conditions of 1.40 g/cm^3 or greater (NRCS). Also, the soil from this experiment differed from field soils in the number of compactions the soil has experienced. Field soils have been subjected to many more passes than the soils in this greenhouse study which could explain the contrary results from other studies.

The results from this study are conflicting with the field study conducted at the University of Wisconsin-Madison where the 5 pass hay treatment was consistently the worst yielding (Williams et al., 2021). Another study conducted in California on sandy loam soil where there were four harvests spread over two years found that when alfalfa plants were hit with multiple tractor passes during a harvest, there was a significant decrease in stand density (Rechel et al., 1991). Another study found that harvesting alfalfa six times in a season reduced yields by 23% when compared to only harvesting four times (Kallenbach et al., 2002).

The differences seen could be due to the varietal differences between Alfagraze and Ameristand. With Alfagraze being a Georgia variety that could be used for both grazing and hay/silage systems, the variety is known to have several harvests in a season—even up to 8. However, Ameristand being the Wisconsin variety is primarily used for hay and silage production systems and is known for fewer harvests in a season—around 4. These slight differences in the soil characteristics and production capabilities could be contributing to the varietal differences in this study. Even though yield was not significantly different throughout

the season, quality was suppressed, especially in Alfagraze. This is conflicting with the results found in a study where Alfagraze, the grazing variety, had as good or better than the modern hay-type alfalfa (Kallenbach et al., 2002). Brummer and Bouton (1991) found that grazing-tolerant varieties, such as Alfagraze, had many morphological differences compared to hay-types including smaller diameter stems, which is similar to what the current study found. These smaller diameter stems can be associated with greater forage quality.

When comparing ADF and NDF values, Kallenbach et al. (2002) found that when alfalfa was harvested four times a year, the ADF and NDF were higher when compared to alfalfa harvested six times a year. These findings also showed that CP was highest when harvested six times a year (Kallenbach et al., 2002). This is consistent with the current study's findings.

The general reduction in shoot growth due to the increased effect of compaction resulting in increased bulk density is in agreement with several studies (Mapfumo et al., 1998); however, they are conflicting with Wolkowski (1991) which found that shoot growth increased as bulk density increased.

These results are supported by Glab (2013) that found that multiple tractor passes significantly change soil properties. The more traffic a field gets, the higher the bulk density gets, which eventually affects plant growth. Grimes et al. (1978) found that penetrometer resistance reached a peak at 15 cm below the surface when evaluating soil compaction due to wheel traffic. Because of this, it was found that 80% of the variation in root length density was due to the increased soil bulk density due to wheel traffic (Grimes et al., 1978).

When comparing the root system of each plant to the productivity of the plant, there are some contradicting results. For example, there was a significant interaction between timing and compaction for damage to the top 8 cm of roots where for crown-only compaction, 1 pass

silage/hay timing had the most damage when compared to the other timings. This is not consistent with the results from the yield of harvest 6. Even though the roots had more cracks and damage, the plant yield did not suffer. However, for soil only compaction for the top 8 cm of damage to the root, 5 pass hay timing had the most damage to the roots when compared to all other timings which is consistent with the results from the yield of harvest 6 where the 5 pass hay timing for the soil only compaction had the lowest yield. Soil bulk density could also be contributing to the damage to the roots in that the soil only compaction had significantly higher bulk densities.

For the mass of the top 8 cm of the root system, Alfagraze had the highest mass for the 1 pass silage/hay timing and the 5 pass silage timing had the lowest average mass. This can be supported by the yield from harvest 6 in that 1 pass silage/hay timing had the highest yield and the 5 pass silage timing had the lowest yield for Alfagraze. This could mean that the roots were aiding in the growth of the plant, and the fewer roots that a plant has, the less growth it will have, which affects yield. For Ameristand, 3 pass silage timing had the lowest average root mass and the lowest yielding for harvest 6.

3.5 Conclusion

From these results, we can conclude that compaction does affect plant yield. There were no discernable trends for yield other than there was a threshold at (between harvests 3 and 4) which compaction started to damage the plant significantly. CP was greater for no compaction controls. The bulk density increased throughout the season but not to a level that restricted root growth. However, the S treatment had a higher bulk density compared to other treatments. For the root evaluations, Ameristand had more total root mass, but the controls of both varieties had the least amount of cracks and damages to the top 8 cm of roots.

The evaluation of long-term results is needed to give important information regarding new management practices. We know that alfalfa stand life is declining. Years ago, alfalfa stands could go five years without having to be re-planted, whereas nowadays, a producer is fortunate to get three good, productive years from a stand before having to re-plant alfalfa. Because of the yield loss, many producers across the Mid-West US are moving away from producing alfalfa because of the extra cost due to stand loss leading to decreasing yields. By quantifying the effect of timing and type of compaction, methods of harvesting can be adapted to help preserve stand life.

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Tables and Figures

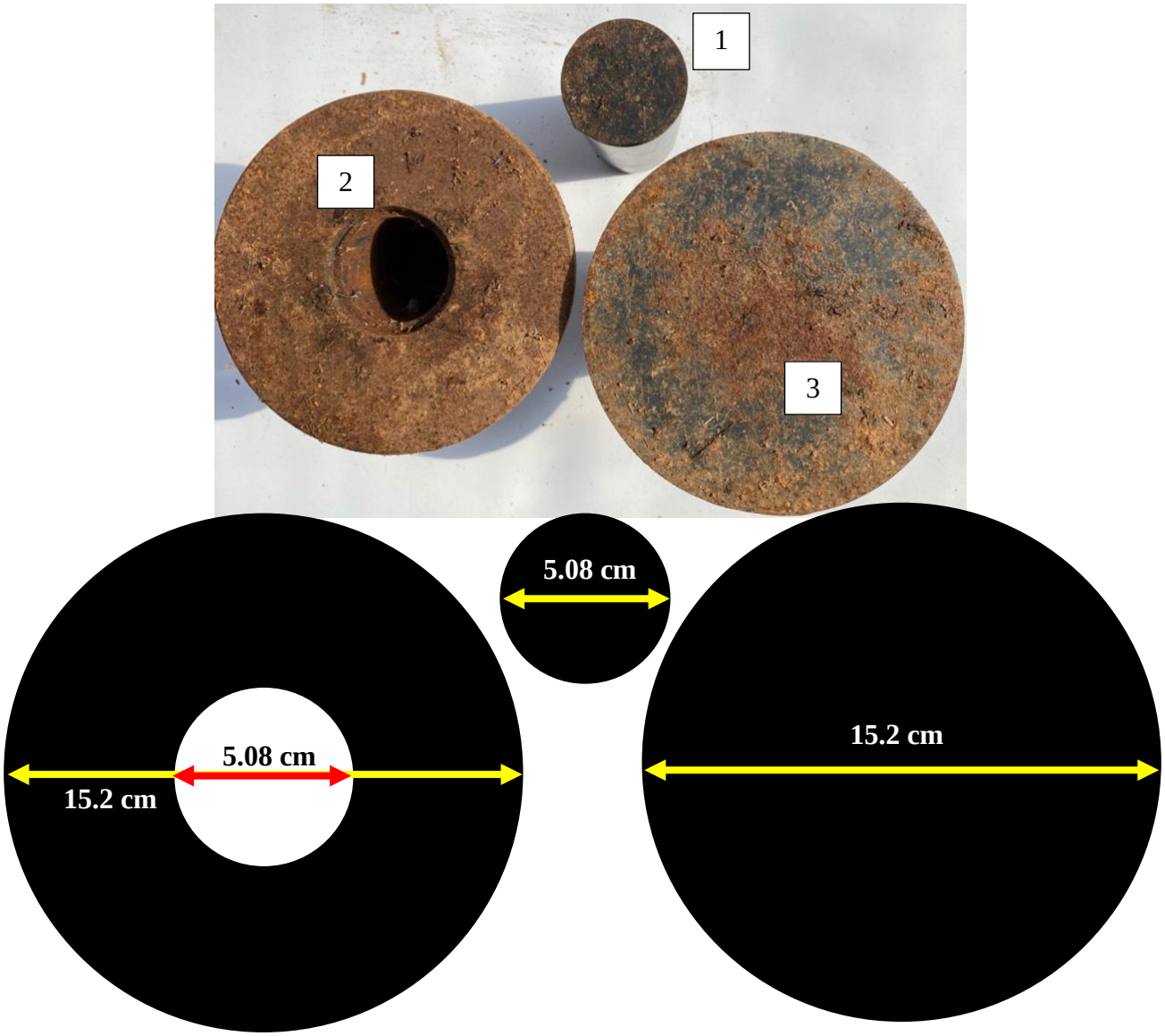

Figure 3.1. Compaction foot used in this study that attached to the pneumatic press and compacted the crown only (1; C), soil only (2; S), or crown and soil (3; CS). The C foot was used to compact the crown of the plant but not the surrounding soil. The S foot was used to compact the soil surrounding the plant, but not the crown of the plant. The CS foot was used to compact both the crown of the plant and the surrounding soil. The device was set to uniformly apply 207 kPa of downforce.

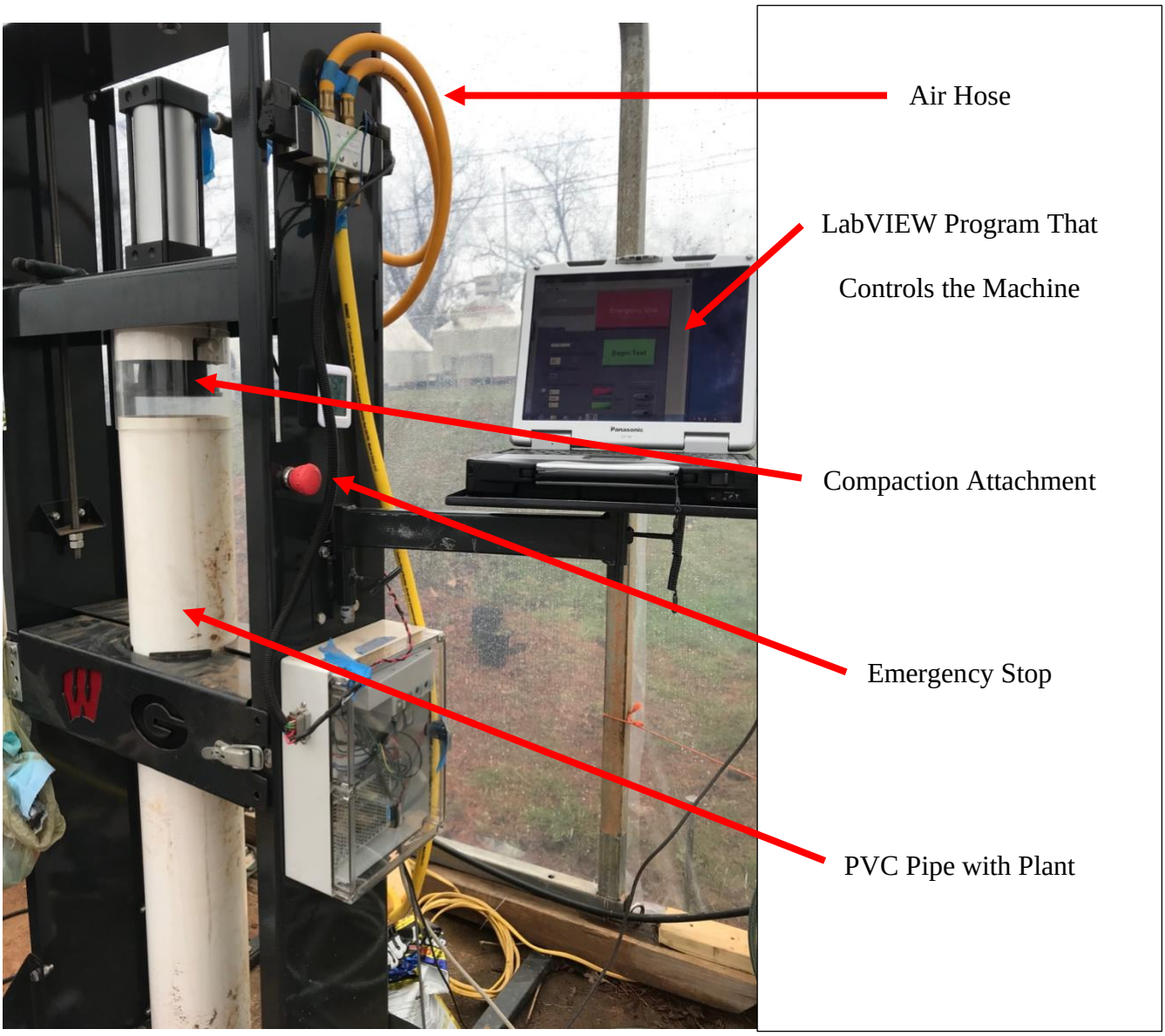

Figure 3.2. Annotated photograph of the pneumatic device used to apply the downforce treatments, which was built at the University of Wisconsin-Madison and described by Willams (2021).

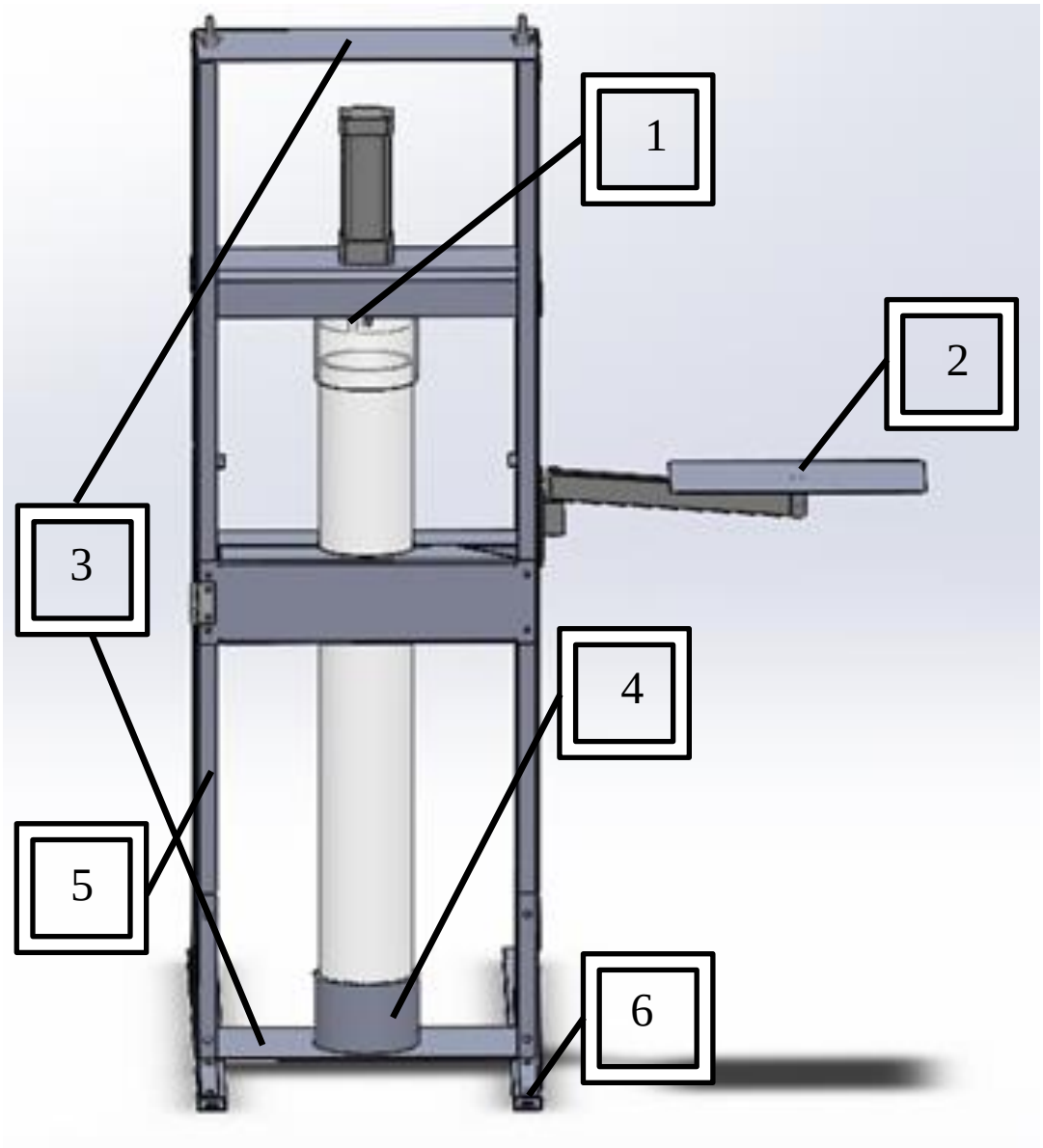

Figure 3.3. Front view of the pneumatic device used to apply the downforce treatments with the compaction attachment in which each attachment was screwed in (1), computer stand (2), top and bottom plates (3), PVC centering tube (4), supporting legs (5), and base legs (6). The pneumatic cylinder was powered by compressed air (not depicted). Figure adapted from Williams (2021).

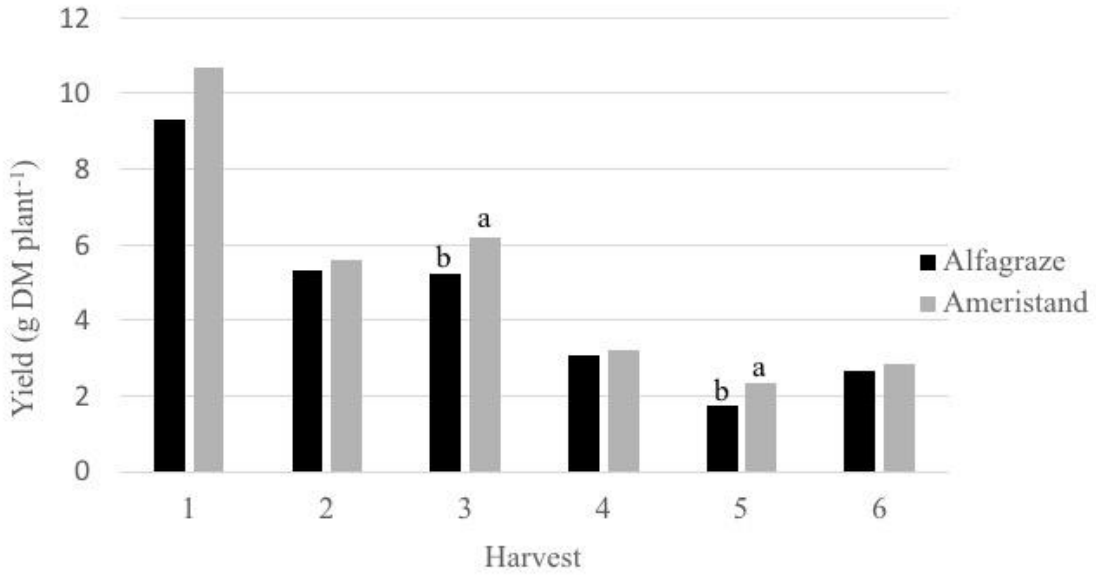

Figure 3.4. Herbage mass (g DM plant^{-1}) produced by Alfagraze 600RR (black columns) and AmeriStand 435 TQ RR (gray columns) at each harvest date during the 2020 growing season. Harvest dates in 2020 were 14 April 2020 (SEM=0.46), 26 May 2020 (SEM=0.22), 23 June 2020 (SEM=0.22), 14 July 2020 (SEM=0.14), 11 August 2020 (SEM=0.12), and 15 September 2020 (SEM=0.11). Within each harvest period, means with different letters indicate a significant difference ($\alpha = 0.05$).

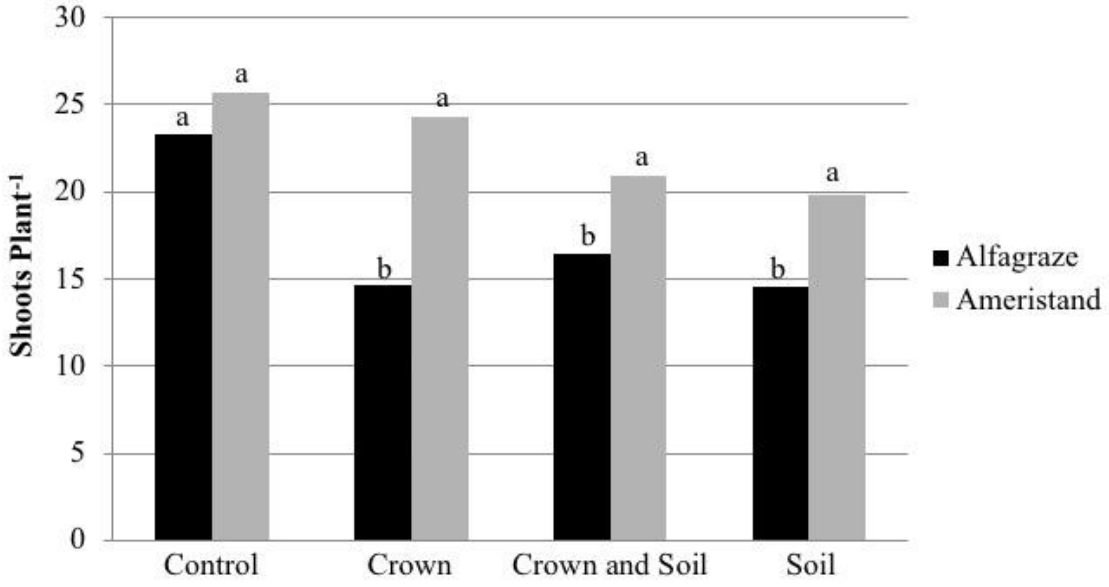

Figure 3.5. Mean shoot production **(**shoots plant^{-1}) at harvest for two varieties, Alfagraze 600RR and AmeriStand 435TQ RR, following the application of the crown, soil, and crown and soil downforce treatments and the untreated control. Data presented are means across harvests 2 through 6, the harvest dates that followed the application of the treatments. Means with differing letters indicate a significant difference ($\alpha = 0.05$) separated by Tukey-Kramer test.

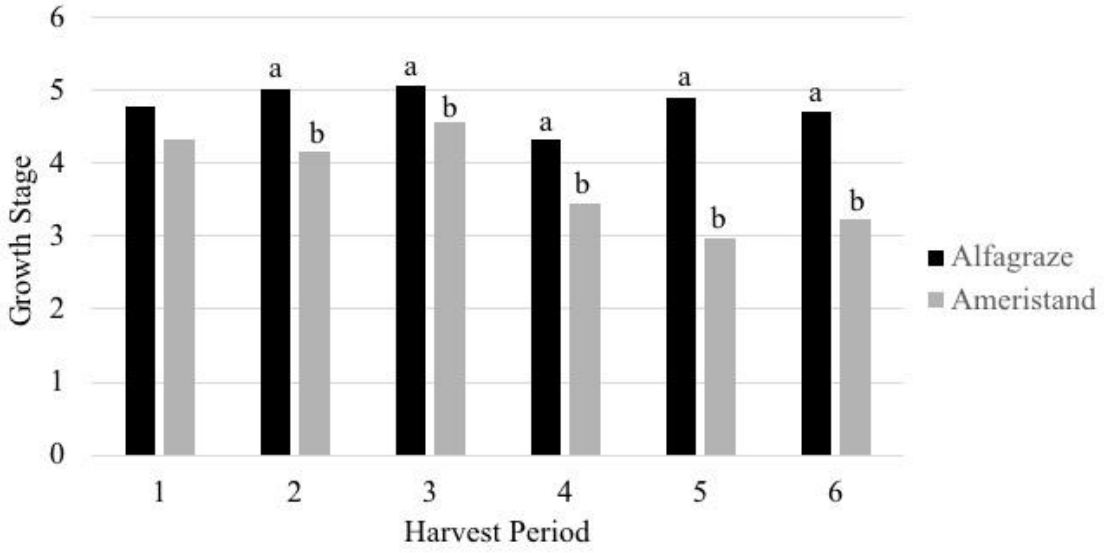

Figure 3.6. Mean stage count of Alfagraze 600 RR (black columns) and AmeriStand 435TQ RR (gray columns) at each harvest date during the 2020 growing season. Harvest dates in 2020 were 14 April 2020 (SEM=0.18), 26 May 2020 (SEM=0.16), 23 June 2020 (SEM=0.13), 14 July 2020 (SEM=0.12), 11 August 2020 (SEM=0.16), and 15 September 2020 (SEM=0.13). Within each harvest period, means with different letters indicate significant difference ($\alpha = 0.05$).

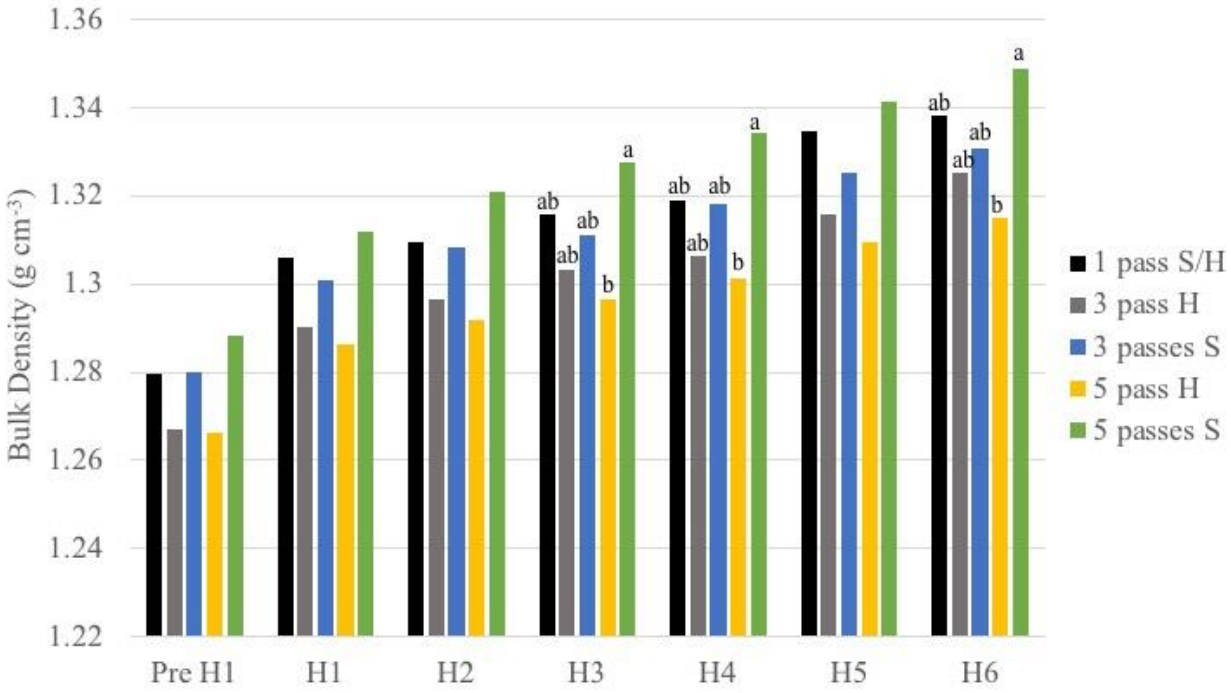

Figure 3.7. Mean bulk density for the five traffic pattern treatments (1-pass silage/hay, black; 3-pass hay, gray; 5-pass hay, blue; 3-pass silage, yellow; and 5 pass-silage, green) before the first harvest (Pre H1) at each of the six harvests (H1 through H6) during 2020. Within each harvest period, means with different letters indicate significant difference ($\alpha = 0.05$).

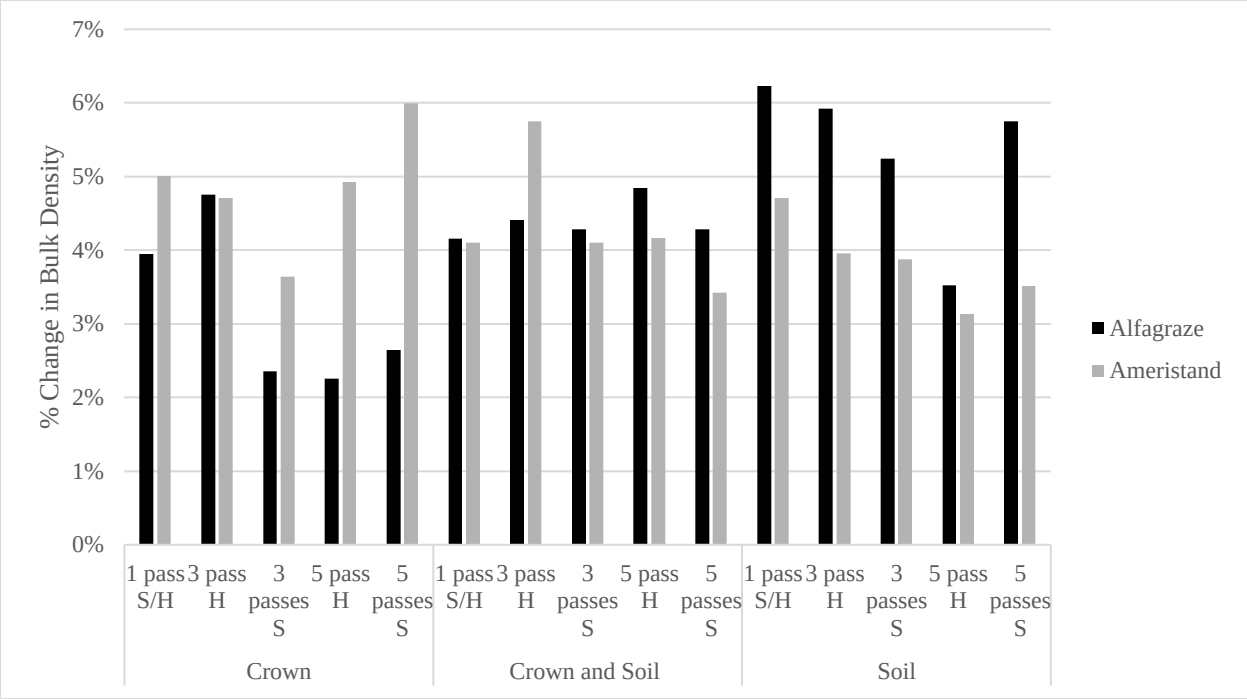

Figure 3.8. Mean change in bulk density (%) for the five traffic pattern treatments (1-pass silage/hay, 3-pass hay, 5-pass hay, 3-pass silage, and 5 pass-silage) within the three compaction types (crown, soil, and crown and soil) for each variety (Alfagraze 600 RR and AmeriStand 435 TQ RR) from before the first harvest (Pre H1) to after the sixth harvest during 2020.

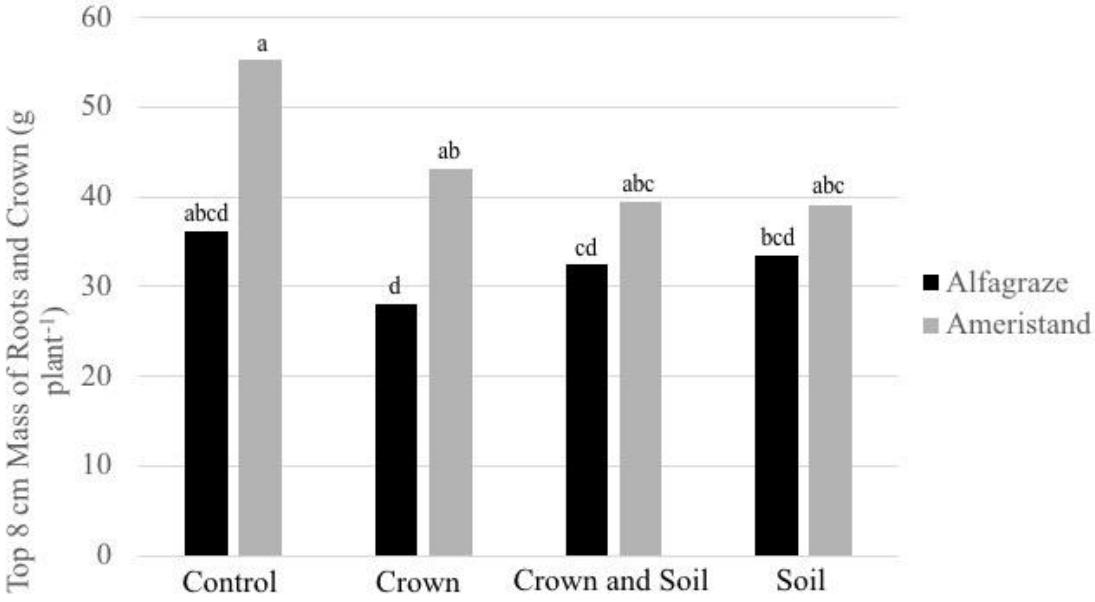

Figure 3.9. Mean mass of the top 8 cm of roots and crown of Alfagraze 600 RR (black columns) and AmeriStand 435 TQ RR (gray columns) at the end of the 2020 growing season. Means with differing letters indicate a significant difference ($\alpha = 0.05$).

Table 3.1. Timing of simulated machinery traffic patterns and the common machinery sequences that were simulated by the treatment patterns in this study. Each simulated traffic pattern treatment represented is mimicking the machinery that would be used in each type of harvest and at the time at which the traffic patterns would occur in the field. 1-pass silage/hay treatment is simulating a mower passing over the alfalfa 0 hrs after cutting (harvest). 3-pass silage treatment represents a mower passing over at 0 hrs after cutting, a merger at 24 hrs post-harvest, and a forage harvester at 26 hrs post-harvest. 5-pass silage treatment represents a mower passing over the plants at harvest, a merger at 24 hrs post-harvest, a rake 24 hrs post-harvest, a forage harvester at 26 hrs post-harvest, and a transport vehicle at 26 hrs post-harvest. 3-pass hay treatment represents a mower passing over the plants at harvest (0 hrs), a merger or rake at 48 hrs post-harvest, and a baler 52 hrs post-harvest. 5-pass hay treatment represents a mower passing through the field at harvest (hr 0), a merger and a rake at 48 hrs post-harvest, and a baler and transport vehicle at 52 hrs post-harvest.

	Machinery Pass Timing	Simulated Machinery
	hrs after cutting	
1 Pass Silage/Hay	0	mower
3 Pass Silage	0, 24, 26	mower, merger, forage harvester
5 Pass Silage	0, 24, 24, 26, 26	mower, merger, rake, forage harvester, transport vehicle
3 Pass Hay	0, 48, 52	mower, merger or rake, baler
5 Pass Hay	0, 48, 48, 52, 52	mower, merger, rake, baler, transport vehicle

Table 3.2. Mean moisture readings taken at the beginning of each day prior to the compaction event specified for each of the six harvests during the season. Harvest dates in 2020 were 14 April 2020 (SEM=0.21), 26 May 2020 (SEM=0.14), 23 June 2020 (SEM=0.19), 14 July 2020 (SEM=0.71), 11 August 2020 (SEM=0.21), and 15 September 2020 (SEM=0.21).

	Harvest Period					
Moisture Reading Hour	**1**	**2**	**3**	**4**	**5**	**6**
	---------- *% vol* ----------					
Hour 0 (harvest)	12.3	6.8	7.8	15.2	9.7	12.3
Hour 24	9.2	7.2	8.1	8.5	7.4	9.2
Hour 48	8.7	6.6	5.9	7.4	6.4	8.7

Table 3.3. Mean herbage accumulation for timing treatments and control (0 passes) for Alfagraze 600 RR and AmeriStand 435TQ RR at each harvest period during 2020. Harvest dates in 2020 were 14 April 2020 (SEM=0.46), 26 May 2020 (SEM=0.22), 23 June 2020 (SEM=0.22), 14 July 2020 (SEM=0.14), 11 August 2020 (SEM=0.12), and 15 September 2020 (SEM=0.11). Means within a column without a common superscript differ ($\alpha = 0.05$).

		Harvest Period					
Variety	**Timing**	**1**	**2**	**3**	**4**	**5**	**6**
Herbage Accumulation		----------*g DM tube^{-1}*----------					
Alfagraze	0 passes	12.67a	5.67a	5.33ab	4.00a	2.00ab	3.67a
	1 pass S/H	8.44a	4.89a	5.00ab	4.00a	1.22b	3.11a
	3 pass hay	8.67a	3.78a	3.44b	1.56a	1.33b	2.22a
	3 passes silage	10.90a	6.70a	6.90a	3.70a	2.30ab	3.10a
	5 pass hay	11.50a	7.00a	6.90a	3.60a	2.10ab	2.50a
	5 passes silage	6.27a	4.09a	3.73b	2.18a	1.55b	2.18a
Ameristand	0 passes	8.00a	5.00a	5.67ab	3.67a	1.67ab	3.00a
	1 pass S/H	8.89a	5.67a	5.11ab	3.67a	1.78ab	3.22a
	3 pass hay	8.80a	5.00a	5.80ab	2.50a	1.50b	2.80a
	3 passes silage	12.67a	5.56a	6.78a	3.00a	3.11a	2.33a
	5 pass hay	11.30a	5.60a	6.70a	3.00a	2.10ab	2.60a
	5 passes silage	12.78a	6.44a	6.78a	3.89a	3.56a	3.33a
	SEM	0.46	0.22	0.22	0.14	0.12	0.11

Table 3.4. Mean herbage accumulation for compaction treatments and control for Alfagraze 600 RR and AmeriStand 435TQ RR at each harvest period during 2020. Harvest dates in 2020 were 14 April 2020 (SEM=0.46), 26 May 2020 (SEM=0.22), 23 June 2020 (SEM=0.22), 14 July 2020 (SEM=0.14), 11 August 2020 (SEM=0.12), and 15 September 2020 (SEM=0.11). Means within a column without a common superscript differ ($\alpha = 0.05$).

		Harvest Period					
Variety	**Compaction Treatment**	**1**	**2**	**3**	**4**	**5**	**6**
		---------- *g DM tube^{-1}* ----------					
Alfagraze	Crown	9.7a	5.3a	5.0a	2.5bc	1.5bc	2.1b
	Soil	9.0a	5.9a	5.9a	3.9ab	2.2abc	3.4a
	Crown and Soil	8.8a	4.6a	4.6a	2.5bc	1.4c	2.3b
	Control	12.7a	5.7a	5.3a	4.0ab	2.0abc	3.7a
Ameristand	Crown	9.1a	5.5a	5.9a	2.3c	2.3ab	2.9ab
	Soil	10.6a	5.8a	6.1a	3.3ab	2.3a	2.8ab
	Crown and Soil	13.0a	5.7a	6.8a	4.0a	2.6a	2.9ab
	Control	8.0a	5.0a	5.7a	3.7abc	1.7abc	3.0ab
	SEM	0.46	0.22	0.22	0.14	0.12	0.11

Table 3.5. Mean forage nutritive values for compaction treatments and control for Alfagraze 600 RR and AmeriStand 435TQ RR at each harvest period during 2020. Harvest dates in 2020 were 14 April 2020, 26 May 2020, 23 June 2020, 14 July 2020, 11 August 2020, and 15 September 2020. Means within a column without a common superscript differ ($\alpha = 0.05$).

		Harvest Period					
Variety	**Compaction Type**	**1**	**2**	**3**	**4**	**5**	**6**
		Crude Protein					
		g kg $^{-1}$					
Alfagraze	Crown	19.3b	21.3b	20.4c	22.7b	22.2c	22.8cd
	Soil	20.3ab	22.2ab	21.5bc	22.3b	22.8c	22.5d
	Crown and Soil	20.4ab	23.2ab	21.7bc	23.6ab	23.3abc	22.8cd
	Control	22.2ab	25.3a	23.7 ab	24.2ab	23.2abc	22.5cd
Ameristand	Crown	23.0a	25.1a	24.9a	24.7a	24.4a	24.8ab
	Soil	20.4ab	23.9a	22.9ab	23.8ab	23.1bc	23.9bc
	Crown and Soil	23.0a	25.2a	23.8a	24.0ab	24.1ab	24.2abc
	Control	24.8a	25.5a	25.6a	25.7a	25.8a	26.1a
	SEM	0.40	0.31	0.26	0.21	0.19	0.19
		Neutral Detergent Fiber					
Alfagraze	Crown	32.2a	32.4a	38.4a	35.3ab	33.7a	35.1a
	Soil	30.8a	32.4a	38.0a	37.0a	32.7a	35.2a
	Crown and Soil	31.3a	28.7b	36.2ab	32.4bc	29.9b	33.2ab
	Control	29.7ab	26.2b	32.8bcd	30.3bc	31.3ab	33.7ab
Ameristand	Crown	26.3b	24.7b	28.6d	29.3c	28.2b	30.4b
	Soil	30.6a	28.0b	33.0bc	32.7b	29.3b	30.9b
	Crown and Soil	29.7ab	25.8b	32.4cd	33.2b	29.3b	32.2b
	Control	24.1b	24.1b	29.3cd	27.3c	26.9b	28.6b
	SEM	0.52	0.53	0.52	0.48	0.39	0.37
		Acid Detergent Fiber					
Alfagraze	Crown	27.1a	27.5a	32.9a	30.7ab	29.0a	31.0a
	Soil	26.2a	27.8a	32.7a	31.9a	28.4a	31.2a
	Crown and Soil	26.5a	24.3b	30.7ab	27.9c	26.2b	29.5ab
	Control	24.8ab	22.1b	27.7bc	25.6cd	28.9ab	29.4abc
Ameristand	Crown	22.8b	21.2b	25.1c	25.2d	24.5bc	26.4cd
	Soil	26.0a	24.3b	28.8b	28.3bc	25.9b	27.3bcd
	Crown and Soil	25.8a	22.5b	27.9bc	28.5bc	25.8b	28.6bc
	Control	20.1b	19.9b	24.3c	23.2d	21.9c	24.3d

	SEM	0.44	0.44	0.44	0.43	0.34	0.35
				IVTDMD48			
Alfagraze	Crown	83.1c	83.7d	78.6c	82.5bc	82.3b	81.8b
	Soil	83.9bc	83.9cd	79.3c	80.8c	84.0b	81.3b
	Crown and Soil	84.2bc	86.6bc	80.8bc	84.5ab	86.0a	82.3b
	Control	85.9abc	89.4ab	83.8ab	86.5ab	85.8ab	82.6ab
Ameristand	Crown	88.4a	90.2a	87.0a	87.6a	88.4a	86.0a
	Soil	85.2bc	88.1ab	83.5ab	84.9ab	87.0a	85.3a
	Crown and Soil	86.6ab	90.2a	84.1a	84.9ab	87.4a	84.8a
	Control	90.4a	90.1ab	87.2a	88.4a	89.0a	87.0a
	SEM	0.45	0.46	0.46	0.42	0.35	0.33

Table 3.6. Mean bulk density for compaction treatments for Alfagraze 600 RR and AmeriStand 435TQ RR at each harvest period during 2020. Harvest dates in 2020 were 14 April 2020 (SEM=0.003), 26 May 2020 (SEM=0.003), 23 June 2020 (SEM=0.004), 14 July 2020 (SEM=0.004), 11 August 2020 (SEM=0.005), and 15 September 2020 (SEM=0.004) with 0 being at the start of the trial. Means within a column without a common superscript differ (α = 0.05).

		Harvest Period						
Variety	**Compaction**	**0**	**1**	**2**	**3**	**4**	**5**	**6**
		g cm^{-3}						
Alfagraze	Crown	1.28ab	1.30ab	1.30ab	1.31ab	1.31ab	1.31b	1.33ab
	Soil	1.29a	1.32a	1.33a	1.33a	1.34a	1.35a	1.35a
	Crown and Soil	1.29a	1.32a	1.32a	1.33a	1.34a	1.34ab	1.35a
Ameristand	Crown	1.26ab	1.28ab	1.29b	1.29b	1.29b	1.32ab	1.33ab
	Soil	1.27ab	1.30ab	1.30ab	1.31ab	1.31ab	1.32ab	1.32ab
	Crown and Soil	1.25b	1.28b	1.29b	1.29b	1.30b	1.30b	1.31b
	SEM	0.003	0.003	0.004	0.004	0.004	0.005	0.004

Table 3.7. Mean bulk density and resistance depth at a penetrometer resistance of 1380 kPa of pressure for Alfagraze 600 RR and AmeriStand 435TQ RR.

Variety	Compaction	Timing	Bulk Density	Resistance Depth
			g cm^{-3}	*cm*
Alfagraze	Crown	1 Pass Silage/Hay	1.34	19.1
		3 Pass Silage	1.31	21.0
		5 Pass Silage	1.31	20.3
		3 Pass Hay	1.34	8.9
		5 Pass Hay	1.31	18.2
	Soil	1 Pass Silage/Hay	1.35	15.2
		3 Pass Silage	1.34	6.7
		5 Pass Silage	1.39	4.4
		3 Pass Hay	1.38	8.9
		5 Pass Hay	1.32	11.4
	Crown and Soil	1 Pass Silage/Hay	1.34	1.8
		3 Pass Silage	1.34	16.9
		5 Pass Silage	1.33	21
		3 Pass Hay	1.36	17.4
		5 Pass Hay	1.38	26.7
Ameristand	Crown	1 Pass Silage/Hay	1.37	17.8
		3 Pass Silage	1.35	12.7
		5 Pass Silage	1.31	8.3
		3 Pass Hay	1.3	21.6
		5 Pass Hay	1.3	16.1
	Soil	1 Pass Silage/Hay	1.35	15.9
		3 Pass Silage	1.36	10.6
		5 Pass Silage	1.39	5.5
		3 Pass Hay	1.27	12.7
		5 Pass Hay	1.26	22.4
	Crown and Soil	1 Pass Silage/Hay	1.28	15.2
		3 Pass Silage	1.28	10.2
		5 Pass Silage	1.33	6.8
		3 Pass Hay	1.34	12.7
		5 Pass Hay	1.32	7
		5 Pass Hay	1.32	7

Table 3.8. Mean count of cracks and damage per plant for the top 8 cm of roots and crown for two varieties 1) Alfagraze 600RR and 2) AmeriStand 435TQ RR each with the three compaction types and untreated control. Means within the column without a common superscript differ (α=0.05).

Variety	Compaction	Cracks and Damage per Plant
Alfagraze	Crown	3.5ab
	Soil	3.4ab
	Crown and Soil	2.4ab
	Control	0b
Ameristand	Crown	3.1ab
	Soil	4.0a
	Crown and Soil	2.2ab
	Control	1.3ab
SEM		1.5

CHAPTER 4

SUMMARY AND CONCLUSION

In 2019, there was over 6.7 million hectares of alfalfa harvested in the United States (USDA/NASS, 2019); this substantial amount of alfalfa production shows the impact of minimizing traffic across fields in order to maximize alfalfa yields. Reduction in alfalfa yield and hay quality is a major reason for growers to decide to remove alfalfa field from production. Because of heavy wheel traffic where the plants are trafficked multiple times per cutting, risk of damage to the crown increases causing decreased root and shoot growth (Schmierer et al., 2004).

The use of machinery to conduct field operation is necessary and cannot be eliminated. However, methods can be utilized to reduce the effect of wheel traffic on crop production, which includes reducing soil compatibility, the amount of vehicle traffic, and the size of the vehicles (Raper, 2005). Numerous experiments have been conducted with varying axle loads that completely covered a plot's area in order to assess the soil properties and crop reduction due to the load. One study conducted in Minnesota found that when applied loads of 9 and 18 Mg applied to two types of soil had little change occurred to the subsoil when the soil was dry; however, when the soil was wet, bulk density increased significantly (Voorhees et al., 1984). Using dual tires has been a method used to spread the load over the soil surface. Spreading the same weight over a larger contact area decreases the ground pressure (Hakansson et al., 1988). Dual tires traffic twice the width of vehicle track and may cause excessive surface compaction

depending on the cropping system (Raper, 2005). Increasing tire size could offer a method to increase the area of a tire that comes in contact with the soil.

In this study, two varieties were chosen as representative varieties for those recommended and grown in Wisconsin (AmeriStand 435QT RR) and Georgia (Alfagraze 600 RR). Each variety has a different fall dormancy rating, but both have been developed to be traffic tested and Roundup Ready. It is known that depth of crown in alfalfa is inversely related to fall dormancy ratings, so these varieties exhibit differing crown locations in the soil profile. Reducing the machinery traffic during alfalfa hay and silage harvests are essential for maintaining stand density and maximizing yield. The effects of wheel traffic machinery at varying times of traffic can have a drastic effect on yield, nutritive value, and bulk density of alfalfa stands. With alfalfa playing an important role as a feed source for livestock, maximizing yields is important to minimizing costs to producers. Considering this, a trial was conducted to 1) quantify the effects of downforce caused by machinery traffic on alfalfa crowns and surrounding soil on yield and nutritive values and 2) determine the effects of compaction on soil bulk density and root development.

Results indicate that compaction does affect yield and nutritive value of alfalfa as well as increases the bulk density of the soil. For yield, there is a threshold at which the plant can take the traffic until it severely affects yield. From this, it is presumed that because this is a young stand of alfalfa, the plant was resilient enough to compensate for the damage by increasing the width of the shoots as well as the height of each shoot. Therefore, yield was not noticeable affected even with less shoots because the plant had overall taller shoots that have growthier, bigger stems. However, the compaction is likely causing the stand to self-thin once it reaches a certain threshold, and in this study, the threshold was between harvest 3 and harvest 4.

Machinery traffic also affects to re-growth vigor of the plant. With more traffic, the plant took longer to recover, and therefore was younger when harvesting affecting nutritive values.

To assess soil changes and how that affects the root system of the plant, samples were taken at the end of the experiment to determine bulk density of each tube. Results from this experiment show that when just the surrounding soil of the plant is compacted, the soil bulk density is higher than if only the crown of the plant were to be compacted. However, in one years time, the soil bulk density did not significantly change or increase to a range in which the plant would observe rooting restrictions.

APPENDIX A

COUNT OF DAMAGED SHOOTS AFTER EACH TIMING OF COMPACTION

Materials and Methods

Machinery traffic can damage many parts of the plant. For some plants, damaging the new shoots would cause the plant to die. However, in alfalfa, new growth stems from the crown. If the shoots are damaged from compaction, the alfalfa is still able to grow unless the crown is damaged. After each hour of simulated compaction, number of damaged shoots were non-destructively counted. Any stems that had been bent more than 45 degrees were counted as damaged.

Results

	Harvest Period					
Timing (Hour)	**1**	**2**	**3**	**4**	**5**	**6**
0	1.97	2.78	3.71	3.59	2.85	3.19
24	3.85	3.67	5.59	5.19	4.47	3.67
26	5.79	4.67	6.31	5.92	5.61	4.19
48	4.77	5.18	5.67	4.46	4.18	4.81
52	5.97	6.12	6.36	5.79	5.03	5.68
SEM	0.19	0.16	0.22	0.18	0.17	0.17

The more the plant was compacted, the more damage to the shoots and crown occurred, as predicted.

APPENDIX B

NORMALIZED DIFFERENCE VEGETATIVE INDEX

Introduction

Vegetative indices have gained popularity in determining the crop health status of plants. Researchers have used vegetative indices to assess and predict presence of disease (Sankaran et al., 2010), insect pressure (Nansen & Elliott, 2016), ground cover (Elmore et al., 2000), and the effects of soil compaction (Al-Gaadi, 2013), using visible light and infrared wavelengths. These indices have the potential to provide instantaneous estimates of plant health without the need to do any time-consuming lab testing.

Vegetative indices are derived by measuring reflectance of plant material with a spectral camera. Photosynthetically active (living) vegetation has a lower reflectance in the visible spectrum than non-photosynthetically active (dead or dormant) vegetation while the reflectance of soil falls between the two (Perry and Lautenschlager, 1984). In addition, leaf reflectance, specifically within the visible light and infrared bands, has been shown to be affected by a variety of physiological stresses (Carter, 1993). Vegetative indices are typically a ratio of linear combinations of the reflectance at discrete wavelengths that highlight the changes in reflectance between plant and non-plant material as well as healthy and stressed plants.

Indices, such as Normalized Difference Vegetative Index (NDVI), provide a means of assessing plant growth and health via remote sensing methods. By measuring the reflectance of alfalfa in the near-infrared band, a linear response to plant growth was provided in alfalfa and in

grasses; however, the response became more than 1.8 Mg ha^{-1} (Hancock & Dougherty, 2007). A negative correlation was found between satellite based NDVI and soil compaction caused by the wheels of center pivot irrigation system in wheat (Al-Gaadi, 2013). Remote sensing and vegetative indices are a proven method for detecting and identifying crop stress conditions throughout the growing cycle and could be used to identify plant stress due to compaction throughout the growing season in order to adjust machine traffic accordingly.

Materials and Methods

After each harvest and compaction, the alfalfa plants were given ten days to re-grow. On the tenth day after harvest, a handheld multispectral sensor (Crop Circle, Holland Scientific) was used to take NDVI measurements. In order to do so, the surrounding plants were covered with a white sheet of paper so that they would not interfere with the reflectance. The NDVI machine was held 30 cm above the plant, and ten measurements were taken. The highest value was recorded for harvest 1-3. After harvest 3, the methodology was changed to record all ten readings and take the average reading to better capture the average of the readings rather than the sigle highest reading.

Results

Table B.1. NDVI values recorded 10 days post harvest to evaluate the alfalfa's re-growth potential. Out of ten values, the highest value was recorded for each treatment.

		Harvest Period		
Variety	**Compaction**	**1**	**2**	**3**
Alfagraze	Crown	0.37_{b}	0.39_{b}	0.53_{a}
	Soil	0.47_{ab}	0.48_{a}	0.45_{ab}
	Crown and Soil	0.40_{b}	0.43_{ab}	0.36_{c}

	Control	0.45_{ab}	0.43_{ab}	0.34_{c}
Ameristand	Crown	0.46_{ab}	0.45_{ab}	0.43_{ab}
	Soil	0.42_{b}	0.46_{ab}	0.40_{bc}
	Crown and Soil	0.55_{a}	0.46_{ab}	0.44_{ab}
	Control	0.51_{ab}	0.47_{ab}	0.54_{a}
SEM		0.02	0.01	0.01

Table B.2. NDVI averages for each treatment for harvest periods 4-6. These measurements were taken as an average of the NDVI readings rather than the maximum readings.

		Harvest Period		
Variety	**Compaction**	**4**	**5**	**6**
Alfagraze	Crown	0.35_{b}	0.43_{a}	0.29_{c}
	Soil	0.36_{b}	0.41_{a}	0.39_{ab}
	Crown and Soil	0.34_{b}	0.39_{a}	0.38_{ab}
	Control	0.47_{a}	0.37_{a}	0.41_{ab}
Ameristand	Crown	0.38_{ab}	0.45_{a}	0.38_{ab}
	Soil	0.39_{ab}	0.41_{a}	0.34_{abc}
	Crown and Soil	0.39_{ab}	0.42_{a}	0.33_{abc}
	Control	0.42_{ab}	0.43_{a}	0.44_{a}
SEM		0.01	0.01	0.01

APPENDIX C

SEMI-AUTOMATED ROOT IMAGE ANALYSIS

Materials and Methods

After the final harvest of the season, the plants and root systems were taken out of the tubes and washed off. Each root system was evaluated and photographed. These photographs were then put into the semi-automated Root Image Analysis program (smRIA) (Narisetti et al., 2019). This program allows for a combination of adaptive thresholding and morphological filtering to determine various quantitative descriptors of the root system architecture such as local width, volume, spatial distribution, and orientation.

Results

Results are currently being analyzed.

APPENDIX D

DIGESTIBLE NEUTRAL DETERGENT FIBER 48 HOURS

Materials and Methods

The samples were dried in a forced air dryer at 60°C until weight was within 0.1 grams of the last measurement and dry matter yield was then obtained. Then each sample was ground to pass a 2-mm screen using a Wiley® Mill (Thomas Scientific, Swedesboro, NJ) and then through a 1-mm screen, in a CT 293 Cyclotec™ Labtec™ Line (Foss, Hillerod, Denmark). Samples were shipped to the University of Wisconsin-Madison to determine digestible Neutral Detergent Fiber at 48 hours (dNDF48) by near-infrared reflectance spectroscopy using a model FOSS 6500 (FOSS NIRS system Inc., Laurel, Maryland) spectrophotometer. The samples were analyzed with the alfalfa hay equation developed by the NIRS Forage and Feed Testing Consortium. Fit statistics calibration for the 2015 Alfalfa Hay NIR equations were as follows: dNDF48, SEC = 1.9956, 1-VR = 0.8854, where SEC = standard of error of calibration and 1-VR = 1-variance ratio is coefficient of determination in cross validation. Statistical comparisons were conducted within harvest periods for the interaction between variety and compaction for all metrics of forage nutritive value.

Results

		Harvest Period					
Variety	**Compaction Treatment**	**1**	**2**	**3**	**4**	**5**	**6**
Alfagraze							
	Crown	13.38a	13.01a	14.45a	14.26a	12.59a	13.66a
	Soil	13.12a	12.77a	14.15a	14.02ab	12.58a	13.39ab
	Crown and Soil	12.9a	11.51ab	13.75ab	12.97cd	11.65b	12.21b
	Control	12.4a	11.05ab	12.65abc	12.43cd	12.24ab	12.80ab
Ameristand							

Crown	11.4a	10.37b	11.29c	12.08d	11.45b	12.44b
Soil	13.0a	11.61ab	12.46bc	13.09c	11.37b	12.23b
Crown and Soil	12.5a	10.74b	12.73ab	13.33bc	11.47b	13.11ab
Control	11.2a	10.14b	11.97bc	11.48d	10.64b	11.86b
SEM	0.2	0.2	0.18	0.14	0.12	0.13

Means within a column without a common superscript differ ($\alpha = 0.05$).

APPENDIX E

HEIGHT OF TALLEST SHOOT

Materials and Methods

Before each harvest, the height of the tallest shoot per experimental unit was measured.

Results

The height of the tallest shoot had a varietal difference ($P < 0.05$) in that Alfagraze was generally a taller plant, whereas Ameristand was a shorter growing plant (Figure E.1). For Alfagraze, when grouping all of the harvests together, the control was significantly shorter compared to the C treatment and the S treatment. For Ameristand, the control was significantly different from the S treatment and the CS treatment.

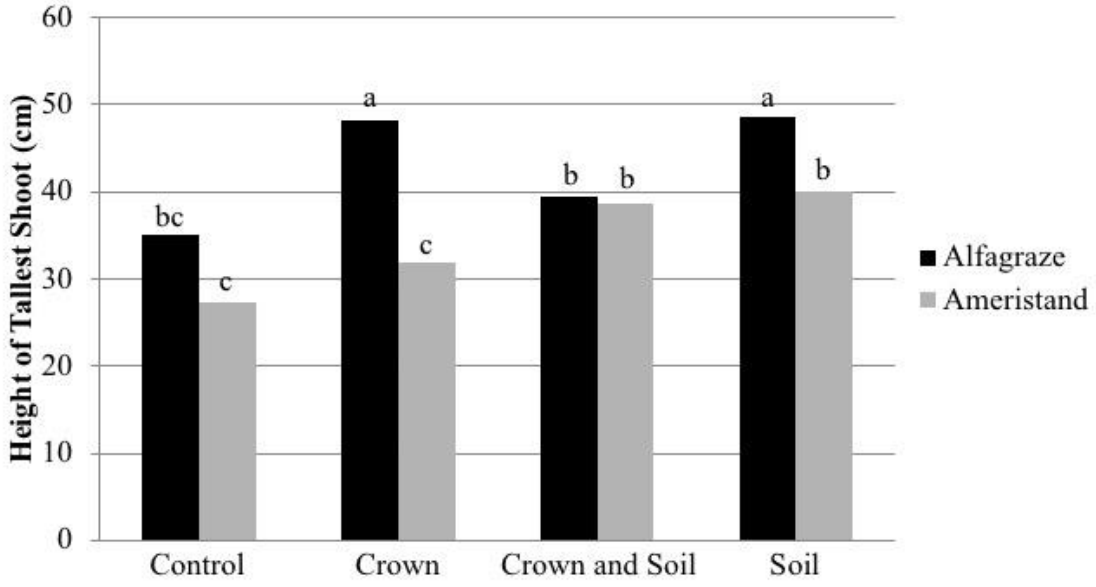

Figure E.1. Height of tallest shoot (cm) at harvest for the two varieties, Alfragraze 600 RR (black) and AmeriStand 435TQ RR (gray), following the application of the crown, soil, and crown and soil downforce treatments and the untreated control. Data presented are means across harvests 2 through 6, the harvest dates that followed application of the treatments. Means with differing letters indicate a significant difference ($\alpha = 0.05$).

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