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Switchgrass Cultivar, Harvest Frequency, Fertilizer Source, and Irrigation Effects on Near-Surface Soil Properties in West-Central Arkansas

Alayna A. Jacobs
University of Arkansas, Fayetteville

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Switchgrass Cultivar, Harvest Frequency, Fertilizer Source, and Irrigation Effects on Near-Surface Soil Properties in West-Central Arkansas

Switchgrass Cultivar, Harvest Frequency, Fertilizer Source, and Irrigation Effects on Near-Surface Soil Properties in West-Central Arkansas

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Crop, Soil and Environmental Science

by

Alayna Jacobs
University of Arizona
Bachelor of Science in Rangeland Ecology and Management, 2008

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University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

Dr. Kristofor Brye
Thesis Director

Dr. Lisa Wood
Committee Member

Dr. Michael Looper
Committee Member

Dr. Larry Purcell
Committee Member

Abstract

Switchgrass (*Panicum virgatum* L.) has been identified as a model bioenergy feedstock crop and is expected to become an important feedstock for future renewable fuel generation. Agronomic management combinations that maximize monoculture switchgrass yield are generally well understood; however, little is known about corresponding effects of differing switchgrass management combinations on near-surface soil properties. The objective of this research was to determine the residual near-surface soil property effects of three years (2008 to 2011) of consistent management combinations to maximize switchgrass biomass production, including cultivar (‘Alamo’ and ‘Cave-in-Rock’), harvest frequency (1-cut and 2-cut systems per year), fertilizer source (poultry litter and commercial fertilizer), and irrigation management (irrigated and non-irrigated). Effects on soil properties were assessed on a Leadvale silt loam (fine-silty, siliceous, semiactive, thermic, Typic Fragiudult) at the USDA-NRCS Booneville Plant Materials Center in Logan County by evaluating soil bulk density, total water stable aggregates (TWSA), soil pH and EC, Mehlich-3 extractable soil nutrients, root density, and surface infiltration. Irrigating switchgrass, which did not increase past biomass production, increased ($p > 0.01$) soil bulk density in treatment combinations where poultry litter was applied (1.40 g cm^{-3}) compared to non-irrigated treatment combinations (1.33 g cm^{-3}). Total WSA concentration was greater ($p < 0.05$) in ‘Alamo’ (0.91 g g^{-1}) than ‘Cave-in-Rock’ (0.89 g g^{-1}) treatment combinations when averaged over all other treatment factors. Root density was greater ($p = 0.031$) in irrigated (2.62 kg m^{-3}) than in non-irrigated (1.65 kg m^{-3}) treatments when averaged over all other treatment factors. Surface infiltration rate under unsaturated conditions was greater ($p = 0.01$) in the 1-cut (33 mm min^{-1}) than 2-cut (23 mm min^{-1}) harvest treatment combinations when averaged over all other treatment factors, while surface infiltration rate under saturated conditions did not differ

among treatment combinations (p > 0.05) and averaged 0.79 mm min^{-1}. Results from this study indicate that management decisions to maximize switchgrass biomass production affect soil properties over relatively short periods of time and further research is needed to develop local best management practices to maximize yield while maintaining or improving soil quality.

Acknowledgments

I cannot fully express my gratitude toward my family, coworkers, mentors, and friends for helping me find the courage to finish this graduate program. Thanks are due first to my parents, Christina and Mike, for teaching me that the only true limits that exist are the ones that I set for myself—their zest for knowledge, love, support, and assiduous determination inspires me to regard major challenges as major opportunities. Though I only inherited a small bit of my mother's nerve, her fighting spirit has carried me through many obstacles. I want to thank my dad for teaching me that persistence makes progress, no matter the task.

When I became a graduate student, my husband and partner-in-crime, Bryan, unknowingly became a unique hybrid of administrative assistant, accountant, therapist, and frozen pizza chef. I am so proud to be his teammate. I want to thank my family for standing with me symbolically and literally by helping me run samples or clean up various messes. Special thanks go to Brandon and Julieann, two wildlife biologists who know more about soil aggregation than they ever cared to learn.

I could not have completed this program without the full support of four very special people at the Booneville Plant Materials Center. I want to thank my supervisor Randy King for encouraging me, accommodating my schedule, and allowing me to run with my ideas; Eddie Pratt for his support and for patiently sharing his extensive technical expertise; Debbie Orick for her invaluable logistical and spiritual support, and Dale Goff for his encouragement and help collecting samples. I will never forget the day Dale pulled me aside and told me everyone had my back at the office, which empowered me to go back to school. I owe them not only for their encouragement, but also for teaching me more than I could ever hope to learn in school. I would also like to thank all the staff members at the Dale Bumpers Small Farms Research Center who were always willing to help with this and any other project.

There are several people who have generously invested their time in my professional and scholastic development. I would like to thank Dr. Ramona Garner for her advice, for expecting great things from me, and for first hiring me on her farm—even after I came in for the interview in a suit and heels. I also want to thank Burthel Thomas for encouraging me to walk in like I already own half the place and I'm about to buy the rest tomorrow—no matter the situation. I am continually inspired by the motivational attitude and the contagious commitment of Ramona and Burthel, who, if they know fear, have never let it keep them from achieving their goals.

My main goal in completing this program was to complete the last step of the scientific method by improving my skills as a technical writer. I would like to thank two people who were excellent role models as technical writers and who were instrumental in helping me achieve this goal: Dr. Kristofor Brye for his seemingly endless patience, insightfulness, and flexibility in allowing me to balance work and school, and Joel Douglas for his invaluable technical advice and dedication to helping me improve my skills as a credible researcher.

Lastly, I would like to thank Michele Helton for her friendship and sampling assistance, Taylor Adams for his help running samples, and Katy Brantley and Jade Ford for their friendship and understanding. I am grateful for the support of my best friend Elsie Stott—thank you for inspiring me with your fearless spirit. I also want to thank my dear friend Julie Osborne for volunteering to help and for always encouraging me.

I feel very fortunate to have had the opportunity to better myself at a great university. I will use the skills gained from this program to work harder as a testament to those who have invested their time and energy in my success.

Dedication

My passion for balancing production agriculture and resource conservation first began during the 6th grade science fair. I installed soil dams and compared the amount of soil erosion occurring at two sites: the neighbor's lush stand of black and blue gramagrass and the overused pasture where I kept my horse. I was lucky to have a very patient land management professional as a consultant. He has been a trusted confidant, mentor, friend, and positive force in my life ever since then. I am extremely grateful to him for encouraging my curiosity in natural systems and helping me gain the confidence to pursue a career in conservation and leadership.

This work is dedicated to Delbert Griego—muchas gracias, Viejo!

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Introduction

Introduction

The United States (U.S.) is the largest consumer of petroleum in the world (18.6 million barrels per day; EIA, 2013a). Even though the U.S. is also the third largest producer of petroleum, domestic production cannot keep pace with demand, as 40% of petroleum products consumed in the U.S. were net imports from other countries (EIA, 2013a). Burning fossil fuels also releases carbon dioxide gas, which contributes to the disruption of global climate processes. Promoting the generation and development of domestic fuel supplies while reducing carbon dioxide gas emissions from fossil fuel combustion has become a central issue in global policy.

Concerns related to the effects of global warming and possible shortages of finite fossil fuel sources have led to government-mandated regulations encouraging development of alternative fuels. Currently, only 12% of electricity generated in the United States is from renewable sources, such as wind, hydroelectric, and biomass (EIA, 2013b). Significant investments have been made by both the public and private sector in order to identify and develop practical solutions to these problems. According to the Energy Policy Act of 2005 and the Renewable Fuel Standard Program of 2007, 36 billion gallons of renewable fuel must be blended into the nation's transportation fuel supply by 2022 (US-EPA, 2013).

One potential solution is the conversion of plant biomass to fuel. Using plant biomass as a source of cellulosic biofuel as an alternative to fossil fuel is attractive because plants use sunlight for energy and capture existing carbon dioxide in the atmosphere. In addition, local economies could produce fuel for domestic use. Though bioenergy derived from lignocellulosic sources may not provide a complete alternative to the massive energy needs of the United States, lignocellulosic bioenergy sources may alleviate a portion of the negative impacts of burning fossil fuels and contribute to an extended supply of fossil fuels for the future (Parrish and Fike, 2005).

Plant biomass can be utilized as a fuel in two major ways: by burning it or mixing it with coal (i.e., co-firing) to generate electricity (Tillman, 2000), or conversion to ethanol. Co-firing is desirable because it reduces the amount of coal burned while maintaining a high level of energy output. Blending biomass into coal in the co-firing process releases less carbon dioxide and other greenhouse gases. Mixing renewable fuels with a non-renewable fuel like coal may also extend the supply of finite resources further into the future.

One reason using plant biomass rather than corn grain to produce ethanol is desirable is the avoidance of sacrificing food for fuel production. Corn is an important food crop for human and livestock consumption. Corn makes up over 95% of the grain rations for fed cattle, and the United States is the world's largest producer of beef (USDA/ERS, 2012). Use of a non-food cellulosic material for conversion to ethanol offers an attractive solution to the problem of competing with the livestock feed industry.

Corn is an annual crop that must be replanted every year, which requires large amounts of nutrients and fertilizers. The extensive preparation required for conventional corn production is regarded as causing more total soil erosion than any other crop grown in the United States (Pimentel et al., 1995). Dedicated energy crops, or crops grown exclusively for conversion to renewable fuel sources, emerged as potential sources of cellulose from American lands. These crops included short-rotation woody crops, such as willow (*Salix* spp.) and cottonwood (*Populus* spp.*)*, annual crop residue from small-grain crops and biomass sorghum (*Sorghum bicolor* L), and perennial grass crops. Ideal energy crops from woody and herbaceous sources would have low fertilizer requirements, be relatively cheap and easy to establish, have a perennial growth habit, be easily integrated with existing U.S. farming practices, and be adapted to sites unsuitable for food or cash crop production.

One species of perennial grass, switchgrass (*Panicum virgatum* L.) was recognized by the US Department of Energy in the 1990s as part of the Bioenergy Feedstock Development Program for its ability to produce large quantities of biomass on relatively poor sites. Annual yields of switchgrass in the United States averaged 11.2 Mg ha^{-1}, and ranged from 4.5 Mg ha^{-1} in the northern plains to 23.0 Mg ha^{-1} in Alabama (McLaughlin and Kszos, 2005). Switchgrass is native to all of the United States except California and the Pacific Northwest and is adapted to a wide range of soil textures and soil drainage classes (Stubbendieck et al., 1998).

Switchgrass is a unique renewable fuel option because it can be used for both livestock forage and for conversion to renewable fuels. Another desirable aspect of switchgrass production is that the American farming community is already familiar with perennial grass production, harvesting strategy, and harvesting equipment (McLaughlin and Kszos, 2005). Flexibility for in choosing when to sell renewable fuels is a core need for agricultural producers who must make decisions based on a complex variety of environmental and market-based factors. In order for producers to commit to growing dedicated energy crops for renewable fuel markets, detailed information about storage, handling, pricing, timing, and transport must be available (Popp, 2007). Since most of that information does not exist for the majority of producers in the U.S., having the option of growing switchgrass as both a source of livestock forage or renewable fuel feedstock may provide added stability for long-term value to producers.

The western portion of Arkansas is largely unsuitable for traditional row-crop production due to steep topography and thin soil, compared to the Mississippi River delta region of eastern Arkansas. Average biomass yield for switchgrass grown in Booneville, Arkansas under a single annual harvest regime was 13.4 Mg ha^{-1} over a four-year period, which is above the national average yield estimated by McLaughlin and Kszos (2005), of 11.2 Mg ha^{-1}. When using the ALMANAC yield prediction computer model, McLaughlin et al. (2006) recognized the Southeast and South-Central United States regions as being more suitable than the upper Midwestern region for providing dependable feedstock supplies of switchgrass biomass for future refineries.

In addition to the projected increase in yield, western Arkansas is widely known for its forage and hay production and for its role in the beef cattle production industry. Agricultural operators in western Arkansas are familiar with grass harvest, distribution, and storage and typically own conventional farm equipment that may be used to harvest switchgrass. The cost of producing one dry ton of switchgrass in Arkansas was estimated to be $26.73 in the third year of production, with an expected useful life of 12 years (Popp, 2007).

Arkansas is the only U.S. state to be ranked in the top 10 producers of broiler chicken (*Gallus gallus domesticus*), turkey (*Meleagris gallopavo)*, and egg production (USDA-NASS, 2014). Poultry litter has been widely considered the most valuable plant manure produced by livestock (Mitchell and Donald, 1995). Many producers use dry, surface-applied poultry litter to fertilize hay and forage production pastures. Poultry litter could provide an affordable, nutrient-rich fertilizer source for switchgrass production in the future.

Providing robust information to assist producers in making sound resource management decisions prior to engaging in renewable fuel production is of paramount importance. Providing comprehensive information to producers is essential in achieving the goal of increasing domestic fuel resources and decreasing carbon dioxide emissions. Proper management of switchgrass as a suitable crop for marginal land is particularly important, as these areas may be prone to accelerated rates of erosion or have increased leaching potential.

Past research has identified agronomic procedures for maximizing switchgrass biomass production using varying systems, including cultivar choice, fertilizer application, irrigation, harvest frequency, and row spacing (Adler et al., 2005; Bransby, 2014; Jacobs and King, 2012; Kering et al., 2012). It is not enough to guarantee large amounts of biomass production, as these practices must also be renewable and nonpolluting. The impact of switchgrass production on below-ground properties such as beneficial fungal relationships (Ker et al., 2012) and unique root characteristics of cultivars and implications for soil structure (Ma et al., 1999) have begun to be evaluated and paired with switchgrass above-ground production information. Further evaluations of the implications associated with switchgrass production systems are needed to seriously determine if switchgrass provides a truly renewable and clean source of domestic energy.

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Chapter One

Literature Review

1. Literature Review

The United States (U.S.) is the largest consumer of petroleum in the world (18.6 million barrels per day) and the third largest producer of petroleum (6.5 million barrels per day) (EIA, 2013a). Domestic petroleum production cannot keep pace with demand, as 40% of petroleum products consumed in the U.S. were net imports from other countries (EIA, 2013a). Burning fossil fuels contributes to the artificial warming of the atmosphere by producing greenhouse gases, which trap solar radiation and disrupt climate patterns. Changes in the climate induced by global warming have widespread consequences for agricultural production, global disease cycles, weather patterns and natural disasters, and alteration of natural habitat for plant and animal species. Carbon dioxide gas was 84% of all U.S. greenhouse gas emissions and increased by 10% from 1990-2011 (US-EPA, 2011). The United States emits 18% of the world's total energy-related carbon dioxide from burning fossil fuels (EIA, 2013a). Carbon dioxide increases primarily occurred in the electricity-generation and transportation sectors.

The main sources of carbon dioxide are coal burning to generate electricity (42%) and petroleum burning for the transportation sector (34%) (EIA, 2013b). Reducing the amount of carbon dioxide and other greenhouse gases released into the atmosphere has become a central issue in global policy. Development of alternative, renewable fuels may help reduce the negative impacts of burning fossil fuels.

Concerns related to the effects of global warming and possible shortages of finite fossil fuel sources have led to government-mandated regulations encouraging development of alternative fuels. Currently, only 12% of electricity generated in the United States is from renewable sources (EIA, 2013b).

2. Biofuel as an Alternative Fuel Source

Reducing the use of non-renewable fuel sources, such as coal, gasoline, and other petroleum products, may be accomplished by developing renewable fuel sources, such as plant biomass. According to the Energy Policy Act of 2005 and the Renewable Fuel Standard Program of 2007, 36 billion gallons (137 L) of renewable fuel must be blended into the nation's transportation fuel supply by 2022 (US-EPA, 2013). The Renewable Fuel Standard of 2007 developed several categories of biofuels, including renewable biofuel, advanced biofuel, biomass-based diesel, and cellulosic biofuel (US-EPA, 2013).

Using plant biomass as a source of cellulosic biofuel as an alternative to fossil fuel is attractive because plants use sunlight for energy and capture existing carbon dioxide in the atmosphere. Native grass grazing lands also have been shown to function as sinks for atmospheric carbon dioxide (Frank et al., 2001). Plant species that produce large amounts of lignocelluloses, or recalcitrant structural carbohydrates, store energy efficiently in plant stalks associated with crop residue. Lignocellulose in crop residues is not digestible by humans, and is usually left on the field after harvest or added as a source of dietary fiber to livestock feed blends. Humans typically utilize lignocellulose only by using residues to feed ruminant animals such as cattle. Lignocellulose provides a major opportunity to convert stored photosynthetic energy into fuel sources. Though bioenergy derived from lignocellulosic sources may not provide a complete alternative to the massive energy needs of the United States, lignocellulosic bioenergy sources may alleviate a portion of the negative impacts of burning fossil fuels and contribute to an extended supply of fossil fuels for the future (Parrish and Fike, 2005).

2.1. Crops for Combustion-based Fuels

Biomass from crops can be utilized as a biofuel by burning it or mixing it with coal (i.e., co-firing) to generate electricity (Tillman, 2000). Co-firing is desirable because it reduces the amount of coal burned while maintaining a high level of energy output. Blending biomass into coal in the co-firing process releases less carbon dioxide and other greenhouse gases. Mixing renewable fuels with a non-renewable fuel like coal may also extend the supply of finite resources further into the future.

Biomass used in the co-firing process must meet strict standards as expensive industrial machinery can get clogged with unwanted residue. There are several criteria that the biomass must satisfy to prevent the formation of unwanted residue. The first requirement is that the biomass must contain a large proportion of stem material relative to leaf material. Stems contain larger amounts of lignocellulose in mature tissues than leaves. The second requirement is delivery of dry biomass because water and water-soluble nutrients may also clog the co-firing equipment (Tillman, 2000). Plant species that produce crops with these characteristics are typically harvested after the plants go dormant and the growing season has ended, when plant moisture is lowest.

There are several challenges associated with the co-firing process. One major challenge is that an extremely large amount of biomass is typically required, sometimes in the thousands of tons or Mg per day, to be economically feasible. Widespread adoption of this process requires vast areas of land devoted to production to ensure that a year-round supply of biomass is available for the power plant. Another challenge is the construction of large storage facilities near the co-firing facilities to keep a continuous supply of dry biomass readily available.

Alternately, to avoid the need for costly storage structures, biomass supplies would need to be produced in the areas surrounding the plant to minimize transportation cost.

2.2. Crops for Ethanol-based Fuels

According to the Renewable Fuel Standard of 2007, only 20% of the 36 billion gallons (137 L) of renewable fuel may come from first-generation sources, ethanol or ethanol derived from corn grain (*Zea mays* L.). Estimates from 2006 state that more than 95% of ethanol blended into the Unites States transportation fuel supply comes from corn, while the remaining amount comes from other sources such as wheat (*Triticum* spp. L.), barley (*Hordeum vulgare* L.), grain sorghum (*Sorghum bicolor* (L.) Moench ssp. *bicolor*), cheese whey, and beverage residues (Urbanchuk, 2005). Once the limit of corn ethanol blended into the nation's fuel supply is reached, which has been referred to as the blend wall, production of advanced biofuels such as cellulosic biofuel fuel sources must increase to meet the 2022 regulation levels.

In addition to policy regulations that limit corn-ethanol production, corn is an important food crop for human and livestock consumption. Corn makes up over 95% of the grain rations for fed cattle, and the United States is the world's largest producer of beef (USDA/ERS, 2012). Use of a non-food cellulosic material for conversion to ethanol offers an attractive solution to the problem of competing with the livestock feed industry.

Corn is an annual crop that must be replanted every year, which requires large amounts of nutrients and fertilizers. The extensive preparation required for conventional corn production is regarded as causing more total soil erosion than any other crop grown in the United States (Pimentel et al., 1995). Due to the concerns associated with corn-based ethanol production, other promising sources of cellulosic material have been under development. Municipal solid waste (MSW), wood chips, and forestry waste have been recognized as possible cellulosic sources. In addition, dedicated energy crops, or crops grown exclusively for conversion to renewable fuel sources, emerged as major sources of cellulose from American lands. These crops included short-rotation woody crops, such as willow (*Salix* spp.) and cottonwood (*Populus* spp.*)*, annual crop residue from small-grain crops and biomass sorghum (*Sorghum bicolor* L), and perennial grass crops. These cellulosic crops have the potential to provide a source of domestic, renewable fuels. Ideal energy crops from woody and herbaceous sources would have low fertilizer requirements, be relatively cheap and easy to establish, have a perennial growth habit, be easily integrated with existing U.S. farming practices, and be adapted to sites unsuitable for food or cash crop production.

2.3. Switchgrass as a Monoculture Bioenergy Crop

One species of perennial grass, switchgrass (*Panicum virgatum* L.) was recognized by the US Department of Energy in the 1990s as part of the Bioenergy Feedstock Development Program. One important desirable aspect of growing switchgrass for a bioenergy crop is the widespread familiarity of the farming community with perennial grass production, harvesting strategy, and harvesting equipment (McLaughlin and Kszos, 2005). Switchgrass is native to all of the United States except California and the Pacific Northwest and is adapted to a wide range of soil textures and soil drainage classes (Stubbendieck et al., 1998).

Switchgrass was already a familiar grass in the native tallgrass prairies of the U.S., has good peak forage value for all classes of livestock, and produces acceptable hay if cut prior to maturity. Switchgrass is a warm season, perennial grass that can reach a height of 3 m, and the flower inflorescence is an open, spreading panicle (Stubbendiek et al., 1998). One key identification characteristic is the presence of a triangular patch of pubescent, hair-like collar at the point where the leaf attaches to the stem (i.e., the ligule).

Many switchgrass cultivars have been developed to provide adaptation to a wide range of environmental conditions, including cultivars adapted to well-drained upland areas as well as poorly drained lowland areas. The Natural Resources Conservation Service's Plant Materials Program has released a total of 18 different switchgrass cultivars adapted to many environments throughout the natural range of the grass (Douglas et al., 2009). There are two major divisions of switchgrass ecotypes: lowland and upland ecotypes. Lowland types of switchgrass are generally taller, i.e. up to 3.7 m, tend to have more of a bunchgrass growth habit, and are better adapted to wetter sites at lower elevations (Parrish and Fike, 2005). Upland types of switchgrass are generally shorter in stature, i.e. up to 1.8 m, and tend to have more of a sod-forming growth habit with many rhizomes (i.e., belowground vegetative stems) (Parrish and Fike, 2005).

Switchgrass can produce large amounts of biomass on relatively poor sites, where water and nutrient availability normally prevent the successful production of conventional crops. McLaughlin and Kszos (2005) estimated that the average annual yield of switchgrass in the United States was 11.2 Mg ha^{-1}, and ranged from 4.5 Mg ha^{-1} in the northern plains to 23.0 Mg ha^{-1} in Alabama. In addition, selections have been made to create switchgrass cultivars capable of withstanding a variety of site challenges to remain productive over long periods of time. Evidence suggests that switchgrass stands may remain productive for long periods of time if proper nutrient levels are maintained. Bransby and Huang (2014) recently reported that eight switchgrass cultivars remained productive in Alabama when harvested twice per year from 1990 to 2009 with only an annual N application of 84 kg N ha^{-1}. This study also showed that yield variation among cultivars due to annual precipitation occurred in upland but not lowland cultivars. The most productive cultivar in that study was 'Alamo', a lowland cultivar that produced an average annual biomass yield of 23.5 Mg ha^{-1} over a 20-year time period.

Herbaceous energy crop production for the biofuels industry focuses on producing maximum biomass yield with low concentrations of water and nitrogen, while also producing biomass with high concentrations of lignocelluloses. Harvesting switchgrass after the grass has gone dormant in the fall has shown to satisfy these conditions (Adler et al., 2005). However, landowners may also choose to utilize switchgrass during the growing season for hay or grazing. Large-scale integration of switchgrass into farming systems may be encouraged by providing options to farmers to choose whether they harvest a switchgrass crop for grazing/haying or sell it as an energy crop. Currently, no local refineries for processing switchgrass biomass products exist in west-central Arkansas; however, this region has the potential to provide large amounts of switchgrass biomass if the market becomes available.

2.4. Potential for Switchgrass Production in West-Central Arkansas

The western portion of Arkansas is largely unsuitable for traditional row-crop production due to steep topography and thin soil, compared to the Mississippi River delta region of eastern Arkansas. Average biomass yield for switchgrass grown in Booneville, Arkansas under a single annual harvest regime was 13.4 Mg ha^{-1} over a four-year period, which is above the national average yield estimated by McLaughlin and Kszos (2005) of 11.2 Mg ha^{-1}. When using the ALMANAC yield prediction computer model, McLaughlin et al. (2006) recognized the

Southeast and South-Central United States regions as being more suitable than the upper Midwestern region for providing dependable feedstock supplies of switchgrass biomass for future refineries.

In addition to the projected increase in yield, western Arkansas is widely known for its forage and hay production and for its role in the beef cattle production industry. Agricultural operators in western Arkansas are familiar with grass harvest, distribution, and storage and typically own conventional farm equipment that may be used to harvest switchgrass.

The cost of producing one dry ton (0.9 Mg) of switchgrass in Arkansas was estimated to be $26.73 in the third year of production, with an expected useful life for 12 years (Popp, 2007). Converting marginal cropland to switchgrass production may provide a source of additional producer income, especially with expected reduction in available irrigation water, and cost increases for synthetic fertilizers, fuel, and herbicides.

Arkansas is the only U.S. state to be ranked in the top 10 producers of broiler chicken (*Gallus gallus domesticus*), turkey (*Meleagris gallopavo)*, and egg production (USDA-NASS, 2014). Poultry litter has been widely considered the most valuable plant manure produced by livestock (Mitchell and Donald, 1995). Many producers use dry, surface-applied poultry litter to fertilize hay and forage production pastures. Poultry litter could provide an affordable, nutrient-rich fertilizer source for switchgrass production in the future. Broiler litter produced in the southeastern US provides an average of 27 kg N, 27 kg, P, and 18 kg of K per ton of dry litter (Mitchell and Donald, 1995). Broiler litter has a fertilizer value of 3-3-2, but not all nutrients are immediately available for plant uptake. In addition to plant nutrients supplied, broiler litter also contains organic matter.

2.5. Switchgrass Production Systems

2.5.1. Cultivar

Several switchgrass cultivars have been developed to optimize biomass production in the southeastern United States. Switchgrass occurs naturally in both upland and lowland ecotypes. Switchgrass cultivars recommended for forage and biomass production in Arkansas include ‘Alamo’ and ‘Cave-in-Rock’ (USDA-NRCS Arkansas, 2009).’Cave-in-rock’ is an upland ecotype and ‘Alamo’ is a lowland ecotype. ‘Alamo’ is generally taller, thicker-stemmed, and more adapted to poorly drained sites compared to ‘Cave-in-Rock’ (Fike et al., 2006). Fike et al. (2006) reported that lowland varieties (15.1 Mg ha^{-1}) produced more biomass when harvested once per year than upland cultivars harvested once and twice per year (10.5 Mg ha^{-1}) from sites in North Carolina, Kentucky, Tennessee, Virginia, and West Virginia. Both lowland and upland cultivars produced more biomass when harvested twice per year compared to once per year. However, upland and lowland cultivars responded differently when harvested twice per year, as upland cultivars increased production by 36%, compared to an increase of only 8% in lowland cultivars. A comprehensive evaluation of sites located across southeastern states concluded that ‘Cave-in-Rock’ yields approached or exceeded lowland cultivar yields when cut twice per year (McLaughlin and Kszos, 2005).

These results are similar to a study conducted in Booneville, Arkansas (Jacobs and King, 2012). ‘Alamo’ yields for one and two-cut systems yielded significantly more biomass than ‘Cave-in-Rock’ over a three-year period. Treatments with ‘Alamo’ under the two-harvest regime yielded an average of 5.1 Mg ha^{-1} more than the single harvest. By contrast, treatments with ‘Cave-in-Rock’ under the two-harvest regime yielded an average of 6.6 Mg ha^{-1} more than the single-harvest regime.

In addition to differences in response to a two-cut harvest regime, ‘Cave-in-Rock’ exhibited lodging when fertilized (Jacobs and King, 2012). Lodging, a condition in which grass stems lay over and complicate mowing, raking, and baling processes, is an undesirable characteristic for both the biofuels market and for hay production since lodging decreases harvest efficiency.

2.5.2. Fertilization

Although switchgrass is widely recommended for tolerance to low-fertility sites, application of some fertilizers to switchgrass crops has been shown to increase yield. For example, a surplus of poultry litter is often available in northwestern Arkansas and must be land-applied to limit water quality concerns. Poultry litter provides nutrients essential for plant growth and development, contains micronutrients that may be beneficial to plants that are not included in commercial fertilizers, and contains organic matter to improve soil health (Edwards and Daniel, 1991). The typical concentration of nutrients (g kg^{-1} poultry litter) in poultry litter supplied were estimated by Edwards and Daniel (1991) to be: 40.8 g N kg^{-1}, 14.3 g total P kg^{-1}, 20.7 g K kg^{-1}, 14 g Ca kg^{-1}, and 3.1 g Mg kg^{-1}. Applying 4.5 Mg ha^{-1} of poultry litter to ‘Coastal’ bermudagrass (*Cynodon dactylon* [L.]) hay fields in Texas increased yields to 7.8 Mg ha^{-1} compared to 4.5 Mg ha^{-1} in unfertilized hay fields (Evers, 2008).

In addition, a large amount of biomass would be required for any renewable energy conversion facility constructed in western Arkansas. Under these conditions, the demand for local cellulosic feedstocks, such as switchgrass, may facilitate the cost-effectiveness of applying commercial fertilizer.

Switchgrass growth is mainly limited by nitrogen (N) supply (Vogel et al., 2002, Muir et al., 2001). Fertilization with only phosphorus (P) or potassium (K) has not shown consistent yield increases (Parrish et al., 2003; Muir et al., 2001). Kering et al. (2012) showed that 'Alamo' switchgrass in Oklahoma fertilized with only K and cut once or twice per year did not produce significantly more biomass than unfertilized switchgrass. Switchgrass is also an efficient user of soil P, as it develops beneficial relationships with fungal mycorrhizae (Brejda, 2000; Muir et al., 2001). Switchgrass yield has been shown to reach a maximum with N fertilization rates of 50 to 120 kg ha^{-1} in the central Great Plains and Midwest (Brejda, 2000), and 168 kg ha^{-1} in Texas (Muir et al., 2001). Studies conducted in Alabama under non-irrigated conditions suggested that yields could be maximized with only 41 kg N ha^{-1} yr^{-1} (Bransby et al., 2002).

2.5.3. Irrigation

Switchgrass is not typically irrigated as it is often planted on marginal sites lacking the necessary water source for irrigation or infrastructure; however, irrigation has been shown to increase switchgrass biomass yields in arid areas. In Texas, Koshi et al. (1982) noted a yield increase from 2 to 6.7 Mg ha^{-1} yr^{-1} under no irrigation and full-season irrigation, respectively. In Washington, 'Alamo' switchgrass grown with irrigation produced 4.0 Mg ha^{-1} (Fransen, 2009). Even though irrigation has potential to increase yield at many locations, the feasibility of switchgrass production is based primarily on the use of otherwise unproductive and unprofitable agricultural lands, which likely do not have access to cost-effective irrigation. In Booneville, Arkansas, the weekly application of 2.54 cm (1 inch) of irrigation delivered by overhead sprinklers during the growing season over a three-year period from 2009-2012 did not significantly increase annual biomass yield for ‘Alamo’ or ‘Cave-in-Rock’ switchgrass (Jacobs and King, 2012).

2.5.4. Harvest Frequency

Annual harvest frequency affects switchgrass biomass yield, stand longevity, and soil nutrients removed from the system. A single annual harvest performed after the first frost of the year minimizes harvesting costs for producers, minimizes biomass moisture content for storage, and maximizes carbon and other plant nutrient translocation to root systems for storage (McLaughlin and Kszos, 2005). A single annual harvest performed after the first frost is the recommended system for biomass/bioenergy production because lower levels of nutrients in plant biomass have less risk of causing slagging problems in co-fired renewable energy production systems (Sanderson and Wolf, 1995). Switchgrass also may be harvested under a two-cut system, with the first cut in June or July and the second cut after the first frost. Under both one-and two-cut systems in the southeast, lowland cultivars ‘Alamo’ and ‘Kanlow’ produced the greatest amount of biomass and provided maximum flexibility for producers to choose between using switchgrass crops for livestock forage or biomass for renewable fuel production (McLaughlin and Kszos, 2005).

Switchgrass can also be grazed or cut for hay in June or July in Arkansas, while regrowth may be cut and baled after a frost in November or December (Jacobs and King, 2012). Grazing switchgrass prior to flowering provides the greatest amount of digestible nutrients for livestock, and baling regrowth may allow livestock producers to sell biomass to a renewable energy production facility (Jacobs and King, 2012). Switchgrass breaks dormancy early in the spring and reaches a height of 30-46 cm several weeks to one month earlier than bermudagrass, a primary warm-season forage grass in Arkansas (USDA-NRCS Arkansas, 2009). In western Arkansas, switchgrass regrowth can usually be grazed a second time 45 days later, as long as a stubble height of 15-16 cm is maintained after late July (USDA-NRCS Arkansas, 2009). Switchgrass, like other native warm-season grass stand, does not persist under continuous grazing and must be managed carefully (i.e., providing rest periods and maintaining adequate stubble height for overwintering; Jacobs and King, 2012). Switchgrass stems become stiff and unpalatable to grazing animals after flowering occurs, so timely grazing is very important (USDA-NRCS Arkansas, 2009).

To ensure regrowth after grazing and to maximize uniform forage utilization, switchgrass pastures should be managed separately from other grazing pastures using electric or barbed-wire fencing (USDA-NRCS Arkansas, 2009). Best management practices for grazing switchgrass include using switchgrass primarily as an early-season forage source and transitioning to other forage sources, such as bermudagrass and tall fescue (*Schedonorus arundinaceus* [Schreb.] Dumort., nom. cons.). Switchgrass is challenging to manage in a grazing system because stocking rates must be high enough to keep up with rapid forage growth in April, May, and June (Jacobs and King, 2012). Switchgrass plants must be kept in the vegetative stage by uniform grazing; if switchgrass is undergrazed, seedheads develop and reproductive growth decreases forage quality (Anderson et al., 1988). In addition, cattle avoid grazing switchgrass once seedheads develop (Anderson et al., 1988). To become familiar rapid spring growth and forage harvest timing, landowners interested in switchgrass production as a forage source are often encouraged to begin managing the switchgrass crop as a hay crop (Jacobs and King, 2012).

Switchgrass may also provide an emergency source of forage during times of drought. Keyser et al. (2011) noted exceptional switchgrass forage production in 2007 during the single worst drought year recorded in Tennessee. Switchgrass plots still produced 11.7 Mg ha^{-1} during 2007, which was much less than the 17.7 Mg ha^{-1} produced in a normal year, but could provide adequate grazing if livestock were supplemented.

Nutrient concentrations of switchgrass forage decline significantly in the winter, requiring N and crude protein supplementation to maintain beef cattle weight (Jacobs and King, 2012; Anderson et al., 1988). Switchgrass stems become woody and highly unpalatable after the first frost in the fall, and cattle typically select other more nutritious forages such as fescue if they are available (USDA-NRCS Arkansas, 2011; Jacobs and King, 2011). Switchgrass also may be managed in the same manner for hay production, though greater amounts of nutrient application may be required to account for nutrient removal off-site, as opposed to partial nutrient redistribution by grazing cattle.

2.6. Switchgrass Biofuel Crop Effects on Soil Quality

2.6.1. Bulk Density

Compared to the relatively large body of research available for using switchgrass for a biofuels crop, much less information is available on the long-term effects of growing switchgrass on soil quality. Soil bulk density, or the dry mass of soil per unit volume, measures soil compaction and depends on soil structure (Hillel, 2004). Management factors affect soil structure and bulk density over time. Schmer et al. (2011) showed that soil bulk density changes after switchgrass establishment were not uniform at sites in North Dakota, South Dakota, and Nebraska. Five years after switchgrass establishment in annual crop production fields, soil bulk density in the top five cm decreased in Huron, SD (1.54 to 1.12 g cm^{-3}), increased in Atkinson, NE (1.31 to 1.45 g cm^{-3}), and did not change in Lawrence, NE (1.21 g cm^{-3}; Schmer et al., 2011). In contrast to production agriculture fields, soil bulk density was 1.10 g cm^{-3} in an native, undisturbed prairie site in Arkansas (Brye and Riley, 2009).

In Ohio, Bonin et al. (2012) measured infiltration, bulk density in the 0-10 cm depth interval, and soil resistance to penetration seven years after establishment of several species of biofuel crops. This study noted that soil sampled from switchgrass had greater infiltration rates, lower bulk density, and less resistance to penetration compared to corn and willow (*Salix* spp.). Study plots were located on a Kokomo silty clay loam (fine, mixed, superactive, mesic, Typic, Argiaquoll) and Strawn-Crosby complex (fine-loamy, mixed, active, mesic Typic Hapludalf; fine, mixed, active, mesic, Aeric, Epiaqualf) on 0-2% slopes. Plots were not subjected to differing management treatment combinations, received recommended amounts of commercial fertilizer for each species, and were harvested once per year (Bonin et al., 2012). Reduced soil bulk density in switchgrass plots in the 0-10 cm depth interval and not in the 10-20 cm depth interval suggests that switchgrass roots may decrease soil bulk density only in the near-surface depths.

Schmer et al. (2011) reported that soil bulk density in the 0-50 cm depth interval decreased by an average of 0.18 Mg m^{-3} 5 years after switchgrass establishment in areas previously engaged in annual row-crops production in North Dakota and South Dakota. However, this study also reported that soil bulk density in the 0-50 cm depth interval increased in Nebraska by an average of 0.16 Mg m^{-3}. The authors suggest the cause of the increased soil bulk density recorded in Nebraska may be due to the timing soil was collected from the site prior to switchgrass establishment, as tillage operations performed there just prior to sampling may have temporarily decreased soil bulk density. This study was conducted at 10 different sites in North Dakota, South Dakota, and Nebraska with different soil series and texture classes. These sites yielded different results, suggesting that soil quality improvement is closely tied to available moisture, residual soil nutrient fertility, past management including tillage history, and overall site potential for soil quality improvement.

2.6.2. Infiltration

Water infiltration is an important parameter for recharging groundwater supplies, limiting excess runoff, and controlling soil erosion. Infiltration is influenced by many factors, including soil antecedent moisture condition, canopy cover, pore-size distribution, and continuity. Land use also plays a prominent role in controlling or modifying water infiltration rate.

Rachman et al. (2002) compared infiltration rates between cropland under no-tillage soybean (*Glycine max* [L.] Merr) production to an adjacent switchgrass hedge system in Iowa on a Monona silt loam (fine-silty, mixed, superactive, mesic Typic Hapludolls). Grass hedges are narrow strips that slow water velocities and runoff in adjacent cropland fields. Ponded infiltration rates (i.e., saturated hydraulic conductivities) measured with a single-ring infiltrometer were seven times greater in the switchgrass hedge than in the adjacent cropland. In addition, tension infiltration in the switchgrass hedge was significantly greater than in the cropland at tensions of -50 and -100 mm, but not at -150 mm of tension.

The effects of switchgrass management considerations, such as cultivar and harvest frequency, on infiltration rate have not been widely studied. Increasing harvest frequency may decrease leaf litter amounts and affect infiltration rate. Applying nutrients in fertilizers with large amounts of organic matter may also encourage the development of larger pore spaces and increase infiltration rate since larger pore spaces drain water at lower tensions (Ankeny et al., 1990).

2.6.3. Aggregate Stability

Soil stability is important in preventing excessive erosion, maintaining adequate soil drainage, and promoting soil aeration. One method to assess soil stability involves measuring water-stable aggregates, or the proportion of soil aggregates that can withstand disruptive forces such as water (WSA) (Karlen et al., 1997). Organic cementing agents from root exudates and associated fungal hyphae have been shown to encourage soil aggregation (Abiven et al., 2007). Management decisions that affect root growth or root decomposition, such as the addition of plant nutrients through fertilizer applications, may affect the corresponding stability of soil aggregates. Adequately fertilized soils in agricultural production typically have greater proportions of WSA than nutrient-deficient soils (Campbell et al., 1993). Nutrient-deficient plants may have poor root systems, which limit production and release of organic compounds that act as cementing agents for soil aggregates. Since switchgrass is a perennial crop, root systems are present year-round and can promote soil aggregation; however, excess fertilizer may discourage root development, as plants do not need to seek nutrients deeper in the soil profile.

In Tennessee, Jung et al. (2011) showed that a greater annual application rate of N fertilizer (202 kg ha^{-1}) on 'Alamo' switchgrass in Tennessee significantly decreased the proportion of soil macroaggregates in the 0-10 cm depth interval compared to lower application rates (0 and 67 kg ha^{-1}). Study plots were located on a Grenada silt loam (fine-silty, mixed, active, thermic, Oxyaquic Fraglossudalfs; Fragic Luvisols). Plots were sampled after 4 years of consistent management, including the application of ammonium nitrate fertilizer at rates of 6, 67, and 202 kg N ha^{-1} yr^{-1}. This study also reported that switchgrass root length density decreased by 50% for the 202 kg N ha^{-1} compared to the 0 kg N ha^{-1} application rate. Even though greater amounts of applied N encourage maximum biomass production, excessive N application may actually lower the proportion of WSA in the soil and negatively affect soil quality over time.

In addition, management decisions that affect fine (0.2 to 1 mm diameter) and very fine root (< 0.2 mm diameter) development have been shown to strongly affect total aggregate stability (Jastrow et al., 1997). Very fine roots directly bind soil, while fine roots indirectly bind soil by enabling mycorrhizal fungi association in the soil (Jastrow et al., 1997).

2.6.4. Root Density

The large biomass production potential of switchgrass is partially attributed to the presence of a well-developed root system. Biomass production is limited during the first year of establishment as root systems are first developed. Once a switchgrass stand is established, plants are capable of efficiently utilizing nutrients and water from deep in the soil profile and re-growing after harvest or grazing (McLaughlin and Kszos, 2005). Switchgrass buffer strips/grass hedges have been used widely to filter sediment and nutrients from adjacent fields (Rachman et al., 2004), and effectiveness have been partially attributed to deep rooting systems that may extend to a depth of 330 cm in the soil (Ma et al., 1999).

Differences in root characteristics among switchgrass cultivars have been recorded. Ma et al. (1999) recorded differences in rooting depth densities and corresponding root mass among

'Cave-in-Rock', 'Alamo', and 'Kanlow'. This study, conducted on a Norfolk sandy loam (fine-loamy, mixed, thermic, Typic Hapludult) in Alabama, Ma et al. (1999) determined that mature stands of 'Cave-in-Rock' (14.48 mg cm^{-3}) switchgrass had significantly greater root weight density compared to both 'Alamo' (8.80 mg cm^{-3}) and 'Kanlow' (7.89 mg cm^{-3}) in the 0-to -15 cm depth interval. Additionally, 'Cave-in-Rock' had greater root mass (18,132 kg ha^{-1}) in the 0- to -15 cm depth interval than 'Alamo' (17,614 kg ha^{-1}) and 'Kanlow' (14,734 kg ha^{-1}). 'Cave-in-Rock' switchgrass had greater root mass than 'Alamo' in the 0- to -15 cm depth interval; conversely, 'Alamo' had greater root mass in deeper soil depth intervals down to a depth of 330 cm. Results of this study could be related to the characteristics of upland and lowland types of switchgrass. 'Cave-in-Rock' is an upland type of switchgrass more adapted for dry sites and may invest more energy in greater root mass in upper soil depths to immediately absorb infrequent precipitation. In contrast, lowland types of switchgrass adapted to wetter sites, such as 'Alamo' and 'Kanlow', may reach deeper soil depths to seek nutrients, as lack of precipitation is not typically the most limiting factor for growth on wetter sites.

Site selection also may be important with regard to soil characteristics, as Ma et al. (1999) recorded significant differences in root weight density and root mass of 'Alamo' switchgrass in different soil series. Root weight density was significantly greater for all soil depth intervals 0- to -150 cm in a Pacolet clay loam (clayey, kaolinitic, thermic, Typic Hapludult) than in a Norfollk sandy loam, Malbis sandy loam (fine-loamy, mixed, thermic, Typic Hapludult), Decatur silty loam (clayey, kaolinitic, thermic, Rhodic Paleudult), and a Hartsells fine sandy loam (fine-loamy, siliceous, thermic, Typic Hapludult) (Ma et al., 1999). Averaged across all sampled soil depth intervals, including averaging values from soil in the switchgrass intrarow and interrow, greatest root weight densities were recorded in the Pacolet clay loam (3.9 mg cm^{-3}) and least were recorded in the Norfolk sandy loam (0.8 mg cm^{-3}).

2.6.5. Soil Extractable Nutrients

Switchgrass has been marketed as a low-input crop compared to conventional or annual crop species for a number of reasons. Switchgrass may tolerate a wide range of soil pH values and are only limited when pH is > 8 and ≤ 4.0 (McLaughlin and Kszos, 2005).

Switchgrass production is typically limited by nitrogen availability in the soil, though the amount of nitrogen in soil is not routinely assessed in typical soil testing procedures. Adequate levels of P and K are important for switchgrass establishment and continued production. Specifications from USDA-NRCS Arkansas (2009) for establishing switchgrass recommend pH levels be > 5.0, P levels equal to 125 lb/ac, and K levels equal to 250 lb/ac prior to establishment. Switchgrass has been shown to be an efficient user of soil nutrients because nutrient uptake may be facilitated by root endophytes. In a recent study, inoculating ‘Cave-in-Rock’ switchgrass seed with plant growth promoting rhizobacteria, *Paenibacillus polymyxa*, increased switchgrass dry matter yield in the seeding year by 40% compared to a non-inoculated control (Ker et al., 2012). This study was conducted on a Chateauguay clay loam, Bearbrook clay and a Chicot fine sandy loam in Canada. Switchgrass seed was inoculated with bacterial populations isolated from 10-year-old switchgrass stands that had not received any N application during the life of the stand. Inoculants included bacteria capable of improving switchgrass growth by producing auxin hormones, increasing P availability to plant roots, and fixing nitrogen. The authors suggest that inoculating switchgrass stands could make switchgrass production more sustainable by decreasing fertilizer requirements.

2.7. Previous Research in West-Central Arkansas

A study was conducted at the NRCS Plant Materials Center in Booneville, Arkansas, to evaluate switchgrass yield and forage quality response to differing treatment combinations. The current study is a continuation of the previous study described in detail by Jacobs and King (2012). Switchgrass was planted in 2007 and treatments were applied in 2008, 2009, 2010 and 2011. Dry matter yield and forage quality of switchgrass was determined in 2008, 2009, 2010, and 2011. Since 2011, no treatments have been applied to the switchgrass stand except for prescribed burning in the spring (March). Annual prescribed burning is recommended at least every three years to maintain bare ground areas for native insect pollinator nesting habitat and also to create cover corridors for other wildlife species in native grass stands (USDA-NRCS Arkansas, 2009). Treatment combinations included two cultivars, ‘Alamo’ and ‘Cave-in-Rock’, harvest frequencies of either once or twice per year, poultry litter or commercial fertilization application, and irrigation or no irrigation (Jacobs and King, 2012).

The primary objective of this study was to develop technical recommendations for NRCS customers in Arkansas about how to maximize switchgrass yield and forage quality for use as grazing forage, as a hay crop, or as a dedicated energy crop. Near-surface soil quality was evaluated in these plots for the purposes of the new study on the exact same plots. The following results regarding yield and forage quality are a summary of the vegetative yield of switchgrass from the study conducted by Jacobs and King (2012).

Switchgrass dry matter yields differed among treatments and cultivars. ‘Alamo’ generally produced significantly more biomass than ‘Cave-in-Rock’ in all treatments. Dry matter yield was numerically greatest in ‘Alamo’ treatment combinations with irrigation and broiler litter fertilization; however, the yield from this treatment combination did not significantly differ from that of ‘Alamo’ with irrigation and commercial fertilizer or ‘Alamo’ that was non-irrigated with commercial fertilizer.

Yields were greater for both cultivars using the two-harvest regime. Increasing the switchgrass harvest frequency to 2-cuts per year induced a greater yield increase in 'Cave-in-Rock’ (6.5 Mg ha^{-1}) than in ‘Alamo’ (5.1 Mg ha^{-1}; Jacobs and King, 2012). Though yields were greater with the two-cut system for all treatments, early spring re-growth in the two-harvest treatment was noticeably slower than in the treatments harvested only once a year. Growth in plots harvested twice per year caught up by the boot stage (i.e., when plants were harvested in the summer), but prolonged use of the double-harvest regime may limit stand vigor over time. This may affect spring grazing rotations, as there is less biomass for livestock to consume. Two-cut systems produced roughly 50% more biomass than single-harvest regimes (Jacobs and King, 2012); however, expenditure of time and equipment for an additional harvest may not be an economically feasible option for farmers.

Treatment combinations with ‘Cave-in-Rock’, especially those receiving either broiler litter or commercial fertilizer, were visually observed to have a greater frequency of lodging compared to unfertilized control plots. Cutting and bailing grasses exhibiting lodging are difficult because leaves often break off on the soil surface and cannot be cut uniformly. Lower ‘Cave-in-Rock’ biomass yields in the winter harvest may be attributed in part to lodging. ‘Cave-in-Rock’ has been widely known as being an upland type of switchgrass that does not typically exhibit lodging; however, the addition of fertilizer may have lodging not normally observed. Based on this study, ‘Alamo’ may be a better choice if producers in the west-central Arkansas are managing for dormant-season biomass harvests.

3. Study Justification

Arkansas has been recently recognized as having a substantial potential land area that could be devoted to biofuel production due to a relatively warm and moist climate and long growing season. However, little is known about the potential long-term effects of switchgrass monoculture on soil quality in the mid-southern US, particularly in west-central Arkansas. In order to provide landowners with the best possible management suggestions and guidelines for establishing and maintaining switchgrass for potential bioenergy production, it is essential that alternative management practice effects on near-surface soil quality be investigated.

4. Study Objective

The objective of this study was to evaluate the effects of switchgrass cultivar (i.e., ‘Alamo’ and ‘Cave-in-Rock’), water management (i.e., irrigation and no irrigation), fertilizer source (i.e., commercial or poultry litter fertilization), and harvest regime (i.e., once-or twice-harvested per year) after three years of consistent management on near-surface soil properties (i.e., bulk density, surface infiltration, root density, water-stable aggregation, soil organic matter, and soil chemical properties) in the southern Ozark Highlands region of western Arkansas. Treatment combinations were assessed using a variety of soil quality parameters and paired with prior knowledge of vegetative production yields to determine landowner recommendations for managing switchgrass biofuel feedstock production in western Arkansas. The field plots to be used in this study were the same ones used in the Jacobs and King (2012) study.

5. Testable Hypotheses

It is hypothesized that three years of consistent management according to different treatment combinations will significantly affect soil properties. It is hypothesized that ‘Alamo’ treatment combinations will have lower soil bulk density, greater root density, greater infiltration rates, and greater soil organic matter content than ‘Cave-in-Rock’ combinations. Cultivar is not expected to affect soil nutrient contents. Since ‘Alamo’ previously produced greater biomass yields in all treatments (Jacobs and King, 2012), increased root density and increased litter amounts available for decomposition to soil organic content are hypothesized to drive changes in soil properties.

Fertilizer source is hypothesized to affect soil-quality measurements. Treatments fertilized with poultry litter rather than commercial fertilizer are expected to have lower soil bulk density and greater infiltration rates, as the addition of the organic material associated with animal manures will increase porosity and soil organic matter content since poultry litter contains complex organic particles that may break down more slowly. Irrigated treatment combinations, however, are hypothesized to have lower organic matter content compared to non-irrigated treatment combinations. Increased soil moisture is associated with increased soil microbial activity and subsequent organic matter breakdown (Gillabel et al., 2007).

Water management (irrigation and no irrigation) is not hypothesized to affect any measured soil property. Irrigation may affect near-surface soil nutrient levels, as some mobile nutrients may be leached below the sample depths of 10 and 20 cm.

It is hypothesized that significant differences in soil quality will occur in plots harvested once versus twice per year. Harvesting switchgrass twice per year removes greater amounts of soil nutrients such as N, P, and K. Plots harvested twice per year are expected to have lower root density, greater bulk density, lower infiltration rates, and lower soil organic matter and nutrient contents than those harvested once per year. Based on prior observation, switchgrass appeared less vigorous in the areas harvested twice per year (Jacobs and King, 2012), which may be caused by a weaker overall root system.

It is also hypothesized that switchgrass biomass yield will be correlated to measured soil quality parameters. It is expected that greatest-yielding treatment combinations may contain the lowest amounts of soil nutrients since a greater proportion of plant nutrients would have been removed from the soil in biomass.

In general, the treatment combinations applied to switchgrass plots from 2008-2011 are expected to induce significant soil property changes. In comparison, much more is known about switchgrass yield response than soil property changes to fertilizer, irrigation, and harvest frequency. Assessing and monitoring the capacity of switchgrass crop management strategies to alter near-surface soil properties may provide robust options for producing truly renewable bioenergy in the future.

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Chapter Two

Soil property differences under switchgrass managed for maximum biomass production in response to cultivar, harvest frequency, fertilizer source, and irrigation

Abstract

Switchgrass (*Panicum virgatum* L.) has been identified as a model bioenergy feedstock crop and is expected to become an important feedstock for future renewable fuel generation. Agronomic management combinations that maximize monoculture switchgrass yield are generally well understood; however, little is known about corresponding effects of differing switchgrass management combinations on near-surface soil properties. The objective of this research was to determine the residual near-surface soil property effects of three years (2008 to 2011) of consistent management combinations to maximize switchgrass biomass production, including cultivar ('Alamo' and 'Cave-in-Rock'), harvest frequency (1-cut and 2-cut systems per year), fertilizer source (poultry litter and commercial fertilizer), and irrigation management (irrigated and non-irrigated). Effects on soil properties were assessed on a Leadvale silt loam (fine-silty, siliceous, semiactive, thermic, Typic Fragiudult) at the USDA-NRCS Booneville Plant Materials Center in Logan County by evaluating soil bulk density, total water stable aggregates (TWSA), soil pH and EC, Mehlich-3 extractable soil nutrients, root density, and surface infiltration. Irrigating switchgrass, which did not increase past biomass production, increased ($p > 0.01$) soil bulk density in treatment combinations where poultry litter was applied (1.40 g cm^{-3}) compared to non-irrigated treatment combinations (1.33 g cm^{-3}). Total WSA concentration was greater ($p < 0.05$) in 'Alamo' (0.91 g g^{-1}) than 'Cave-in-Rock' (0.89 g g^{-1}) treatment combinations when averaged over all other treatment factors. Root density was greater ($p = 0.031$) in irrigated (2.62 kg m^{-3}) than in non-irrigated (1.65 kg m^{-3}) treatments when averaged over all other treatment factors. Surface infiltration rate under unsaturated conditions was greater ($p = 0.01$) in the 1-cut (33 mm min^{-1}) than 2-cut (23 mm min^{-1}) harvest treatment combinations when averaged over all other treatment factors, while surface infiltration rate under

saturated conditions did not differ among treatment combinations ($p > 0.05$) and averaged 0.79 mm min^{-1}. Results from this study indicate that management decisions to maximize switchgrass biomass production affect soil properties over relatively short periods of time and further research is needed to develop local best management practices to maximize yield while maintaining or improving soil quality.

1. Introduction

The United States (U.S.) is the largest consumer of petroleum in the world (18.6 million barrels per day; EIA, 2013a). Even though the U.S. is also the third largest producer of petroleum, domestic production cannot keep pace with demand, as 40% of petroleum products consumed in the U.S. were net imports from other countries (EIA, 2013a). Burning fossil fuels also releases carbon dioxide gas, which contributes to the disruption of global climate processes. Promoting the generation and development of domestic fuel supplies while reducing carbon dioxide gas emissions from fossil fuel combustion has become a central issue in global policy.

Concerns related to the effects of global warming and possible shortages of finite fossil fuel sources have led to government-mandated regulations encouraging development of alternative fuels. Currently, only 12% of electricity generated in the United States is from renewable sources, such as wind, hydroelectric, and biomass (EIA, 2013b). Significant investments have been made by both the public and private sector in order to identify and develop practical solutions to these problems. According to the Energy Policy Act of 2005 and the Renewable Fuel Standard Program of 2007, 36 billion gallons of renewable fuel must be blended into the nation’s transportation fuel supply by 2022 (US-EPA, 2013).

One potential solution is the conversion of plant biomass to fuel. Using plant biomass as a source of cellulosic biofuel as an alternative to fossil fuel is attractive because plants use sunlight for energy and capture existing carbon dioxide in the atmosphere. In addition, local economies could produce fuel for domestic use. Though bioenergy derived from lignocellulosic sources may not provide a complete alternative to the massive energy needs of the United States, lignocellulosic bioenergy sources may alleviate a portion of the negative impacts of burning fossil fuels and contribute to an extended supply of fossil fuels for the future (Parrish and Fike, 2005).

Plant biomass can be utilized as a fuel in two major ways: by burning it or mixing it with coal (i.e., co-firing) to generate electricity (Tillman, 2000), or conversion to ethanol. Co-firing is desirable because it reduces the amount of coal burned while maintaining a high level of energy output. Blending biomass into coal in the co-firing process releases less carbon dioxide and other greenhouse gases. Mixing renewable fuels with a non-renewable fuel like coal may also extend the supply of finite resources further into the future.

One reason using plant biomass rather than corn grain to produce ethanol is desirable is the avoidance of sacrificing food for fuel production. Corn is an important food crop for human and livestock consumption. Corn makes up over 95% of the grain rations for fed cattle, and the United States is the world's largest producer of beef (USDA/ERS, 2012). Use of a non-food cellulosic material for conversion to ethanol offers an attractive solution to the problem of competing with the livestock feed industry.

Corn is an annual crop that must be replanted every year, which requires large amounts of nutrients and fertilizers. The extensive preparation required for conventional corn production is regarded as causing more total soil erosion than any other crop grown in the United States (Pimentel et al., 1995). Dedicated energy crops, or crops grown exclusively for conversion to renewable fuel sources, emerged as potential sources of cellulose from American lands. These crops included short-rotation woody crops, such as willow (*Salix* spp.) and cottonwood (*Populus* spp.*)*, annual crop residue from small-grain crops and biomass sorghum (*Sorghum bicolor* L), and perennial grass crops. Ideal energy crops from woody and herbaceous sources would have low fertilizer requirements, be relatively cheap and easy to establish, have a perennial growth habit, be easily integrated with existing U.S. farming practices, and be adapted to sites unsuitable for food or cash crop production.

One species of perennial grass, switchgrass (*Panicum virgatum* L.) was recognized by the US Department of Energy in the 1990s as part of the Bioenergy Feedstock Development Program for its ability to produce large quantities of biomass on relatively poor sites. Annual yields of switchgrass in the United States averaged 11.2 Mg ha^{-1}, and ranged from 4.5 Mg ha^{-1} in the northern plains to 23.0 Mg ha^{-1} in Alabama (McLaughlin and Kszos, 2005). Switchgrass is native to all of the United States except California and the Pacific Northwest and is adapted to a wide range of soil textures and soil drainage classes (Stubbendieck et al., 1998).

Switchgrass is a unique renewable fuel option because it can be used for both livestock forage and for conversion to renewable fuels. Another desirable aspect of switchgrass production is that the American farming community is already familiar with perennial grass production, harvesting strategy, and harvesting equipment (McLaughlin and Kszos, 2005). Flexibility for in choosing when to sell renewable fuels is a core need for agricultural producers who must make decisions based on a complex variety of environmental and market-based factors. In order for producers to commit to growing dedicated energy crops for renewable fuel markets, detailed information about storage, handling, pricing, timing, and transport must be available (Popp, 2007). Since most of that information does not exist for the majority of producers in the U.S., having the option of growing switchgrass as both a source of livestock forage or renewable fuel feedstock may provide added stability for long-term value to producers.

The western portion of Arkansas is largely unsuitable for traditional row-crop production due to steep topography and thin soil, compared to the Mississippi River delta region of eastern Arkansas. Average biomass yield for switchgrass grown in Booneville, Arkansas under a single annual harvest regime was 13.4 Mg ha^{-1} over a four-year period, which is above the national average yield estimated by McLaughlin and Kszos (2005), of 11.2 Mg ha^{-1}. When using the ALMANAC yield prediction computer model, McLaughlin et al. (2006) recognized the Southeast and South-Central United States regions as being more suitable than the upper Midwestern region for providing dependable feedstock supplies of switchgrass biomass for future refineries.

In addition to the projected increase in yield, western Arkansas is widely known for its forage and hay production and for its role in the beef cattle production industry. Agricultural operators in western Arkansas are familiar with grass harvest, distribution, and storage and typically own conventional farm equipment that may be used to harvest switchgrass. The cost of producing one dry ton of switchgrass in Arkansas was estimated to be $26.73 in the third year of production, with an expected useful life of 12 years (Popp, 2007).

Arkansas is the only U.S. state to be ranked in the top 10 producers of broiler chicken (*Gallus gallus domesticus*), turkey (*Meleagris gallopavo)*, and egg production (USDA-NASS, 2014). Poultry litter has been widely considered the most valuable plant manure produced by livestock (Mitchell and Donald, 1995). Many producers use dry, surface-applied poultry litter to fertilize hay and forage production pastures. Poultry litter could provide an affordable, nutrient-rich fertilizer source for switchgrass production in the future.

Providing robust information to assist producers in making sound resource management decisions prior to engaging in renewable fuel production is of paramount importance. Providing comprehensive information to producers is essential in achieving the goal of increasing domestic fuel resources and decreasing carbon dioxide emissions. Proper management of switchgrass as a suitable crop for marginal land is particularly important, as these areas may be prone to accelerated rates of erosion or have increased leaching potential.

Past research has identified agronomic procedures for maximizing switchgrass biomass production using varying systems, including cultivar choice, fertilizer application, irrigation, harvest frequency, and row spacing (Adler et al., 2005; Bransby, 2014; Jacobs and King, 2012; Kering et al., 2012). It is not enough to guarantee large amounts of biomass production, as these practices must also be renewable and nonpolluting. Thorough evaluations of the implications associated with switchgrass production systems are needed to seriously determine if switchgrass provides a truly renewable and clean source of domestic energy.

The impact of switchgrass production on below-ground properties such as beneficial fungal relationships (Ker et al., 2012) and unique root characteristics of cultivars and implications for soil structure (Ma et al., 1999) have begun to be evaluated and paired with switchgrass above-ground production information.

The objective of this study was to evaluate the effects of switchgrass cultivar (i.e., ‘Alamo’ and ‘Cave-in-Rock’), water management (i.e., irrigation and no irrigation), fertilizer source (i.e., commercial or poultry litter fertilization), and harvest regime (i.e., once-or twice-harvested per year) after three years of consistent management on near-surface soil properties (i.e., bulk density, surface infiltration, root density, water-stable aggregation, soil organic matter, and soil chemical properties) in West-Central Arkansas. Treatment combinations were assessed using a variety of soil quality parameters and paired with prior knowledge of vegetative production yields to determine landowner recommendations for managing switchgrass biofuel feedstock production in West-Central Arkansas.

It is hypothesized that three years of consistent management according to different treatment combinations will significantly affect soil-quality parameters. It is hypothesized that ‘Alamo’ treatment combinations will have lower soil bulk density, greater root density, greater infiltration rates, and greater soil organic matter content than ‘Cave-in-Rock’ combinations. Cultivar is not expected to affect soil nutrient contents. Since ‘Alamo’ previously produced greater biomass yields in all treatments (Jacobs and King, 2012), increased root density and increased litter amounts available for decomposition to soil organic content are hypothesized to drive changes in soil properties.

Fertilizer source is hypothesized to affect soil-quality measurements. Treatments fertilized with poultry litter rather than commercial fertilizer are expected to have lower soil bulk density and greater infiltration rates, as the addition of the organic material associated with animal manures will increase porosity and soil organic matter content since poultry litter contains complex organic particles that may break down more slowly. Irrigated treatment combinations, however, are hypothesized to have lower organic matter content compared to non-irrigated treatment combinations. Increased soil moisture is associated with increased soil microbial activity and subsequent organic matter breakdown (Gillabel et al., 2007).

Water management (irrigation and no irrigation) is not hypothesized to affect any measured soil property. Irrigation may affect near-surface soil nutrient levels, as some mobile nutrients may be leached below the sample depths of 10 and 20 cm.

It is hypothesized that significant differences in soil quality will occur in plots harvested once versus twice per year. Harvesting switchgrass twice per year removes greater amounts of soil nutrients such as N, P, and K. Plots harvested twice per year are expected to have lower root density, greater bulk density, lower infiltration rates, and lower soil organic matter and nutrient contents than those harvested once per year. Based on prior observation, switchgrass appeared less vigorous in the areas harvested twice per year (Jacobs and King, 2012), which may be caused by a weaker overall root system.

It is also hypothesized that switchgrass biomass yield will be correlated to measured soil quality parameters. It is expected that greatest-yielding treatment combinations may contain the lowest amounts of soil nutrients since a greater proportion of plant nutrients would have been removed from the soil in biomass.

2. Materials and Methods

2.1. Site Description

The USDA-NRCS, Plant Materials Center (PMC) was established in Booneville, AR in 1987 and serves the plant material needs of the Southern Ozarks, Arkansas River Valley, and Boston and Ouachita Mountains Major Land Resource Areas (MLRAs 116A, 118A, 117, and 119, respectively). The Booneville Plant Materials Center (PMC) is located along the Petit Jean River in Logan County, Arkansas at an elevation of 146 m (Burner, 2012). The PMC lies along the north edge of the Ouachita National Forest and is in the eastern portion of MLRA 118A, Arkansas Valley and Ridges. The 30-year normal for mean annual precipitation in Booneville is 127 cm and precipitation is delivered more or less evenly throughout the winter (23%), summer (21%), spring (29%), and autumn (27%) seasons (NOAA, 2010). The mean annual air temperature for the region is 15.6 °C, with a winter minimum of 10.5 °C and a summer maximum of 32.4 °C (NOAA, 2010).

The study site was located on a Leadvale silt loam (fine-silty, siliceous, semiactive, thermic Typic Fragiudult; USDA-NRCS, 2003; Appendix A). A fragipan is located at a depth of between 30 and 60 cm in the profile, which can impede water infiltration and plant root growth (Figure 1). The Leadvale soil is poorly drained in late winter and early spring, due to the presence of a perched water table. The fragipan also causes plants to experience drought stress during the summer by limiting the depth of plant roots seeking moisture stored deeper in the soil profile.

The study site was a pasture dominated by tall fescue prior to being prepared for the original yield study in 2006. No fertilizer was applied and the vegetation was kept mowed to a height of approximately 15 cm year-round. Soil samples were collected from throughout the 0-6 cm depth study site prior to planting. Soil samples were analyzed and nutrient levels were brought up to uniform medium production values prior to planting according to recommended values for P and K for native warm-season grass establishment.

2.2. Initial Switchgrass Field and Treatment Establishment

‘Alamo’ and ‘Cave-in-Rock’ switchgrass cultivars were planted at the Booneville PMC in 12.2 m (40 ft) x 12.2 m (40 ft) plots on 5 March 2007. Each plot contained one switchgrass cultivar and fertilizer source (Figure 3). Permanent overhead sprinklers were installed to deliver irrigation to select plots. Each 12.2 m x 12.2 m plot was divided in half, with one subplot harvested once per year and the other subplot harvested twice per year (Figure 2). There were a total of 24 plots including cultivar-irrigation-fertilizer source treatment combinations. There were a total of 48 subplots when harvest frequency (once or twice per year) was included.

Plots were seeded at a rate of 4.4 kg ha^{-1} (5 lb ac^{-1}) pure live seed and planted with a no-tillage native grass drill (Sukup 2050 series, Jonesboro, Arkansas). After drilling, the seedbed was rolled with a water-filled roller to establish good seed-to-soil-contact. Temporary sprinkler irrigation was applied to all plots for initial seed emergence and establishment. A permanent sprinkler irrigation system was installed in replicated irrigation treatments in the summer of 2007. Rain gauges were placed in the irrigated plots to calibrate the irrigation delivery system. Irrigation-treated plots received 2.54 cm of irrigation water from a nearby pond per week during June through August from 2008 to 2011. The average annual precipitation during this study was 131 cm (Burner, 2012), which was slightly greater than the normal 30-year average of 121 cm for this area (NOAA, 2010). Annual rainfall was 127% in 2008, 124% in 2009, 70% in 2010, and 110% in 2011 of the normal 30-year average (Burner, 2012; NOAA, 2010). The average annual air temperature during this study was 15ºC (Burner, 2012), which was numerically less than the 30-yar average of 15ºC (NOAA, 2010). Average annual air temperature was 90% in 2008, 89% in 2009, 93% in 2010, and 99% in 2011 of the normal 30-year average (Burner, 2012; NOAA, 2010).

The study area was burned each year in early March to remove residue stubble, stimulate switchgrass seed production for wildlife, and to remove surface residue for native pollinator nesting habitat and to create corridors for other ground-nesting wildlife species (USDA-NRCS Arkansas, 2009). Fertilizer treatments were applied when green foliage appeared in early April of 2008 to 2011.

Poultry litter was applied at a rate of 4.5 Mg ha^{-1} (2 ton ac^{-1}), while commercial fertilizer was applied to match N, P, and K levels in the applied poultry litter. Litter batches were analyzed annually for nutrient concentrations prior to application.

Two harvest frequencies were imposed to test their effects on annual aboveground biomass production. A single harvest was made in November after the first killing frost for the 1-

cut system. In the two-cut system, harvests occurred twice per year. The first harvest occurred in June just prior to the boot stage (when seedhead emerges from switchgrass), and the second harvest occurred after a killing frost in November.

2.3. Soil, Plant and Hydrologic Property Measurements

Soil samples were collected in all plots from the 0-10 and 10-20 cm depth interval for bulk density, Mehlich-3 extractable soil nutrients, soil organic matter, and soil particle-size determinations. In the top 10 cm, bulk density samples were collected manually with a 5.0-cm diameter, stainless steel core chamber and a slide hammer. For the 10-20 cm depth, bulk density samples were collected with a 5-cm diameter, stainless steel hydraulic probe. Samples from both depths were dried in a forced-air dryer at 70°C for 48 hours, and then weighed for bulk density determinations. Soil from the bulk density samples was portioned and used to measure particle-size distribution using a modified 12-hour hydrometer method (Bouyoucos, 1927), Mehlich-3 extractable soil nutrients (i.e., P, K, Ca, Mg, S, Na, Fe, Mn, Zn, and Cu; Mehlich, 1984; Tucker, 1992), soil pH, and electrical conductivity (EC).

Total water-stable aggregate (TWSA) concentration (i.e., > 0.25-mm diameter) was measured on samples collected from the 0-5 and 5-10 cm depths using a 4.8-cm diameter core chamber and slide hammer using a wet-sieving procedure (Yoder, 1936). Soil core samples were collected from areas in between switchgrass plants in switchgrass rows. Two replications were collected from each subplot. The two samples collected from each subplot were mixed together for one sample per depth interval. Each soil sample was manually broken down by hand and air-dried for 15 days. Approximately 400 g of air-dried soil was used for the wet-sieving procedure, where soil was plunged in tap water at 30 cycles per minute for 5 minutes. Soil retained on the mesh openings of each of the 5 sieves (i.e., 4.0, 2.0, 1.0, 0.5, and 0.25 mm) was rinsed into an aluminum container with tap water. Water was decanted from the container, and remaining soil weighed after being dried at 70°C for 24 hours. Soil mass from each container was summed to calculate total mass of water stable aggregates from each subplot.

Soil samples for root density were collected from the 0-15 cm depth interval using a 7.3-cm diameter core chamber and slide hammer, and prepared according to the procedures followed by Brye and Riley (2009). Root samples were washed on a 2-mm mesh screen to collect the root material, dried at 55°C for 24 hours, and weighed. Root density core samples were collected from areas in between switchgrass plants in rows (interrow). One root core per subplot was collected in September 2013.

Double-ring infiltrometers were used to measure infiltration rates two days after a soaking rainfall. Moist antecedent soil moisture condition was intended to limit horizontal water movement into surrounding dry soil during infiltration measurements; infiltration measurements were intended to measure downward water movement in soil. Mature switchgrass was trimmed using hedge trimmers and residue carefully removed prior to placement of infiltrometers. One double ring infiltrometer measurement was conducted in each subplot in treatment combinations including cultivar, harvest frequency, and fertilizer source. In order to maximize potential infiltration differences among all other treatment combinations, irrigation measurements were only conducted in the non-irrigated plots. Double-ring infiltrometers were placed between switchgrass plants in switchgrass rows after switchgrass was mowed to a height of 6 cm in November 2013. Outer ring diameter was 30 cm, inner ring was 6 cm in diameter, and rings were 10 cm in height. The infiltrometer was inserted approximately 2 cm deep into the soil and outer ring was filled with tap water to act as a buffer between dry soil and saturated soil in the inner ring. The inner ring was filled with tap water and the distance from the top of the soil to the water surface in the inner ring was measured at 0 minutes and after 1, 2, 3, 4, 5, 8, 10, 12, 15, 18, and 20 minutes.

Double-ring infiltration measurements were paired with mini-disk tension infiltrometer measurements (Decagon, Pullman, Washington) where infiltrometer tension was set at -2 cm in each plot. Two mini-disk infiltrometer measurements were conducted in each subplot, with one measurement collected from the center-ring area immediately following double ring infiltrometer measurements and one measurement collected in a nearby location. Two measurements were performed in each subplot for a total of 96 measurements. Both mini-disc and double-ring infiltrometers were placed between switchgrass rows (interrow), and plant bases were avoided to minimize leaking along root channels.

2.4. Statistical Analyses

The effects of cultivar, harvest frequency, irrigation, fertilizer source, soil depth, and their interactions on soil bulk density, SOM, soil chemical properties, particle-size distributions, and TWSA was evaluated by analysis of variance (ANOVA) using SAS (version 9.3, SAS Institute, Inc., Cary, NC). Similarly, an ANOVA was conducted to evaluate the effects of cultivar, harvest frequency, irrigation, fertilizer source, and their interactions on root density using SAS.

An analysis of covariance (ANCOVA) was conducted to evaluate the effects of cultivar, harvest frequency, irrigation, and fertilizer source on the relationship between infiltration rate and time. When appropriate, means were separated by least significant difference (LSD) at $\alpha = 0.05$.

3. Results

3.1. Soil Properties

3.1.1. Particle-size Distribution

Throughout the study site, sand, silt, and clay in the top 20 cm varied somewhat; however, sand, silt and clay remained within the range of a silt-loam surface texture. Sand ranged from 19.8 to 36.8% and averaged 29.5%. Silt ranged from 42.9 to 55.8% and averaged 49.3%. Clay ranged from 14.2 to 29.2% and averaged 21.2%. However, sand, silt, and clay contents in the top 20 cm differed slightly among various treatment combinations, with the largest differences occurring between soil depths, which was expected (Table 1). Sand content differed between soil depths within cultivar-irrigation treatment combinations ($p = 0.04$; Table 1). In both the top 10 cm and in the 10-20 cm depth interval, sand content was greatest in the irrigated-'Alamo' treatment combinations, 32.6 and 30.3%, respectively (Table 2). Sand content in the top 10 cm and 10-20 cm depth interval was lowest in the non-irrigated-'Cave-in-Rock' (26.1%) and non-irrigated-'Alamo' (27.5%) treatment combinations (Table 2).

Averaged over all other treatment factors, silt content differed between soil depths ($p < 0.01$; Table 1), where silt content was greater in the top 10 cm than the 10- to -20 cm depth interval (50.4 and 48.2%, respectively). Silt ($p= 0.04$) and clay ($p = 0.03$) content also differed between fertilizer sources when averaged across all other treatment factors (Table 1), which was unexpected. Silt content was greater in the poultry litter (50%) than the commercial fertilizer

(48.6%) treatment combination. Clay content was greater in the commercial fertilizer (21.7%) than the poultry litter treatment combinations (20.6%). Averaged across all other treatment factors, silt content also differed between cultivars *(p* < 0.01; Table 1). Silt content was greater in 'Cave-in-Rock' (50.2%) than in 'Alamo' (48.4%) treatments. Despite the significant fertilizer source effect on silt and clay and significant cultivar effect on silt content, all silt and clay differences between treatments were less than 2%. Small differences of this magnitude are not likely to affect agronomic management.

Averaged over harvest frequencies, fertilizer sources, and irrigation treatments, clay content also differed between cultivars within soil depths *(p* < 0.01; Table 1). As expected, clay content increased with increasing depth from the top 10 cm (19.5%) to the 10- to -20 cm depth interval (22.9%) for both cultivars (Figure 4). Clay content was greatest and least for 'Alamo' treatment combinations in the 10- to -20 cm (22%) and 0-10 cm (17%) depth intervals, respectively.

The observed differences in sand, silt, and clay contents between soil depths were expected based on the reported textural classes of the top two horizons listed on the Leadvale silt-loam official series description (Appendix 1). Clay accumulation with increasing depth was expected, as the surface horizon (Ap) grades to an argillic (Bt) horizon at approximately 20 cm (Appendix 1). Despite some relatively minor differences in particle-size distribution among various treatment combinations, differences were not large enough to change the soil taxonomic classification anywhere in the study site and would likely not influence practical agronomic management decisions related to switchgrass production.

3.1.2. Bulk density

As expected, averaged over all other treatment factors, soil bulk density differed between soil depths ($p < 0.001$; Table 1). Soil bulk density was greater in the 10- to 20- cm depth (1.44 g cm^{-3}) than in the top 10 cm (1.30 g cm^{-3}).

Averaged over soil depths and cultivars, soil bulk density also differed between irrigation treatments within fertilizer-source-harvest-frequency treatment combinations ($p = 0.004$; Table 1). Soil bulk density was greater in the irrigated-poultry litter treatment combination with either harvest frequency (1.40 g cm^{-3}) than the non-irrigated-1-cut treatment combination with either fertilizer source (1.33 g cm^{-3}; Table 4). Soil bulk density was unaffected by switchgrass cultivar ($p > 0.05$; Table 1).

3.1.3. Aggregate Stability

Averaged over soil depth, cultivar, and harvest frequency, TWSA concentration differed between irrigation treatments within fertilizer sources ($p = 0.03$; Table 1). Total WSA concentration was greater under irrigated (0.93 g g^{-1}) than non-irrigated (0.86 g g^{-1}) with poultry litter, but did not differ between irrigation treatments with commercial fertilizer (0.86 g g^{-1}; Figure 4; Table 1).

Averaged over irrigation, TWSA concentration also differed between soil depths within cultivar-fertilizer-source-harvest-frequency treatment combinations ($p = 0.02$; Table 1). The greatest TWSA concentration was measured in the 'Alamo'-commercial-fertilizer-2-cut treatment combination in the 10- to -20 cm depth (0.93 g g^{-1}), while the lowest TWSA concentration was measured in the 'Cave-in-Rock'-poultry-litter-1-cut treatment combination in the top 10 cm depth (0.87 g g^{-1}; Table 3).

In addition, there were several notable trends in TWSA concentrations. Unexpectedly, TWSA concentration was generally numerically greater in 'Alamo' than in 'Cave-in-Rock' treatment combinations (Table 3). In contrast to hypothesized effects linking increased harvest frequency to decreased TWSA, TWSA concentration was generally numerically greater in the 2-cut than the 1-cut harvest frequency (Table 3). Total WSA concentration was generally numerically greater in the 10- to -20 cm depth than in the top 10 cm (Table 3).

3.1.4. Soil pH and Electrical Conductivity

As expected, averaged over all other treatment factors, soil pH differed between fertilizer sources ($p = 0.001$; Table 7). Soil pH was greater in the poultry litter (pH = 6.1) than in the commercial fertilizer (pH = 5.9). Soil pH was unaffected by switchgrass cultivar, irrigation, harvest frequency, or soil depth. Though soil pH values differed between fertilizer sources, only 0.02 pH units separated the means.

Averaged over fertilizer source and soil depth, soil EC differed between cultivars within irrigation-harvest-frequency treatment combinations ($p = 0.016$; Table 7). Soil EC was greatest in 'Cave-in-Rock' (0.070 dS m^{-1}) and least in 'Alamo' (0.056 dS m^{-1}) treatments without irrigation in the 2-cut harvest frequency (Table 5).

Averaged over harvest frequency and fertilizer source, soil EC differed between soil depths within cultivar-irrigation treatment combinations ($p = 0.006$; Table 7). Soil EC was generally greatest in the top 10 cm (Table 2). Soil EC was the lowest in the non-irrigated-'Alamo' and irrigated-'Cave-in-Rock' treatment combinations in the 10- to -20 cm depth interval, which did not differ (Table 2).

Averaged over cultivar and irrigation, soil EC differed between soil depths within fertilizer-source-harvest-frequency treatment combinations ($p = 0.020$; Table 7). Soil EC was greatest in the 1-cut-poultry-litter treatment combination in the top 10 cm (0.081 dS m^{-1}) compared to all other treatment combinations (Table 6). Soil EC did not differ among harvest-frequency-fertilizer-source treatment combinations in the 10- to -20 cm depth and averaged 0.058 dS m^{-1} (Table 6).

3.1.5. Extractable Soil Nutrients

Averaged over harvest frequency and fertilizer source, extractable soil Mn differed between soil depths within cultivar-irrigation treatment combinations ($p = 0.026$; Table 8). Extractable soil Mn was greater in irrigated-'Alamo' (230.2 kg ha^{-1}) treatment combination in the 10-20 cm depth interval than all other treatment combinations, which did not differ and averaged 176.6 kg ha^{-1} (Table 2).

Unexpectedly, extractable soil K ($p = 0.033$; Table 7) and Na ($p = 0.019$; Table 8) contents differed between cultivars when averaged over all other treatment factors. 'Cave-in-Rock' treatments had greater extractable soil K (95 kg K ha^{-1}) and lower extractable soil Na (43 kg Na ha^{-1}) compared to 'Alamo' (79 kg K and 64 kg Na ha^{-1}) treatments.

Averaged over all other treatment factors, extractable soil Ca ($p = 0.031$; Table 7) and Fe ($p < 0.001$; Table 8) contents differed between soil depths. Extractable soil Ca was greater in the

10- to 20- cm depth (2079 kg ha^{-1}) than in the top 10 cm (1965 kg Ca ha^{-1}). In contrast, extractable soil Fe was greater in the top 10 cm (216 kg Fe ha^{-1}) than in the 0- to -10 cm depth (164 kg Fe ha^{-1}).

Averaged over irrigation, cultivar, and harvest frequency, extractable soil P, K, Mg, S, Na, and Zn contents differed between soil depths within fertilizer-source treatments ($p < 0.04$; Tables 7 and 8). The results for extractable soil P, K, Mg, S, and Zn contents followed similar trends related to treatment combinations and were generally greater in the top 10 cm compared to the 10- to -20 cm depth (Figures 4, 5, and 6). Extractable soil P, K, Mg, S, and Zn contents were greatest in the poultry-litter treatment combinations in the 0- to -10 cm depth and the lowest in the 10- to -20 cm depth treatment combinations of either fertilizer source, which did not differ (Figures 4, 5, and 6). In contrast, extractable soil Na was generally greater in the 10- to 20-cm depth compared to the top 10 cm, while extractable soil Na was greatest in the 10- to -20 cm-depth-poultry-litter and lowest in the 0- to -10 cm-commercial-fertilizer treatment combination (Figure 5).

Extractable soil P, K, Mg, and Zn contents differed between soil depths within harvest frequencies when averaged over irrigation, cultivar, and fertilizer source ($p < 0.02$; Tables 7 and 8). The results for extractable soil P, K, Mg, and Zn contents followed similar trends related to treatment combinations and were generally greater in the top 10 cm compared to the 10- to 20-cm depth (Figures 4, 5, and 6). Extractable soil P, K, Mg, and Zn contents were greatest in the 1-cut treatment combination in the top 10 cm, which supported the hypothesis that harvesting once after switchgrass senescence rather than twice per year allows greater retention of extractable soil nutrients (Figures 4, 5, and 6). Extractable soil P, K, Mg, and Zn contents were lower in the

10- to 20-cm than the 0- to 10-cm depth, but did not differ according to harvest frequency (Figures 4, 5, and 6).

In addition, when averaged over cultivar, harvest frequency, and soil depth, extractable soil Ca and Cu contents differed between fertilizer sources within irrigation treatment combinations *(*$p < 0.03$; Tables 7 and 8). Extractable soil Ca and Cu contents followed similar trends, as both were the lowest in irrigated-commercial-fertilizer and the greatest in irrigated-poultry-litter treatment combination (Figures 4 and 5).

Averaged over harvest frequency, fertilizer source, and soil depth, extractable soil P content differed between cultivars within irrigation treatments *(*$p = 0.016$; Table 7). Extractable soil P was lower in the irrigated-'Cave-in-Rock' than in 'Alamo' of either irrigation treatment and in the non-irrigated-'Cave-in-Rock' treatment combination, which did not differ (Figure 4).

Averaged over cultivar, harvest frequency, and fertilizer source, extractable soil Zn content differed between irrigation within soil depth treatments *(*$p = 0.025$; Table 8). While the greatest extractable Zn content was in the irrigated-0-to-10 cm depth compared to all other treatment combinations, extractable Zn content was generally greater in the top 10 cm than in the 10- to 20-cm depth (Figure 5). Extractable soil Zn was lowest in the 10- to 20-cm depth of either irrigation treatment compared to all other treatment combinations (Figure 5).

In addition, when averaged over soil depth, extractable soil Zn content differed between irrigation within cultivar-fertilizer-source treatments (($p = 0.43$; Table 8). The greatest extractable Zn content was in the irrigated-'Alamo'-poultry-litter (2.3 kg ha^{-1}) treatment, but did not differ from the 'Cave-in-Rock'-poultry-litter treatment of either irrigation combination (Table 11). The lowest extractable Zn content was in the irrigated-'Alamo'-commercial-fertilizer

(0.6 kg ha^{-1}) treatment, but did not differ from all other commercial fertilizer treatments of either irrigation or cultivar treatment combination (Table 11).

The extractable soil Fe (p = 0.003) and Cu (p = 0.009) contents differed by cultivar within fertilizer-source-harvest-frequency treatment combinations when averaged over irrigation and soil depth (Table 8). Both extractable soil Fe and Cu were the greatest in the ‘Alamo’-poultry-litter-1-cut treatment combination and the lowest in the ‘Cave-in-Rock’-commercial-fertilizer-2-cut treatment combination compared to all other treatment combinations (Table 9).

Averaged over cultivar and irrigation, extractable soil Cu content differed by soil depth within harvest frequency-fertilizer-source treatment combinations (p = 0.038; Table 8). Extractable soil Cu content was the greatest in the 1-cut-poultry-litter treatment combination in the top 10 cm (2.9 kg ha^{-1}) and the lowest in the 2-cut-commercial-fertilizer treatment in the 10- to -20 cm depth (0.80 kg ha^{-1}; Table 6). Extractable soil Cu content was generally greater in the top 10 cm and in treatments that included poultry litter (Table 6).

Averaged over harvest and irrigation, extractable soil Cu content also differed by soil depth within cultivar-fertilizer-source treatment combinations (p = 0.032; Table 8). Extractable soil Cu content was lowest in the ‘Alamo’-commercial-fertilizer treatment combination in the 0- to -10 cm depth (0.8 kg ha^{-1}), which did not differ from other treatment combinations in the 10- to -20 cm depth (Table 10). The extractable soil Cu content was greatest in the ‘Cave-in-Rock’-poultry-litter (2.9 kg ha^{-1}) treatment combination (Table 10).

3.2. Plant Properties - Root Density

In contrast to the initial hypothesis that irrigation would have minimal effect on belowground switchgrass growth in the climatic region of west-central Arkansas, averaged across all other treatment factors, switchgrass root density differed between irrigation treatments ($p = 0.031$; Table 1). Switchgrass root density was greater in the irrigated (2.62 kg m^{-3}) than in the non-irrigated (1.65 kg m^{-3}) treatment.

It was hypothesized that increasing the harvest frequency from 1 to 2 cuts per year would significantly decrease switchgrass root density. However, the results did not support this initial hypothesis ($p = 0.058$; Table 1). Root density was also unaffected by switchgrass cultivar and fertilizer source (Table 1).

3.3. Infiltration Characteristics

3.3.1. Infiltration Rates

Water infiltration rates measured with the double-ring infiltrometer did not differ among treatment combinations ($p > 0.05$). The infiltration rates ranged from a low of 0.2 mm min^{-1} in the non-irrigated-‘Alamo’ treatment combination with either fertilizer source to a high of 2.4 mm min^{-1} in the non-irrigated-‘Cave-in-Rock’-poultry-litter treatment combination and averaged 0.79 mm min^{-1} across all treatment combinations.

Unlike infiltration rates measured with the double-ring infiltrometer, infiltration rates measured with the mini-disk infiltrometer at a tension of -2 cm differed between harvest frequencies when averaged across all other treatment factors ($p = 0.034$; Table 12). The tension infiltration rate was greater in the 1-cut (33 mm min^{-1}) than in the 2-cut treatment (24 mm min^{-1})

combinations. The tension infiltration rate was unaffected (*p* > 0.05) by cultivar, irrigation, or fertilizer source (Table 12).

3.3.2. Relationship between Infiltration Rate and Time

3.3.2.1. Double-ring Infiltrometer

Though infiltration measured with the double-ring infiltrometer rates did not differ among treatment factors, the slope of the linear regression of the natural log of the infiltration rate plotted against the natural log of the mid-point time was affected by several treatment factors (Table 12). Averaged over fertilizer treatments, the slope of the linear regression equation differed by cultivar within harvest frequencies (*p* = 0.0042; Table 12). The slope values were greatest for the 'Cave-in-Rock'-2-cut (m = - 0.003) and 'Alamo'-1-cut (m = - 0.066) treatment combinations, which did not differ and are shown with one regression trend line (Figure 7). The slope values were smallest for the 'Cave-in-Rock'-1-cut (m = - 0.400) and 'Alamo'-2-cut (m = - 0.442) treatment combinations, which did not differ and are also shown with one regression trend line (Figure 7).

Averaged over cultivar, the slope of the linear regression equation also differed by fertilizer source within harvest frequencies (*p* = 0.0477; Table 12). The greatest slope values were for the 'Cave-in-Rock'-2-cut (m = -0.003) and 'Alamo'-1-cut (m = -0.066) treatment combinations, which did not differ and are shown with one regression trend line (Figure 7). The smallest slope values were for the 'Cave-in-Rock'-1-cut (m = -0.400) and 'Alamo'-2-cut (m = - 0.442) treatment combinations, which did not differ and are shown with one regression trend line (Figure 7).

3.3.2.2. Mini-disk Infiltrometer

Unlike the double-ring infiltrometer, the slope and the y-intercept of the linear regression equations for the natural log of the infiltration rate plotted against the natural log of the mid-point time were affected by several treatment factors (Table 12). The slope *(p* = 0.0263) and y-intercept *(p* = 0.0492) differed by cultivar within fertilizer-source-harvest-frequency treatment combinations (Table 12). The slope was greatest for the ‘Alamo’-commercial-fertilizer-2-cut (m = -0.162), and smallest for the ‘Cave-in-Rock’-poultry-litter-1-cut (m = -0.319) treatment combinations, while the y-intercept of the linear relationship was greatest in the ‘Cave-in-Rock’-poultry-litter-1-cut (b = 1.852) and smallest in the ‘Alamo’-commercial-fertilizer-2-cut (b = 0.253) treatment combinations (Table 13).

4. Discussion

Overall results of this study indicate treatments imposed on the switchgrass production system affected near-surface properties in the top 20 cm and surficial processes. However, treatment combinations that produced significant differences in the amount of aboveground biomass production noted by Jacobs and King (2012) did not necessarily produce significant differences in the measured soil properties in this study.

4.1. Cultivar Effects

Switchgrass cultivar was not expected to affect most soil properties; however, TWSA and silt concentrations, and Na, Fe, P, and K contents differed between cultivars when averaged over all other treatment factors (Tables 1, 7, and 8). In addition, clay concentration differed by depth within cultivars when averaged over irrigation, harvest frequency, and fertilizer source (Table 1). While the silt and clay differences cannot be readily explained, greater soil extractable P and K contents in 'Cave-in-Rock' treatments may have resulted from lower nutrient removal rates according to lower biomass production compared to 'Alamo' treatments. Average biomass yields at this site over a four-year period were significantly greater from 'Alamo' than from 'Cave-in-Rock' treatments (Jacobs and King, 2012); thus, greater demand for plant macronutrients and lower soil extractable P and K contents would be expected.

While extractable soil nutrient differences were relatively straightforward, TWSA concentrations depend on many factors related to soil, water, and plant relationships. Previous work in Arkansas has shown that TWSA concentration in the top 10 cm of soil is much greater in undisturbed or restored native prairie than in row crop production. Total WSA concentrations in row crop production varied from 0.05 g g^{-1} in a non-irrigated wheat-soybean double-crop system (managed consistently for 10 years; Smith et al., 2014) to 0.11 g g^{-1} in irrigated rice and non-irrigated wheat double-crop system (managed consistently for 6 years; Anders et al., 2010). In contrast, TWSA concentrations of 0.44 g g^{-1} were reported in Brye et al. (2009) in an Arkansas undisturbed native prairie ecosystem composed of native grasses and forbs in a silt loam soil textural class. Interestingly, TWSA concentrations in this study, which averaged 0.89 g g^{-1} in the top 10 cm (Table 3) were much greater than those measured in the undisturbed native prairie ecosystem (0.44 g g^{-1}; Brye et al., 2009). Differences may be attributed to the intensive nature of treatment combinations imposed in this study, such as irrigation and fertilizer applications. Greater TWSA concentrations observed in this study may also be attributed to complex interactions involving plant roots and soil aggregation.

Differences in root density may influence TWSA concentration, but results from this study show that root density did not differ between cultivars (Table 1). Soil organic matter may influence also TWSA concentration, but soil organic matter was not measured as a part of this study. The 0- to 15-cm depth interval where root density was measured in this study may not have captured enough of each cultivar's unique rooting characteristics, which may explain why TWSA concentration and not root density differed between cultivars (Table 1), when averaged over all other factors. Frank et al. (2004) determined that 50% of switchgrass root mass occurred in the top 30 cm of soil. In addition, Jung et al. (2011) reported that switchgrass root partitioning between fine and coarse roots is dynamic and may be altered with differing levels of soil fertility. Due to differing extractable soil nutrient contents between cultivars, the partitioning between fine and coarse roots may not have been accurately captured for all treatments by the 2-mm sieve size used for the root washing procedure used in this study.

4.2. Irrigation Effects

Similar to the cultivar effects previously discussed, it was hypothesized that irrigation treatment effects would have little influence on soil properties. However, irrigation treatments produced significant differences in root density (Table 1). Though application of irrigation to the switchgrass crop did not significantly increase biomass yield (Jacobs and King, 2012), irrigation increased root density compared to the non-irrigated treatments when averaged over all other treatment factors. Irrigation directly stimulated root growth and may have altered additional soil properties measured in this study, such as TWSA concentration.

Averaged over all other treatment factors, the TWSA concentration did not differ at the 0.05 level between irrigation treatments (p = 0.054; Table 1); however, mean TWSA concentrations were numerically greater in the irrigated (0.93 g g^{-1}) compared to the non-irrigated (0.88 g g^{-1}) treatments. The increase in the TWSA concentration may be linked to greater root density, as roots encourage the formation and stabilization of soil aggregates (Six et al., 2004). The lack of a significant effect of irrigation on TWSA concentration was in contrast to Singer (1992), where the rewetting of dry soil during irrigation cycles decreased the concentration of soil macroaggregates compared to a non-irrigated site. The destruction of soil aggregates due to irrigation was attributed to an increase in air pressure inside dry soil macroaggregates during the rewetting process (Singer, 2002). Soil aggregates may not have dried enough for this process to occur in west-central Arkansas, given irrigation did not significantly increase switchgrass biomass yield (Jacobs and King, 2012).

While irrigation did not directly affect bulk density (Table 1), soil bulk density differed between irrigation within harvest-frequency-fertilizer-source treatment combinations when averaged over cultivar and soil depth (Tables 1 and 4). Neither irrigation (p = 0.370) nor fertilizer source (p = 0.745) directly affected soil bulk density (Table 1); however, the interaction of irrigation and fertilizer source treatments produced significant differences in bulk density (p = 0.011; Table 1).

Whalen and Chung (2002) compared soil aggregate stability with differing application rates of cattle manure on cropland in Canada. While the authors hypothesized that soil macroaggregate (> 12.1 mm) stability would increase with increased manure application rate, results showed that the proportion of soil macroaggregates actually decreased with manure application compared to no manure application. The authors cite the dispersive effects of monovalent cations and foreign soil present in cattle manure. Edaño (2013) also determined that the application of manure fertilizer (cattle manure or poultry litter) compared to commercial fertilizer did not encourage macroaggregate formation in switchgrass plots harvested in both 1-and-2-cut systems.

The dispersive effects of monovalent cations typically present in poultry litter, such as Na^+, may have affected soil properties evaluated in this study. For example, irrigation of plots fertilized with poultry litter may have caused greater dispersion by further mobilizing monovalent cations. Results from this study further support the conclusions of Whalen and Chung (2002) and Edaño (2013), as soil bulk density was greater in the irrigated-poultry litter treatment combination with either harvest frequency (1.41 g cm^{-3}) than in the non-irrigated-1-cut treatment combination with either fertilizer source (1.33 g cm^{-3}; Table 4).

4.3. Fertilizer Source Effects

The application of two different fertilizer sources over a four-year period (Jacobs and King, 2012) produced significant differences (Tables 7 and 8) in extractable soil nutrient levels in switchgrass plots. Even though significant differences between fertilizer sources were present in levels of extractable soil nutrient levels after the four-year study period, biomass yield was not affected by fertilizer source (Jacobs and King, 2012). In contrast, Edaño (2013) reported that switchgrass biomass yield was greatest with poultry litter application compared to commercial fertilizer applications, switchgrass seeded with legumes, and an unfertilized control.

It may be useful to repeat this study using a factorial design to further examine fertilizer effects by including unfertilized plots subjected to all other harvest, irrigation, and cultivar treatment variables. These results indicate that both poultry litter and commercial fertilizer are viable options for landowners interested in switchgrass production.

Poultry litter was applied at a rate of 4.5 Mg ha^{-1} (2 ton $acre^{-1}$) and corresponding amounts of N, P, and K were applied as commercial fertilizer. Poultry litter contains more than just N, P, and K, and significant differences between the levels of extractable soil nutrients were apparent in this study. Only one soil nutrient tested (Mn) did not differ according to fertilizer source when averaged across all other treatment factors (Tables 7 and 8). As expected, soil collected from plots fertilized with poultry litter contained significantly greater contents of extractable soil P, K, Ca, Mg, S, Na, Fe, Zn, and Cu. Edaño (2013) observed similar increases in extractable soil P when switchgrass was fertilized with cattle and poultry litter instead of commercial fertilizer.

In addition, both soil pH and soil EC were significantly greater in plots fertilized with poultry litter than those fertilized with commercial fertilizer, which was expected. Results from this study regarding soil pH changes in ‘Alamo’ switchgrass from fertilizer sources were similar to Edaño (2013) in Oklahoma. Soil pH in switchgrass plots slightly increased in plots fertilized with manure (cattle and poultry litter) and slightly decreased in plots fertilized with commercial fertilizer compared to unfertilized plots (Edaño, 2013). The differences in pH would not likely affect agronomic management decisions, especially given that soil pH values of 5.5 to 6.6 are considered optimum for native, warm-season grass establishment in Arkansas (USDA-NRCS Arkansas, 2009).

4.4. Harvest Frequency Effects

The previous study by Jacobs and King (2012) largely focused on the effects of harvest frequency on biomass yield due to the dual-purpose nature of switchgrass production as livestock forage and a renewable energy feedstock. Harvesting once per year in the fall after a frost (i.e., the 1-cut system) yields biomass low in livestock forage quality, but desirable for conversion to renewable fuels; conversely, harvesting twice per year (i.e., the 2-cut system) increases switchgrass crop flexibility for landowners who may harvest the first cutting of switchgrass for hay or grazing when livestock forage quality is greatest. Jacobs and King (2012) noted that the 2-cut system produced significantly more biomass than 1-cut systems, averaged across all other treatment combinations.

Despite the increased yield for switchgrass harvested in the 2-cut system, removing greater amounts of biomass also decreased extractable soil K and Mg. In addition, TWSA concentrations and mini-disk total infiltration rates were significantly (Table 1) lower for plots harvested in the 2-cut than in the 1-cut system. In a similar study, Edaño (2013) noted switchgrass harvested in a 2-cut system had significantly lower extractable soil NO_{3-} concentrations, total microbial biomass, and total mycorrhizal biomass in the top 10 cm than those harvested in a 1-cut system.

The lack of significant effects due to increased harvest frequency on root density are in contrast to harvest frequency effects on aboveground biomass yield. Jacobs and King (2012) reported that mean biomass yield over the four-year study was significantly greater for 2-cut

(17.9 Mg ha^{-1}) compared to 1-cut (12.1 Mg ha^{-1}) treatment when averaged over all other treatment factors. Data from aboveground and belowground plant production further demonstrate that increasing switchgrass yield by harvesting twice per year does not significantly decrease root density in the soil and climatic conditions of west-central Arkansas.

4.5. Infiltration Characteristics

In general, results indicated mean infiltration rates were greater under tension when measured with the mini-disk infiltrometer compared to the double-ring infiltrometer because each method measured different modes of infiltration. Infiltration was only measured in the inner ring for the double-ring infiltrometer while adjacent soil was nearly saturated throughout the 20-minute measurement period. Infiltration measured with the double-ring infiltrometer measured downward or vertical water infiltration (i.e., one-dimensional water infiltration). In contrast, soil around the mini-disk infiltrometer was unsaturated throughout the 20-minute measurement period; thus, infiltration was likely both downward and lateral (i.e., more three-dimensional water infiltration).

Due to the differences associated with measuring infiltration in unsaturated and nearly saturated conditions, only mini-disk infiltration rates were directly affected by harvest frequency (Table 1). The mini-disk infiltration rate was greater in the 1-cut than the 2-cut treatment combinations, which supported the hypothesis that more intensive harvest frequencies decrease water infiltration through soil micropores. Increases in wheel traffic from tractors and other harvesting equipment in 2-cut systems may not consistently increase bulk density, as previous data showed, but may reduce soil micropores. Removal of the switchgrass canopy cover during the growing season (i.e., the June harvest of the 2-cut system) likely exposed more soil than in 1-cut treatment and may have allowed soil micropores to be sealed or clogged by temporary crusting from precipitation or irrigation.

The slope of the linear regression equations relating the natural log of the infiltration rate and natural log of time provided additional information about what could happen to surface water (i.e., precipitation or irrigation) in each treatment combination. Large (i.e., steep) slopes represent greater surface infiltration per unit time, while smaller (i.e., flatter) slopes represent slower surface infiltration per unit time. This relationship is readily apparent when comparing the slopes averaged over fertilizer source for the double-ring infiltration, which differ by cultivar within harvest frequencies (Table 12). The treatment combinations with modest infiltration rates and a smaller slope characterizing the relationship between the natural log of the infiltration rate and the natural log of time included the ‘Cave-in-Rock’-2-cut and ‘Alamo’-1-cut combinations, which did not differ (Figure 7). Conversely, the slopes characterizing the relationship between the natural log of the infiltration rate and the natural log of time associated with the ‘Cave-in-Rock’-1-cut and ‘Alamo’-2-cut treatment combinations were larger and represented a greater surface infiltration per unit time (Figure 7). A similar relationship was observed when the treatments were averaged over cultivar and differed by fertilizer-source within harvest frequencies (Table 12), as the slope of the poultry-litter-1-cut treatment combination was smaller compared to the slope of the commercial-fertilizer-1-cut treatment combination. One reason the slope was smaller for the poultry litter fertilizer treatment combination could be related to the presence of monovalent cations in the poultry litter, such as Na^+. The ecological implications for greater infiltration and storage of surface water in the soil profile over shorter periods are vast and may affect the amount of plant available water for crop growth, the amount of offsite nutrient loss, and the potential for erosion of topsoil.

The mean double-ring infiltration rate into a silt-loam soil, which was measured in this switchgrass production study after four years of continuous and consistent management, was less than that reported by Bonin et al. (2012) for switchgrass harvested in a 1-cut system in Ohio (2.8 mm min^{-1}). Decreased infiltration rates recorded in this study may be due to a variety of site differences among the two studies, including different switchgrass plant population densities resulting from differing initial seeding rates (i.e., 11.2 and 4.4 kg pure live seed ha^{-1} in Ohio and for this study, respectively), differences in soil surface texture (i.e., silty clay loam in Ohio and silt loam in this study), and/or differences in switchgrass stand age (i.e., seven years in Ohio and four years in this study). Another factor that may have contributed to decreased infiltration rates at this site compared to the Ohio site could have been the hydrophobic properties of ash from prescribed burning as part of annual stand management activities. Switchgrass plots were burned each March throughout the four-year treatment application period in this study, while the Ohio site was not burned during the study period. Reducing the frequency of prescribed burns may increase infiltration rate.

Studies that evaluate soil aggregate stability may give ancillary information toward interpreting water infiltration rates because soil aggregate size influences soil pore space. In this study, both the TWSA concentration and the mini-disk infiltration rate were greater in plots harvested in the 1-cut system, which supports Edaño's (2013) supposition that harvesting switchgrass in a 1-cut system has the potential to increase water infiltration rate. Results from this study indicate water infiltration rates do not consistently improve (i.e., increase) with greater

TWSA concentration. In addition, results show that treatment effects may be missed if only saturated water infiltration is evaluated.

4.6. Practical Applications

Switchgrass production technology has improved steadily since being recognized by the US Department of Energy as an ideal cellulosic feedstock in the late 1980's. Modern natural resource concerns, such as Gulf hypoxia and the sharp increase in the cost of commercial fertilizer, have reframed the demand for renewable fuel production to include other ecosystem benefits in addition to feedstock production potential. Producers and other private landowners engaged in feedstock production must make informed management decisions to maximize production while protecting soil and water resources. A first step in providing information to producers and landowners lies in pairing aboveground management strategies to maximize biomass yield, such as cultivar choice, irrigation management, harvest frequency, and choice of fertilizer, with belowground consequences.

This study evaluated the belowground consequences of common strategies to maximize aboveground switchgrass biomass yield in west-central Arkansas. Soil property changes were examined through the lens of biomass yield to give producers and private landowners the most useful context for choosing a management strategy.

Averaged over cultivar and fertilizer source, mean biomass yield over four years differed by harvest frequency as yields were significantly greater in the 2-cut (17.9 Mg ha^{-1}) compared to 1-cut (12.1 Mg ha^{-1}) system (Jacobs and King, 2012). Jacobs and King (2012) also noted that each switchgrass cultivar responded differently to the 2-cut harvest frequency, even though mean annual production over the four-year period did not differ significantly between cultivars within harvest frequency averaged over fertilizer source. The ‘Cave-in-Rock’-2-cut treatment combination produced an average of 62% more biomass compared to 1-cut system, while the ‘Alamo’-2-cut treatment combination only produced an average of 35% more biomass compared to the 1-cut system. The results regarding cultivar response to the 2-cut harvest frequency were similar to those reported by Fike et al. (2006), where maximum switchgrass biomass yield was achieved by harvesting lowland cultivars, e.g., ‘Alamo’, in a 1-cut harvest frequency and upland cultivars, e.g. ‘Cave-in-Rock’, in a 2-cut harvest frequency (Fike et al., 2006). This study also supported Edaño’s (2013) conclusion that lowland cultivars are better suited to dedicated energy crop production, while upland cultivars are better suited as dual-use livestock forage and energy crop production.

Biomass yield information coupled with soil hydraulic properties, such as mini-disk infiltration rates, provide valuable information to landowners in making management decisions. For example, landowners may choose to harvest twice per year only if ‘Cave-in-Rock’ is used, knowing that increased biomass yield could be balanced by the trade-off of decreased water infiltration rates. Similarly, landowners may only harvest ‘Alamo’ once per year, as harvesting twice per year may only increase yields by 35%, while also decreasing infiltration rates.

Results from this study indicate that, while biomass yield was unaffected by fertilizer source (Jacobs and King, 2012), fertilizer source directly affected the resulting content of every extractable soil nutrient that was evaluated (Tables 7 and 8). Fertilizer source also influenced complex relationships with other strategies, such as irrigation. Though irrigation of switchgrass crops is not a common practice, future energy subsidies may eventually encourage some producers or landowners to consider switchgrass irrigation. Irrigating switchgrass that was fertilized with poultry litter resulted in greater soil bulk density, likely due to the dispersive effects of monovalent cations that are naturally present in poultry litter (Whalen and Chang, 2002). In contrast, application of poultry litter in non-irrigated treatments resulted in the lowest soil bulk density. Subtleties associated with these management strategies may become important if switchgrass is grown on the vast areas needed to support industrial facilities for renewable fuel production.

Inferences may also be made about cultivar choice, as TWSA concentration was greater for ‘Alamo’ than ‘Cave-in-Rock’ treatments when averaged across all other treatment factors. Landowners who are interested in converting highly erodible cropland to switchgrass production may choose to plant ‘Alamo’ instead of ‘Cave-in-Rock’ to decrease the potential for soil erosion.

5. Summary and Conclusions

This study showed that four years of consistent agronomic management strategies to maximize switchgrass production in west-central Arkansas produced significant and residual soil property differences. Results from this study also illuminate new opportunities for producers and landowners to customize switchgrass management systems to address specific natural resource goals. In general, ‘Alamo’ produced greater biomass yield and greater TWSA concentration, which resulted in greater depletion of extractable soil P and K contents over time compared to ‘Cave-in-Rock’. Irrigating switchgrass, though not currently cost-effective or recommended for marginal sites, significantly increased TWSA concentration and switchgrass root density when averaged over all other treatment factors. Harvesting switchgrass in a 2-cut system significantly decreased TWSA concentration, extractable soil K and Mg contents, and mini-disk water infiltration rate. Fertilizing switchgrass with poultry litter rather than commercial fertilizer generally increased soil pH, EC, and P, K, Ca and Mg contents. Further investigations are needed to evaluate the effect of management strategies when no fertilizer is applied to assess soil property change if or when the bulk of fertilizers are diverted for growing food crops to feed a growing world population. More information is needed about the fate of surface water and infiltration characteristics associated with switchgrass production strategies as the importance of surface water and groundwater recharge only increase with time. Finally, this study demonstrates the need to enlarge the scope of discussion when assessing the feasibility and natural resource consequences of producing energy crops in America.

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Table 1. Analysis of variance summary of the effects of cultivar, irrigation, harvest frequency, fertilizer source, and, where appropriate, soil depth, and their interactions on soil physical properties.

Source of Variation	BD†	TWSA†	Sand	Silt	Clay	RD†	MD IR†
				p			
Cultivar (C)	0.657	0.005	0.290	0.002	0.967	0.827	0.482
Irrigation (I)	0.370	0.054	0.194	0.171	0.484	0.031	-
Harvest Frequency (H)	0.150	0.030	0.468	0.765	0.673	0.058	0.034
Fertilizer Source (F)	0.745	0.285	0.775	0.039	0.030	0.126	0.186
Soil Depth (D)	<0.001	0.037	0.095	<0.001	<0.001	-	-
C x I	0.871	0.302	0.955	0.611	0.986	-	-
C x H	0.258	0.426	0.629	0.057	0.476	-	0.454
C x F	0.296	0.381	0.926	0.859	0.942	-	0.860
C x D	0.594	0.380	0.007	0.475	0.006	-	-
I x H	0.173	0.662	0.135	0.474	0.418	0.429	-
I x F	0.011	0.029	0.327	0.069	0.479	0.244	-
I x D	0.116	0.056	0.357	0.763	0.204	-	-
H x F	0.950	0.225	0.137	0.794	0.310	0.422	0.898
H x D	0.902	0.285	0.722	0.959	0.712	-	-
F x D	0.110	0.768	0.259	0.071	0.960	-	-
C x I x H	0.395	0.826	0.412	0.842	0.441	-	-
C x I x F	0.094	0.527	0.496	0.618	0.490	-	-
C x I x D	0.691	0.069	0.042	0.079	0.235	-	-
C x F x H	0.139	0.122	0.479	0.813	0.505	-	0.263
C x F x D	0.732	0.434	0.434	0.708	0.240	-	-
C x H x D	0.691	0.557	0.573	0.368	0.216	-	-
I x H x F	0.004	0.513	0.765	0.990	0.815	0.627	-
I x H x D	0.071	0.624	0.936	0.090	0.269	-	-
H x F x D	0.557	0.844	0.616	0.771	0.696	-	-
F x I x D	0.859	0.922	0.979	0.311	0.524	-	-
C x I x H x F	0.691	0.770	0.306	0.098	0.877	-	-
C x I x H x D	0.902	0.434	0.594	0.192	0.137	-	-
C x I x F x D	0.594	0.175	0.521	0.678	0.650	-	-
C x F x H x D	0.348	0.019	0.797	0.225	0.257	-	-
I x H x F x D	0.902	0.244	0.927	0.835	0.798	-	-
C x I x H x F x D	0.181	0.493	0.736	0.884	0.776	-	-
Whole-model statistics							
R^2	0.83	0.93	0.76	0.82	0.81	-	0.64
CV	5.4	2.3	11.2	3.9	13.5	-	36.8
p-value	0.004	<0.001	0.080	0.005	0.008	-	0.063

† BD, bulk density; TWSA, aggregate stability; RD, root density; MD IR, mini-disk infiltration rate; CV, coefficient of variation

Table 2. Summary of the effects of soil depth, cultivar, and irrigation on sand and extractable Mn concentrations and electrical conductivity (EC). For each soil property, means followed by different letters differ significantly at the 0.05 level.

		Alamo		Cave-In-Rock	
Soil Property	Soil Depth (cm)	Irrigated	Non-irrigated	Irrigated	Non-irrigated
Sand (%)	0-10	32.6a	31.4ab	30.3abc	26.1d
	10-20	30.3ab	27.5cd	29.0bc	28.9bc
Mn (kg ha^{-1})	0-10	183.2b	170.9b	179.3b	169.4b
	10-20	230.7a	168.9b	178.7b	185.5b
EC[†] (dS m^{-1})	0-10	0.070a	0.072a	0.071a	0.070a
	10-20	0.060bc	0.053c	0.053c	0.067ab

[†] EC, electrical conductivity

Table 3. Summary of the effects of soil depth, harvest frequency, cultivar, and fertilizer source on aggregate stability (AS). Means followed by different letters differ significantly at the 0.05 level.

			Alamo		Cave-In-Rock	
Soil Property	Soil Depth (cm)	Harvest Frequency	PL[†]	CF[†]	PL	CF
AS (g g^{-1})	0-10	1	0.90bcde	0.91abc	0.87f	0.89cdef
		2	0.89cdef	0.92ab	0.91abc	0.88def
	10-20	1	0.90bcde	0.92ab	0.88ef	0.89cdef
		2	0.92ab	0.93a	0.90bcde	0.90bcd

[†] PL, poultry litter; CF, commercial fertilizer

Table 4. Summary of the effects of harvest frequency, fertilizer source, and irrigation on soil bulk density. Means followed by different letters differ significantly at the 0.05 level.

Soil Property	Harvest Frequency	Poultry Litter		Commercial Fertilizer	
		Irrigated	Non-irrigated	Irrigated	Non-irrigated
Bulk density (g cm $^{-3}$)	1	1.40a	1.32d	1.33d	1.39abc
	2	1.40ab	1.36c	1.39abc	1.36bc

Table 5. Summary of the effects of harvest frequency, cultivar, and irrigation on soil electrical conductivity (EC). Means followed by different letters differ significantly at the 0.05 level.

		Alamo		Cave-In-Rock	
Soil Property	Harvest Frequency	Irrigated	Non-irrigated	Irrigated	Non-irrigated
EC[†] (dS m^{-1})	1	0.063abc	0.069ab	0.067abc	0.067abc
	2	0.067abc	0.056c	0.057bc	0.070a

[†] EC, electrical conductivity

Table 6. Summary of the effects of harvest frequency, soil depth, and fertilizer source on extractable soil Cu and electrical conductivity (EC). For each soil property, means followed by different letters differ significantly at the 0.05 level.

		0-10 cm depth		10-20 cm depth	
Soil Property	Harvest Frequency	PL†	CF†	PL	CF
Cu (kg ha^{-1})	1	2.9a	2.0c	1.0d	0.9de
	2	2.5b	2.01c	1.0de	0.8e
EC (dS m^{-1})	1	0.081a	0.067b	0.059c	0.059c
	2	0.068b	0.067b	0.060bc	0.055c

† PL, poultry litter; CF, commercial fertilizer

Table 7. Analysis of variance summary of the effects of cultivar, irrigation, harvest frequency, fertilizer source, soil depth, and their interactions on soil chemical properties.

Source of Variation	pH	EC[†]	P	K	Ca	Mg
	p					
Cultivar (C)	0.537	0.745	0.002	0.033	0.140	0.397
Irrigation (I)	0.378	0.393	0.789	0.330	0.555	0.501
Harvest Frequency (H)	0.100	0.163	0.079	0.044	0.120	<0.001
Fertilizer Source (F)	0.001	0.035	<0.001	0.008	0.023	0.003
Soil Depth (D)	0.846	<0.001	<0.001	<0.001	0.031	<0.001
C x I	0.825	0.406	0.016	0.528	0.340	0.733
C x H	0.206	0.885	0.986	0.757	0.213	0.122
C x F	0.806	0.209	0.236	0.365	0.975	0.300
C x D	0.144	0.326	0.181	0.057	0.589	0.692
I x H	0.359	0.772	0.269	0.683	0.603	0.582
I x F	0.474	0.263	0.372	0.246	<0.001	0.234
I x D	0.917	0.501	0.296	0.689	0.474	0.899
H x F	0.450	0.507	0.281	0.822	0.793	0.423
H x D	0.633	0.176	0.017	0.002	0.301	0.011
F x D	0.887	0.265	0.001	0.001	0.748	<0.001
C x I x H	0.317	0.016	0.826	0.749	0.106	0.552
C x I x F	0.541	0.610	0.450	0.419	0.760	0.684
C x I x D	0.338	0.006	0.183	0.858	0.561	0.845
C x F x H	0.359	0.413	0.458	0.667	0.210	0.564
C x F x D	0.413	0.516	0.325	0.142	0.570	0.316
C x H x D	0.331	0.326	0.594	0.831	0.120	0.803
I x H x F	0.779	0.413	0.436	0.876	0.676	0.301
I x H x D	0.654	0.420	0.135	0.073	0.415	0.191
H x F x D	0.994	0.020	0.125	0.275	0.561	0.282
F x I x D	0.118	0.544	0.426	0.993	0.214	0.244
C x I x H x F	0.805	0.433	0.543	0.620	0.368	0.161
C x I x H x D	0.303	0.052	0.380	0.427	0.231	0.561
C x I x F x D	0.475	0.265	0.515	0.944	0.191	0.738
C x F x H x D	0.834	0.516	0.728	0.384	0.961	0.467
I x H x F x D	0.982	0.057	0.367	0.689	0.929	0.959
C x I x H x F x D	0.799	0.686	0.411	0.389	0.243	0.333
Whole-model statistics						
R^2	0.71	0.87	0.91	0.93	0.77	0.93
CV[†]	4.5	13.9	41.5	22.4	12.2	18.2
p-value	0.251	0.002	<0.001	<0.001	0.045	<0.001

[†] EC, electrical conductivity; CV, coefficient of variation

Table 8. Analysis of variance summary of the effects of cultivar, irrigation, harvest frequency, fertilizer source, soil depth, and their interactions on extractable soil nutrients.

Source of Variation	S	Na	Fe	Mn	Zn	Cu
	p					
Cultivar (C)	0.573	0.019	0.043	0.346	0.285	0.459
Irrigation (I)	0.960	0.816	0.102	0.202	0.131	0.368
Harvest Frequency (H)	0.993	0.375	0.049	0.510	0.054	0.013
Fertilizer Source (F)	0.014	0.035	0.036	0.996	<0.001	<0.001
Soil Depth (D)	<0.001	<0.001	<0.001	0.040	<0.001	<0.001
C x I	0.241	0.159	0.495	0.138	0.304	0.666
C x H	0.114	0.602	0.402	0.286	0.536	0.028
C x F	0.384	0.704	0.986	0.635	0.350	0.182
C x D	0.892	0.803	0.824	0.298	0.116	0.083
I x H	0.344	0.336	0.283	0.727	0.519	0.744
I x F	0.266	0.402	0.642	0.331	0.021	0.027
I x D	0.590	0.719	0.746	0.255	0.025	0.572
H x F	0.824	0.563	0.749	0.279	0.096	0.161
H x D	0.512	0.071	0.345	0.873	0.012	0.430
F x D	0.013	0.032	0.263	0.722	<0.001	<0.001
C x I x H	0.436	0.496	0.593	0.769	0.876	0.744
C x I x F	0.242	0.368	0.885	0.394	0.043	0.966
C x I x D	0.121	0.306	0.989	0.026	0.163	0.970
C x F x H	0.418	0.601	0.023	0.594	0.756	0.009
C x F x D	0.470	0.582	0.714	0.325	0.365	0.032
C x H x D	0.215	0.562	0.338	0.684	0.250	0.247
I x H x F	0.713	0.746	0.995	0.255	0.588	0.546
I x H x D	0.271	0.721	0.713	0.409	0.289	0.734
H x F x D	0.879	0.567	0.529	0.277	0.051	0.038
F x I x D	0.446	0.312	0.162	0.616	0.570	0.609
C x I x H x F	0.474	0.547	0.867	0.479	0.109	0.678
C x I x H x D	0.425	0.501	0.306	0.777	0.551	0.475
C x I x F x D	0.580	0.821	0.968	0.973	0.116	0.430
C x F x H x D	0.966	0.159	0.336	0.869	0.875	0.678
I x H x F x D	0.472	0.744	0.957	0.828	0.349	0.850
C x I x H x F x D	0.949	0.102	0.663	0.279	0.471	0.734
Whole-model statistics						
R^2	0.77	0.92	0.86	0.77	0.93	0.96
CV†	30.6	24.2	12.6	19.0	49.3	16.2
p-value	0.051	<0.001	<0.001	0.045	<0.001	<0.001

† CV, coefficient of variation

Table 9. Summary of the effects of harvest frequency, cultivar, and fertilizer source on extractable soil Cu and Fe contents. For each soil property, means followed by different letters differ significantly at the 0.05 level.

		Alamo		Cave-In-Rock	
Soil Property	Harvest Frequency	PL[†]	CF[†]	PL	CF
Cu (kg ha^{-1})	1	2.0a	1.5b	1.9a	1.5b
	2	1.6b	1.4b	2.0a	1.4b
Fe (kg ha^{-1})	1	212.5a	184.2b	193.3ab	189.5b
	2	195.5ab	188.8b	192.6ab	160.9c

[†] PL, poultry litter; CF, commercial fertilizer

Table 10. Summary of the effects of soil depth, cultivar, and fertilizer source on extractable soil Cu content. Means followed by different letters differ significantly at the 0.05 level.

		Alamo		Cave-In-Rock	
Soil Property	Soil Depth (cm)	PL†	CF†	PL	CF
Cu (kg ha^{-1})	0-10	2.5b	2.1c	2.9a	2.0c
	10-20	1.1d	0.8d	1.0d	0.9d

† PL, poultry litter; CF, commercial fertilizer

Table 11. Summary of the effects of fertilizer source, cultivar, and irrigation on extractable soil Zn content. Means followed by different letters differ significantly at the 0.05 level.

		Alamo		Cave-In-Rock	
Soil Property	Fertilizer Source	Irrigated	Non-irrigated	Irrigated	Non-irrigated
Zn (kg ha^{-1})	Poultry litter	2.3a	1.3b	2.2a	2.0a
	Commercial fertilizer	0.6c	0.7c	0.7c	0.7c

Table 12. Analysis of variance summary of the effects of cultivar, harvest frequency, and fertilizer source and their interactions on the relationship between LN infiltration rate and time. Means followed by different letters differ significantly at the 0.05 level.

	Double-ring		Mini-disk	
Source of Variation	Slope (m)	Y-intercept	Slope (m)	Y-intercept
Cultivar (C)	0.301	0.334	0.002	0.107
Harvest Frequency (H)	0.882	0.087	0.314	0.011
Fertilizer Source (F)	0.652	0.150	0.169	0.158
C x H	0.004	0.057	0.603	0.548
C x F	0.965	0.758	0.445	0.683
H x F	0.048	0.111	0.765	0.732
C x F x H	-	-	0.026	0.049

Table 13. Summary of parameters that characterize the relationship between the LN of mini-disk (tension) infiltration rate and time. Means followed by different letters differ significantly at the 0.05 level.

Cultivar	Fertilizer Source	Harvest Frequency	Slope (m)	Y-Intercept
Alamo	Commercial Fertilizer	1	-0.088ab	1.109b
		2	0.047a	0.253c
	Poultry Litter	1	-0.126abcd	1.270ab
		2	-0.212cd	1.266ab
Cave-In-Rock	Commercial Fertilizer	1	0.131abcd	1.190ab
		2	-0.196bcd	0.873bc
	Poultry Litter	1	-0.126abcd	1.852a
		2	-0.106abc	0.909bc

Figure 1. Leadvale silt-loam profile near study site at the Booneville Plant Materials Center. Note the fragipan (i.e., Btx horizon) that is present at a depth of approximately 50 cm. Tape units are metric.

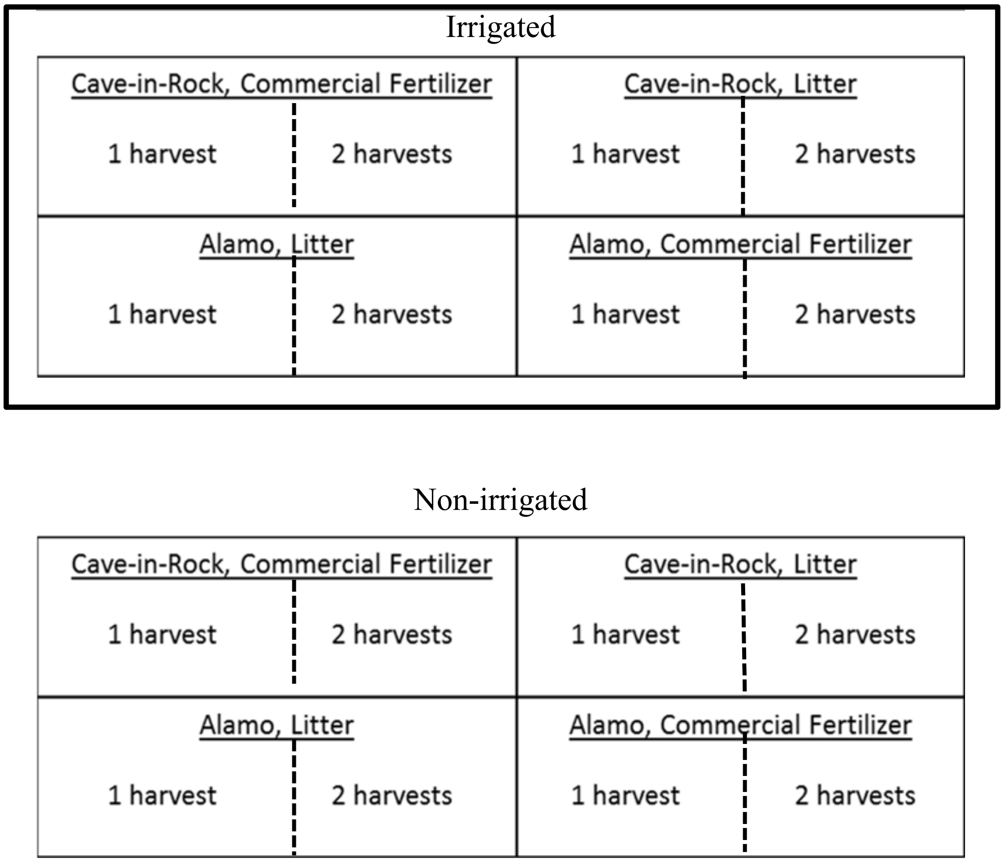

Figure 2. Diagram of plot plan used at the Booneville Plant Materials Center (one replication shown).

Figure 3. Google maps Aerial image of switchgrass study plots at the Booneville Plant Materials Center.

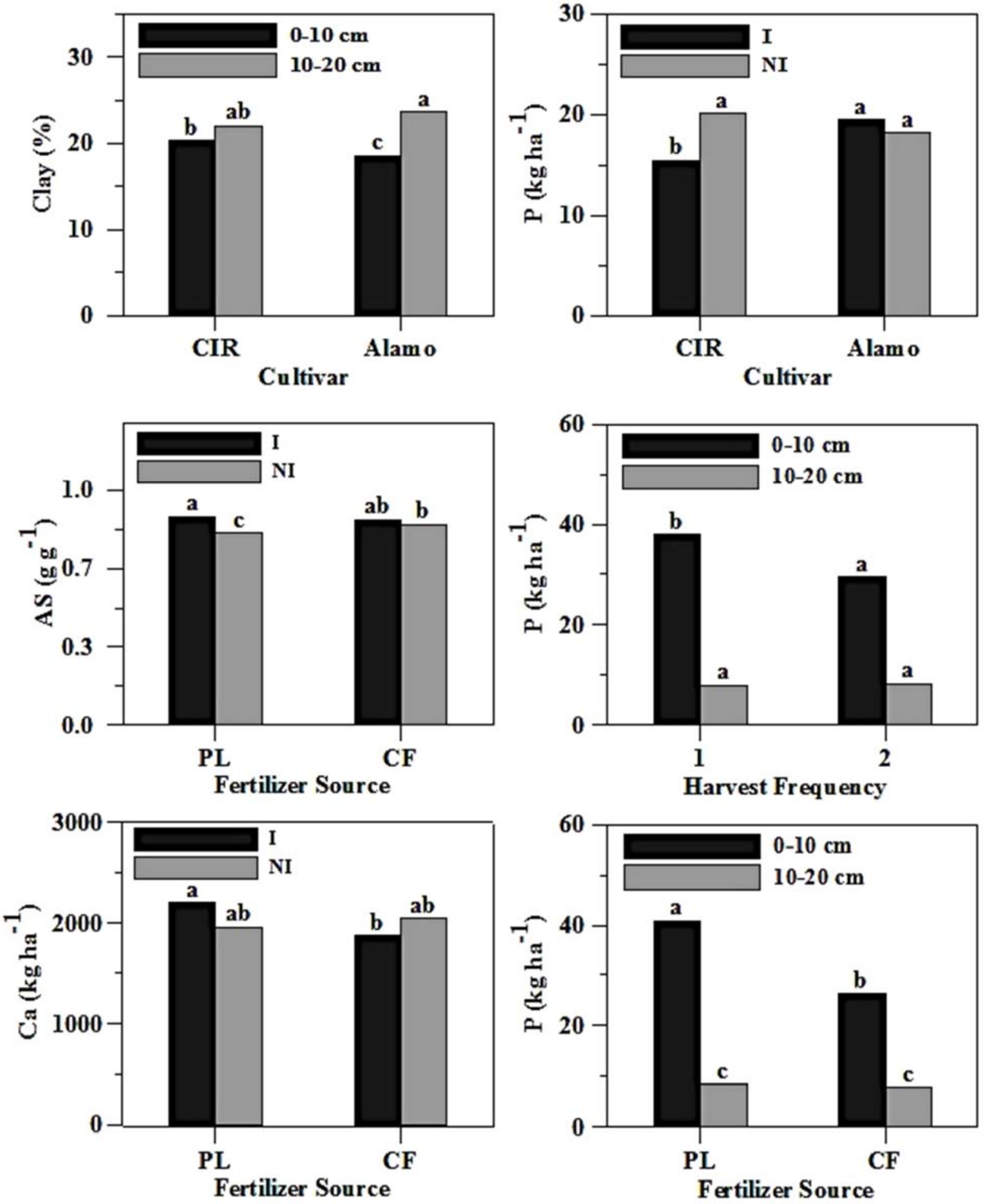

Figure 4. Soil clay content, aggregate stability (AS), and extractable soil phosphorus (P) and calcium (Ca) as affected by soil depth, irrigation [irrigated (I) and non-irrigated (NI)], cultivar [‘Cave-in-Rock’ (CIR) and ‘Alamo’], harvest frequency [one (1) harvest per year and two (2) harvests per year], and/or fertilizer source [poultry litter (PL) and commercial fertilizer (CF)]. Different letters atop bars within a soil property indicate a significant difference at the 0.05 level.

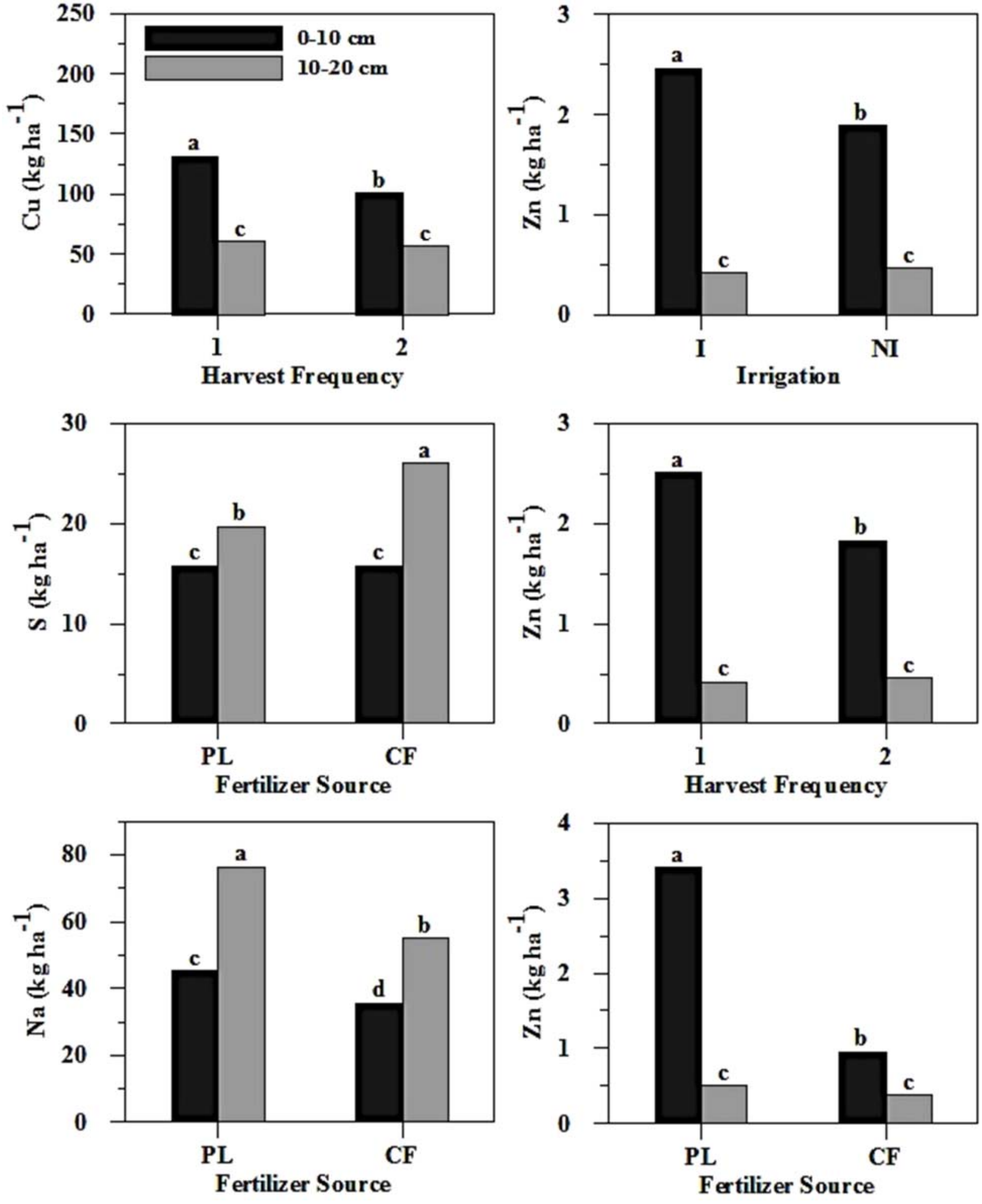

Figure 5. Extractable soil copper (Cu), zinc (Zn), sulfur (S), and sodium (Na) contents as affected by soil depth, irrigation [irrigated (I) and non-irrigated (NI)], harvest frequency [one (1) harvest per year and two (2) harvests per year], and/or fertilizer source [poultry litter (PL) and commercial fertilizer (CF)]. Different letters atop bars within a soil property indicate a significant difference at the 0.05 level.

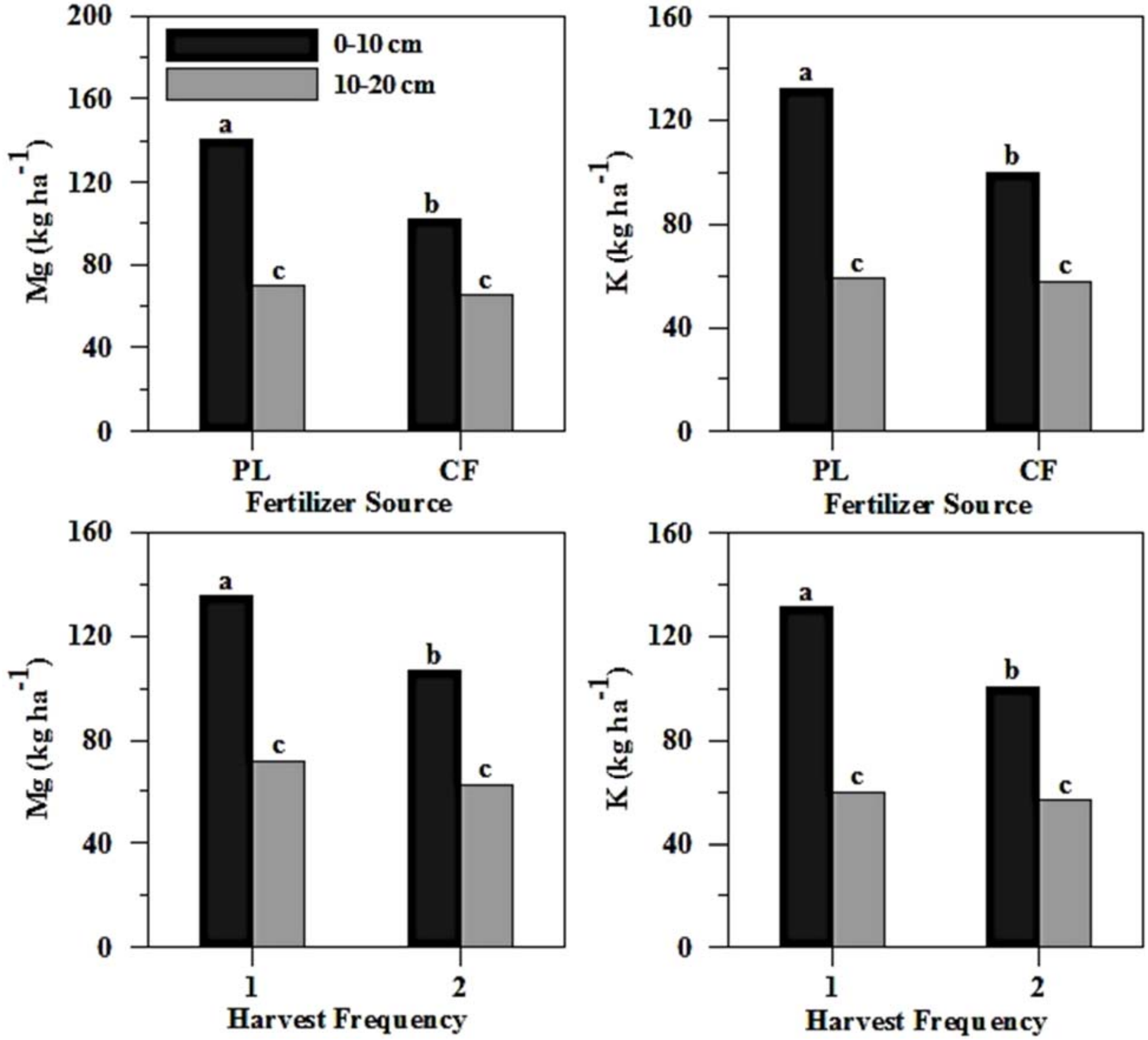

Figure 6. Extractable soil potassium (K) and magnesium (Mg) as affected by soil depth and fertilizer source [poultry litter (PL) and commercial fertilizer (CF)] or harvest frequency [one (1) harvest per year and two (2) harvests per year]. Different letters atop bars within a soil property indicate a significant difference at the 0.05 level.

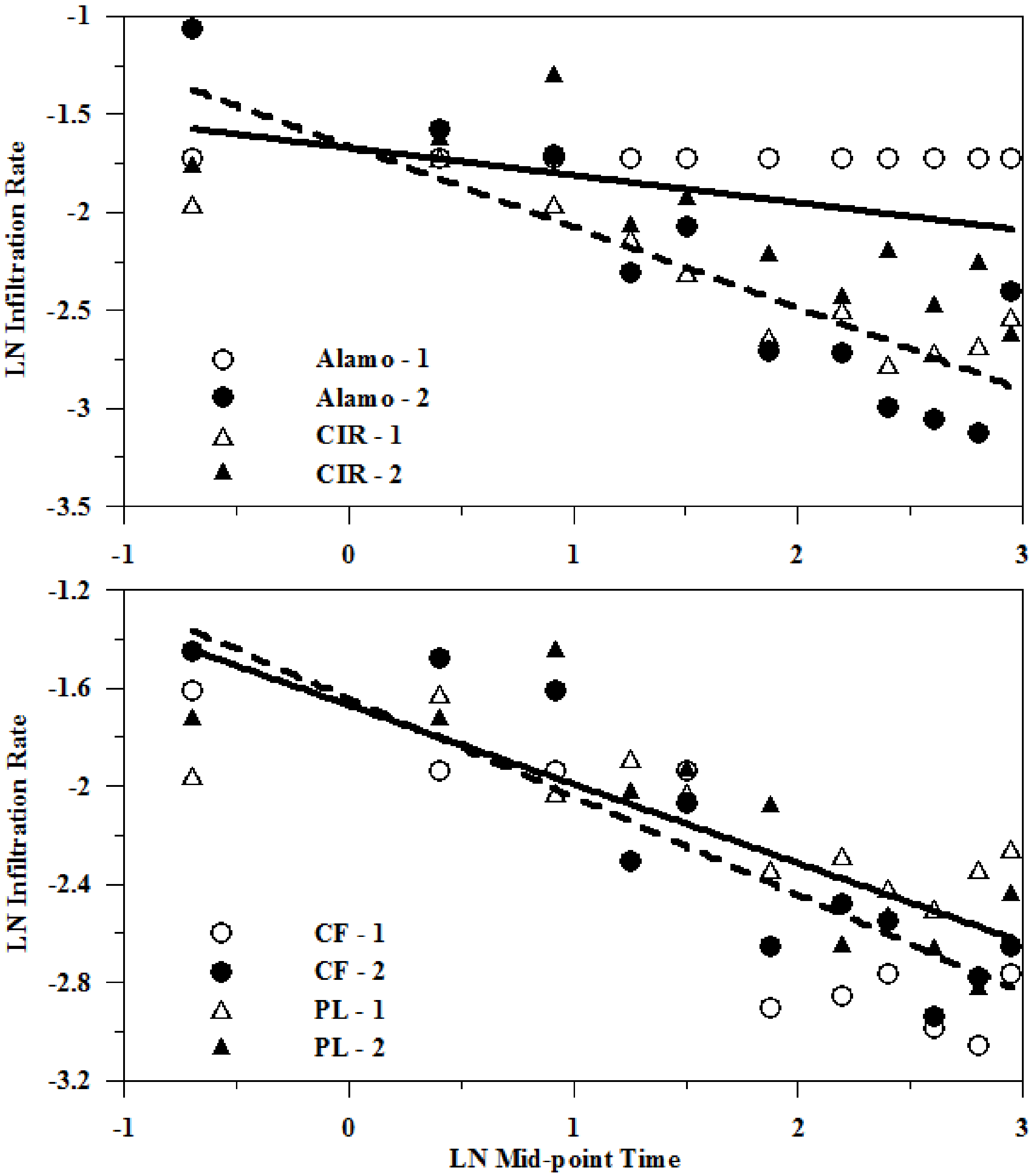

Figure 7. Top. LN of double-ring infiltration rate per LN mid-point time as affected by cultivar [‘Cave-in-Rock’ (CIR) and ‘Alamo’] and harvest frequency [one (1) harvest per year and two (2) harvests per year], or fertilizer source [Poultry Litter (PL) and Commercial Fertilizer (CF)] and harvest frequency. Solid regression line (top) includes CIR-2 and Alamo-1, which did not differ according to slope. Dashed regression line (top) includes CIR-1 and Alamo-2, which did not differ according to slope. Solid regression line (bottom) includes PL-1, CF-2, and PL-2, which did not differ. Dashed regression line (bottom) includes CF-1, PL-2, and CF-2, which did not differ.

Appendix A. Official Leadvale soil series description (USDA-NRCS, 2003).

The Leadvale series consists of deep to very deep, moderately well drained soils with a fragipan. These soils formed in silty materials in uplands or local silty alluvium from nearby uplands underlain largely by shale and siltstone or in places by sandstone, phyllite, and slate. Leadvale soils are on slightly concave toe slopes, benches, and terraces. Slope is dominantly less than 7 percent but ranges from 0 to 15 percent.
TAXONOMIC CLASS: Fine-silty, siliceous, semiactive, thermic Typic Fragiudults

TYPICAL PEDON: Leadvale silt loam--pasture. (Colors are for moist soil unless otherwise stated.)

Ap--0 to 8 inches; brown (10YR 4/3) silt loam; weak medium granular structure; friable; many roots; medium acid; clear smooth boundary. (5 to 10 inches thick)

Bt--8 to 23 inches; yellowish brown (10YR 5/6) silt loam; moderate medium subangular blocky structure; friable; common fine roots; few fine black concretions; few faint clay films on faces of peds; strongly acid; clear wavy boundary. (10 to 28 inches thick)

Btx--23 to 48 inches; yellowish brown (10YR 5/6) silty clay loam; common fine and medium distinct strong brown (7.5YR 5/6), light brownish gray (10YR 6/2), and pale brown (10YR 6/3) mottles; weak thick platy structure, parting to moderate medium subangular blocky structure; firm and brittle; few fine dark brown and black concretions; few faint clay films on faces of peds; few channels of gray silty clay, and fine pockets of gray silt; very strongly acid; gradual wavy boundary. (15 to 35 inches thick)

B't--48 to 58 inches; light yellowish brown (10YR 6/4) silty clay; common fine and coarse distinct strong brown (7.5YR 5/6) and light brownish gray (10YR 6/2) mottles; weak coarse angular blocky structure; very firm; few fine dark brown and black concretions; few fine soft fragments of shale; few faint clay films; very strongly acid. (0 to 24 inches thick)

R--58 inches; acid shale.

TYPE LOCATION: Bradley County, Tennessee; 3.0 miles east of Cleveland, 0.5 mile west of Macedonia Church.

RANGE IN CHARACTERISTICS: Depth to fragipan ranges from 16 to 38 inches. Depth to rock, most commonly shale, ranges from about 4 to more than 8 feet. Solum thickness ranges from 40 to 60 inches. Weathered shale fragments or pebbles in each horizon of the solum range from 0 to about 10 percent by volume. Reaction is strongly acid or very strongly acid except where limed. Base saturation below the Ap horizon is less than 35 percent, and most commonly it is less than 20 percent.

The Ap horizon has hue of 10YR, value of 4 to 6 and chroma of 2 or 3. Some pedons have A horizons less than 6 inches thick that have hue of 10YR, value of 2 or 3 and chroma of 1 or 2. Texture is silt loam or rarely loam or fine sandy loam.

Some pedons have a thin transitional horizon with similar color and texture to the adjacent horizons. The Bt horizon has hue of 7.5YR or 10YR, value of 5 or 6 and chroma of 4 to 8. Some pedons have brown and red mottles, and in some pedons there is a 3 to 5 inch thick layer just above the fragipan which has mottles of chroma of 2 or less. Texture is silt loam, loam, or silty clay loam, which contains between 20 and 32 percent clay and from about 3 to 15 percent fine sand and coarser.

The Btx horizon has hue of 7.5YR to 2.5Y, value of 5 or 6 and chroma of 4 to 8. Some pedons lack a matrix color and are mottled. The Bx horizon is silt loam or silty clay loam. The characteristics of the horizon below the fragipan are variable. This horizon ranges from a C horizon having massive or coarse platy relict rock structure and few to many shale fragments to a Bt horizon having blocky structure and clay films. Color is similar to the Btx horizon. It is silty clay loam, silty clay, or clay.

COMPETING SERIES: These are the Lax, and Shatta series. Lax soils have sola with a gravelly lithologic discontinuity in the lower portion. Shatta soils have fine sandy loam to sandy clay loam textures below the fragipan.

GEOGRAPHIC SETTING: Leadvale soils are on slightly concave toeslopes, benches, and terraces. Slope gradients are mostly between 2 and 7 percent and range from 0 to 15 percent. They formed in silty materials in the uplands or local silty alluvium from nearby uplands underlain largely by shale and siltstone. In some places in the watershed, there are sandstone, phyllite, and slate. Average annual air temperature is 59.1 degrees F. and average annual rainfall is 50 inches near the type location.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Armuchee, Enders, Litz, Montevallo, and Sequoia series. All of these soils are on higher lying adjacent hills and ridges. None of these soils have a fragipan. In addition, Armuchee, Enders, and Sequoia soils have a clayey control section. Litz and Montevallo soils are loamy-skeletal.

DRAINAGE AND PERMEABILITY: Leadvale soils are moderately well drained. Runoff is slow or medium and permeability is slow or moderately slow. A perched water table is at a depth of 2 to 3 feet late in Winter and early in the spring.

USE AND VEGETATION: Most areas are cleared. The main crops are hay, pasture, small grains, and some tobacco and cotton. Forested areas are mostly hardwoods, oaks, hickories, maple, beech, and elm, and some shortleaf, loblolly, and Virginia pine

DISTRIBUTION AND EXTENT: The Valley of East Tennessee, northwest Georgia, Arkansas, Maryland, and northeast Alabama. The series is of large extent.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Morgantown, West Virginia

SERIES ESTABLISHED: Jefferson County, Tennessee; 1936.

REMARKS: Diagnostic features recognized in this pedon are:

Ochric epipedon - 0 to 8 inches (Ap horizon)
Argillic horizon - 8 to 58 inches (Bt, Btx, and B't horizons)
Fragipan horizon - 23 to 48 inches (Btx horizon)

Additional remarks - The Leadvale series was classified as a Red-Yellow Podzolic soil with a fragipan.

Appendix B

This appendix contains examples of SAS programs used to analyze the various soil property and process data presented in this thesis and the actual input file data used to conduct the statistical analyses.

Example SAS program used to statistically analyze the soil bulk density, particle-size distribution, soil pH and EC, and Mehlich-3 extractable soil nutrient data.

```
Title 'Alaynas BD Data';
options ls = 110 ps = 68;

data soil;
 infile 'BD data.csv' firstobs = 2 delimiter = "," truncover LRECL = 600;
 input rep Cult $ Fert $ Irr $ Har Depth $ BD;
run;

proc print data = soil;

proc glm data = soil;
class Cult Fert Irr Har Depth rep;
model BD = Cult | Fert | Irr | Har | Depth rep*Irr rep*Cult*Irr
          rep*Fert*Cult*Irr rep*Har*Fert*Cult*Irr;
random rep*Irr rep*Cult*Irr rep*Fert*Cult*Irr rep*Har*Fert*Cult*Irr / test;
means Depth / lsd lines;
means Fert*Har*Irr;
run;
quit;
```

Example SAS program used to statistically analyze the root density data.

```
Title 'Alaynas Root Density Data';
options ls = 110 ps = 68;

data soil;
 infile 'root density data.csv' firstobs = 2 delimiter = "," truncover LRECL = 600;
 input rep Cult $ Fert $ Irr $ Har roots;
run;

proc print data = soil;

proc glm data = soil;
class Cult rep;
model roots = Cult;
```

```
run;
quit;

proc glm data = soil;
class Irr rep;
model roots = Irr;
run;
quit;

proc glm data = soil;
class Fert rep;
model roots = Fert;
run;
quit;

proc glm data = soil;
class Har rep;
model roots = Har;
run;
quit;

proc glm data = soil;
class Fert Irr Har rep;
model roots = Fert | Irr | Har rep*Irr rep*Fert*Irr rep*Har*Fert*Irr;
random rep*Irr rep*Fert*Irr rep*Har*Fert*Irr / test;
means Irr / lsd lines e = rep*Irr;
means Har / lsd lines e = rep*Fert*Har*Irr;
means Fert Fert*Irr*Har;
run;
quit;
```

Example SAS program used to statistically analyze the infiltration rate data from the double-ring infiltrometer.

```
Title 'Alaynas Doublering Infiltration Rate Data';
options ls = 110 ps = 68;

data soil;
 infile 'doublering infiltration data.csv' firstobs = 2 delimiter = "," truncover LRECL = 600;
 input plot rep Cult $ Fert $ Irr $ Har TotInfilRate;
run;

proc print data = soil;

proc glm data = soil;
class Cult rep;
```

```
model TotInfilRate = Cult;
run;

proc glm data = soil;
class Fert rep;
model TotInfilRate = Fert;
run;

proc glm data = soil;
class Har rep;
model TotInfilRate = Har;
run;

proc glm data = soil;
class Cult Fert rep;
model TotInfilRate = Cult | Fert rep*Cult rep*Fert*Cult;
random rep*Cult rep*Fert*Cult / test;
run;

proc glm data = soil;
class Cult Har rep;
model TotInfilRate = Cult | Har rep*Cult rep*Har*Cult;
random rep*Cult rep*Har*Cult / test;
run;

proc glm data = soil;
class Fert Har rep;
model TotInfilRate = Fert | Har rep*Fert rep*Har*Fert;
random rep*Fert rep*Har*Fert / test;
run;
quit;
```

Example SAS program used to statistically analyze the infiltration rate data from the minidisk infiltrometer.

```
Title 'Alaynas Minidisk Infiltration Rate Data';
options ls = 110 ps = 68;

data soil;
 infile 'minidisk infiltration data.csv' firstobs = 2 delimiter = "," truncover LRECL = 600;
 input rep Cult $ Fert $ Irr $ Har TotInfilRate AdjInfilRate;
run;

proc print data = soil;
```

```
proc glm data = soil;
class Cult Fert Har rep;
model TotInfilRate AdjInfilRate = Cult | Fert | Har rep*Cult
          rep*Fert*Cult rep*Har*Fert*Cult;
random rep*Cult rep*Fert*Cult rep*Har*Fert*Cult / test;
means Har / lsd lines e = rep*Har*Fert*Cult;
run;
quit;
```

Example SAS program used to statistically analyze the LN-transformed infiltration rate vs. time data from the double-ring infiltrometer.

```
Title 'Alaynas Doublering LN Infiltration Rate vs. Time Data';
options ls = 110 ps = 68;

data soil;
 infile 'doublering LN infiltration rate_time data.csv' firstobs = 2 delimiter = "," truncover
LRECL = 600;
 input plot rep Cult $ Fert $ Irr $ Har mslope yintercept;
run;

proc print data = soil;

proc glm data = soil;
class Cult Fert rep;
model mslope yintercept = Cult | Fert rep*Cult rep*Fert*Cult;
random rep*Cult rep*Fert*Cult / test;
means Fert / lsd lines e = rep*fert*cult;
run;
quit;

proc glm data = soil;
class Cult Har rep;
model mslope yintercept = Cult | Har rep*Cult rep*Har*Cult;
random rep*Cult rep*Har*Cult / test;
means Cult*Har;
run;
quit;

proc glm data = soil;
class Fert Har rep;
model mslope yintercept = Fert | Har rep*Fert rep*Har*Fert;
random rep*Fert rep*Har*Fert / test;
means Fert*Har;
run;
```

```
quit;
```

Example SAS program used to statistically analyze the LN-transformed infiltration rate vs. time data from the minidisk infiltrometer.

```
Title 'Alaynas Minidisk LN Infiltration Rate vs. Time Data';
options ls = 110 ps = 68;

data soil;
 infile 'minidisk LN infiltration rate_time data.csv' firstobs = 2 delimiter = "," truncover LRECL
= 600;
 input rep Cult $ Fert $ Irr $ Har mslope yintercept rsquared;
run;

proc print data = soil;

proc glm data = soil;
class Cult Fert Har rep;
model mslope yintercept = Cult | Fert | Har rep*Cult
          rep*Fert*Cult rep*Har*Fert*Cult;
random rep*Cult rep*Fert*Cult rep*Har*Fert*Cult / test;
means Cult*Fert*Har;
run;
quit;
```

SAS input files

Bulk density (BD, g cm^{-3}), aggregate stability (AS, g g^{-1}), and root density data (RD, kg m^{-3}). Rep, replication; CIR, 'Cave-in-Rock'; Fert, fertilizer source; PL, poultry litter; CF, commercial fertilizer; Irrig, irrigation; I, irrigated; NI, non-irrigated; Har, harvest frequency; 1, 1-cut system; 2, 2-cut system.

Rep	Cultivar	Fert	Irrig	Har	BD 0-10 cm	BD 10-20 cm	AS 0-10 cm	AS 10-20 cm	RD 0-10 cm
1	CIR	PL	I	1	1.31	1.4	0.91	0.93	1.35
1	CIR	CF	I	1	1.26	1.45	0.92	0.89	2.15
1	Alamo	PL	I	1	1.36	1.52	0.94	0.94	1.49
1	Alamo	CF	I	1	1.28	1.43	0.94	0.96	2.75
1	CIR	CF	NI	1	1.37	1.45	0.86	0.87	1.86
1	Alamo	CF	NI	1	1.34	1.41	0.88	0.91	1.02
1	Alamo	PL	NI	1	1.18	1.33	0.82	0.84	2.36
1	CIR	PL	NI	1	1.31	1.35	0.79	0.81	2.34
2	CIR	PL	I	1	1.27	1.57	0.95	0.89	1.34
2	CIR	CF	I	1	1.32	1.45	0.86	0.88	2.44
2	Alamo	PL	I	1	1.38	1.54	0.95	0.94	0.28
2	Alamo	CF	I	1	1.27	1.34	0.89	0.93	1.78
2	CIR	PL	NI	1	1.33	1.45	0.87	0.89	0.55
2	CIR	CF	NI	1	1.31	1.49	0.88	0.89	2.06
2	Alamo	PL	NI	1	1.39	1.44	0.90	0.90	1.18
2	Alamo	CF	NI	1	1.26	1.47	0.95	0.94	0.79
3	CIR	CF	I	1	1.14	1.49	0.94	0.92	5.19
3	CIR	PL	I	1	1.28	1.45	0.91	0.91	3.93
3	Alamo	CF	I	1	1.08	1.45	0.94	0.91	1.74
3	Alamo	PL	I	1	1.29	1.49	0.93	0.91	1.19
3	CIR	CF	NI	1	1.37	1.42	0.89	0.88	0.99
3	CIR	PL	NI	1	1.16	1.34	0.77	0.83	1.48
3	Alamo	CF	NI	1	1.39	1.44	0.87	0.90	1.19
3	Alamo	PL	NI	1	1.36	1.26	0.87	0.87	1.34
1	CIR	PL	I	2	1.21	1.44	0.95	0.94	2.96
1	CIR	CF	I	2	1.28	1.39	0.94	0.92	1.92
1	Alamo	PL	I	2	1.33	1.5	0.95	1.00	2.22
1	Alamo	CF	I	2	1.28	1.5	0.95	0.95	5.49
1	CIR	CF	NI	2	1.17	1.43	0.90	0.89	1.95
1	Alamo	CF	NI	2	1.25	1.45	0.92	0.91	3.71
1	Alamo	PL	NI	2	1.21	1.4	0.86	0.84	3.32
1	CIR	PL	NI	2	1.31	1.39	0.86	0.86	0.93
2	CIR	PL	I	2	1.39	1.56	0.99	0.92	2.26
2	CIR	CF	I	2	1.44	1.51	0.85	0.86	6.23
2	Alamo	PL	I	2	1.38	1.42	0.83	0.93	1.13

Rep	Cultivar	Fert	Irrig	Har	BD 0-10 cm	BD 10-20 cm	AS 0-10 cm	AS 10-20 cm	RD 0-10 cm
2	Alamo	CF	I	2	1.23	1.46	0.93	0.93	4.10
2	CIR	PL	NI	2	1.35	1.44	0.92	0.93	1.13
2	CIR	CF	NI	2	1.16	1.53	0.85	0.92	1.32
2	Alamo	PL	NI	2	1.27	1.56	0.90	0.95	1.16
2	Alamo	CF	NI	2	1.39	1.46	0.90	0.94	2.92
3	CIR	CF	I	2	1.24	1.53	0.90	0.94	1.92
3	CIR	PL	I	2	1.38	1.33	0.94	0.93	1.82
3	Alamo	CF	I	2	1.36	1.47	0.95	0.95	2.80
3	Alamo	PL	I	2	1.38	1.5	0.95	0.95	4.31
3	CIR	CF	NI	2	1.29	1.4	0.84	0.89	1.21
3	CIR	PL	NI	2	1.3	1.35	0.80	0.83	0.83
3	Alamo	CF	NI	2	1.34	1.46	0.90	0.92	1.95
3	Alamo	PL	NI	2	1.38	1.35	0.86	0.87	1.92

Mehlich-3 extractable soil nutrients (kg ha^{-1}) for the 0-10 cm depth interval.

Rep	Cultivar	Fert	Irrig	Har	P	K	Ca	Mg	S	Na	Fe	Mn	Zn	Cu
1	CIR	PL	I	1	51.9	201.7	2331.8	184.7	18.6	26.1	221.4	174.2	5.0	3.4
1	CIR	CF	I	1	32.8	105.8	2034.9	119.7	15.6	27.7	201.6	170.1	2.4	2.0
1	Alamo	PL	I	1	43.4	142.3	2297.2	175.5	14.3	52.9	238.2	188.5	4.5	2.8
1	Alamo	CF	I	1	36.6	123.2	1888.4	132.0	14.8	24.1	199.6	175.1	0.9	2.1
1	CIR	CF	NI	1	37.7	132.9	2460.5	117.8	17.5	18.2	191.8	200.0	1.2	1.6
1	Alamo	CF	NI	1	19.1	92.9	2294.4	122.4	17.8	82.8	216.6	200.5	0.8	2.5
1	Alamo	PL	NI	1	43.6	170.2	1652.3	134.7	15.0	40.7	237.9	129.8	2.7	2.6
1	CIR	PL	NI	1	44.4	137.6	1873.3	117.9	17.2	28.3	245.0	169.0	3.4	2.8
2	CIR	PL	I	1	32.6	102.9	2051.1	133.4	14.5	38.9	210.8	193.0	2.7	3.0
2	CIR	CF	I	1	25.3	113.5	1766.2	88.4	16.6	15.3	209.9	202.0	0.7	2.2
2	Alamo	PL	I	1	43.0	121.9	2615.1	157.8	16.9	54.6	209.2	221.7	3.8	3.0
2	Alamo	CF	I	1	25.1	86.4	2028.2	115.6	15.1	37.6	222.3	193.0	0.8	1.9
2	CIR	PL	NI	1	51.5	102.4	2086.8	139.7	16.9	59.7	271.3	196.8	4.1	3.1
2	CIR	CF	NI	1	34.2	134.9	1916.5	110.0	18.2	15.3	210.9	178.2	1.0	2.5
2	Alamo	PL	NI	1	21.1	83.4	2146.2	105.6	17.2	63.2	265.5	208.5	1.1	2.5
2	Alamo	CF	NI	1	13.9	114.7	2021.0	112.1	15.0	57.7	184.0	171.4	0.8	2.0
3	CIR	CF	I	1	13.8	74.4	1943.3	102.2	17.2	40.6	171.0	169.8	0.8	1.6
3	CIR	PL	I	1	49.9	171.5	2292.5	175.4	17.0	47.4	239.4	208.6	5.0	2.9
3	Alamo	CF	I	1	14.0	76.7	1642.7	73.4	12.2	35.2	187.9	142.6	0.6	2.1
3	Alamo	PL	I	1	38.7	135.5	2122.1	170.3	15.4	44.4	234.8	192.2	4.9	2.8
3	CIR	CF	NI	1	43.3	167.1	2035.8	121.9	18.2	21.1	293.2	156.2	1.1	2.5
3	CIR	PL	NI	1	81.8	265.6	2037.0	208.8	14.4	18.8	204.2	136.9	6.7	2.7
3	Alamo	CF	NI	1	40.3	122.3	2267.1	136.2	15.0	40.6	240.5	169.6	1.1	1.5
3	Alamo	PL	NI	1	70.7	171.4	2241.3	193.1	17.1	71.7	247.5	138.7	4.2	2.9
1	CIR	PL	I	2	30.7	92.0	2193.7	122.2	12.9	31.3	158.5	131.9	2.7	2.7
1	CIR	CF	I	2	27.9	84.5	2246.4	110.1	17.2	37.8	170.2	208.6	1.3	1.9
1	Alamo	PL	I	2	31.3	86.6	2361.8	115.7	12.9	66.2	225.9	193.7	3.3	2.4
1	Alamo	CF	I	2	26.0	74.2	2097.9	75.5	16.8	33.9	170.2	165.1	0.9	1.9
1	CIR	CF	NI	2	23.3	62.0	2144.6	69.0	16.5	24.8	194.2	187.2	0.8	1.9
1	Alamo	CF	NI	2	35.6	102.5	2045.0	101.3	18.8	63.9	222.5	187.5	0.8	2.1
1	Alamo	PL	NI	2	19.8	73.3	1748.0	88.8	13.3	44.1	226.0	156.2	1.3	2.0
1	CIR	PL	NI	2	50.6	114.0	1903.4	102.2	16.2	54.8	196.5	186.0	3.5	2.8
2	CIR	PL	I	2	54.5	208.5	2104.5	183.5	15.6	12.5	209.9	180.7	3.9	2.8
2	CIR	CF	I	2	33.6	79.2	1618.6	67.7	15.8	17.3	201.6	181.4	0.6	2.2
2	Alamo	PL	I	2	58.2	103.5	2503.3	135.2	16.3	52.2	242.9	191.8	5.4	2.8
2	Alamo	CF	I	2	18.7	73.8	1899.1	93.5	15.3	56.0	234.9	184.5	1.0	2.2
2	CIR	PL	NI	2	35.2	139.1	1975.1	113.4	18.8	15.8	217.4	183.6	1.1	2.6
2	CIR	CF	NI	2	18.0	117.2	1718.0	78.9	11.5	11.1	148.5	134.6	0.7	1.9
2	Alamo	PL	NI	2	28.6	96.5	1957.1	106.7	13.0	43.7	198.1	190.5	2.5	2.3
2	Alamo	CF	NI	2	20.2	69.5	2287.9	83.4	17.1	53.4	211.3	180.7	0.8	2.5

Rep	Cultivar	Fert	Irrig	Har	P	K	Ca	Mg	S	Na	Fe	Mn	Zn	Cu
3	CIR	CF	I	2	12.2	109.1	1856.3	110.4	14.4	19.5	176.1	143.8	0.9	1.9
3	CIR	PL	I	2	34.1	121.4	2497.8	136.6	17.0	66.9	251.2	187.7	3.7	3.2
3	Alamo	CF	I	2	20.6	94.6	2169.7	107.8	11.4	45.5	199.4	170.4	0.9	2.2
3	Alamo	PL	I	2	20.0	90.7	2127.3	109.2	15.2	57.6	211.1	180.0	2.3	2.0
3	CIR	CF	NI	2	33.2	99.3	2120.8	96.8	15.2	25.3	206.4	141.9	1.0	2.3
3	CIR	PL	NI	2	33.0	137.8	2095.6	149.5	15.6	34.8	250.9	162.5	2.7	2.6
3	Alamo	CF	NI	2	27.7	88.4	2134.6	97.8	14.5	49.8	230.5	171.5	0.9	1.7
3	Alamo	PL	NI	2	13.7	103.5	1927.9	109.0	17.0	57.7	237.4	146.3	1.0	2.1

Mehlich-3 extractable soil nutrients (kg ha^{-1}) for the 10-20 cm depth interval.

Rep	Cultivar	Fert	Irrig	Har	P	K	Ca	Mg	S	Na	Fe	Mn	Zn	Cu
1	CIR	PL	I	1	15.7	74.4	2101.9	75.6	18.0	35.7	131.7	137.5	0.7	1.1
1	CIR	CF	I	1	8.9	54.1	2331.9	80.5	18.0	54.0	152.1	232.2	0.5	1.2
1	Alamo	PL	I	1	7.7	58.8	1995.7	57.4	19.6	92.7	170.5	195.4	0.4	0.9
1	Alamo	CF	I	1	8.6	53.6	2148.9	52.8	15.0	39.6	122.7	116.5	0.2	0.7
1	CIR	CF	NI	1	10.2	80.5	1926.3	46.4	30.8	31.9	161.8	229.2	0.3	0.9
1	Alamo	CF	NI	1	6.2	52.3	2153.3	77.7	25.7	119.6	174.8	206.6	0.6	1.1
1	Alamo	PL	NI	1	12.4	67.2	2233.1	56.2	15.6	72.0	221.2	143.5	0.7	1.3
1	CIR	PL	NI	1	7.6	58.3	1696.5	61.4	24.0	59.1	173.1	131.0	0.3	0.9
2	CIR	PL	I	1	6.3	47.5	2255.6	84.7	13.8	93.5	158.9	229.8	0.6	0.8
2	CIR	CF	I	1	14.2	70.6	1419.2	64.0	35.0	26.4	168.3	154.1	0.2	0.8
2	Alamo	PL	I	1	10.0	48.6	2549.1	84.1	19.1	90.7	170.1	325.1	0.6	1.8
2	Alamo	CF	I	1	6.4	53.0	2062.7	88.4	16.2	47.4	158.4	242.0	0.4	1.1
2	CIR	PL	NI	1	5.5	35.8	1792.8	66.6	15.1	123.7	150.6	282.8	0.3	0.6
2	CIR	CF	NI	1	6.9	54.8	2275.8	69.9	15.4	32.1	172.3	244.6	0.4	1.0
2	Alamo	PL	NI	1	7.6	50.7	2290.9	56.9	17.7	83.6	190.3	226.3	0.5	1.1
2	Alamo	CF	NI	1	7.5	56.6	1773.4	50.8	33.1	84.6	160.8	152.1	0.2	0.7
3	CIR	CF	I	1	6.5	53.4	1859.9	85.7	37.4	83.4	149.9	169.8	0.2	0.7
3	CIR	PL	I	1	6.3	59.2	1657.3	78.9	42.8	103.3	170.0	177.7	0.3	0.8
3	Alamo	CF	I	1	6.0	64.0	1528.3	60.7	37.5	62.3	168.1	183.2	0.3	0.7
3	Alamo	PL	I	1	6.4	72.3	2430.5	107.7	15.2	78.7	189.0	263.9	0.7	1.3
3	CIR	CF	NI	1	5.7	70.7	1595.7	68.9	27.4	46.6	191.7	121.2	0.3	1.0
3	CIR	PL	NI	1	5.7	91.7	1883.2	84.9	19.8	56.9	142.9	158.9	0.6	0.8
3	Alamo	CF	NI	1	6.3	67.1	2649.4	98.7	12.8	62.2	175.0	182.4	0.7	1.2
3	Alamo	PL	NI	1	5.7	47.0	1966.8	72.5	13.4	108.5	175.8	118.7	0.3	1.0
1	CIR	PL	I	2	13.0	56.6	2271.3	86.7	19.3	60.5	136.4	182.5	0.5	1.3
1	CIR	CF	I	2	9.8	52.2	2164.7	101.3	19.7	62.3	141.5	280.3	0.4	1.2
1	Alamo	PL	I	2	6.7	47.2	1988.0	48.0	20.6	83.4	205.9	228.7	0.3	1.0
1	Alamo	CF	I	2	10.1	40.7	1498.6	44.0	34.3	41.1	137.1	226.2	0.2	0.6
1	CIR	CF	NI	2	7.5	45.0	2040.1	50.0	33.6	48.5	155.1	213.9	0.6	0.9
1	Alamo	CF	NI	2	6.3	56.4	1817.3	58.1	44.1	91.1	204.3	243.8	0.8	1.1
1	Alamo	PL	NI	2	7.0	55.0	1832.0	51.8	22.7	83.9	169.9	121.0	0.8	0.8
1	CIR	PL	NI	2	12.0	60.8	1375.6	21.3	23.6	4.2	217.5	154.3	0.2	1.0
2	CIR	PL	I	2	13.4	81.2	1893.2	68.7	26.3	23.1	171.0	141.6	0.3	1.1
2	CIR	CF	I	2	9.5	38.5	771.7	34.1	20.6	27.9	81.4	79.9	0.1	0.3
2	Alamo	PL	I	2	11.6	51.9	2045.7	52.9	19.2	74.8	140.9	234.7	0.9	1.1
2	Alamo	CF	I	2	6.9	50.2	2097.3	67.6	18.3	63.7	188.0	249.2	0.5	1.0
2	CIR	PL	NI	2	13.8	54.2	2224.2	56.3	16.0	38.6	152.7	135.8	0.6	1.2
2	CIR	CF	NI	2	12.0	111.6	2188.5	73.2	16.2	26.8	145.4	239.9	0.3	0.9
2	Alamo	PL	NI	2	6.8	66.4	2364.8	65.5	18.7	97.2	168.8	221.7	0.5	1.0
2	Alamo	CF	NI	2	6.8	45.4	1536.4	38.7	37.5	53.8	163.2	119.4	0.2	0.6

Rep	Cultivar	Fert	Irrig	Har	P	K	Ca	Mg	S	Na	Fe	Mn	Zn	Cu
3	CIR	CF	I	2	6.6	53.3	1616.4	67.5	37.5	42.5	169.6	184.5	0.6	0.8
3	CIR	PL	I	2	5.6	48.0	2096.7	81.5	21.8	124.8	174.8	174.4	0.5	0.9
3	Alamo	CF	I	2	5.8	50.5	2238.4	65.3	13.2	65.5	162.3	239.6	0.2	0.7
3	Alamo	PL	I	2	6.2	49.3	2046.8	57.4	16.2	95.1	175.2	264.5	0.4	0.9
3	CIR	CF	NI	2	6.8	68.3	2120.2	71.6	16.6	50.4	140.3	132.7	0.6	0.8
3	CIR	PL	NI	2	6.1	81.2	2341.3	124.5	13.7	77.0	174.3	181.6	0.9	1.3
3	Alamo	CF	NI	2	5.8	47.0	1687.6	49.4	27.6	57.5	141.9	169.3	0.2	0.6
3	Alamo	PL	NI	2	5.4	52.2	1460.1	66.9	20.0	72.7	143.7	121.8	0.2	0.5

Sand, silt, and clay percentage for the 0-10 and 10-20 cm depth intervals.

					0-10 cm			10-20 cm		
Rep	Cultivar	Fert	Irrig	Har	sand	silt	clay	sand	silt	clay
1	CIR	PL	I	1	36.19	49.63	14.17	29.80	48.10	22.10
1	CIR	CF	I	1	34.44	50.33	15.23	30.33	48.03	21.64
1	Alamo	PL	I	1	33.43	46.23	20.34	29.63	46.27	24.10
1	Alamo	CF	I	1	31.43	48.73	19.84	34.26	43.18	22.55
1	CIR	CF	NI	1	35.27	48.50	16.23	32.16	46.69	21.14
1	Alamo	CF	NI	1	28.71	43.05	28.24	28.30	47.10	24.60
1	Alamo	PL	NI	1	31.10	45.06	23.85	26.99	51.37	21.64
1	CIR	PL	NI	1	30.71	54.13	15.17	23.81	52.04	24.15
2	CIR	PL	I	1	33.43	50.84	15.73	31.57	49.13	19.30
2	CIR	CF	I	1	30.54	52.79	16.67	29.40	50.30	20.30
2	Alamo	PL	I	1	32.26	50.50	17.23	31.94	47.01	21.06
2	Alamo	CF	I	1	29.87	52.96	17.17	28.16	46.19	25.65
2	CIR	PL	NI	1	31.73	52.07	16.20	31.10	49.57	19.34
2	CIR	CF	NI	1	19.80	52.60	27.60	29.26	49.90	20.84
2	Alamo	PL	NI	1	34.53	48.30	17.17	29.66	50.70	19.64
2	Alamo	CF	NI	1	34.77	49.00	16.23	26.97	46.93	26.10
3	CIR	CF	I	1	22.29	51.66	26.05	27.92	47.73	24.35
3	CIR	PL	I	1	23.48	51.87	24.65	25.42	49.23	25.35
3	Alamo	CF	I	1	31.26	49.00	19.74	27.15	43.69	29.16
3	Alamo	PL	I	1	34.70	49.14	16.17	29.77	48.17	22.06
3	CIR	CF	NI	1	21.48	52.87	25.65	29.59	47.56	22.85
3	CIR	PL	NI	1	20.63	55.77	23.60	27.40	50.30	22.30
3	Alamo	CF	NI	1	32.43	50.33	17.23	30.97	47.43	21.60
3	Alamo	PL	NI	1	29.43	53.84	16.73	29.99	48.86	21.14
1	CIR	PL	I	2	34.77	49.50	15.73	28.61	49.83	21.56
1	CIR	CF	I	2	35.57	47.23	17.20	32.33	45.02	22.65
1	Alamo	PL	I	2	30.54	47.21	22.26	29.99	47.86	22.14
1	Alamo	CF	I	2	29.59	49.57	20.84	34.47	42.93	22.60
1	CIR	CF	NI	2	33.37	48.97	17.66	32.10	48.06	19.84
1	Alamo	CF	NI	2	32.53	48.30	19.16	29.13	47.27	23.60
1	Alamo	PL	NI	2	29.07	52.73	18.20	23.48	50.37	26.15
1	CIR	PL	NI	2	33.10	52.67	14.23	28.04	56.69	15.27
2	CIR	PL	I	2	31.10	50.67	18.24	26.90	50.30	22.80
2	CIR	CF	I	2	31.20	52.13	16.67	28.09	49.57	22.34
2	Alamo	PL	I	2	36.77	48.50	14.73	30.94	46.51	22.55
2	Alamo	CF	I	2	32.77	50.50	16.73	24.48	50.37	25.15
2	CIR	PL	NI	2	24.47	51.43	24.10	30.76	49.40	19.84
2	CIR	CF	NI	2	21.62	52.83	25.55	29.37	48.37	22.26
2	Alamo	PL	NI	2	30.37	51.96	17.66	27.45	49.00	23.55

					0-10 cm			10-20 cm		
Rep	Cultivar	Fert	Irrig	Har	sand	silt	clay	sand	silt	clay
2	Alamo	CF	NI	2	33.10	49.67	17.23	26.15	46.69	27.15
3	CIR	CF	I	2	24.82	50.03	25.15	28.59	47.06	24.35
3	CIR	PL	I	2	25.82	49.03	25.15	29.59	48.56	21.84
3	Alamo	CF	I	2	35.07	49.23	15.70	31.66	48.20	20.14
3	Alamo	PL	I	2	33.43	49.83	16.73	30.80	47.60	21.60
3	CIR	CF	NI	2	21.14	53.21	25.65	27.59	47.56	24.85
3	CIR	PL	NI	2	19.81	54.04	26.15	26.07	45.63	28.30
3	Alamo	CF	NI	2	33.07	48.73	18.20	28.16	45.19	26.65
3	Alamo	PL	NI	2	28.07	53.23	18.70	22.80	50.10	27.10

Soil surface double-ring infiltration rate (cm min^{-1}) per time midpoint (min) and total infiltration rate (cm min^{-1}). TIR, total infiltration rate.

					Time midpoint											
Rep	Cultivar	Fert	I	Har	0.5	1.5	2.5	3.5	4.5	6.5	9	11	13.5	16.5	19	TIR
1	CIR	CF	NI	1	0.00	0.00	0.10	0.00	0.00	0.03	0.05	0.05	0.03	0.00	0.05	0.030
1	Alamo	CF	NI	1	0.20	0.00	0.10	0.10	0.10	0.00	0.05	0.00	0.03	0.03	0.00	0.040
1	Alamo	PL	NI	1	0.20	0.20	0.10	0.00	0.10	0.03	0.10	0.10	0.10	0.07	0.10	0.090
1	CIR	PL	NI	1	0.10	0.50	0.40	0.10	0.10	0.27	0.15	0.15	0.17	0.13	0.25	0.200
2	CIR	PL	NI	1	0.20	0.20	0.10	0.10	0.10	0.10	0.10	0.05	0.10	0.10	0.05	0.100
2	CIR	CF	NI	1	0.10	0.00	0.00	0.10	0.00	0.07	0.05	0.00	0.07	0.03	0.05	0.045
2	Alamo	PL	NI	1	0.10	0.10	0.00	0.10	0.00	0.07	0.05	0.00	0.00	0.07	0.00	0.040
2	Alamo	CF	NI	1	0.40	0.30	0.30	0.10	0.30	0.20	0.10	0.10	0.07	0.13	0.10	0.160
3	CIR	CF	NI	1	0.00	0.10	0.00	0.00	0.10	0.03	0.00	0.05	0.07	0.03	0.00	0.035
3	CIR	PL	NI	1	0.20	0.10	0.10	0.20	0.10	0.07	0.10	0.05	0.03	0.10	0.10	0.090
3	Alamo	CF	NI	1	0.20	0.10	0.00	0.00	0.00	0.03	0.05	0.00	0.00	0.00	0.00	0.025
3	Alamo	PL	NI	1	0.10	0.30	0.10	0.40	0.40	0.20	0.15	0.15	0.07	0.13	0.10	0.165
1	CIR	CF	NI	2	0.50	0.30	0.20	0.10	0.10	0.17	0.20	0.15	0.13	0.10	0.00	0.155
1	Alamo	CF	NI	2	0.00	0.00	0.00	0.10	0.00	0.03	0.00	0.00	0.00	0.03	0.00	0.015
1	Alamo	PL	NI	2	0.00	0.00	0.00	0.10	0.00	0.00	0.05	0.05	0.00	0.03	0.00	0.020
1	CIR	PL	NI	2	0.10	0.00	0.00	0.10	0.00	0.00	0.05	0.00	0.07	0.00	0.00	0.025
2	CIR	PL	NI	2	0.10	0.10	0.20	0.20	0.00	0.00	0.05	0.00	0.03	0.07	0.05	0.055
2	CIR	CF	NI	2	0.10	0.00	0.00	0.10	0.10	0.03	0.00	0.05	0.00	0.00	0.05	0.030
2	Alamo	PL	NI	2	0.20	0.10	0.10	0.10	0.10	0.00	0.05	0.05	0.07	0.00	0.05	0.055
2	Alamo	CF	NI	2	0.60	0.90	0.20	0.10	0.20	0.13	0.10	0.05	0.03	0.07	0.10	0.160
3	CIR	CF	NI	2	0.10	0.10	0.00	0.10	0.00	0.00	0.05	0.10	0.00	0.00	0.00	0.030
3	CIR	PL	NI	2	58.00	0.50	0.50	0.20	0.30	0.23	0.20	0.20	0.17	0.17	0.15	0.235
3	Alamo	CF	NI	2	0.00	0.10	0.00	0.00	0.00	0.00	0.05	0.00	0.03	0.07	0.00	0.025
3	Alamo	PL	NI	2	0.00	0.20	0.30	0.00	0.10	0.07	0.10	0.00	0.07	0.03	0.15	0.080

Soil surface mini-disk infiltration rate (cm min^{-1}) per time midpoint (min), total infiltration rate (cm min^{-1}), and adjusted infiltration rate (cm min^{-1}). TIR, total infiltration rate; AIR, adjusted infiltration rate.

					Time midpoint												
Rep	Cultivar	Fert	I	Har	0.5	1.5	2.5	3.5	4.5	6.5	9	11	13.5	16.5	19	TIR	AIR
1	CIR	CF	NI	1	2.00	3.00	2.00	2.00	2.00	2.33	2.50	2.00	2.00	1.00	2.00	2.50	2.50
1	Alamo	CF	NI	1	6.00	3.00	3.00	3.00	2.00	2.33	2.25	2.25	2.00	2.33	2.00	2.00	2.00
1	Alamo	PL	NI	1	4.00	3.00	3.00	3.00	3.00	2.67	3.00	2.75	2.83	3.00	2.50	2.90	2.90
1	CIR	PL	NI	1	4.00	4.00	3.00	3.00	5.00	3.00	3.50	3.25	3.50	3.33	3.75	3.48	3.48
2	CIR	PL	NI	1	6.00	5.00	4.50	4.50	3.50	3.83	3.50	3.00	3.33	2.83	3.75	3.70	3.70
2	CIR	CF	NI	1	4.00	3.00	2.00	3.00	2.00	2.33	2.50	2.50	2.33	2.17	2.25	2.45	2.45
2	Alamo	PL	NI	1	6.00	8.00	7.00	7.00	7.50	6.83	7.25	7.50	-	-	-	4.45	7.05
2	Alamo	CF	NI	1	4.00	3.00	3.00	3.00	3.00	2.67	2.75	2.50	2.50	2.33	3.00	2.75	2.75
3	CIR	CF	NI	1	11.00	8.00	7.00	7.00	7.00	6.67	6.00	5.50	-	-	-	4.40	6.77
3	CIR	PL	NI	1	8.00	6.00	5.00	5.00	5.00	4.33	5.00	4.50	4.00	3.00	3.00	4.40	4.40
3	Alamo	CF	NI	1	3.50	2.00	1.50	2.00	2.00	1.33	1.50	1.50	1.33	1.67	1.50	1.65	1.65
3	Alamo	PL	NI	1	2.00	4.00	2.00	3.50	3.50	2.67	2.75	3.25	3.00	3.33	3.00	3.00	3.00
1	CIR	CF	NI	2	4.00	1.00	1.00	2.00	1.00	1.17	1.25	1.00	1.00	1.00	1.00	1.25	1.25
1	Alamo	CF	NI	2	3.00	4.00	3.50	4.50	3.50	4.00	4.25	4.50	3.67	4.33	4.00	4.00	4.00
1	Alamo	PL	NI	2	4.00	4.00	4.00	4.00	3.00	3.00	3.00	2.50	2.67	3.00	2.50	3.05	3.05
1	CIR	PL	NI	2	3.00	4.00	3.00	3.00	3.00	2.67	3.00	2.50	2.67	3.00	2.50	2.85	2.85
2	CIR	PL	NI	2	5.50	5.00	5.00	6.00	5.00	5.33	4.50	5.00	4.33	-	-	4.33	4.92
2	CIR	CF	NI	2	3.00	4.00	3.00	3.00	4.00	3.33	3.00	3.50	3.50	3.50	4.00	3.45	3.45
2	Alamo	PL	NI	2	4.00	6.00	2.00	3.50	3.50	3.00	3.50	2.75	3.50	3.00	3.00	3.30	3.30
2	Alamo	CF	NI	2	8.00	5.00	5.00	4.00	4.00	3.67	3.50	3.25	3.17	3.33	1.25	3.63	3.63
3	CIR	CF	NI	2	2.50	2.50	1.00	2.00	2.00	1.50	1.50	1.50	1.50	1.00	1.50	1.55	1.55
3	CIR	PL	NI	2	2.50	2.50	1.50	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.50	2.08	2.08
3	Alamo	CF	NI	2	5.00	4.00	4.50	3.50	4.00	3.33	3.75	3.75	3.00	3.33	3.25	3.58	3.58
3	Alamo	PL	NI	2	6.00	3.00	4.00	3.50	2.00	3.50	3.50	3.00	3.00	3.00	3.00	3.30	3.30

LN of soil surface double-ring infiltration rate per LN mid-point time linear regression equation parameters.

Rep	Cultivar	Fert	I	Har	mslope	yintercept
1	CIR	CF	NI	1	-0.7931	-0.33230
1	Alamo	CF	NI	1	-0.1593	-1.40150
1	Alamo	PL	NI	1	-0.3278	-1.56150
1	CIR	PL	NI	1	-0.0242	-1.67140
2	CIR	PL	NI	1	-0.3103	-1.78920
2	CIR	CF	NI	1	-0.4943	-0.94690
2	Alamo	PL	NI	1	0.3089	-1.90390
2	Alamo	CF	NI	1	-0.4379	-1.10000
3	CIR	CF	NI	1	-0.4940	-0.73810
3	CIR	PL	NI	1	-0.2823	-1.90920
3	Alamo	CF	NI	1	0.3413	-1.50190
3	Alamo	PL	NI	1	-0.1209	-1.62450
1	CIR	CF	NI	2	-0.1298	-1.39670
1	Alamo	CF	NI	2	-0.2957	0.03385
1	Alamo	PL	NI	2	-0.5432	-0.16440
1	CIR	PL	NI	2	0.1702	-1.21880
2	CIR	PL	NI	2	-0.1355	-1.58720
2	CIR	CF	NI	2	-0.0118	-1.46230
2	Alamo	PL	NI	2	-0.0519	-1.96100
2	Alamo	CF	NI	2	-0.7575	-0.73390
3	CIR	CF	NI	2	0.4669	-1.88230
3	CIR	PL	NI	2	-0.3779	-0.74250
3	Alamo	CF	NI	2	-0.4041	-0.36840
3	Alamo	PL	NI	2	-0.5971	-0.66040

LN of soil surface mini-disk infiltration rate per LN mid-point time linear regression equation parameters.

Rep	Cultivar	Fert	Irrig	Har	mslope	yintercept	R^2 value
1	CIR	CF	non	1	-0.0913	0.8524	0.146
1	CIR	CF	non	1	-0.2534	1.3723	0.782
1	Alamo	CF	non	1	-0.0839	1.2232	0.639
1	Alamo	CF	non	1	-0.0329	1.317	0.0554
1	Alamo	PL	non	1	-0.1823	1.6584	0.8211
1	Alamo	PL	non	1	-0.1262	1.1252	0.4677
1	CIR	PL	non	1	-0.504	2.2609	0.3781
1	CIR	PL	non	1	-0.1069	1.2271	0.6916
2	CIR	PL	non	1	-0.6432	2.4925	0.597
2	CIR	PL	non	1	-0.2304	1.9142	0.8417
2	CIR	CF	non	1	-0.2007	0.8812	0.651
2	CIR	CF	non	1	0.0727	0.957	0.1349
2	Alamo	PL	non	1	-0.2687	0.6679	0.4711
2	Alamo	PL	non	1	0.0697	1.2468	0.3882
2	Alamo	CF	non	1	-0.1467	1.4021	0.7301
2	Alamo	CF	non	1	-0.0689	1.1843	0.3557
3	CIR	CF	non	1	-0.3498	1.9042	0.3522
3	CIR	CF	non	1	0.0341	1.1723	0.1011
3	CIR	PL	non	1	-0.0924	1.352	0.1493
3	CIR	PL	non	1	-0.3377	1.8662	0.7098
3	Alamo	CF	non	1	-0.172	0.7615	0.3874
3	Alamo	CF	non	1	-0.024	0.7676	0.0332
3	Alamo	PL	non	1	-0.1137	1.5033	0.717
3	Alamo	PL	non	1	-0.137	1.4197	0.337
1	CIR	CF	non	2	-0.306	0.3948	0.5804
1	CIR	CF	non	2	-0.0592	0.9956	0.0993
1	Alamo	CF	non	2	0.0548	-0.3652	0.0322
1	Alamo	CF	non	2	0.3392	-0.2679	0.856
1	Alamo	PL	non	2	-0.5668	2.2562	0.5517
1	Alamo	PL	non	2	-0.3614	1.9783	0.347
1	CIR	PL	non	2	-0.0413	0.768	0.0635
1	CIR	PL	non	2	-0.0652	0.4263	0.0875
2	CIR	PL	non	2	0.0262	1.2311	0.0165
2	CIR	PL	non	2	-0.1113	0.6253	0.298
2	CIR	CF	non	2	-0.117	0.0547	0.3821
2	CIR	CF	non	2	-0.3614	1.9783	0.347
2	Alamo	PL	non	2	-0.2411	0.458	0.3697
2	Alamo	PL	non	2	0.0241	0.4604	0.0571
2	Alamo	CF	non	2	-0.0723	0.9528	0.0097

Rep	Cultivar	Fert	Irrig	Har	mslope	yintercept	R^2 value
2	Alamo	CF	non	2	0.0409	1.0678	0.0605
3	CIR	CF	non	2	-0.0606	0.4501	0.1453
3	CIR	CF	non	2	-0.272	1.3628	0.3198
3	CIR	PL	non	2	-0.3739	1.9055	0.361
3	CIR	PL	non	2	-0.072	0.5006	0.0745
3	Alamo	CF	non	2	-0.0027	0.4794	0.0002
3	Alamo	CF	non	2	-0.0796	-0.3462	0.0594
3	Alamo	PL	non	2	-0.0971	1.3363	0.2656
3	Alamo	PL	non	2	-0.0314	1.1071	0.0538

Overall Conclusions

Overall Conclusions

This study showed that four years of consistent agronomic management strategies to maximize switchgrass production in west-central Arkansas produced significant and residual soil property differences. Results from this study also illuminate new opportunities for producers and landowners to customize switchgrass management systems to address specific natural resource goals. In general, 'Alamo' produced greater biomass yield and greater TWSA concentration, which resulted in greater depletion of extractable soil P and K contents over time compared to 'Cave-in-Rock'. Irrigating switchgrass, though not currently cost-effective or recommended for marginal sites, significantly increased TWSA concentration and switchgrass root density when averaged over all other treatment factors. Harvesting switchgrass in a 2-cut system significantly decreased TWSA concentration, extractable soil K and Mg contents, and mini-disk water infiltration rate. Fertilizing switchgrass with poultry litter rather than commercial fertilizer generally increased soil pH, EC, and P, K, Ca and Mg contents. Further investigations are needed to evaluate the effect of management strategies when no fertilizer is applied to assess soil property change if or when the bulk of fertilizers are diverted for growing food crops to feed a growing world population. More information is needed about the fate of surface water and infiltration characteristics associated with switchgrass production strategies as the importance of surface water and groundwater recharge only increase with time. Finally, this study demonstrates the need to enlarge the scope of discussion when assessing the feasibility and natural resource consequences of producing energy crops in America.