IMPROVING NITROGEN USE EFFICIENCY, SOIL PROPERTIES AND GRAIN YIELD OF MAIZE (*Zea mays* L.) AND WINTER WHEAT (*Triticum aestivum* L.) WITH BIOCHAR AND NO-TILLAGE PRACTICE

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Abstract: The first study (chapter 1) of this dissertation was conducted to establish possible synergies in applying inorganic fertilizer nitrogen (N) in combination with biochar (NBC) and the subsequent role in optimizing maize (*Zea mays* L.) grain yield, N use efficiency (NUE), and soil chemical properties. Field trials were conducted in 2018 and 2019 at Efaw and Lake Carl Blackwell (LCB) both located near Stillwater, Oklahoma. Results from this study showed an overall positive effect of NBC on grain yield, NUE, and soil properties relative to inorganic fertilizer N applied solely. However, the positive observation was not consistent across experimental locations. While results were inconsistent, the significant response to NBC was evident at LCB with a fine sandy loam soil but not at Efaw with silty clay loam. Therefore, application of biochar in combination with inorganic N could improve soil properties, NUE and grain yield of maize cultivated on coarse textured sandy soils with poor chemical properties compared to soils with fine texture.

The second chapter of this dissertation used data from long-term continuous winter wheat (*Triticum aestivum* L.) experiments to compare the change from conventional tillage (CT) to no-tillage (NT) on grain yield, NUE, and soil properties. Experiments 222 at Stillwater and 502 at Lahoma, Oklahoma established in 1969 and 1970, respectively were used. Both experiments were managed under CT until 2010 and changed to NT in 2011. Results from this study showed significant impact of changing winter wheat production from CT to NT. However, positive results were not consistent across experimental locations. No-tillage advantages were only observed in comparatively shallow soil. Overall, it is evident from this study that NT positively influences grain yield, NUE, and soil properties. Therefore, NT is likely a sustainable long-term strategy for improving soil quality and crop productivity in a continuous mono-cropping system.

TABLE OF CONTENTS

Chapter Page

Chapter Page

Chapter Page

LIST OF TABLES

Table Page

Table Page

Table Page

LIST OF FIGURES

Figure Page

Figure Page

CHAPTER I

THE EFFECT OF INORGANIC N – FAST PYROLYSIS PINE WOOD BIOCHAR COMPLEX ON NITROGEN USE EFFICIENCY, SOIL PROPERTIES, AND YIELD OF MAIZE (*Zea mays* L.)

Abstract

Biochar as a soil amendment has shown promise in improving crop productivity. However, its interaction with inorganic nitrogen (N) is not well understood. The objectives of this chapter were to evaluate: (i) the effect of inorganic fertilizer N-biochar-combination (NBC) on maize (*Zea mays* L.) grain yield, grain N uptake, and grain N use efficiency (NUE), (ii) changes in total soil N (TSN), soil organic carbon (SOC), and inorganic N (NO_3 & NH_4) following application of NBC, and (iii) changes in cation exchange capacity (CEC), soil pH and soil electrical conductivity (EC) following application of NBC. Field trials were conducted in 2018 and 2019 at Efaw and Lake Carl Blackwell (LCB) both located near Stillwater, OK. A randomized complete block design with three replications and ten treatments consisting of a check, three N fertilizer rates (50, 100, 150 kg N ha^{-1}) and three biochar rates (5, 10, and 15 t ha^{-1}) was used. Results from this study showed an overall positive effect of NBC on grain yield, NUE, and soil properties relative to inorganic fertilizer N (NF). However, the positive observation was not consistent across experimental locations. Results at LCB averaged over years indicate that grain yield, N uptake, and NUE under NBC was higher by 25, 28, and 46%, respectively compared to NF. Total soil N, SOC, NO_3-N, and NH_4-N were higher under NBC by 5, 18, 24, and 10%, respectively compared to NF. Cation exchange capacity, pH, and soil EC was higher under NBC by 16, 3, and 7%, respectively than observed under NF. At Efaw, grain yield, N uptake, and NUE decreased under NBC by 5%, 7%, and 19%, respectively compared to NF. Total soil N, and SOC were higher under NBC compared to NF by 3 and 21%, respectively, no percentage difference between NBC and NF was observed for soil NH_4-N while NO_3-N was lower under NBC by 7% compared to NF. Cation exchange capacity and pH was higher under NBC by 4 and 4%, respectively while soil EC was lower by 11% than observed under NF. Whereas results were inconsistent across experimental locations, the significant response to NBC was evident at LCB with fine sandy loam soil but not at Efaw with silty clay loam. Therefore, application of biochar in combination with inorganic N could improve soil properties, NUE and grain yield of maize cultivated on coarse textured sandy soils with poor chemical properties compared to soils with fine texture.

1.1 INTRODUCTION

1.1.1 Background

Nitrogen (N) fertilizer management is one of the most challenging tasks for cereal farmers around the world with agronomic, economic, and/or environmental complexities (Tilman et al., 2002; Philip and Swinton, 2005). The increasing rate of nitrous oxide and other greenhouse gases emissions to the atmosphere, as a result of fertilizer N application and/or soil N transformations, has called for numerous approaches to forfend the trend (Stavins, 2017). Because of high demand in food production and processing to feed the increasing world population, agriculture and industrialization have collectively played a big role in increasing greenhouse gases (Foley et al., 2011). The apparent global concern is how these threats to the environment can be ameliorated. For this reason, current campaigns and strategies are geared towards reducing the emissions of greenhouse gases, especially carbon dioxide and nitrous oxide from agricultural fields alongside increasing crop yields (Alluvione et al., 2010; Singh et al., 2010; Jones and Kammen, 2011).

Over the years, many studies have focused on carbon sequestration using several approaches (Spigarelli and Kawatra, 2013; Stavins, 2017). The production of biochar is currently seen as a noble approach to lock carbon in a more stable form that can last for an extended period of time in the soil (Crombie et al., 2013; Jindo et al., 2014). This involves the combustion of bio-based organic materials in the absence of oxygen (pyrolysis) to form char. Pyrolysis also yield biogas and bio-liquids in addition to biochar in varying proportions depending on the process conditions (Jahirul et al., 2012). Several studies have documented other benefits of using biochar in addition to sequestering greenhouse gases and production of biofuel. These include, among others, treatment of waste water (Inyang et al., 2016), removal of heavy metals from contaminated soil (Inyang et al, 2012; Liang et al., 2014), and improving the productivity of agricultural soils (Atkinson et al., 2010; Jeffery et al., 2011).

Biochar can be used as a soil amendment where it offers immediate benefits to farmers through improvement in crop productivity besides reducing emissions and increasing sequestration of greenhouse gases (Lehmann et al., 2006). It is reported to be beneficial in improving soil physical and chemical properties. These include, among others, water retention capacity, cation exchange capacity, and soil pH, hence contributing to fertility (Atkinson et al., 2010; Singh et al., 2010). These benefits directly translate to increased crop biomass and grain yield. For instance, Jeffery et al. (2011) reported a 10% mean increase in crop yield in a statistical meta-analysis of fields applied with biochar. The authors noted that crop yield increase varies majorly depending on the type of soil and the materials used as pyrolysis feedstock. However, Asai et al. (2009), while complementing the benefits of biochar as a soil amendment, noted that optimum crop grain yield can be achieved through application of biochar in combination with inorganic fertilizers. This is true, especially since N is always limited within the biochar fraction.

Nitrogen fertilizers are of great importance for cereal grain yield and yet many reports have documented its low use efficiency. Raun and Johnson (1999) estimated global N use efficiency (NUE) for selected cereal crops at 33%. Recently, Omara et al. (2019c) did not observe any significant increase in world cereal NUE (35%) since the initial estimate. This indicates that past research efforts for nearly 2 decades have barely contributed significant impact in improving NUE. Maize, in particular, is one of the cereal crops that requires heavy N fertilization in comparison with others. The undisputed fact is that N is by far the most important nutrient element required in the largest amount and very vital for maximizing maize grain yield (Hirel et al., 2001, 2007). In some instances, maize producers have used heavy N application rate to crop as “insurance” and yet the likely outcome may be undesirable (Schröder et al., 2000). Environmental, economic and/or agronomic implications are the unforeseen consequences to high N input.

To a producer, the important concern is the loss of N fertilizer itself which directly correlates to farm profits. Application of N fertilizers at rates above the agronomic recommendation will undoubtedly result in low NUE (Sheriff, 2005). This is due to leaching losses, run-off, volatilization, denitrification among others. Leaching of fertilizer N in particular leads to N depletion from the soils, if not controlled, which is counter-beneficial for crop growth. Biochar application to the soil is believed to greatly reduce N fertilizer loss because of its high sorption capacity (Mukherjee et al., 2011). It is also important to note that ammonium N adsorbed by biochar is readily bioavailable when placed in the soil for plant uptake (Taghizadeh-Toosi et al., 2012; Güereña et al., 2013). This is because it is held on the exchange site by a weak electrostatic force. As ammonium in soil solution are taken up by the plants, more are released from the exchange site into the soil solution.

1.1.2 Rationale

Much as biochar application to the soil contributes to crop grain yield increase, it is important to note that its ability to achieve the desired cereal crop grain yield in an intensive mono-cropping system is limited (Asai et al., 2009). If biochar is a sole external crop nutrient source, one needs to apply unrealistically high rates to achieve certain desired yield levels. Some researchers have documented up to 100 t ha^{-1} of biochar application to obtain the desired optimum yield levels (Jeffery et al., 2011). In the real world, no farmer will have time and resources to apply these rates while still expecting good returns on investments. Secondly, biochar is limited in the quality of nutrient content. The nature of the feedstock and pyrolysis parameters will largely dictate its plant nutrient status. Increasing process temperatures above 300^{o}c increases the availability of ash minerals like potassium, magnesium and calcium among others while limiting volatile nutrients like nitrogen, chlorine and sulphur within the biochar fraction (Gaskin et al., 2008; Cantrell et al., 2012). Irrespective of pyrolysis conditions, type and nature of the feedstock, certain specific biochar properties responsible for improving crop productivity are compromised during its production. Hence, application of biochar alone as a soil amendment is not adequate to improve crop production. Clare et al. (2014) recommended that biochar research should shift away from on-farm production and application of pure biochar, towards combined biochar-inorganic fertilizer products as commercially produced biochar is uneconomical when used independently. Studying a combination of mineral fertilizer N and fast-pyrolysis pine-wood biochar may help determine possible synergies that can be drawn from the two input sources. This could explain the trend associated with NUE and maize grain yield as a result of applying a combination of inorganic fertilizer N and biochar.

1.1.3 Objectives and Hypotheses

The main objective of this study is to establish possible synergies in a biochar-N fertilizer complex in optimizing NUE, maize grain yield, and improving soil chemical properties.

1.1.4 Specific Objectives

i. To evaluate the effect of combined biochar-N fertilizer on maize grain yield, grain N uptake, and grain nitrogen use efficiency (NUE).

ii. To evaluate changes in total soil nitrogen (TSN), soil organic carbon (SOC), and inorganic nitrogen (NO_3 & NH_4) following a combined biochar-N fertilizer application.

iii. To evaluate changes in cation exchange capacity (CEC), soil pH and soil electrical conductivity (EC) following a combined biochar-N fertilizer application.

1.1.5 Research Hypotheses

i. Maize grain yield, grain N uptake, and NUE increase following a combined biochar-fertilizer N application.

ii. Total soil nitrogen, SOC, and inorganic nitrogen (NO_3 & NH_4) increase following a combined biochar-fertilizer N application.

iii. Cation exchange capacity, soil pH, and soil EC increase following a combined biochar-fertilizer N application.

1.2 LITERATURE REVIEW

1.2.1 History and Production of Biochar

Biochar is a stable carbon rich solid formed through pyrolysis (heating in the absence of oxygen) of bio-based or organic materials (Chan et al., 2007; Woolf et al., 2010). Generally, it is referred to us "biomass derived black carbon" or "charcoal" with potential to act as a sink for atmospheric carbon dioxide over an extended period of time (Lehmann et al., 2006). Because of recent interest in its use as soil amendments, some researchers have referred to it as "agrichar" or charcoal for agricultural use (Laine, 2012; Yao et al., 2012; Abewa et al., 2013). It is believed to have been first used by the pre-Columbian indigenous people of the Amazon region in the ages 500 to 9000 years BP (Solomon et al., 2007).

In the recent past, interest in the use of biochar increased as a result of environmental concerns and a quest to search for alternative sources of energy. Additionally, a number of researches have been conducted on biochar soil amendments and its effect on improving agricultural productivity. Currently, large scale commercial application of biochar as a soil amendment is still limited as many studies apparently look at feasibility of improving crop yield by analyzing chemical and physical properties of biochar at the laboratory level with limited field trials (Wu et al., 2012; Quilliam et al., 2012). Although limited, it is important to note that these laboratory and/or greenhouse studies have 'set the stage' for field investigations with highly variable and hard-to-control environmental conditions on the potential of biochar in improving crop production.

Production of biochar is accomplished under anaerobic conditions at varying temperature range. The yield and quality of the char produced depends on a number of factors including process parameters such as temperature and residence time. Important to note is also the nature and/or conditions of the feedstock such as moisture content, presence or absence of cellulose and hemicellulose (Tripathi et al., 2016). Biochar production at temperatures over 300 °C decreases biochar yield and increases loss of volatile compounds like nitrogen, chlorine and sulphur while the ash minerals such as calcium, potassium and magnesium are sequestered in the biochar fraction. Wright (2014) reported increasing production temperature from 300^{o}c to 400 ^{o}c and residence time from 1 to 3 hours decreased biochar mass yield by about 50% on average. At lower production temperatures, below 300^{o}c, the biochar produced has sorption capacity while biochar produced at high temperatures, above 300^{o}c, is mainly good for raising soil pH (Mukherjee at al., 2011). At high temperatures, the volatile material component of the biochar lost carries its acidity, negative charge, and thus, complexation ability, hence the low sorption capacity for cations. In otherward, the char at this temperature contain ash minerals like potassium, calcium among others that can be used in the alkalization of acidic pH.

1.2.2 Nitrogen Use Efficiency

Nitrogen (N) is one of the most important yield limiting nutrient in cereal crop production. Because N is highly mobile within the soil system, its application presents a number of management challenges (Moser et al., 2006; Zhang and Raun, 2006). As a result of the management concerns, many studies have focused on N use efficiency (NUE). Grain NUE is the total cereal N removed in grain minus N coming from soil and deposited in rainfall combined divided by total N applied in fertilizer (Raun and Johnson, 1999). In summary, NUE can be defined as “the grain produced per unit of fertilizer N applied”. It gauges the plants’ ability to take up applied N in fertilizer and assimilation into grain (Ciampitti and Vyn, 2011). Nitrogen use efficiency measures the relative proportion of the fertilizer N in the grain versus the quantity remaining in the soil and/or lost in the atmosphere.

Currently, grain NUE worldwide for cereals is estimated at approximately 35% (Omara et al., 2019c). Plant emission, ammonia volatilization, soil denitrification, leaching and surface runoff of fertilizer N are factors responsible for low NUE (Raun et al., 2002). These factors present a case to find better ways of improving NUE. In addition to posing serious environmental concerns, N loss result to low monetary value gained from the farming business (Garnett et al., 2009). Contrary to the low world NUE for cereal crops, NUE in Sub Saharan Africa was estimated to be more than 100% (Edmonds et al., 2009). This was due to the low fertilizer N application rates, and the mining of the already N-depleted soil. Therefore, small N application that unrealistically increases NUE, as exhibited in Sub Saharan Africa, will counter the optimum yield targets.

Nitrogen uptake, and therefore use efficiency, decreases with increasing fertilizer N application rate. In addition to the increasing rate of application, Barbieri et al. (2008) explained that the low NUE at high N fertilizer rates could be due to improper timing of application. However, low NUE cannot be significantly improved by simply timing of N application. The behavior of N within the soil system following application determines its fate and thus use efficiency. Conditions that enhance adsorption of N or simply increase cation exchange capacity of the soil would reduce N losses through leaching (Singh et al., 2010). Because of a net negative charge, biochar (especially those produced under low temperatures), has very high sorption capacity for cations (Mukherjee et al., 2011). In addition, biochar is also known to increase anion exchange capacity of the soil due to presence of pyridinium and oxonium groups and protonation of aromatic rings (Lawrinenko and Laird, 2015). Application of biochar together with inorganic N could help improve NUE and hence improving soil productivity and crop yield.

1.2.3 Maize Grain Yield

Maize is one of the most important crops extensively cultivated throughout the world (Lobell et al., 2011). It significantly contributes to over 20% of the estimated total consumed calories in parts of Africa and Mesoamerica and accounts for 73% in Sub Saharan Africa, 46% in South Asia, and 44% in Latin-America (Shiferaw et al., 2011). In the developed world however, up to 70% of the total maize produced are used as animal feeds. In addition, there has been a growing interest in recent years in using maize as a source of energy in an attempt to replace the fossil fuels (Persson et al., 2009).

Generally, maize grain yield in developing world are less than 2.0 Mg ha^{-1} compared to the average grain yield of over 4.0 Mg ha^{-1} in the developed world (Smale et al., 2013). The high maize grain yield in the developed world is a result of high use of inputs such as fertilizers, insecticides, quality seeds, and good agronomic practices. Application of high fertilizer rates, especially N, account for the majority of the high maize grain yield in the developed world. Because of the low NUE and the associated environmental impact, alternative research efforts are being sought to find a better approach of applying N to improve use efficiency and reduced environmental contamination. Biochar applied in combination with N fertilizer has the potential to increase maize grain yield and NUE while reducing risk of nitrous oxide emissions to the atmosphere (Singh et al., 2010; Abewa et al., 2013).

Research conducted in the central great plain of China recorded increases in maize grain yield of 8.8 and 12.1% when wheat straw biochar was applied at a rate of 20 and 40 t ha^{-1}, respectively in combination with a uniform rate of 300 kg N ha^{-1} (Zhang et al., 2012). Varying a combination of biochar and N fertilizer rates shows a trend of yield increase. In a four-year experiment, Major et al. (2010) did not observe any significant yield increase within the first year when biochar was used as a sole source of soil amendment. However, at 20 t ha^{-1} of biochar, 20, 30, and 140% yield increases were observed in the second, third and fourth years, respectively. This study suggests that the benefit of using biochar as a sole source of soil amendment is cumulative with little or no positive effect in the first or second year. However, according to Güereña et al. (2013), crop yield benefits of applying biochar can only be achieved in tropical soils, with no effect in fertile soils of temperate climate.

1.2.4 Soil Organic Carbon

Soil organic carbon (SOC) is one of the most important chemical properties that indicate the quality of soil. It plays a key role in the control of soil fertility and crop productivity and can be affected by poor production process (Jobbagy and Jackson, 2000). Anthropogenic activities thus contribute significantly to the reduction or increase in SOC stock. For instance, the addition of plant residue to the soil increases the abundance of SOC where its storage is in turn controlled by decomposition rate. Stability at deeper layers are maintained when there is no further addition of crop residues (Fontaine et al., 2007). Some research reports have documented the contribution of high application rate of fertilizer N to increasing SOC stock. Aula et al. (2016) reported a significant accumulation of SOC at N application rate above 90 kg ha^{-1}. Additionally, they indicated that manure application also increases the accumulation of SOC in the surface soil profile. For biochar however, there are contradictory conclusions on its contribution to SOC stock. Some researchers have reported negative priming effect of biochar to the native SOC as a result of increase in the rate of evolution of carbon dioxide hence less storage (Jones et al., 2011; Wardle et al., 2008). It would be premature to conclude negative priming unless we know the intrinsic SOC status. If the soil is inherently poor in SOC, addition of biochar will reduce the evolution of CO_2 while the opposite would be observed in soils rich in organic carbon (Kimetu and Lehmann, 2010). Besides, carbon loss is always very small relative to the amount of carbon stored within the biochar itself (Jones et al., 2011). In contrast, Cross and Sohi (2011) reported that addition of biochar did not, for the most part, indicate negative priming of native SOC and that application of biochar could stabilize native SOC in grassland soils. Addition of a combination of N and biochar could contribute to the increase in the SOC storage.

1.2.5 Total Soil Nitrogen

Total soil nitrogen (TSN) is one of the most significant soil quality parameter that has been documented to range between 0.6 g kg^{-1} and 5 g kg^{-1} in the surface layers of most cultivated soils and could reach up to 25 g kg^{-1} in peat (Bremner & Mulvaney, 1982; Xu et al., 2013). In the soil system, N occurs both in organic and inorganic forms. Normally, the organic forms dominate, including both particulate organic N and dissolved organic N. The particulate organic N includes the N in living organisms and in detritus. On the other hand, dissolved organic N consists of a wide range of organic substances, such as free amino acids, proteins, among others (Howarth, 2014).

Biochar soil incorporation is suggested to increase the buildup of organic N. To optimize the potential of biochar in enhancing soil organic N, some research reports suggest the application of combined biochar-fertilizer N. For instance, Prommer et al. (2014) reported that addition of inorganic fertilizer-N in combination with biochar activated the belowground build-up of soil organic N. They explained that biochar reduces the transformation rates of the native soil organic N as plants and microbes draw from the inorganic fertilizer N. Bai et al. (2015) added that changes in microbial processes and activities on soil organic N following biochar soil amendment are mediated primarily by abiotic factors. Therefore, biochar present an enormous potential in the buildup of soil organic N.

1.2.6 Inorganic Nitrogen

Plants take up N in the form of nitrate (NO_3-N), most oxidized form, and ammonium (NH_4-N), the most reduced form. The NO_3-N is the predominant form of inorganic N in agricultural soils (Bhattacharya, 2018), probably due to the fast oxidation of NH_4-N under aerobic soil environment. Although non-symbiotic and symbiotic fixation, and addition of N in rainfall contribute to inorganic N pool (Peoples et al., 1995; Sullivan et al., 2014), a greater proportion comes from fertilizer. While these are readily available for immediate plant use, they are also very susceptible to losses. Pathways for inorganic N loss, including gaseous plant emission, soil denitrification, surface runoff, volatilization, and leaching have been previously documented (Raun and Johnson, 1999; Fageria and Baligar, 2005; Omara et al., 2019c). It is important to note that the rate at which N losses occur is chiefly controlled by the abiotic factors such as temperature, pH, soil texture, and soil moisture level which in turn affects biotic components. For instance, pH above 7 favors volatilization of ammonia while soil with high proportion of sand and low cation exchange capacity does not support retention of fertilizer N applied. For these reason, management of inorganic N fertilizer is one of the most challenging tasks for cereal farmers worldwide. This has called for a renewed interest in exploring strategies that can effectively address N losses. Several research reports have suggested soil amendment of biochar as one of the strategies in managing fertilizer N. The main mechanism for increase in the retention of soil inorganic N following biochar amendment is its ability to alter cation and anion exchange capacity in the soil (Jiang et al., 2012; Lawrinenko and Laird, 2015; Agegnehu et al., 2016). Actually, most studies reporting effectiveness of biochar in enhancing fertilizer N retention has been realized in soils with high sand proportion and with low cation and anion exchange capacity (Uzoma et al., 2011; Bruun et al., 2014; Gao et al., 2016; Amin and Eissa, 2017). The increased anion exchange capacity of biochar reduces leaching of anionic (NO_3) nutrients while the cation exchange capacity increases the adsorption of cation (NH_4) nutrients. Therefore, this implies that application of inorganic fertilizer N alongside biochar improves retention and uptake of both NO_3 and NH_4.

1.2.7 Cation Exchange Capacity

Cation Exchange Capacity (CEC) of gives a measure of the ability of the soil to retain cation nutrients against leaching. Organic matter and clay content are the two major factors that significantly influence the CEC of soils. Helling et al. (1964) reported 19 to 45% as the relative contribution of organic matter to total soil CEC in the studied soil while the contribution of clay content to the total soil CEC varied from 3.3 to 13.3 percent. It is important to note that these were pH dependent and the highest contribution was registered at high pH (8.0) while the lowest percentage was obtained at a pH of 2.5. It is apparent that any soil amendment that contributes to increase in the number of colloids increases the CEC for that soil. Biochar is believed to have a net negative charge as a result of the oxidation of aromatic C and formation of carboxyl or phenolic functional groups (Glaser et al., 2002; Liang et al., 2006). Laird et al. (2010) reported up to 20% contribution of biochar to improvement of cation exchange capacity of the soil. The high cation exchange capacity of biochar increases the sorption capacity of soil and is believed to greatly reduce the ammonium N fertilizer leaching (Mukherjee et al., 2011). The nitrogen-biochar complex could be efficient in improving CEC and facilitating ammonium retention in the soil.

1.2.8 Soil pH

Soil reaction, commonly referred to as soil pH, is the degree of acidity or alkalinity of the soil. It determines the suitability of soil as a medium for plant growth by influencing the availability of nutrients and their uptake via plant roots and also influences thriving of desirable microbes in the soil (Fageria and Baligar, 2008). Most cultivated crops grow well near neutral pH, slightly below or above pH of 7. Application of N fertilizers especially at excessive rates over a long period of time is known to lower the pH of soils to levels that most crops do not tolerate. Aula et al. (2016) reported a significant increase in acidification of surface soils (0-15 cm) at N rates above 90 kg ha^{-1} where pH dropped to 4.3 compared to initial values ranging from 5.1 to 7.5. At low pH, the high hydrogen ion concentration increases fixation of phosphorus by aluminum and iron, rendering them unavailable for crops (Mozaffari et al., 2002). The high hydrogen ion concentrations also increase leaching losses of base cations since the former displace the latter from the exchange complex. Historically, lime has been used to neutralize soil acidity but it is important to note that the amount of lime used depends on the buffer capacity of the soil. Studies have shown that application of biochar in the soil can help neutralize acidic soils. Chintala et al. (2014) demonstrated the effectiveness of biochar application in ameliorating soil acidity. They however, noted that this greatly depended on type of feed stock used in the pyrolysis process. By correlating the liming effect of biochar and soil acidity, Yuan and Xu (2011) concluded that application of biochar from crop residues, and especially leguminous plants, could decrease soil exchangeable acidity and exchangeable Al, and increase soil pH. Application of biochar in combination with mineral N fertilizer could remedy soil acidification as always experienced at high N application rates.

1.2.9 Soil Electrical Conductivity

The level of concentration of soluble salts in the soil, soil electrical conductivity (EC), is known to affect crop performance and grain yield. Major anthropogenic trigger of increase in the salt levels of soil include use of poor quality or saline irrigation water, excessive application of none saline irrigation water which raises water table and inappropriate application of fertilizers (Maas and Grattan, 1999; Lichtfouse, 2013). In arid and semi-arid areas, application of irrigation water in excessive quantities is the main reason for increase in salinity level of soils. If there are no deliberate efforts to invest in adequate drainage solutions, excessive application of irrigation water will undoubtedly result in accumulation of salts in the root zones (Wichelns and Qadir, 2014). Lichtfouse (2013) demonstrated that increase in the application rate of cattle manure resulted to increase in the soil EC. This can result to low crop yield. The accumulation of salt and nitrate as a result of excessive application of fertilizers may lead to soil deterioration. In vegetable and wheat-maize field experiments, Ju et al. (2007) reported that EC was significantly higher in the vegetable fields but not in the wheat-maize field. This implies that the extent to which the increase and accumulation of salts in soils due to excessive application of fertilizer affects crop performance depends on the type of crop cultivated. In addition, the increase in soil EC following biochar soil amendment depend on pyrolysis temperature. Hossain et al. (2011) reported that biochar produced at higher temperatures, 700 ^{o}c, was alkaline in nature hence high EC. Similarly, Brewer et al. (2011) noted that biochars effect on EC of soils varies according to the source of the pyrolysis materials and temperature. They added that EC of soils applied with urea was higher than those amended with biochar. Even with biochars produced at high temperatures, it is important to note that elevated EC in soils amended with these biochars are not significant to cause poor crop performance and yield decline. Thus addition of biochar together with mineral fertilizers could help reduce the salt accumulation as a result of fertilizer application.

1.2.10 Summary

In order to comprehend the functional properties of biochar, literature on history and production of biochar was briefly highlighted. Whereas these were not the main aim of this study, they were nonetheless helpful in further understanding practical implication of biochar use on crop production. Overall, the literature underscored the importance of biochar in agricultural production. It examined the effectiveness of soil biochar amendment in enhancing maize grain yield, N uptake, and NUE. In addition, important soil chemical properties, including SOC, TSN, NO_3, NH_4, CEC, pH, and EC, were reviewed. While previous findings were inconsistent, the review demonstrated the apparent significance of soil biochar amendment in improving soil productivity. Generally, previous findings indicated that the effectiveness of biochar soil amendment in improving soil productivity is highly dependent on, among others, soil type, biochar application rate, biochar feedstock, and pyrolysis temperature. This suggests a unique setup of field studies to further explore the importance of biochar in agricultural production. Thus this study, whose methodology is discussed in the following section of this dissertation, was designed to explore synergistic relationship between biochar and inorganic fertilizer N.

1.3 MATERIALS AND METHODS

1.3.1 Experimental Sites

Field trials were conducted for two years in the summer cropping season of 2018 and 2019 at two locations; Efaw and Lake Carl Blackwell research farms, all located near Stillwater, Oklahoma, USA. Efaw Agronomy Research Station is on an Ashport silty clay loam (fine-silty, mixed, superactive, thermic Fluventic Haplustoll) soil. Lake Carl Blackwell is situated on a Pulaski fine-sandy loam (coarse/loamy, mixed nonacid, themic Udic Ustifluvent) soil (Soil Survey Staff, 2020). Total rainfall and average air temperature were computed for the maize growing period (April to September) using data obtained from The Oklahoma Mesonet, www.mesonet.org (Table 1.1). In addition, 10-year-average (2008 to 2017) monthly rainfall and average temperature prior to the first year of the trial setup were compiled for both experimental sites.

1.3.2 Experimental Design

The study used a randomized complete block experimental design with three replications. There were 10 treatments that consisted of 3 levels of N fertilizers; 50, 100, and 150 kg ha^{-1} and three levels of biochar; 5, 10, and 15 t ha^{-1}. The treatment structure was set to evaluate the effect of increasing N, biochar and biochar-N complex rates on NUE, maize grain yield, and selected soil chemical properties (SOC, TSN, CEC, EC, pH, NH_4, and NO_3). In addition, a check treatment with no N or biochar was added to the treatment structure (Table 1.2). Biochar was obtained from Wakefield Agricultural Carbon (Columbia, Missouri, USA), a USDA certified biochar producing company. Physical and chemical properties of soft wood (Southern

Yellow Pine) biochar supplied as well as initial soil properties are included in Table 1.3. All the N and biochar treatments were applied prior to maize planting. Nitrogen was applied as urea ammonium nitrate - UAN (28:0:0). Nitrogen, biochar and biochar-N complex treatments were surface applied and incorporated at 15 cm into the soil. This incorporation ensured an in-depth mixing of the biochar-N fertilizer complex with soil materials for the respective treatment rates.

1.3.3 Experimental Management

Maize hybrid P1690AM (DuPont Pioneer, Johnston, Iowa, USA) was planted for all treatments with row and intra-row spacing of 0.76 m and 0.17 m, respectively using John Deere MaxEmerge 2 Vacuum Planter (John Deere, Moline, Illinois, USA). Each plot consisted of four rows where the center two rows were harvested and the two outside rows were considered borders. A uniform plot size for each treatment of 9 m^2 across all replications and experimental sites. Post-emergence herbicide glyphosate was applied at a rate of 1.5 to 2 L as active ingredient and at 120 L ha^{-1} of solution, for each case depending on the weed pressure to suppress weed growth after re-emergence. At V8 maize development stage, experimental plots were mechanically spot-weeded using a hand hoe.

1.3.4 Data Collection and Analysis

Maize grain was harvested from experimental plots at maturity using an 8-XP Kincaid Plot Combine (Kincaid, Haven, Kansas, USA). Grain yields were adjusted to 12.5% moisture content. Sub-samples were collected for each plot and dried in an oven at 65°C for 48 hours.

Samples were ground to pass a 1mm sieve size. Finely ground grain was achieved by rolling in a bottle with stainless steel rods for 24 hours before analysis for total N that was accomplished using dry combustion analysis (Schepers et al., 1989). A LECO Truspec CN628 dry combustion analyzer (LECO Inc, St. Joseph, Michigan, USA) was used. For each sample, 150 mg of sample by treatment and replication was weighed, wrapped in aluminum foil, and combusted at 950°C.

Grain N uptake was determined by multiplying percent grain N with harvested yield. Grain nitrogen use efficiency (NUE) was calculated according to Raun and Johnson (1999). The difference method was adopted as described by equation 1 (Eq. [1]).

$$\text{NUE} = \frac{\text{Grain N uptake (fertilized)} - \text{Grain N uptake (unfertilized)}}{\text{Total fertilizer N applied}} \text{ X } 100 \qquad [1]$$

Composite soil samples, 15–20 cores per plot at 0–15 cm, were collected following maize grain harvest, about five months after biochar application, each year reported in this study. Soil samples from the field were sieved through a 2-mm screen, oven-dried for 48 h at 65°C, and ground to pass through a 1-mm sieve size. Various extraction procedures and dry combustion analysis were completed according to each specific soil chemical property measured.

The extraction for soil exchangeable cations (Ca, K, and Mg) were accomplished using Mehlich 3 solution (20 ml Mehlich 3 /2g of soil), shaken for 5 min on a rotary shaker at 200 rpm (Mehlich, 1984). Mehlich-3 extracts were filtered with 0.45-µm filters, and the Ca, K, and Mg levels were determined using an inductively coupled plasma optical emission spectrometers (ICP-OES). The SPECTRO ARCOS FHS26 ICP (SPECTRO/AMETEK, Kleve, Germany) was used. The estimated soil cation exchange capacity (CEC; meq 100 g^{-1}) was estimated according to Ross and Ketterings (1995). An indirect method was adopted by summing up the exchangeable Ca, K, and Mg as summarized in equation 2 (Eq. [2]).

$$\mathrm{CEC}\ (\mathrm{meq}\ 100\ \mathrm{g} - 1) = \frac{\mathrm{Ca}\ (\mathrm{mg\ kg} - 1)}{200} + \frac{\mathrm{Mg}\ (\mathrm{mg\ kg} - 1)}{120} + \frac{\mathrm{K}\ (\mathrm{mg\ kg} - 1)}{390} \qquad [2]$$

Soil pH and soil electrical conductivity (EC) were simultaneously determined using a Seven Excellence dual pH and EC meter (METTLER TOLEDO, Schwerzenbach, Switzerland) at a soil to water ratio of 1:2, using distilled water. Electrical conductivity was measured and recorded in micro Siemens per centimeter (µS/cm).

Determination of soil organic carbon (SOC) and total soil nitrogen (TSN) were completed using dry combustion analysis (Schepers et al., 1989). LECO Truspec CN dry combustion analyzer LECO CN628 (LECO Inc., St. Joseph, Michigan, USA) was used. For each sample, 200 mg of soil by treatment and replication was weighed, wrapped in aluminum foil, and combusted at 950°C.

The extraction for inorganic nitrogen (nitrate and ammonium) was completed using 1 M KCl solution (25 ml 1 M KCl/5 g of soil) and shaken for 30 min on a rotary shaker at 200 rpm. The extracts for each sample was then filtered with 25-µm whatman filter paper. After filtering, ammonium and nitrate were simultaneously measured using automated Lachat QuickChem 8500 Series 2 Flow Injection Analyzer (Hach Co., Loveland, Colorado, USA)

1.3.5 Statistical Analysis

The GLM procedure from SAS package was used for analysis of variance (SAS Institute, 2013). For all response variables, the difference between treatment means from nitrogen-biochar combination (NBC) and nitrogen fertilizer (NF) were compared using single-degree-of-freedom orthogonal contrasts (Abdi and Williams, 2010; Nogueira, 2004). The standard error (SE) of means for each treatment and the coefficient of variation (CV) were used to indicate the precision of measurement and the extent of variability within and between groups, respectively. Charts, produced using the MS Excel (2016), were used to show visual differences and treatment means separated by using Tukey's HSD (honestly significant difference) test at $p < 0.05$.

1.4 RESULTS

1.4.1 Maize Grain Yield

At Efaw, the analysis of variance for maize grain yield in 2018 showed an overall significant difference ($p = 0.0023$) between treatments (Table 1.4). However, differences between nitrogen-biochar-combination (NBC) and nitrogen fertilizer (NF) could not be established using single-degree-of-freedom contrasts at each fertilizer rate. With N applied at 50 and 100 kg N ha^{-1}, NBC increased grain yield by 17 and 13%, respectively when compared to the same rates under NF. At, 150 kg N ha^{-1}, grain yield decreased by 14% when NBC was compared to NF. Generally, yield increased with an increase in fertilizer rate under both NBC and NF (Figure 1.1). The highest yield in 2018 of 7.3 Mg ha^{-1} was attained under NF at 150 kg N ha^{-1} and the lowest of 3.5 Mg ha^{-1} was obtained in the control plot with 0 kg N ha^{-1} and 0 kg biochar ha^{-1} applied.

In 2019, similar observations were made with an overall significant difference ($p = 0.0124$) in grain yield between treatments (Table 1.5). However, no difference could be established between NBC and NF using single-degree-of-freedom contrasts. On average, NBC resulted in 13.9% lower grain yield than N applied without biochar. At each rate, the NBC decreased grain yield by 15, 14 and 19% at 50, 100, 150 kg N ha^{-1}, respectively. Grain yield increased with increasing fertilizer rate and this was consistent with observations of 2018 at both NBC and NF (Figure 1.1). The highest yield in 2019 of 2.3 Mg ha^{-1} was harvested at 150 kg N ha^{-1} under NF while the lowest of 1.1 Mg ha^{-1} was achieved in the control plot. Overall, grain yield in 2019 was lower than observed in 2018 and this is probably attributed to the water stress at vegetative stage with up to 430 mm of rainfall in May of 2019 compared to the 10-year average

(Table 1.1). In addition, there was heavy precipitation with over 200 mm experienced in the month of August which delayed harvest in 2019.

At the Lake Carl Blackwell (LCB) location, analysis of variance showed an overall significant difference ($p < .0001$) between treatments in 2018 (Table 1.6). Although contrasts did not result in observable difference ($p = 0.327$) between NBC and NF at 50 kg N ha^{-1}, differences were observed at 100 kg N ha^{-1} ($p = 0.0052$) and 150 kg N ha^{-1} ($p = 0.003$). The differences at 100 and 150 kg N ha^{-1} correspond to yield benefits of 30 and 21%, respectively under NBC compared to NF. While no difference was seen at 50 kg N ha^{-1}, NBC still resulted to a yield advantage of 8% compared to NF. Generally, yield increased with increase in fertilizer rate where the highest of 5.0 Mg ha^{-1} was observed at 150 kg N ha^{-1} under NBC while the least yield of 2.6 Mg ha^{-1} was harvested in the control plot (Figure 1.1).

In 2019, Analysis of variance did not show an overall significant difference ($p = 0.1264$) in grain yield among treatments (Table 1.7). Contrasts did not show significant differences between NBC and NF at 50 kg N ha^{-1} ($p = 0.4311$) and 100 kg N ha^{-1} ($p = 0.1544$). However, a significant difference was observed at 150 kg N ha^{-1} ($p = 0.0338$). The observed differences correspond to yield benefits under NBC of 21, 31, and 39% at 50, 100, and 150 kg N ha^{-1}, respectively. As observed in 2018, grain yield increased with an increase in fertilizer rate where the highest yield of 2.2 Mg ha^{-1} was obtained at 150 kg N ha^{-1} under NBC while the lowest yield of 0.65 Mg ha^{-1} was obtained in the control plot with 0 kg N ha^{-1} applied. Generally, yields at this location were lower in both years compared to Efaw.

1.4.2 Grain Nitrogen Uptake

At Efaw, analysis of variance in 2018 for grain N uptake showed an overall significant difference ($p = 0.0003$) between treatments (Table 1.4). However, contrasts did not reveal significant differences between NBC and NF. Nonetheless, when compared to NF at 50 and 100 kg N ha^{-1}, grain N uptake increased with NBC by 9 and 11%, respectively. Conversely, grain N uptake decreased by 23% at 150 kg N ha^{-1} under NBC compared to NF. Generally, grain N uptake increased with increasing fertilizer rate under both NBC and NF (Figure 1.2). Grain N uptake was generally higher in 2018 than observed in 2019. The highest grain N uptake in 2018 of 102 kg ha^{-1} was attained under NF at 150 kg N ha^{-1} and the lowest of 41 kg ha^{-1} was obtained in the control plot.

The result in 2019 mirrored that of 2018 with an overall significant difference ($p = 0.001$) in grain N uptake between treatments (Table 1.5). At each fertilizer rate, the NBC decreased grain N uptake by 6, 23, and 12% at 50, 100, and 150 kg N ha^{-1}, respectively. Grain N uptake increased with increase fertilizer rate and this is consistent with observations of 2018 under both NBC and NF (Figure 1.2). The highest grain N uptake of 30 kg ha^{-1} in 2019 was obtained at 150 kg N ha^{-1} under NF while the lowest of 12 kg ha^{-1} was achieved at 0 kg N ha^{-1} with 15 t ha^{-1} of biochar. There was an overall low grain N uptake in 2019 compared to 2018 and this can be attributed to the low grain yield harvested in 2019.

Analysis of variance at LCB showed an overall significant difference ($p < .0001$) in grain N uptake between treatments in 2018 (Table 1.6). Using contrasts, significant differences were observed at 100 kg N ha^{-1} ($p = 0.0006$) and 150 kg N ha^{-1} ($p = 0.0016$) and these correspond to a grain N uptake advantage under NBC of 38 and 29%, respectively compared to NF.

Although no significant difference (p = 0.6927) was seen at 50 kg N ha^{-1}, the observed benefits under NBC was 5% greater than NF. Generally, grain N uptake increased with increase in fertilizer rate where the highest of 67 kg ha^{-1} was observed at 150 kg N ha^{-1} under NBC while the least grain N uptake of 28 kg ha^{-1} was obtained in the control plot (Figure 1.2).

In 2019, an overall significant difference (p = 0.0395) in grain N uptake was seen between treatments (Table 1.7). Contrasts between NBC and NF in 2019 also showed significant differences at 100 kg N ha^{-1} (p = 0.0258) 150 kg N ha^{-1} (p = 0.0071). The observed differences corresponded to a grain N uptake advantage under NBC of 45 and 46% at 100 and 150 kg N ha^{-1}, respectively. Although no significant difference was seen at 50 kg N ha^{-1} (p = 0.8195), NBC advantage over NF was still evident with 6% grain N uptake. Like in 2018, grain N uptake increased with an increase in fertilizer rate where the highest of 28 kg ha^{-1} was obtained at 150 kg N ha^{-1} under NBC while the lowest grain N uptake of 7 kg ha^{-1} was observed in the control plot. Generally, grain N uptake at this location was lower in both years compared to Efaw.

1.4.3 Grain Nitrogen Use efficiency

The analysis of variance for the experiment conducted at Efaw in 2018 did not show significant difference (p = 0.07) in nitrogen use efficiency (NUE) between treatments (Table 1.4). At each fertilizer rate, NUE was higher under NBC compared to NF at 50 kg N ha^{-1} and 100 kg N ha^{-1}, which correspond to 21 and 20%, respectively. However, NUE at 150 kg N ha^{-1} was higher under NF 12% than observed under NBC. A general trend for NUE to decrease with N rate was observed under both NBC and NF (Figure 1.3). The highest NUE of 59% was observed under NBC at 50 kg N ha^{-1} while the lowest of 28% was also observed under NBC at 150 kg N ha^{-1}. This was expected as the absorption and utilization efficiency decreases with increase in fertilizer rate.

Results for the 2019 experiment mirrored that of 2018 where no significant difference ($p = 0.8522$) was observed between treatments (Table 1.5). At each fertilizer rate, NUE was higher under NF than NBC by 2, 4, and 2% at 50 kg N ha^{-1}, 100 kg N ha^{-1} and 150 kg N ha^{-1}, respectively. No trend for an increase in NUE with fertilizer rate was seen under both NBC and NF. The highest NUE of 12% was observed under NF at 150 kg N ha^{-1} while the lowest of 7% was observed under NBC at 100 kg N ha^{-1} (Figure 1.3).

At LCB, results for 2018 showed an overall significant difference ($p = 0.0105$) in NUE between treatments (Table 1.6). Single-degree-of-freedom contrasts showed significant differences between NBC and NF at 100 kg N ha^{-1} ($p = 0.0012$) and 150 kg N ha^{-1} ($p = 0.0298$). These corresponded to 22 and 13% higher NUE under NBC compared to NF at 100 kg N ha^{-1} and 150 kg N ha^{-1}, respectively. At 50 kg N ha^{-1}, no significant difference ($p = 0.4768$) was observed but NBC still had NUE 4% higher than observed under NF. Nitrogen use efficiency was highest (32%) under NBC at 100 kg N ha^{-1} while the lowest (10%) was also observed at 100 kg N ha^{-1} under NF (Figure 1.3).

Results for the 2019 experiment were similar to that of 2018 where analysis of variance showed an overall significant difference ($p = 0.0034$) in NUE between treatments (Table 1.7). At each N rate, contrasts did not show significant ($p = 0.5282$) difference between NUE under NBC and NF at 50 kg N ha^{-1}. However, NBC still had higher NUE than NF by 1%. Significant differences were observed between NBC and NF at 100 kg N ha^{-1} ($p = 0.0041$) and 150 kg N ha^{-1} ($p = 0.0109$). Nitrogen use efficiency was higher under NBC than observed under NF by 10 and 8% at 100 and 150 kg N ha^{-1}, respectively. There was a general trend for NUE to decrease as N rate was increased under both NBC and NF (Figure 1.3). The highest NUE (17%) was observed under NBC at 50 kg N ha^{-1} while the lowest (6%) was observed under NF at both 100 and 150 kg N ha^{-1}.

1.4.4 Total Soil Nitrogen

At Efaw, the analysis of variance did not show significant difference ($p = 0.3316$) in total soil nitrogen (TSN) between treatments in 2018 (Table 1.8). In comparing NBC and NF at each N rate, TSN was 14% lower under NBC than observed under NF at 50 kg N ha^{-1}. At 100 and 150 kg N ha^{-1}, TSN was higher under NBC than NF by 6 and 5%, respectively. An overall trend for decrease in TSN with fertilizer rate was observed under both NBC and NF (Figure 1.4). The highest TSN of 0.82 g kg^{-1} was observed at 50 kg N ha^{-1} under NF while the lowest (0.68 g kg^{-1}) was obtained at 150 kg N ha^{-1} under NF.

In 2019, similar observations were made where no significant difference ($p = 0.6854$) in TSN among treatments (Table 1.9). At 50 kg N ha^{-1}, TSN was higher under NBC than NF by 10%. Total soil nitrogen was unexpectedly lower under NBC than NF by 3% at 100 kg N ha^{-1} while an increase of 10% was observed under NBC compared to NF at 150 kg N ha^{-1}. The percentage values indicate no particular trend of increase in TSN with fertilizer rate under both NBC and

NF (Figure 1.4). The highest TSN of 0.83 g kg^{-1} was observed under NBC at 50 kg N ha^{-1} while the lowest of 0.72 g kg^{-1} was obtained at 15 t biochar ha^{-1} with no N applied.

At the LCB location, results for 2018 did not show any significant difference ($p = 0.6466$) in TSN between treatments (Table 1.10). Although no significant difference was seen, there was a tendency of more TSN to accumulate under NBC than observed under NF. The observed TSN advantage under NBC corresponds to 7, 9, and 5% at 50, 100, and 150 kg N ha^{-1}, respectively compared to NF. Total soil nitrogen did not show any trend of increase under both NBC and NF (Figure 1.4). The highest TSN of 0.84 g kg^{-1} was observed at 10 t biochar ha^{-1} with no N applied while the lowest of 0.75 g kg^{-1} was observed at 100 kg N ha^{-1} under NF.

Similar observations were made in 2019 where analysis of variance did not indicate significant difference ($p = 0.2424$) in TSN among treatments (Table 1.11). At each fertilizer rate, TSN was higher under NBC than NF at 50 and 100 kg N ha^{-1} by 4 and 11%, respectively. However, a decrease in TSN was observed at 150 kg N ha^{-1} under NBC compared to NF by 4%. No trend of increase in TSN with fertilizer rate was observed under both NBC and NF (Figure 1.4). The highest TSN of 0.84 g kg^{-1} was observed under NBC at 100 kg N ha^{-1} while the lowest of 0.75 g kg^{-1} was seen at 100 kg N ha^{-1} under NF. Overall, there was a slight increase in TSN in 2019 compared to that of 2018.

1.4.5 Soil Organic Carbon

The 2018 analysis of variance at Efaw indicated an overall significant difference ($p = 0.0016$) in soil organic carbon (SOC) between treatments (Table 1.8). Orthogonal contrasts comparing

NBC and NF at 50 kg N ha^{-1} did not show significance difference (p = 0.6542) while significance differences in SOC were seen at 100 kg N ha^{-1} (p = 0.0064) and 150 kg N ha^{-1} (p = 0.0018). Higher SOC observed under NBC than NF correspond to 5, 27, and 31% at 50, 100, and 150 kg N ha^{-1}, respectively. There was a trend of increase in SOC with fertilizer rate under NBC but not under NF (Figure 1.5). The highest SOC (9.6 g kg^{-1}) was observed under NBC at 150 kg N ha^{-1} while the lowest (6.6 g kg^{-1}) was obtained at 150 kg N ha^{-1} under NF.

Similar observations were made in 2019 where significant differences (p = 0.0007) in SOC were seen between treatments (Table 1.9). Although contrasts did not reveal significant difference (p = 0.7147) between NBC and NF at 50 kg N ha^{-1}, NBC advantage over NF was 4%. Contrasts analysis revealed significant differences between NBC and NF at 100 kg N ha^{-1} (p = 0.018) and 150 kg N ha^{-1} (p = 0.0007). The NBC registered higher SOC than NF by 22 and 35% at 100 and 150 kg N ha^{-1}, respectively. A trend for increase in SOC with fertilizer rate was observed under NBC but not under NF (Figure 1.5). The highest SOC (11 g kg^{-1}) was observed under NBC at 150 kg N ha^{-1} while the lowest (6.7 g kg^{-1}) was obtained at the control plot. Overall, the SOC in 2019 was higher than observed in 2018 probably due to cumulative effect of biochar addition.

At LCB, results for the analysis of variance in 2018 did not show an overall significant differences (p = 0.0758) in SOC between treatments (Table 1.10). For each fertilizer rate, contrasts analysis comparing NBC with NF did not show significant difference at 50 kg N ha^{-1} (p = 0.0858) but differences were seen at 100 kg N ha^{-1} (p = 0.0058) and 150 kg N ha^{-1} (p = 0.0006). The SOC under NBC was higher than observed under NF by 17, 21, and 28% at 50, 100, and 150 kg N ha^{-1}, respectively. There was a trend for SOC to increase with increase in fertilizer rate under NBC but not under NF (Figure 1.5). The highest SOC (12 g kg^{-1}) was observed at 150 kg N ha^{-1} under NBC while the lowest (8.2 g kg^{-1}) was observed at 50 kg N ha^{-1} under NF.

In 2019, overall analysis of variance showed significant differences ($p = 0.0015$) in SOC between treatments (Table 1.11). Contrasts analysis between NBC and NF showed significant differences at 50 kg N ha^{-1} ($p = 0.0415$), 100 kg N ha^{-1} ($p = 0.0241$), and 150 kg N ha^{-1} ($p = 0.0335$). The observed differences showed higher SOC under NBC than under NF by 14, 15, and 12% at 50, 100, and 150 kg N ha^{-1}, respectively. A trend for increase in SOC with increase in fertilizer rate was observed under NBC but not under NF (Figure 1.5). The highest SOC (13 g kg^{-1}) was observed under NBC at 150 kg N ha^{-1} while the lowest (8.2 g kg^{-1}) was seen at 50 kg N ha^{-1} under NF. Generally, there appeared to be no increase in SOC in 2019 compared to 2018.

1.4.6 Inorganic Nitrogen

The analysis of variance at Efaw location in 2018 did not show significant difference in both soil nitrate-N ($p = 0.0534$) and ammonium-N content ($p = 0.892$) between treatments (Table 1.8). At each fertilizer rate, soil nitrate was higher under NBC than NF by 5 and 7% at 50 and 100 kg N ha^{-1}, respectively. At 150 kg N ha^{-1}, orthogonal contrast showed that NBC was significantly ($p = 0.0259$) lower than NF by 31%. The soil ammonium content was higher under NBC compared to NF by 8 and 9% at 50 and 100 kg N ha^{-1}, respectively while a decrease under NBC by 3% was observed at 150 kg N ha^{-1} compared to NF. No trend for increase in both nitrate (Figure 1.6) and ammonium (Figure 1.7) with fertilizer rate was seen. The highest soil nitrate (6.4 mg kg^{-1}) was observed under NF at 150 kg N ha^{-1}, and the highest ammonium (21.2 mg kg^{-1}) was seen under NBC at 100 kg N ha^{-1}. The lowest nitrate (3.8 mg kg^{-1}) was observed at 10 t ha^{-1} biochar with no N applied and the lowest ammonium (17.6 mg kg^{-1}) was observed at the check plot.

In 2019, analysis of variance showed significant differences in both soil nitrate ($p < .0001$) and ammonium content ($p = 0.0009$) between treatments (Table 1.9). However, contrasts between NBC and NF did not show significant difference in both soil nitrate and ammonium. Soil nitrate was lower under NBC than observed under NF by 5, 9, and 5% at 50, 100, and 150 kg N ha^{-1}, respectively. The soil ammonium content was barely higher (≤ 1%) under NBC compared to NF at 50 and 100 kg N ha^{-1} while a decrease under NBC by 13% was observed at 150 kg N ha^{-1} compared to NF. The highest soil nitrate (5.9 mg kg^{-1}) and ammonium (5.5 mg kg^{-1}) were both observed under NF at 150 kg N ha^{-1} while the lowest nitrate (4.05 mg kg^{-1}) and ammonium (3.9 mg kg^{-1}) were both observed with 5 t ha^{-1} of biochar with no N applied. A trend for increase in both nitrate (Figure 1.6) and ammonium (Figure 1.7) with fertilizer rate was evident.

At LCB, the 2018 analysis of variance results showed an overall significant differences in soil nitrate ($p < .0001$) and ammonium ($p = 0.016$) between treatments (Table 1.10). For each fertilizer rate, contrasts between NBC and NF did not show significant difference in soil nitrate at 50 kg N ha^{-1} ($p = 0.1702$). However, significant differences were seen at 100 kg N ha^{-1} ($p = 0.0003$) and 150 kg N ha^{-1} ($p = <.0001$). Similar to nitrate, contrasts did not show significant difference in soil ammonium at 50 kg N ha^{-1} ($p = 0.3546$) while significant differences were seen at 100 kg N ha^{-1} ($p = 0.026$) and 150 kg N ha^{-1} ($p = 0.0182$). Nitrate under NBC was higher than observed under NF by 11, 29, and 40% at 50, 100, and 150 kg N ha^{-1}, respectively and ammonium was higher under NBC than NF by 6, 14, and 14% at 50, 100, and 150 kg N ha^{-1}, respectively. The highest nitrate (3.9 mg kg^{-1}) was seen under NBC at 100 kg N ha^{-1} while that for ammonium (31 mg kg^{-1}) was observed at 150 kg N ha^{-1} under NBC. The lowest soil nitrate (2.0 mg kg^{-1}) was observed at 150 kg N ha^{-1} under NF while lowest soil ammonium (23 mg kg^{-1}) was observed at 10 t ha^{-1} of biochar with no N fertilizer applied.

In 2019, results for the analysis of variance were similar to that of 2018 where significant differences in nitrate ($p = 0.001$) and ammonium ($p < .0001$) were observed between treatments (Table 1.11). Contrasts between NBC and NF did not show significant difference in nitrate at 50 kg N ha^{-1} ($p = 0.3134$) and 100 kg N ha^{-1} ($p = 0.0891$), while significant differences was observed at 150 kg N ha^{-1} ($p = 0.02$). Contrasts did not show significant difference in soil ammonium at 50 kg N ha^{-1} ($p = 0.8881$) and 100 kg N ha^{-1} ($p = 0.1078$) while significant difference was seen at 150 kg N ha^{-1} ($p = 0.0026$). The observed differences showed higher nitrate under NBC than under NF by 16, 23, and 27% at 50, 100, and 150 kg N ha^{-1}, respectively. Soil ammonium were higher under NBC than NF by 1, 8, and 15% at 50, 100, and 150 kg N ha^{-1}, respectively. The highest soil nitrate (7.0 mg kg^{-1}) and ammonium (5.2 mg kg^{-1}) were observed under NBC at 150 kg N ha^{-1} while the lowest soil nitrate (3.7 mg kg^{-1}) and ammonium (4.1 mg kg^{-1}) were both observed at the check plot. A general trend of increase in nitrate (Figure 1.6) and ammonium (Figure 1.7) content with increase in fertilizer rate were seen under both NBC and NF.

1.4.7 Cation Exchange Capacity

At Efaw, the analysis of variance for 2018 experiment did not show any significant difference ($p = 0.7552$) in cation exchange capacity (CEC) between treatments (Table 1.12). Contrast for the average between NBC and NF was not significantly different ($p = 0.1127$). Although contrasts between NBC and NF at each fertilizer rate were also not significant, CEC was higher under NBC than observed under NF by 6, 2, and 7% at 50, 100, and 150 kg N ha^{-1}, respectively. No trend for increase in CEC was observed under both NBC and NF (Figure 1.8). The highest CEC (11.5 meq/100g soil) was observed under NBC at 100 and 150 kg N ha^{-1} while the lowest (10.3 meq/100g soil) was obtained at 50 kg N ha^{-1} under NF.

In 2019, similar observation was made where no overall significant difference ($p = 0.3372$) in CEC was seen between treatments (Table 1.13). At each fertilizer rate, slight advantage of NBC over NF were observed. These correspond to 2, 1, and 8% at 50, 100, and 150 kg N ha^{-1}, respectively. Contrast for the average between NBC and NF was not significantly different ($p = 0.2299$). No trend of increase in CEC with increase in fertilizer rate was seen under both NBC and NF (Figure 1.8). The highest CEC (12.4 meq/100g soil) was observed under NBC at 100 kg N ha^{-1} while the lowest (11.0 meq/100g soil) was obtained at 15 t ha^{-1} of biochar with no N fertilizer. Overall, the CEC in 2019 was higher than observed in 2018.

At LCB, analysis of variance for 2018 experiment did not show overall significant differences ($p = 0.7021$) in CEC between treatments (Table 1.14). However, contrast for the average between NBC and NF was significantly different ($p = 0.0132$). For each fertilizer rate, contrasts between NBC and NF did not show significant difference at 50 kg N ha^{-1} ($p = 0.7253$). However, significant differences were seen at 100 kg N ha^{-1} ($p = 0.0317$) and 150 kg N ha^{-1} (p

= 0.0446). The CEC under NBC was higher than observed under NF by 4, 24, and 23% at 50, 100, and 150 kg N ha^{-1}, respectively. There was a trend of increase in CEC with fertilizer rate under NBC but not under NF (Figure 1.8). The highest CEC (8.2 meq/100g soil) was observed at 150 kg N ha^{-1} under NBC while the lowest (6.2 meq/100g soil) was observed at 100 kg N ha^{-1} under NF.

In 2019, overall analysis of variance did not show significant differences (p = 0.5131) in CEC between treatments similar to observations in 2018 (Table 1.15). However, contrast for the average between NBC and NF was significantly different (p = 0.0091). Contrasts did not show significant difference at 50 kg N ha^{-1} (p = 0.6641), while significant differences were observed at 100 kg N ha^{-1} (p = 0.0372) and 150 kg N ha^{-1} (p = 0.0237). The observed differences showed higher CEC under NBC than under NF by 4, 20, and 22% at 50, 100, and 150 kg N ha^{-1}, respectively. A trend for increase in CEC with increase in fertilizer rate was observed under NBC but not under NF (Figure 1.8). The highest CEC (10.2 meq/100g soil) was observed under NBC at 100 and 150 kg N ha^{-1} while the lowest (7.9 meq/100g soil) was seen at 100 and 150 kg N ha^{-1} under NF. Generally, there appeared to be no increase in CEC in 2019 compared to 2018.

1.4.8 Soil pH

At Efaw, the analysis of variance for the 2018 experiment showed an overall significant difference in pH (p = 0.0063) between treatments (Table 1.12). At each rate, contrasts between NBC and NF did not show significant differences at 50 kg N ha^{-1} (p = 0.329) and 100 kg N ha^{-}

^{1} (p = 0.2756). However, significant difference was seen at 150 kg N ha^{-1} (p = 0.0005). Contrast for the average between NBC and NF was also significantly different (p = 0.002). Soil pH was higher under NBC compared to NF by 2, 2, and 8% at 50, 100, and 150 kg N ha^{-1}, respectively. A trend for increase in pH with fertilizer rate was evident under NBC but not NF (Figure 1.9). The highest pH (6.1) was observed under NBC at 150 kg N ha^{-1} while the lowest (5.6) was observed under NF at 150 kg N ha^{-1}.

In 2019, the overall analysis of variance did not show significant difference (p = 0.0641) in pH between treatments (Table 1.13). However, contrast for the average between NBC and NF was significantly different (p = 0.0078). At each rate, contrasts between NBC and NF did not show significant differences at 50 kg N ha^{-1} (p = 0.5134) and 100 kg N ha^{-1} (p = 0.0768) while significant differences was seen at 150 kg N ha^{-1} (p = 0.0129). Soil pH was higher under NBC compared to NF by 1, 4, and 6% at 50, 100, and 150 kg N ha^{-1}, respectively. A trend for increase in pH with fertilizer rate was evident under NBC but while a decrease was seen under NF (Figure 1.9). The highest pH (6.0) was observed under NBC at 100 kg N ha^{-1} while the lowest (5.6) was observed under NF at 150 kg N ha^{-1}. Soil pH appeared to be lower in 2019 than compared to 2018.

At LCB, analysis of variance results did not show significant differences in soil pH (p = 0.0761) between treatments for the 2018 experiment (Table 1.14). For each fertilizer rate, contrasts between NBC and NF did not show significant difference in soil pH at 50 kg N ha^{-1} (p = 0.0842) and 100 kg N ha^{-1} (p = 0.765). However, significant difference was observed at 150 kg N ha^{-1} (p = 0.0003). Soil pH under NBC was higher than that observed under NF by 3, 1, and 7% at 50, 100, and 150 kg N ha^{-1}, respectively. The highest pH (6.2) was seen under NBC at 150 kg

N ha^{-1} while the lowest soil pH (5.7) was observed at 150 kg N ha^{-1} under NF. A trend for increase in pH with fertilizer rate was seen under NBC but not under NF (Figure 1.9).

In 2019, the overall analysis of variance showed significant difference (p = 0.0498) in pH between treatments (Table 1.15). Contrasts for the average between NBC and NF was also significantly different (p = 0.0035). At each rate, contrasts between NBC and NF did not show significant difference at 50 kg N ha^{-1} (p = 0.3332) while significant differences were seen at 100 kg N ha^{-1} (p = 0.0383) and 150 kg N ha^{-1} (p = 0.0122). Soil pH was higher under NBC compared to NF by 2, 3, and 4% at 50, 100, and 150 kg N ha^{-1}, respectively. A trend for increase in pH with fertilizer rate was evident under NBC but while a decrease was seen NF (Figure 1.9). The highest pH (6.0) was observed under NBC at 150 kg N ha^{-1} while the lowest (5.7) was observed under NF at 150 kg N ha^{-1}. Just like at Efaw, Soil pH at this location appeared to be lower in 2019 than compared to 2018.

1.4.9 Soil Electrical Conductivity

At Efaw, analysis of variance did not show any significant difference (p = 0.6668) in soil electrical conductivity (EC) between treatments in 2018 (Table 1.12). Contrasts could not reveal any significant difference between NBC and NF. Soil EC was barely higher under NBC than observed under NF by 2, 1, and 2% at 50, 100, and 150 kg N ha^{-1}, respectively. A trend for increase in EC with fertilizer rate was observed (Figure 1.10). The highest soil EC (224 µS/cm) was observed under NBC at 150 kg N ha^{-1} while the lowest (184 µS/cm) was observed at the check plot.

In 2019, the analysis of variance did not reveal an overall significance difference (p = 0.1856) in EC between treatments (Table 1.13). Contrasts did not show significance difference at all fertilizer rates. However, soil EC was lower under NBC than NF by 5, 2, and 25% at 50, 100, and 150 kg N ha^{-1}, respectively. The EC appeared to increase under NBC with increase with fertilizer rate while a decrease under NF was observed as fertilizer rate increased (Figure 1.10). The highest EC (126 µS/cm) was observed under NF at 100 kg N ha^{-1} while the lowest (83 µS/cm) was observed under NBC at 150 kg N ha^{-1}. Generally, soil EC in 2019 was lower than observed in 2018 at this location.

At LCB, analysis of variance results did not show any significant difference (p = 0.9552) in soil EC between treatments for the 2018 experiment (Table 1.14). Contrasts could not reveal any significant difference between NBC and NF. No difference was also observed using contrasts for the average EC between NBC and NF (p = 0.4755). Soil EC was higher under NBC than NF by 13 and 3% at 100 and 150 kg N ha^{-1}, respectively. A trend for decrease in EC with fertilizer rate was seen (Figure 1.10). The highest soil EC (197 µS/cm) was observed under NBC at 100 kg N ha^{-1} while the lowest (160 µS/cm) was observed under NF at 150 kg N ha^{-1}.

The results for the 2019 analysis of variance mirrored the observation in 2018 with no overall significant difference in soil EC between treatments (Table 1.15). No significant difference could be established using contrasts at each fertilizer rate. However, soil EC was observed to be higher under NBC than NF by 3, 9, and 11%, respectively. Under both NBC and NF, soil EC appeared to be increasing with increase in fertilizer rate (Figure 1.10). The highest soil EC (129 µS/cm) was observed at 5 t ha^{-1} of biochar with no fertilizer N applied while the lowest

(105 µS/cm) was observed under NF at 50 kg N ha^{-1}. Similar to the observation at Efaw, soil EC at this location was lower in the second year (2019) compared to the first year (2018).

1.5 DISCUSSION

1.5.1 Maize Grain Yield

The results from this study demonstrate the significant effect of applying a combination of biochar and inorganic nitrogen fertilizer on maize grain yield. However, the yield advantage consequential to the addition of biochar was not consistent across experimental locations. Several reports have documented positive and negative effects of biochar addition on maize grain yield (Gaskin et al., 2010; Major et al., 2010; Uzoma et al., 2011; Agegnehu et al., 2016). The disparities in results of maize grain yield response to biochar addition are attributed to different application rates, soil characteristics, biochar feedstock, and process parameters. For instance, in a greenhouse study, Uzoma et al. (2011) observed up to 150% increase in maize grain yield with 15 t ha^{-1} of cow-manure biochar. Averaged over sites and years, biochar addition in this study led to 9.8% increase in maize grain yield. Grain yield advantage under biochar amendment was seen with 10 and 15 t ha^{-1} of biochar in combination with 100 and 150 kg N ha^{-1}, respectively and was more pronounced in a comparatively low-yielding environment (LCB) dominated by sand. This was probably due to improvement in soil chemical properties. Application of biochar evidently increased soil organic carbon and cation exchange capacity that eventually contribute to plant nutrient retention. Both soil nitrate and soil ammonium were significantly enhanced at the site with significant maize grain yield response to biochar application. This is similar to a report by Agegnehu et al. (2016) which concluded that the increase in maize grain yield following biochar application was due to improvement in soil nutrient and organic carbon content. The researchers observed that maize grain yield was significantly correlated with soil nutrients. In the same light, Cornelissen et al. (2013) found that the base saturation increased by over 50% as a result of the addition of biochar and that impacted maize grain yield. Furthermore, observations by Major et al. (2010), who documented 77-320% more available Ca and Mg in the biochar-amended soil, support that increased maize grain yield is due to better nutrient uptake. Therefore, this study agrees with the above findings that associate maize grain yield increases from biochar addition with improved CEC, soil organic carbon and availability of inorganic nutrients. In addition to enhancing plant nutrients, some authors attribute the increase in crop yield from biochar addition to its ability to raise soil pH which has an indirect effect on crop nutrient availability (Lehmann et al., 2003; Yamato et al., 2006; Rondon et al., 2007). Such indirect increases in plant nutrients are related to the reduction in toxic Al^{3+} availability. Although no evidence is presented here to demonstrate detrimental effect of low pH on maize grain yield in the study site, biochar significantly increased pH by nearly 0.5 units. However, it is considered unlikely that the observed increase in yield was solely due to an increase in soil pH following biochar amendment. Besides, similar increases in pH were observed at the site that did not show significant response in maize yield to biochar addition.

1.5.2 Grain Nitrogen Uptake

Maize grain N uptake results from this study were significantly increased by biochar addition. Like observed with grain yield, these increases were not consistent across experimental sites. Averaged over sites and years, biochar amendments resulted to a 10.3% increase in grain N uptake. This is similar to reports by several authors that documented positive impact of biochar application on grain N uptake (Laird et al., 2010; Rajkovich et al., 2012; Huang et al., 2014;

Syuhada et al., 2016). The improved grain N uptake in this study could have been a result of biochar on the retention of both soil and applied N. Postharvest soil samples indicated significant levels of soil nitrate and ammonium under biochar treatment. Although not significant, biochar soil amendment also resulted to increased total soil N content. In addition to increased N retention in the soil, Zheng et al. (2013) added that biochar soil amendment can improve N bioavailability within the soil system. Huang et al. (2014) reported that biochar soil amendment resulted in a 25% increase in fertilizer N uptake. The authors measured fertilizer loss and established that biochar addition reduced fertilizer loss by 9.5%. Using just 2.6 t ha^{-1} of biochar at 300°C, Rajkovich et al. (2012) reported maize N uptake of 15% under biochar treatment compared to the fully fertilized control. The authors observed higher N uptake (15%) with just 2.6 t ha^{-1} of biochar than in the current (10%) probably because their study was conducted in a controlled environment. Therefore, the significant impact of the addition of biochar on grain N uptake in this study is attributed to improvement in N retention within the soil system similar to findings by other authors. Generally, grain N uptake in 2019 was lower than observed in 2018 and this is probably attributed to the water stress during the vegetative stage with up to 430 mm of rainfall in May.

1.5.3 Grain Nitrogen Use efficiency

The positive influence of NUE following biochar soil amendment was not consistent across experimental locations like the observation for grain yield and N uptake. Averaged across sites and years, applying biochar in combination with inorganic N improved NUE by 13.5%. This positive influence of biochar soil amendment on NUE is consistent with reports from several authors (Yao et al., 2012; Zheng et al., 2013; Mandal et al., 2016; de Sousa Lima et al., 2018). The premise that increased N retention and decreased N loss with biochar soil amendment enhance crop N uptake, NUE would be expected to improve under such condition. Zheng et al. (2013) offered a similar interpretation that increased NUE under biochar soil amendment is credited to the reduction in N leaching and increased N retention. Furthermore, linking improved crop N uptake to increased N bioavailability, as asserted by Zheng et al. (2013) suggests adequate justification for improved NUE under biochar soil amendment. Yao et al. (2012) expounded that increased retention of N is attributed to the high sorption capacity of biochar. This offers good agronomic and environmental benefits such as reduced demand of fertilizer for maize growth. Therefore, evidence from the study to support improvement in NUE under biochar soil amendment is likened to those in the scientific literature.

1.5.4 Total Soil Nitrogen

Total soil nitrogen (TSN) was not significantly improved following biochar soil amendment. Although not significant, an overall observed increment in TSN under biochar soil amendment was 3.7%. This finding is similar to observation by Agegnehu et al. (2016), using waste willow wood (*Salix spp*) as biochar feedstock. The authors did not see significant difference between TSN of N fertilizer treatment and a combination of biochar with inorganic fertilizer N. The non-significant response of TSN to biochar addition in the above scenarios is probably attributed to limited N in biochar from woody sources, and that was insufficient to support TSN accretion within experimental periods and rates used in these studies. Total soil N is a quantity that builds up in soil over a period of time. To illustrate this viewpoint, Omara et al.

(2019b) observed a significant trend in buildup of TSN in a long term experiment where N fertilizer was applied on a yearly basis. Therefore, the element of time and rate of application, beside biochar N content, is paramount in explaining the behavior of TSN following biochar soil amendment. Contrary to these findings, Uzoma et al. (2011) observed significant increase in TSN with biochar soil amendment using dry cow manure as a source of biochar feedstock at comparable rate of application (15 t ha^{-1}). Using dry cow manure biochar could have resulted to the significant difference in TSN buildup as compared to biochar from woody sources within the rates used in the current study.

1.5.5 Soil Organic Carbon

Soil organic carbon (SOC) was significantly increased with biochar application. Results averaged across experimental sites and years indicate a 19.3% increase in SOC under biochar soil amendment. The significant impact of biochar on SOC have been well documented (Laird et al., 2010; Uzoma et al., 2011; Agegnehu et al., 2016). For instance, Liu et al. (2016) observed as high as 40% increase in SOC under biochar treatment. At just 8 t ha^{-1} of biochar derived from wheat straw, Zhang et al. (2017) observed 34 - 80% increase in SOC. Soil organic carbon increased at all biochar rates used in the current study. The apparent explanation for the increased SOC under biochar soil amendment is the fact that biochar contains high proportion of carbon by weight compared to other elements. In this study, the pine wood biochar used contained 87% organic carbon by composition. Indeed application of material with such high organic carbon content will certainly increase the SOC of the amended soil and that can persist for a long period of time. In the latter case, some researchers have presented evidence on the stability of biochar in the soil and suggested its application as a strategy for soil carbon sequestration (Lorenz and Lal, 2014; Wang, et al., 2016). This implies that application of biochar in agricultural soil are important both from the agronomic and environmental perspectives.

1.5.6 Inorganic Nitrogen

The soil nitrate and ammonium content were both significantly improved with biochar amendment. Nitrate across site and years increased by 8.8% while ammonium N increased by 4.8%. Similar observations were made by Yao et al. (2012) who reported 34% and 35% retention in nitrate and ammonium, respectively following biochar soil amendment. In addition, Singh et al. (2010) observed up to 94% retention in soil ammonium under biochar amendment. It is important to note that most of the studies reporting high proportion of retained inorganic N were soil column leaching experiment compared to the current study that was conducted under field conditions. In an attempt to offer explanation, Zheng et al. (2013) indicated the increase in soil water holding capacity, ammonium adsorption, and enhanced N immobilization as the main reasons for the increase in retention of inorganic N following biochar soil amendment. Indeed increasing the capacity of the soil to hold water increases chances of retaining both nitrate and ammonium within soil solution. The enhanced adsorption of ammonium has been attributed to increase in cation exchange capacity (CEC) as a result of the oxidation of aromatic carbon and formation of carboxyl groups (Liang et al., 2006). Lawrinenko and Laird (2015) reported increase in the anion exchange capacity (AEC) of biochar which reduces leaching of anionic nutrients. They explained that the increased AEC is due to the formation of oxonium functional group (-O^+) and non-specific proton adsorption by condensed aromatic rings.

1.5.7 Cation Exchange Capacity

The cation exchange capacity (CEC) of soil in the current study was higher under biochar treatment by 10.3%. Although positive impact of biochar was present, this observation was not consistent across experimental locations. Related studies on biochar soil amendment reported similar findings (Glaser et al, 2002; Liang et al., 2006; Jiang et al., 2012; Agegnehu et al., 2016). Xu et al. (2012) studied the effect of biochar from different sources of feedstock on many soil types. They observed that CEC of biochar-amended soil increased between 19 and 83%. Their result varied depending on soil type and type of feedstock used in making biochar. At application rates 52, 104, and 156 t ha^{-1}, Chintala et al. (2014) observed that Corn stover biochar increased CEC by 87%, 120%, and 142% and switchgrass biochar by 58%, 89%, and 122%. Cornelissen et al. (2013) observed over 60% increase in CEC under biochar treatment using maize cob and wood feedstock. In this study, CEC significantly increased in location with sandy loam soil compared to location with silty clay loam soil. The increase in CEC following biochar soil treatment have be attributed to the oxidation of aromatic carbon and formation of carboxyl groups (Liang et al., 2006). This is known to contribute to increase in adsorption capacity of biochar as a result of increased negative charges on biochar surfaces. In addition, Lawrinenko and Laird (2015) noted that hydroxyl and carbonyl functional groups are also generally believed to contribute to biochar CEC because they may carry negative charges and serve as Lewis bases for the sorption of cations. Thus increased CEC under biochar treatment leads to enhanced adsorption of cations relative to the untreated soil.

1.5.8 Soil pH

The soil pH in this study was significantly increased with the application of inorganic N combination with biochar compared to fertilizer N alone. Across experimental sites, years and N rates, pH was increased by 3.5%, approximately 0.2 units. However, this was seen mainly with 15 t ha^{-1} of biochar application rate. Studies that report the alleviation of acidic pH via biochar soil amendment indicate that the effectiveness of biochar is dependent on feedstock type and process parameters such as pyrolysis temperature and residence time. For instance, Chintala et al. (2014) observed relatively larger increases in pH of an acidic soil amended with switchgrass biochar compared to maize stover biochar. Yuan and Xu (2011) reported that biochar from the legume feedstock led to a greater increase in soil pH compared with that from non-legume feedstocks. In the current study, small increase in pH was observed consistent with the pH of the pinewood biochar (7.4) used. The mechanism for increase soil pH following biochar soil amendment have been previously suggested. Chintala et al. (2014) explained that biochar has higher proton consumption capacity that cause higher increase in soil pH and decrease in exchangeable acidity relative to non-amended soils. This is due to increase in adsorption capacity of biochar as a result of increased negative charges on biochar surfaces. In the current study, CEC was evidently improved with biochar addition relative to non-amended treatment. In addition to increase in soil pH, Chan et al. (2008) noted that biochar releases base cations into low pH soils that potentially replace exchangeable acidity on the soil surface during the exchange reactions. Therefore, this study indicate that using pinewood biochar pyrolyzed at 500 ^{o}C at application rate below 15 t ha^{-1} may not cause a marked change in soil pH

1.5.9 Soil Electrical Conductivity

Application of biochar did not significantly increase soil electrical conductivity (EC) in the current study. This is in contrast with a report by Burrell et al. (2016) who observed increases in soil EC using wood biochar. This could be due to the high rate of biochar (39 t ha^{-1}) applied compared to a maximum of 15 t ha^{-1} used in this study. Most research findings agree that most plants are sensitive to soil salinity with EC levels of or greater than 4 dS/m (Silvertooth, 2001; Blanco et al., 2008; Panta et al., 2014). However, maize specifically has lower tolerance level and grain yield begins to reduce as EC is increased above 2 dS/m (Hassan et al., 1970; Blanco et al., 2008). Soil salinity above the plant tolerance level is known to impose ion toxicity, osmotic stress, nutrient (N, Ca, K, P, Fe, Zn) deficiency and oxidative stress on plants, and thus limits water uptake from soil (Shrivastava and Kumar, 2015). The soil EC in this study was observed to be lower in the second year of the experiment compared to the first year at both experimental locations. This is probably due to the timing of soil sample collections. In 2019, soil samples were collected immediately following a high precipitation levels in August with over 200 mm of rainfall. This could have had negative effect on the levels of soluble salts soil. Soil ammonium for instance was evidently low in 2019 compared to 2018. The EC in the present study was recorded in micro Siemens per centimeter (µS/cm) as per the instrument used (Seven Excellence dual pH and EC meter, Mettler Toledo). Using a conversion factor of 100, and with the average EC of less than 200 µS/cm (2.0 dS/m), the EC reported in this study did not surpass the limit of 4 dS/m to be classified as a saline soil at the maximum biochar application rate of 15 t ha^{-1}. This implies that farmers intending to use pine wood biochar pyrolyzed at 500 ^{o}C should not worry about raising soluble salt contents to levels that can adversely affect crop growth.

1.6 SUMMARY AND CONCLUSION

The main objective of this study was to establish possible synergies in a biochar-N fertilizer complex in optimizing NUE, maize (*Zea mays* L.) grain yield, and improving soil chemical properties. Results showed an overall positive effect of applying a combination of biochar and inorganic fertilizer N (NBC) on grain yield, NUE, and soil properties relative to inorganic N fertilizer (NF). However, the positive observation was not consistent across experimental locations. Additionally, positive results were observed at biochar application rate ≥ 10 t ha^{-1}. Results at Lake Carl Blackwell (LCB) averaged over years indicate that grain yield, N uptake, and NUE under NBC was higher by 25, 28, and 46%, respectively compared to NF. Total soil N, SOC, $NO_{3,}$ and NH_4 were higher under NBC by 5, 18, 24, and 10%, respectively compared to NF. Cation exchange capacity, pH and soil EC was higher under NBC by 16, 3, and 7%, respectively than observed under NF. At Efaw, grain yield, N uptake, and NUE decreased under NBC by 5%, 7%, and 19%, respectively compared to NF. Total soil N, and SOC were higher under NBC compared to NF by 3 and 21%, respectively, no percentage difference between NBC and NF was observed for soil NH_4 while NO_3 was lower under NBC by 7% compared to NF. Cation exchange capacity and pH was higher under NBC by 4 and 4%, respectively while soil EC was lower by 11% than observed under NF. Whereas results were inconsistent across experimental locations, the significant response to NBC was evident at LCB site with fine sandy loam soil but not at Efaw with silty clay loam. In addition to other salient limitations of using biochar to improve crop productivity, which were outside the context this study, maize producers cultivating silty clay loam soil may not realize any benefits of using biochar as soil amendment in combination with inorganic N at rates ≤ 15 t B ha^{-1}.

Nonetheless, application of biochar in combination with inorganic N could improve soil properties, NUE and grain yield of maize cultivated on coarse textured sandy soils with poor chemical properties compared to soils with fine texture. This implies that producers intending to use biochar to improve crop productivity require soil analysis to determine potential crop response to biochar soil amendment.

CHAPTER II

INFLUENCE OF NO-TILLAGE ON SOIL PROPERTIES, WINTER WHEAT (*Triticum aestivum* L.) GRAIN YIELD AND NITROGEN USE EFFICIENCY

Abstract

No-tillage (NT) can improve soil properties and crop yield. However, there are contrasting reports on its benefits compared to conventional tillage (CT). Dataset (2003-2018) from long-term continuous winter wheat (*Triticum aestivum* L.) experiments 222 (E222) at Stillwater and 502 (E502) at Lahoma in Oklahoma, established in 1969 & 1970, respectively was used. Both experiments were managed under CT until 2010 and changed to NT in 2011. In each tillage system, treatments included nitrogen (N) rates at E222 (0, 45, 90, and 135 kg N ha^{-1}) and E502 (0, 22.5, 45, 67, 90, and 112 kg N ha^{-1}). The objective was to determine the change in wheat grain yield, grain N uptake, N use efficiency (NUE), soil organic carbon (SOC) and total soil nitrogen (TSN) associated with the change to NT. Grain yield was recorded and post-harvest soil samples taken from 0-15 cm were analyzed for TSN and SOC. Average TSN and SOC under NT were significantly above those under CT at both locations while grain yield differences were inconsistent. Under both tillage systems, grain yield, TSN and SOC increased with N rates. At E222, grain yield, TSN, SOC, and NUE under NT were 23%, 17%, 29%, and 39% respectively more than recorded under CT. At E502, grain yield and grain N uptake were lower under NT than CT by 14% and 4%, respectively while TSN, SOC, and NUE were higher by 11%, 13%, and 13%, respectively. Averaged over experimental locations, wheat grain yield, TSN, SOC, grain N uptake and NUE were 5%, 14%, 21%, 4.5%, and 23%, respectively higher under NT compared to CT. Therefore, NT positively influenced grain yield, TSN, and SOC and is likely a sustainable long-term strategy for improving soil quality and crop productivity in a continuous mono-cropping system.

2.1 INTRODUCTION

2.1.1 Background

The depletion of soil resources as a result of poor production practices and the subsequent decline in crop yields has resulted in a search for sustainable approaches in crop production. No-tillage (NT) production systems, synonymous with zero tillage (ZT) or conservation tillage agriculture (CA) and sometimes minimum tillage (MT), is one of these sustainable crop production approaches sought by scientists around the world (Farooq and Siddique, 2015). This approach has gained attention in the past years and there is a growing trend for adoption by crop producers globally. Derpsch et al. (2010) reported a world adoption rate of 6 M ha per year between 1999 and 2009 where field crop area grew to 111 M ha. By 2013, the land area under NT increased to 157 M ha, equivalent to approximately 11% of the total field production area (Kassam et al., 2015). In 2016, the total global land area increased to 180 M ha corresponding to approximately 12.5% (Kassam et al., 2019). The global increase in the rate of adoption and expansion of land area under NT is a result of numerous benefits associated with this farming practice. Generally, the benefits of NT originate from the three main principles: reduced soil disturbance, improved soil cover from crop residues, and increased species diversity through crop rotation (Hobbs et al., 2007; Tarolli et al., 2019). Therefore, the improvement in soil chemical and physical properties such as soil organic carbon (SOC), total porosity and water holding capacity, among others under NT follow these principles (Pareja-Sánchez et al., 2017).

Soil organic carbon and total soil nitrogen (TSN) are indicators of soil quality and provide structural stability to the soil matrix. However, there is a significant reduction in the rate of buildup and possible depletion under CT system (Omara et al., 2019a). Halvorson et al. (2002) reported a decreasing pattern in SOC as NT< MT< CT where the most SOC was retained under NT. Practices that limit soil disturbance and encourage residue retention help in the restoration of these important soil quality parameters. Farooq and Siddique (2015) asserted that NT increases SOC content by adding fresh plant residues that protect the enriched topsoil from rapid chemical and physical weathering. On sloping terrain, the implementation of NT leads to SOC accumulation by reducing the rate of severe soil erosion (Bhattacharyya et al., 2008). The retention of residue on the surface of the soil through NT also helps in moderating temperature and moisture fluctuations. These abiotic factors are, in turn, responsible for controlling the rate of accumulation of SOC.

In addition to the improvement of soil structural stability, NT plays an important role in the reduction of production costs through reduced labor requirements for land tilling. It is, however, important to note that this approach requires a particular type of equipment for seed drilling (Hobbs et al., 2007). This could be a setback for farmers in developing countries that are yet to adopt the use of such implements. Additionally, in developed countries, the initial cost of switching implements or re-configuring the existing equipment to accommodate NT practice is high, and this seems to be a reason why producers are sometimes reluctant to adopt the practice (D’Emden et al., 2008).

Other NT benefits relating to improvement in crop productivity may depend on the specific production environment. For instance, De Vita et al. (2007) reported that the contribution of NT to grain yield improvement may be realized in environments where precipitation is less than 300 mm per year. According to the authors, NT may not significantly produce higher grain yield compared to the CT system in areas with adequate precipitation. This is especially true if moisture conservation and improved water infiltration are important (Rao et al., 1998; Govaerts et al., 2007). Hansen et al. (2012) added that NT is a key management strategy with the apparent temporal and spatial climate variability. Furthermore, grain yield improvement depends on the length of production under NT practice (Gwenzi et al., 2009). Much as structural stability could be realized under NT within a short-term production period, grain yield benefits under NT are possible after long-term crop production cycles.

Some researchers report decreases in root growth and grain yield under NT for many reasons. Soil compaction, which decreases soil aeration and water infiltration can reduce crop yield under NT (Ferreras et al., 2000). The decrease in crop yield can also result from reduced N use efficiency of surface-applied urea due to volatilization losses (Rozas et al., 1999). The use of slow-release N fertilizers such as sulfur-coated urea and delayed urea application may improve the efficiency of fertilizer N under NT. Arvidsson et al. (2014) reported a 10% decline in crop yield under NT relative to CT system. This decrease in yield was attributed to poor crop establishment due to improper seedbed preparation that they referred to as “lack of seedbed”.

In addition to yield reduction, NT has also been scrutinized for the emergence of herbicide-resistant weeds as a result of over dependence on the use of chemicals (Duzy et al., 2016). The latter can increase the risk of sub-surface flow of chemicals that escalate the potential for environmental pollution. Therefore, the agronomic and environmental impact or the success of NT seems to be environment specific and the improvement in soil chemical and physical properties under NT translate to increases in crop yield after long-term implementation of this practice.

2.1.2 Rationale

Data used in this study were taken from two long-term experiments in Oklahoma. At the time of the establishment of these experiments, NT was not popular as research reports documenting its benefits were limited. Therefore, both experiments 222 and 502 were initiated under CT. Many research articles in the 1990s and early 2000 indicated the superiority of NT over CT in improving crop yield and soil properties. This prompted a widespread adoption by a significantly large number of farmers all over the United States, especially those in the Great Plains (Hansen et al., 2012). Consequently, the conversion of these long-term experiments from CT to NT took place in 2011 when CT was stopped in 2010 (Aula et al., 2016).

Generally, the effect of tillage practices including NT and CT on soil physical, chemical and biological properties have been previously investigated under various field settings and cropping systems. However, a comparison between NT and CT on winter wheat grain yield, SOC TSN and their impact on grain NUE have not been conclusively studied under a continuous winter wheat-summer fallow cropping system. Furthermore, the behavior of these soil quality parameters under NT and CT have been scarcely investigated under continuous winter wheat-summer fallow cropping system with varying levels of N fertilization from a long-term perspective. Many research reports have inconsistently indicated the benefits of NT practice on grain NUE compared with CT practice (Rao &

Dao, 1996; Rozas et al., 1999; Litcht & Kaisi, 2005; Liu et al., 2015). Comparing grain NUE of continuous winter wheat-summer fallow under NT and CT practice is important in establishing a practice that sustainably fits within this production system. Since grain NUE decreases with increasing N rate, the wide range in fertilizer rates used in this study could help establish NUE that predicts optimum wheat grain yield commensurate with maximum gross revenue.

2.1.3 Objectives and Hypotheses

The main objective of this study was to determine the change in soil chemical properties, grain yield and NUE associated with the conversion from CT to NT under continuous winter wheat-summer fallow cropping system.

2.1.4 Specific Objectives

1. To determine the effect of a change from conventional tillage (CT) to no-tillage (NT) on winter wheat grain yield.
2. To determine the effect of a change from CT to NT on total soil nitrogen (TSN) and soil organic carbon (SOC).
3. To determine the effect of a change from CT to NT on winter wheat grain N uptake and grain nitrogen use efficiency (NUE).

2.1.5 Research Hypotheses

1. No-tillage increases winter wheat grain yield compared to CT practice.
2. No-tillage increases TSN and SOC compared to CT practice.
3. No-tillage improves grain N uptake and NUE compared to CT practice.

2. 2 LITERATURE REVIEW

2.2.1 Definition and History of No-tillage

Phillips et al. (1980) defined NT as “one in which the crop is planted either entirely without tillage or with just sufficient tillage to allow placement and coverage of the seed with soil to allow it to germinate and emerge”. Zero tillage (ZT) is sometimes used synonymously with NT. Derpsch (1998) noted that NT is used mostly in North America while ZT is used commonly in the United Kingdom and Europe in general. The modification of the system has led to the coining of the term “conservation tillage” which includes NT, MT, direct drilling, and ridge tillage, among others (Baker et al., 2002) where the main aim is to maintain at least 30% of the crop residue on the soil surface. Generally, the practice of NT involves growing crops on a piece of land, either continuously or through rotation, without disturbing the soil through tillage.

No-tillage crop production has been used since ancient times when no implements were available to prepare the seedbed (Derpsch, 1998). Hobbs (2007) attributed the birth of NT agriculture in the US Great Plains as a response to the Dust Bowl in the 1930s that occurred due to excessive tillage and exposure of the soil surface to wind. During World War II, plant growth regulators were developed in the mid-1940s. In 1955, Paraquat was invented and commercially released by the Imperial Chemical Company in the early 1960s. The commercial release of herbicides therefore initiated the modern mechanized NT with the first few commercial farmers adopting the practice (Derpsch, 1998). In addition, the development of special NT equipment by equipment manufacturers further increased the spread of NT (Gebhardt et al., 1985; Schneider et al., 2012). This brief history is important in understanding and appreciating how perspectives on NT have changed over time before divulging into specific benefits that are discussed in the following section.

2.2.2 Overall Benefits of No-tillage

No-tillage is associated with numerous biophysical and socio-economic benefits relative to the CT practice. Research reports indicate benefits of NT to include, but are not limited to, reduced labor and input requirements, increase in the retention of organic matter which is an important indicator of soil health, improved water and nutrient use efficiency, reduction in the rate of soil erosion and improvement in many other soil chemical and microbiological properties. All these benefits, briefly discussed, directly or indirectly relate to improvement in crop yield under NT practice.

The first and most important benefit of NT to farmers is that it plays a vital role in the reduction of the cost of production. The practice reduces labor and input requirements for land tilling (Pittelkow et al., 2015). Although some reports indicate high initial cost from switching of equipment or reconfiguring the existing ones (D'Emden et al., 2008), this seems to be offset by the reduced labor and fuel requirement and appear economically important from a long-term perspective. Derpsch (1998) reported a reduction in the production cost of Soybean in the USA by $14.18 per acre and in Brazil by $11.50 per acre. In addition, the relative superiority in value of NT over CT could increase if beneficial environmental effects such as less erosion and pollution were taken into consideration in calculating total process cost (Tebrügge and Böhrnsen, 1997). Generally, cost savings from NT implementation is dependent on many other variables.

Secondly, the practice increases retention of organic matter on the surface soil profile. Because of its ability to retain organic matter, the system has been credited for sequestering carbon with subsequent reduction in the level of greenhouse gas emissions (Bayer et al., 2006). The increase in the retention of organic matter is always accompanied by cycling of certain nutrients. Depending on the nature of the organic matter, availability of nutrients such as N can increase with NT compared to CT practice under ambient environmental conditions. For instance, House et al. (1984) reported that NT recycle N by immobilization near the soil surface. The immobilized N can be made plant available through mineralization under favorable environmental conditions.

Furthermore, the practice improves water retention and infiltration into the soil. The enhancement of soil water status is due to reduction in the rate of evaporation. As reported by De Vita et al. (2007), the comparative advantage of NT to CT in reducing the rate of water evaporation is because of the crop residue that is left on the soil surface. Soil water conservation with NT is important in areas that receive comparatively limited annual precipitation. De Vita et al. (2007) observed that water use efficiency was significantly improved with NT relative to CT when annual precipitation was less than 300 mm. Accordingly, the practice is important for farmers producing crops under rain-fed conditions with limited irrigation capabilities.

The reduction in the rate, or elimination, of soil erosion is probably the most important function of the NT practice for land terrain with significant slope impact on soil quality and crop yield. Bayer et al. (2006) noted that adoption of practices such NT on soils prone to erosion is critical in minimizing loss of soil carbon stock. Crop residue left on the surface of the soil helps reduce the rate of soil runoff. Langdale et al. (1979) reported a reduction in erosion rate from 17.8% under CT to 9.7% under NT on land with an average slope of 3.4%. Seta et al (1993) reported that both runoff rate, runoff volume and total soil loss were significantly reduced with NT compared to CT on a silt loam soil. Basic et al. (2004) reported a reduction in the rate of erosion in maize and soybean experimental fields by 40% and 65%, respectively. Therefore, the contribution of NT as a management strategy in soil prone to erosion cannot be overlooked.

2.2.3 Soil Organic Carbon and Total Nitrogen under No-tillage

Soil organic carbon (SOC) is an important indicator of soil quality and provides structural stability to the soil matrix. The largest terrestrial pool of organic carbon is in the soil much as some agricultural activities such as burning, cultivation and deforestation among others contribute considerably to the atmospheric carbon pool (Lal & Kimble, 1997). Omara et al. (2019a) noted that CT practice significantly reduced the rate of buildup with possible depletion on a long-term perspective under such a practice. No-tillage is an important farming practice that is believed to increase the sequestration of carbon in the soil. Several studies have reported increased SOC with NT relative to CT practice (Havlin et al., 1990; Dolan et al., 2006; Blanco-Canqui & Lal, 2008; Lafond et al., 2011). These studies also generally agree that the rate of buildup of SOC under NT is only significant on the surface soil profile below 20-cm depth. The rate of accumulation would also depend on other factors such as N fertilizer application.

Considering all categories under the umbrella of conservation tillage, comparison across these categories indicate differences in the rate of carbon storage. For instance, Halvorson et al. (2002) reported a decreasing pattern in SOC as NT< MT< CT where the most SOC was retained under NT practice. Practices that limit soil disturbance and encourage residue retention help in the restoration of this important soil quality parameter. Farooq and Siddique (2015) asserted that NT increases SOC content by adding fresh plant residues that protect the enriched topsoil from rapid chemical and physical weathering. On sloping terrain, the implementation of NT practice leads to SOC accumulation by reducing the rate of severe soil erosion (Bhattacharyya et al., 2008). The retention of residue on the surface of the soil through NT also helps in moderating temperature and moisture fluctuations. These abiotic factors are in turn responsible for controlling the rate of accumulation of SOC.

In addition to SOC, TSN is another important parameter that is used to assess the quality of soil for crop production. Total soil N in the surface layers of most cultivated soils ranges between 0.6 g kg^{-1} and 5 g kg^{-1} and varies depending on the land use and management system although it could reach up to 25 g kg^{-1} in peat (Bremner & Mulvaney, 1982; Xu et al., 2013). Omara et al. (2019a) indicated that agriculture especially crop production plays a central role in its depletion. Poor crop production practices such as burning, continuous cultivation among others significantly reduces the level of TSN on the surface layer of the soil. No-tillage practice is known to increase TSN relative to CT practice as established by many research reports (Havlin et al., 1990; Mikha & Rice, 2004; Dolan et al., 2006; Malhi & Kutcher, 2007; Wang et al., 2008). Research conducted in Shanxi, on the Chinese Loess Plateau by Wang et al. (2008) showed 51% increase in TSN at 0-10 cm soil depth with NT relative to CT practice. The rate of buildup of TSN was highly dependent on fertilizer N application rate. As fertilizer N application rate increased, TSN level in the soil also increased.

The carbon to nitrogen ratio (C:N) is an important criterion in determining the quality of organic matter and the probable rate of N mineralization. High C:N ratio indicates high soil carbon content relative to N while the opposite is true. Since NT practice conserves carbon in the soil, it is believed generally that the C:N ratio will be high under NT relative to CT practice. Diekow et al. (2005) observed lower C:N ratio on the upper soil layer below 10-cm depth of bare soil compared to grassland and associated this to higher level of decomposition of organic matter. The authors also reported that N fertilization level did not change the qualitative parameter of C:N ratio. Leite et al. (2003) observed few differences between C:N ratio in all layers and system studied whereas larger ratio was under forest cover compared to NT. This was related to the residue input of plant material with higher lignin and cellulose content. The lower C:N ratio was due to the higher mineralization rate of N (Six et al., 2002).

2.2.4 Crop Grain Yield under No-tillage

The primary objective of embracing a NT practice by farmers is its ability to improve crop yield although researchers consider other soil health or environmental benefits. Crop yield advantage under NT is associated with the improvement in soil chemical and physical properties. In a global meta-analysis that included 678 peer-reviewed publications, Pittelkow et al. (2015) reported that crop yield benefits due to NT were realized mainly under rain-fed conditions in dry climates where yields were either equal to or higher than CT. De Vita et al. (2007) reported that the contribution of NT to grain yield improvement is possible in environments where precipitation is less than 300 mm per year. The authors indicated that NT may not significantly produce higher crop yield compared to the CT practice in areas with adequate precipitation. Although the effect of NT on crop yield are evident, it is dependent on other circumstances in the crop production environment.

Important to note is the duration of production under NT practice. Much as structural stability could be realized under NT within a short production period, grain yield benefits under NT are possible after comparatively long crop production cycles (Gwenzi et al., 2009). Yield benefits under NT are therefore additive and can only be significant on a long-term perspective. Also, the crop yield increases are due to improvement in soil properties. In most cases, positive changes in soil properties as a result of NT use are realized under long-term crop production cycle. For instance, improved crop yield as a result of improved soil organic matter is only possible when the practice leads to its buildup. The longer the practice, the more improvement in soil chemical and/or microbiological properties with subsequent positive impact on crop yield.

Some reports that indicate reduced crop yield under NT compared to CT highlight the unique difference in the crop production environment. In certain production environments, NT practice may boost the buildup of disease pathogens that later contribute to crop yield decline. Tiarks (1977) reported maize grain yield decline due to *Pythium graminicola* that causes dumping off due to root and/or seed rot. Generally, for NT to perform better than CT practice, there must be yield limiting factors such as land terrain that encourage soil erosion, low organic matter content, and limited soil water among others (Triplett & Dick, 2008). Consequently, in a production environment where crops can perform with no major limiting factors, grain yield differences between NT and CT may be insignificant.

2.2.5 Nitrogen Use Efficiency and No-tillage

Nitrogen use efficiency (NUE) has been a focus of many agronomic research for both economic and environmental reasons (Omara et al., 2019c). The use efficiency of fertilizer N is known to be influenced by many factors including the type of farming practices adopted. No tillage is believed to be one of the farming practices that have significant influence on the use efficiency of applied fertilizer N in comparison to CT practice. However, research reports on this subject are inconsistent with both positive and negative consequences of NT on grain NUE (Rao & Dao, 1996; Rozas et al., 1999; Litcht & Kaisi, 2005; Liu et al., 2015). These conflicting findings are due to differences in method of fertilizer application, type of crop and other environmental variables.

The low NUE associated with NT is mainly due to surface volatilization when N is applied as urea. Rozas et al. (1999) reported a decrease in crop yield as a result of reduced N use efficiency of surface-applied urea through volatilization losses. Volatilization of surface applied urea can sometimes be as high as 50% of the total applied (Sommer et al., 2004). While comparing volatilization losses between CT and NT, Bacon and Freney (1989) found that volatilization of surface applied urea under NT reached 24% but was negligible under CT practice. Rochette et al. (2009) explained that the high volatilization losses of urea are, in part, due to the presence of residue and associated high urease activity on the surface of NT field. In a maize trial consisting of 4-site years of data, Litcht and Kaisi (2005) did not observe any difference in N uptake and use efficiency in corn between CT and NT practice. In the latter study, authors did inject liquid fertilizer N. Therefore, volatilization losses of N were avoided since N losses are most common when urea is broadcast on the surface.

Nitrogen use efficiency under NT is improved as a result of the reduction of N fertilizer runoff. Nitrogen losses through fertilizer runoff from the total N applied were summarized by Raun and Johnson (1999) to be between 1 and 13%. Generally, the losses are lower under NT compared to CT. By reducing the rate of fertilizer runoff, NT significantly improves the use efficiency of the applied fertilizer N. Fertilizer loss due to volatilization when urea is applied to the surface without incorporation are generally greater with increasing temperature and soil pH. This implies that the surface mulch covering the soil coupled with the right method of N application can reduce volatilization losses by lowering soil pH (Billeaud & Zajicek, 1989). No-tillage practice improved winter wheat grain yield by 32% after banding 60 kg N ha^{-1} at 10 cm below the seed row compared to broadcast urea (Rao and Dao, 1996). Seed drilling should be accompanied with N banding in order to improve NUE under NT practice.

2.2.6 Adoption Rate of No-tillage

The commercial use of NT practice gained attention in the past years with a growing trend for global adoption. The world adoption rate was reported at 6 M ha per year between 1999 and 2009 where field crop area grew to 111 M ha (Derpsch et al., 2010). By 2013, the land area under NT increased to 157 M ha, equivalent to approximately 11% of the total field production area (Kassam et al., 2015). In 2016, the total global land area increased to 180 M ha, corresponding to approximately 12.5% (Kassam et al., 2019). The global increase in the rate of adoption and expansion of land area under NT follows the benefits that can be accrued from this farming practice and that has been well documented in the literature.

At individual country level, data obtained in 2016 indicate that the United States was the leading country in the world with the largest area of 43.2 M ha under NT (Kassam et al., 2019). This was followed by Brazil and Argentina with 32 and 31 M ha, respectively, under NT practice. Australia and Canada were the fourth and fifth world leading adopters of NT with 22.3 and 19.9 M ha, respectively (Kassam et al., 2019). Most of the countries least adopting NT practice are found in Africa, Asia and Europe. Reasons for low adoption rate in these countries/regions of the world are briefly discussed in the following section.

2.2.7 Reasons for Low Adoption

Despite a wealth of research reports documenting the benefits of NT, the adoption has been comparatively low in some countries and/or regions of the world. The adoption rate is slow in Europe, Africa and Asia compared to the Americas. There are a number of socio-economic and biophysical factors against NT system. One of the most important economic reasons is the initial cost of switching implements or re-configuring the existing equipment to accommodate NT farming practice. The initial cost is high and seems to be a major reason why producers are sometimes reluctant to take up the practice (D'Emden et al., 2008). In support of this notion, Basch et al. (2008) added that there are limited agricultural machinery manufacturers producing NT equipment in regions with low adoption rates compared to South and North America. With limited access to affordable NT equipment, the number of adopters will certainly be low.

In addition to inadequate NT machinery, Derpsch and Friedrich (2009) indicated that inadequate availability of suitable herbicide to facilitate weed management, especially in the developing world, is one of the most important barriers to successful adoption of NT practice. The successful implementation of a NT practice heavily requires the use of herbicides to help in weed management. If farmers do not have access to an effective means of weed control, mechanical or tillage measures of weed control will be used. Because of herbicide cost and recurrence of herbicide resistant weeds, some researchers report effectiveness of weed control with integrated weed management (IWM). For instance, Chikowo et al. (2009) noted that the use of IWM allows for long-term control of arable weeds and reduced reliance on herbicide use. Therefore, reports that recommend effective alternatives of weed control to farmers such as mechanical method or IWM reduce chances of adoption of NT practice that entirely rely on herbicide use.

Sometimes, mindset and knowledge on how the system operates act as important barriers to the adoption and implementation of the NT practice. This is true especially in areas where inadequate availability of resources limits the holistic and concerted efforts of researchers, scientists and extension workers to spread the use of NT practice. In a study reviewing the adoption of soil health practices including NT in the United States, Carlisle (2016) reported that farmers with more knowledge on the agronomic and environmental benefits were more likely to adopt compared to those with no or limited knowledge of such benefits. Therefore, it seems that overcoming the attitude and knowledge barrier through building social and technical knowledge networks can greatly influence the adoption of NT practice.

Another reason reported for low adoption of NT practice is soil compaction. This reduces aeration and water infiltration in the soil, subsequently affecting crop yield (Ferreras et al., 2000). Generally, NT practice results in poor crop establishment due to improper seedbed preparation from the compacted soil (Arvidsson et al., 2014). Because of the lack of permeable soil, there are high chances of loss of surface-applied urea through volatilization (Rozas et al., 1999). Although volatilization rate is increased by factors such as calcareous soil with a pH above 7, use of slow-release N fertilizer such as sulfur-coated urea and delayed urea application can optimize N use and increase crop grain yield under NT. As indicated by Billeaud and Zajicek (1989), the covering of the soil with surface mulch coupled with the right method of N application can reduce volatilization losses by lowering soil pH.

From an environmental perspective, NT has been strongly scrutinized for the emergence of herbicide-resistant weeds as a result of over dependence on the use of chemicals (Duzy et al., 2016). With pronounced use of herbicide, there can be increased risk of sub-surface flow with the potential for environmental pollution. This seems to be the main reason why environmental advocates who argue against the practice. In Europe, environmental lobbies have demanded the withdrawal of herbicides (such as atrazine, simazine and glyphosate) in some countries, hence reducing the effectiveness of weed management under NT (Basch et al., 2008). If farmers are discouraged from using herbicides in weed management, use of other weed management strategies will reduce the chances of farmers trying the NT practice.

2.2.8 Summary

To appreciate the significance of NT as a sustainable approach to improving crop productivity relative to CT, it is imperative to review literature from historical perspective and examine adoption rate over time. While history and adoption of NT were not the main aim of this study, they were nevertheless valuable pieces of tillage puzzle that further helped in understanding practical implementation of the practice. Local history, in particular, was important in understanding the development process and how perspectives on NT have changed over time. With respect to exploring the benefits of NT relative to

CT, the literature review highlighted the biophysical and socio-economic significance of these farming practices. Specifically, the literature review examined the behavior of TSN, SOC, grain yield, and NUE under both practices. The review indicated that data supporting the benefits of NT on marginal landscapes with low organic matter, erosion-prone soils and presence of other crop yield limiting factors, present strong arguments for its practice relative to CT. However, the inconsistencies in previous findings evidently suggest a need for further work to conclusively address them. The methodology used in this study, including experimental design and management, sampling and sample processing, are discussed in the following section of this dissertation.

2.3 MATERIALS AND METHODS

2.3.1 Site Description

This study used data from two long-term experiments; experiment 222 (E222) and 502 (E502). The E222 trial was established in 1969 on a well-drained, deep and slowly permeable Kirkland silt loam (fine, mixed, thermic Udertic Paleustoll) at the Agronomy Research Station in Stillwater, Oklahoma-USA with an altitude of 272 masl. Experiment 502, established in 1970, is located on a well-drained, deep and moderately permeable Grant silt loam (fine-silty, mixed, thermic Udic Argiustoll) at the North Central Research Station in Lahoma, Oklahoma-USA with an altitude of 396 masl. For both experimental sites, total rainfall and average air temperature were computed for the winter wheat growing periods (October to June) for each year reported (Figure 2.1). Comparisons in grain yield were made for varieties planted under both tillage systems to determine whether or not significant differences existed between the tillage systems with the same wheat variety at both sites (Figure 2.2).

2.3.2 Experimental Design and Management

The experimental design at E222 was a randomized complete block with thirteen treatments and four replications. Only 4 of the treatments, 1 2, 3, and 4 with 0, 45, 90, and 135 kg N ha^{-1}, respectively, were used for this section of the dissertation (Table 2.1). Each of these treatments had fixed phosphorus (P) and potassium (K) rates of 29 and 37 kg ha^{-1}, respectively. Fertilizer N was applied as urea (46-0-0) pre-plant. The treatment with the maximum N rate (135 kg ha^{-1}) was split, 67.5 kg ha^{-1} pre-plant and another 67.5 kg ha^{-1} applied mid-season. Fertilizer P and K were applied pre-plant as triple superphosphate (0-22-0) and potassium chloride (0-0-52), respectively. The design at E502 was a randomized complete block with fourteen treatments and four replications. For this section of the dissertation, however, only six treatments; 2, 3, 4, 5, 6 and 7 with 0, 22.5, 45, 67, 90, and 112 kg N ha^{-1}, respectively were used (Table 2.1). For each of these treatments, P and K were applied at fixed rates of 20 and 56 kg ha^{-1}, respectively. Nitrogen, P and K were applied pre-plant as urea (46-0-0), triple superphosphate (0-22-0) and potassium chloride (0-0-52), respectively.

Both trials were established as continuous winter wheat-summer fallow under CT system until 2010 and are presently managed under NT (Aula et al., 2016). Under CT, disc harrow and chisel plough were used in the preparation of the trials prior to planting seeds while Roundup (Glyphosate) and WeedMaster (Dicamba: 12.4% and 2,4-D: 35.7%) herbicides were applied at a rate of 1 to 2 L ha^{-1}, depending on the weed pressure under the NT. Winter wheat seeds were drilled using the Great Plains 2010 Drill (Great Plains Ag, Salina-Kansas, USA). Planting dates varied from one year to another but seeds were generally drilled in October of each year reported in this study (2003 to 2018). Experimental fields were managed under rain-fed conditions with no irrigation water applied.

2.3.3 Sampling and Sample Processing

Winter wheat grain yield data used in this section were obtained over eight years for each tillage system; from 2003 to 2010 and from 2011 to 2018 under CT and NT, respectively.

Experimental plots were harvested at maturity using a Massey Ferguson 8XP self-propelled combine. Grain yields were adjusted to 12.5% moisture content. Data on soil SOC and TSN were available for only four years each under CT and NT, not eight years as reported for grain yield. Under CT, data were obtained from 2007 to 2010 while under NT, data were obtained from 2011 to 2014. Similar to SOC and TSN, data used to estimate NUE was obtained over 6 years each under NT and CT. Under CT, data were obtained from 2005 to 2010 while under NT, data were obtained from 2011 to 2016. In July of each year, 15 to 20 post-harvest soil cores were collected from 0-15 cm soil depth and composited for each treatment. These samples were oven-dried for 48 hours at 65°C and later ground to pass a 1mm sieve. Soil OC and TSN determination were completed using LECO Truspec CN dry combustion analyzer (Schepers et al., 1989). The LECO CN628 dry combustion analyzer was used. For each sample, 200 mg of soil by treatment and replication was weighed, wrapped in aluminum foil and combusted at 950˚C. The difference method was used to compute NUE from grain N uptake using the following equation (Eq. [1]).

$$\mathrm{NUE} = \frac{\text{Grain N uptake (fertilized)} - \text{Grain N uptake (unfertilized)}}{\text{Total fertilizer N applied}}\ \mathrm{X}\ 100 \qquad [1]$$

2.3.4 Statistical Analysis

Data were analyzed using the SAS statistical software package (SAS Institute, 2013). The GLM procedure was used to conduct the analysis of variance appropriate for a randomized complete block design for grain yield, TSN and SOC. Single-degree-of-freedom orthogonal contrasts were used to compare grain yield, TSN, and SOC treatment means from CT and NT (Nogueira, 2004; Abdi & Williams, 2010). To associate grain yield with soil quality parameters, the relationships between grain yield and TSN as well as grain yield and SOC were evaluated using the SAS PROC REG procedure (SAS Institute, 2013).

2.4 RESULTS

2.4.1 Wheat Grain Yield

Analysis of variance showed an overall significant difference ($p < .0001$) in mean grain yield between CT and NT at E222 (Table 2.2). For specific N rates, no significant ($p = 0.1074$) difference was observed between CT and NT in the check plot (0 kg N ha^{-1}). However, significant grain yield differences were observed at 45 kg N ha^{-1} ($p = 0.006$), 90 kg N ha^{-1} ($p = 0.0281$), and 135 kg N ha^{-1} ($p = 0.0209$) and yields were 30, 21 and 21% higher under NT than seen under CT system, respectively. Generally, grain yield across all treatments was 23% higher under NT than observed under CT. Grain yield increased with N rates under both practices. Although the increase was generally higher under NT for all N application rates, the trend was similar to that observed under CT (Figure 2.3).

At E502, overall results showed a significant difference ($p < .0001$) in grain yield mean values between treatments (Table 2.3). When specific and equal N rates under CT and NT were contrasted to each other, an overall significant difference was seen ($p = 0.0002$). No grain yield differences were observed at 0 kg N ha^{-1} ($p = 0.3933$), 22.5 kg N ha^{-1} ($p = 0.3095$), 45 kg N ha^{-1} ($p = 0.0802$), 67 kg N ha^{-1} ($p = 0.1511$), and 90 kg N ha^{-1} ($p = 0.0588$). Nevertheless, a significant difference ($p = 0.0178$) was observed with an application rate of 112 kg N ha^{-1} where grain yield under CT was 0.7 Mg ha^{-1} higher than recorded under NT. Generally, average wheat grain yield across treatments was 14% higher under CT than NT practice. This result did not mirror the observation at E222 where grain yields at all N rates were higher under NT than under the CT system.

2.4.2 Total Soil Nitrogen

Total soil N at E222 was significantly different ($p = 0.0247$) between CT and NT at 0 kg N ha^{-1} where the latter was 19% higher than the former (Table 2.2). At 45 kg N ha^{-1}, no significant difference ($p = 0.0705$) in TSN accumulation was observed between CT and NT. Nevertheless, significant differences were observed at 90 kg N ha^{-1} ($p = 0.018$) and 135 kg N ha^{-1} ($p = 0.0345$) where TSN was 18 and 16% higher under NT than observed under CT at the respective N rates. Considering average values across treatments, TSN was 17% higher under NT than recorded under CT. A pattern of buildup in TSN was observed for both practices (Figure 2.3). Under NT, positive linear relationships between TSN and grain yield were observed across N rates (Table 2.4).

For E502, orthogonal contrast between CT and NT showed an overall significant difference ($p = 0.0006$) in TSN (Table 2.3). However, N application rates of 0, 22.5, 45, and 67 kg N ha^{-1} at E502 did not result in a significant difference in TSN between CT and NT. Nonetheless, significant differences in TSN between NT and CT were seen at 90 kg N ha^{-1} ($p = 0.0269$) and 112 kg N ha^{-1} ($p = 0.0486$) where the NT produced 15 and 12% higher TSN than for CT. Averaged across treatments, NT had 11% higher TSN than CT. The observation at E502 is similar to that at E222 although the latter was 6% higher than the former. Unlike E222, the slopes of the linear relationship between TSN and grain yield under NT were negative for each N rate at E502 (Table 2.4).

2.4.3 Soil Organic Carbon

Significant differences in the buildup of SOC were observed in all treatments with an average significant difference in orthogonal contrasts between CT and NT ($p < .0001$) at E222 (Table 2.2). The average orthogonal contrast Soil organic carbon was 29, 30, 29, and 28% higher under NT than recorded under CT at 0, 45, 90 and 135 kg N ha^{-1}, respectively. This result does not show any pattern of percentage difference in SOC buildup under NT with N rates although a non-significant trend for increased SOC with applied N was present for both practices (Figure 2.3). It is also evident that the increase was higher under NT than CT. Averaged across treatments, SOC under NT was 29% higher than that recorded for CT. Under NT, positive linear relationships between SOC and grain yield were observed across N rates (Table 2.4).

At E502, SOC was significantly different ($p < .0001$) both between treatments and orthogonal contrasts comparing CT and NT at all N application rates (Table 2.3). At treatment levels of 0, 22.5, 45, 67, 90, and 112 kg N ha^{-1}, SOC under NT was 10, 8, 14, 10, 18, and 11% higher, respectively, compared to CT. Averaged across all treatments, SOC was 13% higher under NT than CT. This result mirrored the observation at E222 with an overall significant difference between NT and CT under all N rates. However, the overall difference was 16% higher at E222 compared to E502. The linear relationships for each N rate between SOC and grain yield under NT had negative slopes at E502 and did not mirror observations at E222 (Table 2.4).

2.4.4 Nitrogen Use Efficiency

Analysis of variance showed an overall significant difference ($p = 0.0002$) in NUE between treatments (Table 2.5). As was expected, NUE decreased with increasing N rate under both tillage practices. Nitrogen use efficiency decreased by 11 and 8% from 45 to 90 and 90 to 135 kg N ha^{-1}, respectively, under CT. Observations under NT indicated a decrease of 20 and 16% between application rate of 45 to 90 and 90 to 135 kg N ha^{-1}. Generally, NUE was higher under NT compared to CT (Table 2.5). Orthogonal contrast analysis at the same N rate indicated that NUE was significant at application of 45 kg N ha^{-1} ($p = 0.001$) and 90 kg N ha^{-1} ($p = 0.0166$) while no significant differences were observed between CT and NT at an application rate of 135 kg N ha^{-1}. An overall orthogonal contrast analysis indicated significant difference in NUE between NT and CT ($p < 0.0001$), with the former being 7% higher than the latter.

At E502, NUE at different N application rates were not significantly different under both tillage practices (Table 2.6). Although there was a tendency for NUE to decrease with increasing fertilizer N rate, no clear pattern was present under both CT and NT. For instance, the lowest NUE of 36% under CT was observed at fertilizer rate of 67 kg N ha^{-1} compared to 41.1% at 112 kg N ha^{-1}. Similar observations were made under NT where the lowest NUE was not observed at the highest fertilizer N rate. Orthogonal contrast between CT and NT did not indicate significant differences in NUE between the two practices at this location ($p = 0.8755$). Nevertheless, NUE under NT exceeded NUE under CT by 3%. With respect to understanding the changes in NUE with N rate, this result did not mirror observations at E222 where a significant decrease in NUE occurred with increasing N rate.

2.4.5 Grain Nitrogen Uptake

Grain N uptake generally increased with N rate under both CT and NT at E222 (Table 2.5). The lowest grain N uptake of 28 and 27.2 kg ha^{-1} were recorded in check plots under CT and NT, respectively. Under CT, grain N increased by 21, 14, and 11% from application rate of 0 to 45, 45 to 90, and 90 to 135 kg N ha^{-1}, respectively. The percent incremental differences from 0 to 45, 45 to 90, and 90 to 135 kg N ha^{-1} under NT were 33, 16, and 11%, respectively. Although grain N appeared generally to be higher under NT, orthogonal contrast analysis between CT and NT at this location (E222) did not show any significant differences at individual N application rates. Overall average grain N under NT was significantly higher than CT by 13% ($p = 0.047$), possibly due to improved soil chemical properties that resulted to better utilization of the applied fertilizer N under NT relative to CT.

At E502, a similar pattern in grain N uptake was observed where grain N increased with fertilizer application rate (Table 2.6). The lowest grain N of 37.2 and 31.8 kg ha^{-1} were observed in check plots under CT and NT, respectively. The highest grain N uptake was registered at an application rate of 112 kg N ha^{-1} and was 51 and 55% more than that in check plots under NT and CT, respectively. Generally, grain N uptake was greater under CT compared to NT at individual N rates. While this was true, contrasting grain N uptake at respective N rate between CT and NT did not show any significant difference. The same observation was made for the overall contrast analysis ($p = 0.369$).

2.4.6 Winter Wheat Varieties

Being a long-term study, several winter wheat varieties were used over the study period. For grain yield, varieties that were planted under both tillage practices were significantly different. At E502, the variety ‘Bullet’ yielded significantly higher under NT than CT (Figure 2.2). Similarly, comparison of varieties at E222 showed that ‘Endurance’, planted under both tillage systems, yielded significantly higher under NT than under CT (Figure 2.2). In addition, grain N uptake and NUE were significantly affected by varieties planted at both locations irrespective of the tillage practice (Table 2.7). At E502, comparison was made for the only variety (Bullet) planted under both tillage practices. Grain N uptake with the same variety ‘Bullet’ under NT was 36% higher than that under CT (Table 2.7). This observation was similar for NUE where the same variety ‘Bullet’ significantly performed better under NT compared to CT by 30.3%. Similar comparison was made at E222 for variety ‘Endurance’ that was planted under both tillage practices. The results mirrored observations at E502 where grain N uptake for ‘Endurance’ was 55.6% higher under NT compared to CT. Nitrogen use efficiency was also significantly higher under NT (27.8 %) than under CT (10.9 %) with the same variety ‘Endurance’. Comparisons of performance of other varieties were not possible since they were not uniformly planted under both tillage practices. The observations at both locations for varieties planted under both tillage practices generally indicate superiority of grain N uptake and NUE under NT compared to CT. Furthermore, it indicates that the observed differences were due to tillage effects rather than varieties used in this study.

2.5 DISCUSSION

2.5.1 Wheat Grain Yield

Results from the present study showed that grain yield under NT was significantly higher than those under CT system. However, the yield benefit accrued under NT was not consistent across experimental sites. Overall, grain yield under NT was higher than those under CT system by 5% when averaged across locations. Although higher for NT, a trend for increased grain yield with N rates was observed at both sites and under both systems. The increase in grain yield with fertilizer N under NT was most likely due to improved N utilization. This is in agreement with work by Triplett and Dick (2008), reporting that NT improved fertilizer use efficiency. Improved soil structural stability under NT coupled with increases in potential mineralizable N could have had an impact on grain yield. Doran et al. (1980) reported between 20 to 101 kg ha^{-1} as potentially mineralizable N under NT compared to CT system. In a maize-wheat sequence, Ghuman and Sur (2001) observed an overall grain yield advantage of NT over CT but noted that yields were much higher with the application of residue mulch of 3 Mg ha^{-1} from the previous season. From another perspective, De Vita et al. (2007) noted that the overall grain yield advantage for NT over CT was realized in environments where precipitation was less than 300 mm per year. In the current study, however, average annual rainfall at both locations was above 300 mm. Over the study period, the average annual rainfall was 715 mm and 856 mm at E502 and E222, respectively. With average grain yield comparatively lower at E222 than at E502, this demonstrates the advantage of NT system in relatively low yielding environments. It is important to note that the gap between NT and CT was wider than observed at E502, again illustrating the positive impact of a NT practice in low yielding environments. Overall, comparisons of varieties planted under both tillage systems showed that wheat grain yield under NT was greater than those under CT, an indication that the observed differences were due to tillage rather than varietal effect.

2.5.2 Total Soil Nitrogen

Total soil N at both locations increased with an increase in N applied for both CT and NT when averaged over treatments, consistent with several research reports (Ismail et al., 1994; Raun et al., 1998; Halvorson et al., 1999; Dolan et al., 2006). Ortas et al. (2013) explained that increase in TSN with N fertilizer rate was a result of improved plant biomass production with decreased C:N ratio. Even under CT, TSN increased with increased N applied. In a long-term continuous CT system, Raun et al. (1998) also observed an increase in TSN with increased fertilizer N rates. Generally, similar trends for increased TSN were seen for both systems although TSN under NT was significantly higher than those under CT. The current study showed that TSN was 14% higher for NT when compared to CT, and that was similar to a report by Mikha and Rice (2004). According to Havlin et al. (1990), increased TSN under NT was greater for crop rotation practices with high surface residue compared to CT. Malhi and Kutcher (2007) also reported higher TSN under NT compared to CT when crop residue was returned to the soil surface. By design, NT automatically leaves residue on the soil surface (Campbell et al., 1996). Consistent with these reports, the current study indicates that high fertilizer N input under NT improves

TSN buildup better than under CT although positive linear relationships with grain yield were not consistent across locations.

2.5.3 Soil Organic Carbon

In general, SOC was significantly higher under NT than CT system at all experimental sites. The tendency of SOC to increase with N rates was observed under both systems. This is consistent with a report by Lafond et al. (2011) who observed high SOC under high levels of N application. The high SOC under NT could be a result of increased biomass production associated with high N rates. At high N rates, increased biomass production compared to the control treatment with no N applied increases the possibility of surface buildup of SOC under NT (Ismail et al., 1994; Aula et al., 2016). In a long-term study, Havlin et al. (1990) also reported greater SOC under NT compared to CT. However, the authors indicated that there was a tendency for soil to accumulate more SOC under a rotation system compared to continuous mono-cropping because of increased species diversity. The current study, under continuous mono-cropping practice, shows an average of 21% more SOC under NT than CT. From another perspective, the rate of SOC accumulation is likely dependent on how long production has taken place under NT. For instance, Lafond et al. (2011) reported significantly higher SOC under long-term NT (39 years) compared to short-term NT (9 years). In their study, long-term NT produced 17% more SOC than short-term NT from the 0-15 cm soil layer while no differences were observed between samples obtained from a 15-30 cm soil depth. In the present study, the inconsistent positive linear relationships between NT and grain yield could be due to relatively shorter production cycle (8 years) under this practice or could be a result of differences in the production environment. Dolan et al. (2006) reported over 30% more SOC in a 0-20 cm soil layer under NT than for CT. Under native prairie or long-term NT, the residue decomposition rate is slow, and surface accumulation explains the high SOC at 0-15 cm. The CT practice aerates the soil system allowing for decomposition to take place much faster. In the process, more carbon is oxidized. Therefore, producers have to practice NT on a long-term basis in order to realize a significant improvement in soil quality and crop yield.

2.5.4 Nitrogen Use Efficiency

Mechanisms for the improvement of NUE under NT relative to CT have been previously explained by many scholars. Raun and Johnson (1999) indicated that NT improves the use efficiency of the applied fertilizer N by reducing losses of fertilizer in runoff. Similarly, Cassman et al. (2002) added that NT improves N utilization by reducing erosion that can ultimately help reduce N runoff to surface waters. From another perspective, NT is believed to improve NUE through the beneficial action of arbuscular mycorrhizal fungi on N uptake efficiency, with regards to both soil N availability and N transfer to the host plant (Verzeaux et al., 2017). Hu et al. (2015) observed that NT increased the external mycorrhizal mycelium length relative to CT in a maize-wheat rotation. The reduced physical disturbance of the topsoil under NT stimulates an increase in propagule density leading to better colonization by the fungi relative to CT (Verzeaux et al., 2017).

Dalal et al. (2011) did not observe any difference in NUE between CT and NT in a vertisol soil. The authors explained that the insignificant tillage effect on NUE could have been due to the shrink-swell/cracking properties of vertisol soil, which minimizes the nutrient stratification associated with NT. In the same study (Dalal et al., 2011), residue management had a significant impact on NUE. Compared to 'residue burned', NT with 'residue retained' showed greater NUE under a low rate of fertilizer N application.

Fredrickson et al. (1982) recovered more of the applied ^{15}N-labeled fertilizer under NT relative to CT when ammonium sulphate was used as N source. In the current study, urea fertilizer, which is prone to volatilization loss, was used as a source of N. Similar to the present study, Yadvinder-Singh et al. (2009) observed inconsistency in results where differences in NUE between NT and CT depended on experimental locations with different soil types. The authors reported that NUE was 7% higher under NT compared to CT on a silt loam soil. On a sandy loam soil, NUE was 5% lower under NT compared to CT. Giller et al. (2004) indicated that NUE for rice was improved when NT drill was used to deep-place fertilizer N during planting. Therefore, the contribution of NT in improving NUE relative to CT seems dependent on certain site specific conditions.

2.5.5 Grain Nitrogen Uptake

Grain N uptake increased with fertilizer N rate under both tillage practices. Results averaged across experimental sites and N rate indicate a 10% higher grain N uptake under NT than observed under CT. However, the difference between NT and CT was not consistent across experimental locations. As observed with wheat grain yield, grain N uptake between NT and CT was detected only at E222 but not at E502. The lack of differences in grain N uptake between NT and CT at E502 was similar to observations of previous studies (Thomsen & Sorensen, 2006; Constantin et al., 2010). Licht and Al-Kaisi (2005) also did not observe any differences in N uptake between NT and chisel plow. In the current study, the differential response of tillage practices in N uptake between experimental locations was probably due to substantial precipitation in late winter or early spring that could have increased nitrate-leaching losses in some years. Over the study period, E222 received 104 mm of rainfall more than E502. Consequently, NT advantage in a low yielding environment was evident in this study.

2.6 SUMMARY AND CONCLUSION

The current study examined the benefits of changing from CT to NT in a continuous winter wheat-summer fallow practice. Generally, the results showed an overall positive influence of NT on winter wheat grain yield, TSN, SOC, grain N uptake, and NUE. However, the extent to which NT practice impacted these parameters varied with experimental locations and were more positive in low yielding environments. The site specific results for E222 indicated that grain yield, TSN, SOC, and NUE under NT were 23%, 17%, 29%, and 39% respectively, more than recorded under CT. At E502, grain yield and grain N uptake were lower under NT than CT by 14% and 4%, respectively, while TSN, SOC, and NUE were higher by 11%, 13%, and 13%, respectively under NT relative to CT. Averaged over experimental locations, wheat grain yield, TSN, SOC, grain N uptake and NUE were 5%, 14%, 21%, 4.5%, and 23%, respectively higher under NT compared to CT. The small (5%) increase in grain yield could be due to a shorter production cycle (8 years) under NT. This is consistent with a conclusion by Lafond et al. (2011) that soil quality parameters and crop yield are additive under NT. The authors reported 17% higher SOC under long-term NT (39 years) compared to short-term NT (9 years). With regard to site differences in soil N and carbon storage, the low yielding environment (E222) had a marked difference between NT and CT, where N and carbon were 7 and 18% higher compared E502 that had relatively high grain yield. The differences in grain yield between NT and CT in this study was seen in environment with relatively better accretion rate of carbon and N within the study period. Nonetheless, NT was generally a better alternative crop production practice compared to CT and is likely a sustainable long-term strategy for improving soil quality and crop productivity in a continuous mono-cropping system.

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Table 1.1 Total rainfall and average air temperature (April to September) in 2018 and 2019 at Lake Carl Blackwell and Efaw Agronomy Research Station, Stillwater, Oklahoma.

Month	Rainfall (mm)			Temperature (^{o}C)		
	2018	2019	10 yr. avg¶	2018	2019	10 yr. avg¶
			Stillwater			
April	52.3	134.4	122.2	12.3	16.1	16.0
May	98.6	439.4	110.1	24.0	19.6	20.1
June	151.6	106.9	86.9	26.6	24.4	26.5
July	79.2	19.3	96.4	27.8	27.4	28.2
August	142.0	209.8	78.5	26.2	27.2	27.0
September	79.8	165.4	61.9	22.9	26.2	22.8
			Lake Carl Blackwell			
April	51.1	111.0	121.8	12.0	15.7	15.6
May	75.7	413.5	125.8	23.7	19.2	19.7
June	214.9	102.6	119.5	26.3	24.1	26.1
July	71.4	33.3	94.5	27.1	26.9	27.9
August	151.1	208.0	73.1	25.9	27.0	26.6
September	70.6	163.6	68.4	22.6	25.8	22.3

¶ 10 year average (2008 - 2017) prior to the first year of initiating experiment

Table 1.2 Treatment structure for the effect of inorganic N - biochar complex on Nitrogen use efficiency (NUE), yield of maize (Zea mays L.) and soil chemical properties

Treatment	Input	Description	N rate (kg ha^{-1})	Biochar rate (t ha^{-1})
1	Check	No fertilizer applied	0	0
2	NF	Nitrogen fertilizer	50	0
3	NF	Nitrogen fertilizer	100	0
4	NF	Nitrogen fertilizer	150	0
5	B	Biochar	0	5
6	B	Biochar	0	10
7	B	Biochar	0	15
8	NBC	Nitrogen-biochar combination	50	5
9	NBC	Nitrogen-biochar combination	100	10
10	NBC	Nitrogen-biochar combination	150	15

Nitrogen fertilizer was applied as UAN; biochar was applied immediately following nitrogen fertilizer and incorporated into the soil at a depth of 15 cm.

Table 1.3 Physical and chemical properties of soft wood (Southern Yellow Pine) biochar supplied by Wakefield Biochar, Columbia, Missouri; the initial soil chemical properties at Lake Carl Blackwell (LCB) and Efaw research sites, Stillwater, Oklahoma.

Biochar/Site	pH	K	Ca	Mg	Mn	Fe	BD	Total Phosphate	TN	TOC
	unit	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	g cm^{-1}	mg kg^{-1}	g kg^{-1}	g kg^{-1}
Biochar	7.4	612	4128	1225	234	595	0.48	4.53	5.9	876.7
LCB	5.7	349	804	207	x	x	x	12	0.8	9.1
Efaw	5.6	153	1466	354	x	x	x	13	0.7	6.8

TP, Total phosphate; TN, Total nitrogen; TOC, Total organic carbon; BD, Bulk density; x, values not determined.
Initial soil properties were determined before the first year of biochar application.

Table 1.4 Mean maize grain yield, grain N uptake, and nitrogen use efficiency (NUE) for treatments plus the associated contrasts between nitrogen fertilizer and biochar-nitrogen combinations at Efaw, Stillwater, OK. 2018.

Treatment	N rate (kg ha^{-1})	Biochar (t ha^{-1})	Grain yield (Mg ha^{-1})		Grain N uptake (kg ha^{-1})		NUE (%)	
			mean	± S.E	mean	± S.E	mean	± S.E
1	0	0	3.48	0.74	41.34	8.53	x	x
2	50	0	4.76	0.32	59.82	9.60	53.44	26.76
3	100	0	5.84	0.51	77.52	10.18	36.18	3.11
4	150	0	7.30	0.50	102.34	7.10	40.66	8.34
5	0	5	3.51	0.28	42.11	1.96	x	x
6	0	10	3.62	0.09	42.87	1.51	x	x
7	0	15	3.85	0.95	43.79	10.75	x	x
8	50	5	5.71	0.69	71.02	8.13	59.36	4.98
9	100	10	6.68	1.12	86.78	14.76	45.44	6.67
10	150	15	6.43	0.76	83.48	8.42	28.09	0.90
Pr > F			0.0023		0.0003		0.0707	
C.V, %			23.1		23.3		35.5	
			contrast level of significance					
			F Value	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*
2 vs. 8			0.89	0.3649	0.2	0.6646	1.05	0.3268
3 vs. 9			0.69	0.4212	0.46	0.5124	0.6	0.4525
4 vs. 10			0.75	0.402	1.89	0.1947	1.11	0.3131
2,3 & 4 vs. 8,9 & 10			0.27	0.6105	0.02	0.8859	0.19	0.6745

C.V, Coefficient of variation between treatments; S.E, standard error for replicated means (± SE, n = 3); x, missing NUE value from plots with no fertilizer N applied.

Nitrogen fertilizer was applied as urea ammonium nitrate – UAN (28:0:0)

Biochar was applied immediately following UAN application and incorporated to about 15 cm depth.

Table 1.5 Mean maize grain yield, grain N uptake, and nitrogen use efficiency (NUE) for treatments plus the associated contrasts between nitrogen fertilizer and biochar-nitrogen combinations at Efaw, Stillwater, OK. 2019.

Treatment	N rate (kg ha^{-1})	Biochar (t ha^{-1})	Grain yield (Mg ha^{-1})		Grain N uptake (kg ha^{-1})		NUE (%)	
			mean	± S.E	mean	± S.E	mean	± S.E
1	0	0	1.08	0.04	12.53	0.58	x	x
2	50	0	1.59	0.22	18.10	2.82	11.14	4.65
3	100	0	1.88	0.21	23.95	2.00	11.42	1.43
4	150	0	2.29	0.28	30.02	3.34	11.66	2.01
5	0	5	1.40	0.20	16.03	1.96	x	x
6	0	10	1.65	0.31	19.50	4.14	x	x
7	0	15	1.13	0.16	12.12	1.89	x	x
8	50	5	1.39	0.09	17.08	1.52	9.10	3.65
9	100	10	1.65	0.13	19.48	1.17	6.95	1.74
10	150	15	1.92	0.24	26.76	3.60	9.49	2.78
Pr > F			0.0124		0.001		0.8522	
C.V, %			22		22.5		51.1	
			contrast level of significance					
			F Value	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*
2 vs. 8			0.5	0.4946	0.08	0.7841	0.24	0.6322
3 vs. 9			0.62	0.4449	1.51	0.2429	1.16	0.3029
4 vs. 10			1.58	0.2332	0.8	0.3889	0.27	0.611
2,3 & 4 vs. 8,9 & 10			2.52	0.1384	1.92	0.1906	1.46	0.2508

C.V, Coefficient of variation between treatments; S.E, standard error for replicated means (± SE, n = 3); x, missing NUE value from plots with no fertilizer N applied.

Nitrogen fertilizer was applied as urea ammonium nitrate – UAN (28:0:0)

Biochar was applied immediately following UAN application and incorporated to about 15 cm depth.

Table 1.6 Mean maize grain yield, grain N uptake, and nitrogen use efficiency (NUE) for treatments plus the associated contrasts between nitrogen fertilizer and biochar-nitrogen combinations at Lake Carl Blackwell, Stillwater, OK. 2018.

Treatment	N rate (kg ha^{-1})	Biochar (t ha^{-1})	Grain yield (Mg ha^{-1})		Grain N uptake (kg ha^{-1})		NUE (%)	
			mean	± S.E	mean	± S.E	mean	± S.E
1	0	0	2.59	0.15	27.49	2.83	x	x
2	50	0	3.18	0.06	35.36	1.11	15.74	4.72
3	100	0	3.55	0.21	37.03	1.53	9.54	2.80
4	150	0	3.95	0.07	47.72	2.61	13.49	0.44
5	0	5	3.25	0.06	39.56	4.01	x	x
6	0	10	3.49	0.11	45.63	5.10	x	x
7	0	15	4.18	0.09	52.94	2.50	x	x
8	50	5	3.46	0.20	37.31	2.63	19.64	5.73
9	100	10	4.49	0.34	59.38	6.67	31.89	4.45
10	150	15	4.97	0.14	67.33	2.82	26.59	1.34
Pr > F			<.0001		<.0001		0.0105	
C.V, %			7.7		13.7		33.4	
			contrast level of significance					
			F Value	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*
2 vs. 8			1.04	0.327	0.16	0.6927	0.54	0.4768
3 vs. 9			11.59	0.0052	21.48	0.0006	17.67	0.0012
4 vs. 10			13.77	0.003	16.53	0.0016	6.07	0.0298
2,3 & 4 vs. 8,9 & 10			22.07	0.0005	27.64	0.0002	18.26	0.0011

C.V, Coefficient of variation between treatments; S.E, standard error for replicated means (± SE, n = 3); x, missing NUE value from plots with no fertilizer N applied.

Nitrogen fertilizer was applied as urea ammonium nitrate – UAN (28:0:0)

Biochar was applied immediately following UAN application and incorporated to about 15 cm depth.

Table 1.7 Mean maize grain yield, grain N uptake, and nitrogen use efficiency (NUE) for treatments plus the associated contrasts between nitrogen fertilizer and biochar-nitrogen combinations at Lake Carl Blackwell, Stillwater, OK. 2019.

Treatment	N rate (kg ha^{-1})	Biochar (t ha^{-1})	Grain yield (Mg ha^{-1})		Grain N uptake (kg ha^{-1})		NUE (%)	
			mean	± S.E	mean	± S.E	mean	± S.E
1	0	0	0.65	0.21	6.65	2.05	x	x
2	50	0	1.09	0.30	14.17	3.08	15.03	2.07
3	100	0	1.18	0.27	12.26	2.53	5.60	0.85
4	150	0	1.34	0.20	15.01	2.29	5.57	0.41
5	0	5	1.40	0.42	15.32	4.21	x	x
6	0	10	1.05	0.56	13.09	8.01	x	x
7	0	15	1.08	0.22	10.89	1.97	x	x
8	50	5	1.38	0.24	15.08	1.84	16.86	1.28
9	100	10	1.72	0.23	22.21	3.50	15.56	3.48
10	150	15	2.19	0.25	27.69	3.03	14.02	2.18
Pr > F			0.1264		0.0395		0.0034	
C.V, %			41		41.9		28.4	
contrast level of significance								
			F Value	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*
2 vs. 8			0.66	0.4311	0.05	0.8195	0.42	0.5282
3 vs. 9			2.31	0.1544	6.47	0.0258	12.54	0.0041
4 vs. 10			5.74	0.0338	10.49	0.0071	9.04	0.0109
2,3 & 4 vs. 8,9 & 10			7.46	0.0182	12.06	0.0046	17.27	0.0013

C.V, Coefficient of variation between treatments; S.E, standard error for replicated means (± SE, n = 3); x, missing NUE value from plots with no fertilizer N applied.

Nitrogen fertilizer was applied as urea ammonium nitrate – UAN (28:0:0)

Biochar was applied immediately following UAN application and incorporated to about 15 cm depth.

Table 1.8 Mean of total soil nitrogen (TSN), soil organic carbon (SOC), nitrate, and ammonium for treatments plus the associated contrasts between nitrogen fertilizer and biochar-nitrogen combinations at Efaw, Stillwater, OK. 2018.

Treatment	N rate (kg ha^{-1})	Biochar (t ha^{-1})	TSN (g kg^{-1})		SOC (g kg^{-1})		NO_3-N (mg kg^{-1})		NH_4-N (mg kg^{-1})	
			mean	± S.E	mean	± S.E	mean	± S.E	mean	± S.E
1	0	0	0.71	0.01	6.76	0.35	4.24	0.42	17.63	0.59
2	50	0	0.82	0.06	7.05	0.10	4.76	0.14	18.53	1.23
3	100	0	0.70	0.05	6.76	0.37	4.94	0.23	19.33	1.22
4	150	0	0.68	0.01	6.61	0.25	6.38	0.22	20.72	1.25
5	0	5	0.78	0.02	7.79	0.06	4.45	0.70	19.70	2.47
6	0	10	0.72	0.04	8.69	1.03	3.80	0.39	19.03	0.81
7	0	15	0.73	0.01	9.37	0.20	4.02	0.63	19.26	3.53
8	50	5	0.71	0.02	7.39	0.38	5.01	0.35	20.17	1.53
9	100	10	0.75	0.04	9.22	0.96	5.29	0.32	21.15	2.08
10	150	15	0.71	0.06	9.58	0.64	4.86	0.85	20.07	2.54
Pr > F			0.3316		0.0016		0.0534		0.9268	
C.V, %			8.8		11.8		17.3		14.9	
			contrast level of significance							
			F Value	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*
2 vs. 8			2.77	0.1221	0.21	0.6542	0.17	0.6838	0.46	0.5121
3 vs. 9			0.49	0.4954	10.87	0.0064	0.35	0.564	0.56	0.4676
4 vs. 10			0.3	0.5921	15.79	0.0018	6.45	0.0259	0.07	0.7953
2,3 & 4 vs. 8,9 & 10			0.06	0.817	19.92	0.0008	0.78	0.3944	0.45	0.5156

C.V, Coefficient of variation between treatments; S.E, standard error for replicated means (± SE, n = 3)
Nitrogen fertilizer was applied as urea ammonium nitrate – UAN (28:0:0)
Biochar was applied immediately following UAN application and incorporated to about 15 cm depth.

Table 1.9 Mean of total soil nitrogen (TSN), soil organic carbon (SOC), nitrate and ammonium for treatments plus the associated contrasts between nitrogen fertilizer and biochar-nitrogen combinations at Efaw, Stillwater, OK. 2019.

Treatment	N rate (kg ha^{-1})	Biochar (t ha^{-1})	TSN (g kg^{-1})		SOC (g kg^{-1})		NO_3-N (mg kg^{-1})		NH_4-N (mg kg^{-1})	
			mean	± S.E	mean	± S.E	mean	± S.E	mean	± S.E
1	0	0	0.79	0.04	6.86	0.43	4.05	0.24	4.21	0.07
2	50	0	0.74	0.05	7.25	0.44	4.81	0.54	5.01	0.27
3	100	0	0.80	0.06	7.13	0.13	5.33	0.11	5.15	0.29
4	150	0	0.73	0.04	7.34	0.31	5.88	0.18	5.51	0.38
5	0	5	0.79	0.04	8.48	1.13	4.05	0.02	3.87	0.32
6	0	10	0.81	0.04	10.09	0.55	4.22	0.03	4.26	0.10
7	0	15	0.72	0.03	7.03	0.36	4.18	0.12	4.27	0.06
8	50	5	0.83	0.04	7.55	0.63	4.58	0.04	4.40	0.11
9	100	10	0.77	0.04	9.37	0.58	4.88	0.17	4.49	0.15
10	150	15	0.80	0.05	11.01	0.99	5.58	0.01	4.82	0.18
Pr > F			0.6854		0.0007		<.0001		0.0009	
C.V, %			9.7		13.2		7.7		8.3	

contrast level of significance

	F Value	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*
2 vs. 8	1.62	0.2268	0.14	0.7147	0.43	0.5222	3.09	0.1044
3 vs. 9	0.16	0.699	7.5	0.018	1.63	0.2262	3.51	0.0854
4 vs. 10	1.32	0.273	20.11	0.0007	0.74	0.4067	3.95	0.0702
2,3 & 4 vs. 8,9 & 10	1.37	0.2647	19.24	0.0009	2.6	0.1326	10.52	0.007

C.V, Coefficient of variation between treatments; S.E, standard error for replicated means (± SE, n = 3)

Nitrogen fertilizer was applied as urea ammonium nitrate – UAN (28:0:0)

Biochar was applied immediately following UAN application and incorporated to about 15 cm depth.

Table 1.10 Mean of total soil nitrogen (TSN), soil organic carbon (SOC), nitrate and ammonium for treatments plus the associated contrasts between nitrogen fertilizer and biochar-nitrogen combinations at Lake Carl Blackwell, Stillwater, OK. 2018.

Treatment	N rate (kg ha^{-1})	Biochar (t ha^{-1})	TSN (g kg^{-1})		SOC (g kg^{-1})		NO_3-N (mg kg^{-1})		NH_4-N (mg kg^{-1})	
			mean	± S.E	mean	± S.E	mean	± S.E	mean	± S.E
1	0	0	0.80	0.03	9.14	0.98	2.13	0.24	24.43	1.23
2	50	0	0.76	0.04	8.24	0.21	2.66	0.17	24.42	1.13
3	100	0	0.75	0.08	8.40	0.16	2.76	0.18	24.25	0.78
4	150	0	0.78	0.00	8.76	0.12	1.96	0.06	26.32	0.86
5	0	5	0.73	0.03	10.23	1.60	2.15	0.17	24.76	2.27
6	0	10	0.84	0.04	9.79	0.19	2.14	0.06	23.60	0.61
7	0	15	0.78	0.04	10.46	1.38	2.24	0.26	23.98	1.11
8	50	5	0.82	0.05	9.64	0.09	2.98	0.03	25.90	1.44
9	100	10	0.82	0.03	10.91	0.71	3.87	0.26	28.15	0.67
10	150	15	0.82	0.05	12.23	1.04	3.27	0.12	30.52	1.38
Pr > F			0.6466		0.0758		<.0001		0.016	
C.V, %			9		14.9		11.5		8.4	

contrast level of significance

	F Value	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*
2 vs. 8	0.85	0.374	3.5	0.0858	2.13	0.1702	0.93	0.3546
3 vs. 9	1.39	0.2609	11.22	0.0058	25.02	0.0003	6.45	0.026
4 vs. 10	0.37	0.5533	21.51	0.0006	34.6	<.0001	7.47	0.0182
2,3 & 4 vs. 8,9 & 10	2.45	0.1432	28.27	0.0002	50.79	<.0001	12.96	0.0036

C.V, Coefficient of variation between treatments; S.E, standard error for replicated means (± SE, n = 3)

Nitrogen fertilizer was applied as urea ammonium nitrate – UAN (28:0:0)

Biochar was applied immediately following UAN application and incorporated to about 15 cm depth.

Table 1.11 Mean of total soil nitrogen (TSN), soil organic carbon (SOC), nitrate and ammonium for treatments plus the associated contrasts between nitrogen fertilizer and biochar-nitrogen combinations at Lake Carl Blackwell, Stillwater, OK. 2019.

Treatment	N rate (kg ha^{-1})	Biochar (t ha^{-1})	TSN (g kg^{-1})		SOC (g kg^{-1})		NO_3-N (mg kg^{-1})		NH_4-N (mg kg^{-1})	
			mean	± S.E	mean	± S.E	mean	± S.E	mean	± S.E
1	0	0	0.79	0.03	8.53	0.19	3.71	0.71	4.06	0.03
2	50	0	0.77	0.04	8.23	0.21	3.94	0.21	4.19	0.16
3	100	0	0.75	0.02	8.58	0.16	4.39	0.17	4.24	0.14
4	150	0	0.81	0.06	10.39	0.37	5.11	0.28	4.43	0.09
5	0	5	0.85	0.03	10.48	0.46	3.95	0.09	4.10	0.01
6	0	10	0.77	0.01	9.32	0.73	4.00	0.11	4.11	0.05
7	0	15	0.87	0.00	11.18	1.40	4.09	0.07	4.09	0.06
8	50	5	0.81	0.05	9.58	0.57	4.67	0.70	4.22	0.16
9	100	10	0.84	0.03	10.11	0.25	5.68	0.21	4.59	0.17
10	150	15	0.78	0.02	12.72	0.72	6.98	0.88	5.21	0.15
Pr > F			0.2424		0.0015		0.001		<.0001	
C.V, %			7.2		10.9		16.6		4.6	
			contrast level of significance							
			F Value	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*
2 vs. 8			0.39	0.5462	5.21	0.0415	1.11	0.3134	0.02	0.8881
3 vs. 9			2.63	0.1309	6.65	0.0241	3.42	0.0891	3.02	0.1078
4 vs. 10			0.38	0.5512	5.76	0.0335	7.18	0.02	14.31	0.0026
2,3 & 4 vs. 8,9 & 10			0.88	0.3654	17.58	0.0012	10.39	0.0073	10.7	0.0067

C.V, Coefficient of variation between treatments; S.E, standard error for replicated means (± SE, n = 3)
Nitrogen fertilizer was applied as urea ammonium nitrate – UAN (28:0:0)
Biochar was applied immediately following UAN application and incorporated to about 15 cm depth.

Table 1.12 Mean of cation exchange capacity (CEC), soil pH and soil electrical conductivity (EC) for treatments plus the associated contrasts between nitrogen fertilizer and biochar-nitrogen combinations at Efaw, Stillwater, OK. 2018.

Treatment	N rate (kg ha^{-1})	Biochar (t ha^{-1})	CEC (meq/100g)		pH		EC (µS/cm)	
			mean	± S.E	mean	± S.E	mean	± S.E
1	0	0	11.08	0.40	5.74	0.06	184.37	14.84
2	50	0	10.30	0.35	5.70	0.02	196.13	10.20
3	100	0	11.18	0.51	5.87	0.06	199.67	21.14
4	150	0	10.64	0.21	5.64	0.03	220.67	8.97
5	0	5	11.27	0.35	5.83	0.02	213.37	11.79
6	0	10	10.99	0.34	5.93	0.07	246.57	54.98
7	0	15	11.54	0.98	5.98	0.12	185.23	6.87
8	50	5	10.95	0.42	5.80	0.10	200.67	15.37
9	100	10	11.45	0.62	5.98	0.09	200.87	18.93
10	150	15	11.49	0.25	6.10	0.07	224.47	18.16
Pr > F			0.7552		0.0063		0.6668	
C.V, %			7.7		2.2		18.7	
			contrast level of significance					
			F Value	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*
2 vs. 8			1.17	0.3014	1.04	0.329	0.04	0.8455
3 vs. 9			0.21	0.6579	1.3	0.2756	0	0.9588
4 vs. 10			2.04	0.1782	21.81	0.0005	0.03	0.8702
2,3 & 4 vs. 8,9 & 10			2.93	0.1127	15.55	0.002	0.06	0.8131

C.V, Coefficient of variation between treatments; S.E, standard error for replicated means (± SE, n = 3)

Nitrogen fertilizer was applied as urea ammonium nitrate – UAN (28:0:0)

Biochar was applied immediately following UAN application and incorporated to about 15 cm depth.

Table 1.13 Mean of cation exchange capacity (CEC), soil pH and soil electrical conductivity (EC) for treatments plus the associated contrasts between nitrogen fertilizer and biochar-nitrogen combinations at Efaw, Stillwater, OK. 2019.

Treatment	N rate (kg ha^{-1})	Biochar (t ha^{-1})	CEC (meq/100g)		pH		EC (µS/cm)	
			mean	S.E	mean	S.E	mean	S.E
1	0	0	11.52	0.51	5.65	0.22	161.60	47.32
2	50	0	11.17	0.59	5.75	0.11	118.63	10.42
3	100	0	12.30	0.44	5.76	0.10	125.63	4.36
4	150	0	11.31	0.33	5.60	0.01	103.30	5.06
5	0	5	11.94	0.51	5.80	0.11	106.27	7.55
6	0	10	11.96	0.66	5.97	0.17	118.73	5.12
7	0	15	11.01	0.42	5.83	0.10	109.47	1.38
8	50	5	11.38	0.24	5.83	0.03	112.97	12.99
9	100	10	12.38	0.36	5.99	0.05	123.37	4.57
10	150	15	12.28	0.40	5.95	0.13	82.83	22.53
Pr > F			0.3372		0.0641		0.1856	
C.V, %			6.8		2.5		18.6	
			contrast level of significance					
			F Value	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*
2 vs. 8			0.14	0.7138	0.45	0.5134	0.11	0.7423
3 vs. 9			0.02	0.8813	3.75	0.0768	0.02	0.8951
4 vs. 10			2.77	0.1222	8.52	0.0129	1.48	0.2475
2,3 & 4 vs. 8,9 & 10			1.6	0.2299	10.19	0.0078	0.95	0.3494

C.V, Coefficient of variation between treatments; S.E, standard error for replicated means (± SE, n = 3)

Nitrogen fertilizer was applied as urea ammonium nitrate – UAN (28:0:0)

Biochar was applied immediately following UAN application and incorporated to about 15 cm depth.

Table 1.14 Mean of cation exchange capacity (CEC), soil pH and soil electrical conductivity (EC) for treatments plus the associated contrasts between nitrogen fertilizer and biochar-nitrogen combinations at Lake Carl Blackwell, Stillwater, OK. 2018.

Treatment	N rate (kg ha^{-1})	Biochar (t ha^{-1})	CEC (meq/100g)		pH		EC (µS/cm)	
			mean	± S.E	mean	± S.E	mean	± S.E
1	0	0	6.70	0.76	5.82	0.08	171.60	21.44
2	50	0	6.71	0.91	5.76	0.06	175.73	30.66
3	100	0	6.21	0.37	5.88	0.08	170.07	21.93
4	150	0	6.27	0.52	5.72	0.04	160.60	11.60
5	0	5	7.46	0.54	5.85	0.07	186.30	10.07
6	0	10	6.99	1.56	5.92	0.15	186.30	32.66
7	0	15	7.07	0.45	5.87	0.11	182.33	16.12
8	50	5	7.01	0.86	5.93	0.11	176.03	4.42
9	100	10	8.20	0.23	5.91	0.02	196.73	12.94
10	150	15	7.78	0.36	6.18	0.02	164.83	7.17
Pr > F			0.7021		0.0761		0.9552	
C.V, %			18.5		2.5		18.8	
			contrast level of significance					
			F Value	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*
2 vs. 8			0.13	0.7253	3.54	0.0842	0	0.9904
3 vs. 9			5.91	0.0317	0.09	0.765	1.19	0.2969
4 vs. 10			5.03	0.0446	25.66	0.0003	0.03	0.8654
2,3 & 4 vs. 8,9 & 10			8.44	0.0132	17.54	0.0013	0.54	0.4755

C.V, Coefficient of variation between treatments; S.E, standard error for replicated means (± SE, n = 3)

Nitrogen fertilizer was applied as urea ammonium nitrate – UAN (28:0:0)

Biochar was applied immediately following UAN application and incorporated to about 15 cm depth.

Table 1.15 Mean of cation exchange capacity (CEC), soil pH and soil electrical conductivity (EC) for treatments plus the associated contrasts between nitrogen fertilizer and biochar-nitrogen combinations at Lake Carl Blackwell, Stillwater, OK. 2019.

Treatment	N rate (kg ha^{-1})	Biochar (t ha^{-1})	CEC (meq/100g)		pH		EC (µS/cm)	
			mean	S.E	mean	S.E	mean	S.E
1	0	0	8.47	0.61	5.79	0.03	106.40	6.31
2	50	0	8.66	1.09	5.83	0.09	105.57	7.95
3	100	0	7.87	0.27	5.75	0.06	108.13	9.17
4	150	0	7.93	0.64	5.70	0.03	110.07	6.88
5	0	5	9.68	0.53	5.89	0.01	128.67	2.38
6	0	10	9.66	2.16	5.85	0.05	119.80	5.25
7	0	15	9.33	0.74	5.95	0.05	119.73	1.87
8	50	5	8.55	0.55	5.91	0.07	108.43	5.64
9	100	10	10.23	0.18	5.95	0.08	118.27	5.84
10	150	15	10.16	0.50	5.96	0.02	123.53	5.12
Pr > F			0.5131		0.0498		0.4464	
C.V, %			17.2		1.8		10.7	
contrast level of significance								
			F Value	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*
2 vs. 8			0.2	0.6641	1.02	0.3332	0.09	0.7743
3 vs. 9			5.49	0.0372	5.41	0.0383	1.07	0.3203
4 vs. 10			6.7	0.0237	8.69	0.0122	1.9	0.1934
2,3 & 4 vs. 8,9 & 10			9.64	0.0091	13.15	0.0035	2.44	0.1439

C.V, Coefficient of variation between treatments; S.E, standard error for replicated means (± SE, n = 3)
Nitrogen fertilizer was applied as urea ammonium nitrate – UAN (28:0:0)
Biochar was applied immediately following UAN application and incorporated to about 15 cm depth.

Table 2.1 Treatment structure with pre-plant N, P and K rates at Experiment 222 (E222) in Stillwater, and Experiment 502 (E502) in Lahoma, Oklahoma

Treatment	N rate (kg N ha^{-1})	P rate (kg P ha^{-1})	K rate (kg K ha^{-1})	Treatment	N rate (kg N ha^{-1})	P rate (kg P ha^{-1})	K rate (kg K ha^{-1})
		E222			E502		
1†	0	29	37	1	0	0	0
2†	45	29	37	2†	0	20	56
3†	90	29	37	3†	22	20	56
4†	135‡	29	37	4†	45	20	56
5	90	0	37	5†	67	20	56
6	90	15	37	6†	90	20	56
7	90	44	37	7†	112	20	56
8	90	29	0	8	67	0	56
9	90	29	74	9	67	10	56
10	0	0	0	10	67	29	56
11	135‡	44	74	11	67	39	56
12	135‡	44	0	12	67	29	0
13	90	29	37	13	112	39	56
x	x	x	x	14	67	20	56

N, P and K - Nitrogen, Phosphorus and Potassium applied as Urea (46-0-0), Triple Super Phosphate (0-22-0) and Potassium Chloride (0-0-52), respectively.

†1 – 4 at E222, Treatments used in this study because they all have constant P and K rates

†2 – 7 at E502, Treatments used in this study because they all have constant P and K rates

‡N rate split to 67.5 N kg applied in Fall and 67.5 N kg applied in Spring

Table 2.2 Treatment means for grain yield, TSN, and SOC and single-degree-of-freedom orthogonal contrasts between CT and NT treatments at E222 (Stillwater), Oklahoma-USA, 2003-2018.

Treatment	Tillage	N rate (kg ha^{-1})	Grain yield (Mg ha^{-1})†		TSN (g kg^{-1})‡		SOC (g kg^{-1})‡	
			mean	S.E	mean	S.E	mean	S.E
1	CT	0	1.32	0.11	0.80	0.04	8.53	0.14
2	CT	45	1.53	0.12	0.88	0.04	9.14	0.24
3	CT	90	1.94	0.17	0.91	0.04	9.61	0.31
4	CT	135	2.04	0.22	0.97	0.03	10.05	0.27
1	NT	0	1.70	0.1	0.99	0.07	12.07	1.25
2	NT	45	2.17	0.16	1.03	0.06	13.15	1.43
3	NT	90	2.45	0.17	1.11	0.07	13.61	1.39
4	NT	135	2.59	0.20	1.15	0.06	14.02	1.52
C.V (%)			45.0		21.5		34.3	
p-value			<.0001		0.0006		0.0008	
			Contrast level of significance					
			F Value	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*
1	CT1 vs NT1	0	2.61	0.1074	5.2	0.0247	5.13	0.0257
2	CT2 vs NT2	45	7.68	0.006	3.34	0.0705	6.56	0.0119
3	CT3 vs NT3	90	4.88	0.0281	5.79	0.018	6.56	0.0119
4	CT4 vs NT4	135	5.41	0.0209	4.59	0.0345	6.44	0.0127
Average	CT vs NT		19.91	<.0001	18.73	<.0001	24.63	<.0001

C.V, Coefficient of variation between treatments; S.E, standard error for replicated means; CT, conventional tillage, NT, no-tillage; TSN, total soil nitrogen; SOC, soil organic carbon, †Treatment means for grain yield were obtained under CT (2003-2010) and NT (2011-2018), ‡Treatment means for TSN and SOC were obtained under CT (2007-2010) and NT (2011-2014).

Table 2.3 Treatment means for grain yield, TSN and SOC and single-degree-of-freedom orthogonal contrasts between CT and NT treatments at E502 (Lahoma), Oklahoma-USA, 2003-2018.

Treatment	Tillage	N rate (kg ha^{-1})	Grain yield (kg ha^{-1})†		TSN (g kg^{-1})‡		SOC (g kg^{-1})‡	
			mean	SE	mean	SE	mean	SE
2	CT	0	1.98	0.13	0.79	0.02	7.79	0.17
3	CT	22.5	2.51	0.17	0.82	0.02	8.06	0.20
4	CT	45	3.03	0.21	0.82	0.02	7.89	0.17
5	CT	67	3.33	0.24	0.85	0.02	8.47	0.20
6	CT	90	3.78	0.28	0.80	0.06	7.80	0.55
7	CT	112	4.06	0.28	0.91	0.01	8.78	0.22
2	NT	0	1.74	0.09	0.85	0.05	8.64	0.16
3	NT	22.5	2.23	0.09	0.89	0.06	8.76	0.19
4	NT	45	2.54	0.11	0.91	0.06	9.12	0.17
5	NT	67	2.94	0.19	0.90	0.05	9.41	0.20
6	NT	90	3.25	0.21	0.94	0.05	9.47	0.12
7	NT	112	3.39	0.23	1.03	0.06	9.84	0.20
C.V (%)			38		20.0		10.9	
Pr > F			<.0001		0.0055		<.0001	
			Contrast level of significance					
			F Value	*Pr > F*	*F Value*	*Pr > F*	*F Value*	*Pr > F*
2	CT2 vs NT2	0	0.73	0.3933	0.89	0.3471	6.44	0.012
3	CT3 vs NT3	22.5	1.04	0.3095	1.35	0.2469	4.36	0.0381
4	CT4 vs NT4	45	3.08	0.0802	2.04	0.1545	13.55	0.0003
5	CT5 vs NT5	67	2.07	0.1511	0.63	0.4287	8.02	0.0052
6	CT6 vs NT6	90	3.59	0.0588	4.98	0.0269	24.95	<.0001
6	CT7 vs NT7	112	5.66	0.0178	3.94	0.0486	10.17	0.0017
Average	CT vs NT		14.64	0.0002	12.17	0.0006	62.24	<.0001

C.V. = Coefficient of variation, CT = conventional tillage, NT = no-tillage, TSN = total soil nitrogen, SOC = soil organic carbon,

†Treatment means for grain yield were obtained under CT (2003-2010) and NT (2011-2018),

‡Treatment means for TSN and SOC were obtained under CT (2007-2010) and NT (2011-2014).

Table 2.4 Summary of relationships between wheat grain yield, TSN and SOC under NT at E222 (Stillwater) and E502 (Lahoma), Oklahoma-USA, 2007-2014.

		TSN vs. grain yield			SOC vs. grain yield		
Treatment	N rate (kg ha^{-1})	p-value	R^2	Equation	p-value	R^2	Equation
				E222			
1	0	0.0036	0.59	y = 1777.8x - 727	0.0076	0.53	y = 412.15x - 2946
2	45	0.0058	0.55	y = 2183.2x - 931	<.0001	0.95	y = 615.2x - 5020
3	90	0.2087	0.15	y = 1139.8x + 376	0.0029	0.6	y = 418.36x - 2900
4	135	0.0951	0.25	y = 1544.1x - 223	0.0206	0.43	y = 402.05x - 2840
				E502			
2	0	0.0154	0.35	y = -2732.5x + 4280	0.2003	0.11	y = -477.8x + 6094
3	22.5	0.0008	0.56	y = -3659.2x + 5745	0.0491	0.25	y = -741.33x + 8983
4	45	0.004	0.46	y = -3571.1x + 6273	0.0015	0.53	y = -1455.9x + 16290
5	67	0.0053	0.42	y = -5196.7x + 7919	0.1457	0.14	y = -734.62x + 10194
6	90	0.0041	0.54	y = -5344.8x + 8852	0.3068	0.09	y = -1059.8x + 13849
7	112	0.0133	0.44	y = -4621.5x + 9196	0.0285	0.37	y = -1265x + 16803

E502, experiment 502; E222, experiment 222; n=16 for each treatment; NT, no-tillage; TSN, total soil nitrogen; SOC, soil organic carbon.

Table 2.5 Treatment means for Grain N uptake and nitrogen use efficiency (NUE) and single-degree-of-freedom orthogonal contrasts between CT and NT treatments at E222 (Stillwater), OK. 2005-2016.

Treatment	Tillage	N rate (kg ha^{-1})	Grain N Uptake (kg ha^{-1})†		NUE (%)‡	
			mean	S.E	mean	S.E
1	CT	0	28.0	3.6	x	x
2	CT	45	35.5	4.1	16.8	2.43
3	CT	90	41.4	4.2	14.9	1.75
4	CT	135	46.4	5.7	13.7	2.23
1	NT	0	27.2	2.6	x	x
2	NT	45	40.8	3.8	30.2	4.23
3	NT	90	49.4	3.8	24.6	2.12
4	NT	135	54.3	4.2	20.0	1.78
C.V (%)			43.6		58.8	
Pr > F			<.0001		0.0002	
			Contrast level of significance			
			F Value	*Pr > F*	*F Value*	*Pr > F*
	CT1 vs		0.9022	0.02		
1	NT1	0			x	x
	CT2 vs		0.3553	0.86	11.34	
2	NT2	45				0.001
	CT3 vs		0.1653	1.94	5.92	
3	NT3	90				0.0166
	CT4 vs		0.1737	1.87	2.54	
4	NT4	135				0.1141
Average	CT vs NT	x	0.0767	3.18	18.21	<.0001

CT, conventional tillage; NT, no-tillage; NUE, nitrogen use efficiency; S.E, standard error of means for each treatment (within group)

C.V, coefficient of variation between groups (treatments)

†Treatment means for grain N uptake were obtained under CT (2005-2010) and NT (2011-2016)

‡Treatment means for NUE were obtained under CT (2005-2010) and NT (2011-2016).

Table 2.6 Treatment means for Grain N uptake and nitrogen use efficiency (NUE) and single-degree-of-freedom orthogonal contrasts between CT and NT treatments at E502 (Lahoma), OK. 2005-2016.

Treatment	Tillage	N rate (kg ha^{-1})	Grain N Uptake (kg ha^{-1})†		NUE (%)‡	
			mean	S.E	mean	S.E
2	CT	0	37.15	2.49	x	x
3	CT	22.5	44.20	3.73	46.75	9.37
4	CT	45	55.54	3.79	41.28	4.99
5	CT	67	61.26	4.48	35.99	4.64
6	CT	90	68.45	5.49	38.37	4.82
7	CT	112	82.58	5.44	42.12	4.02
2	NT	0	31.76	1.48	x	x
3	NT	22.5	42.71	1.55	48.64	7.00
4	NT	45	50.42	2.09	41.46	3.36
5	NT	67	61.36	3.00	44.17	4.48
6	NT	90	71.55	4.42	44.21	4.71
7	NT	112	78.86	4.91	42.05	4.05
C.V (%)			31.5		58.8	
Pr > F			<.0001		0.8755	
			Contrast level of significance			
			F Value	*Pr > F*	*F Value*	*Pr > F*
2	CT2 vs NT2	0	1.08	0.2987	x	x
3	CT3 vs NT3	22.5	0.07	0.7858	1.15	0.2848
4	CT4 vs NT4	45	0.96	0.3289	0	0.9808
5	CT5 vs NT5	67	0	0.9855	1.28	0.2587
6	CT6 vs NT6	90	0.32	0.5743	0.58	0.4485
7	CT7 vs NT7	112	0.49	0.4827	0	0.9927
Average	CT vs NT	x	0.93	0.3367	1.76	0.1856

CT, conventional tillage; NT, no-tillage; NUE, nitrogen use efficiency; S.E, standard error of means for each treatment (within group)

C.V, coefficient of variation between groups (treatments)

†Treatment means for grain N uptake were obtained under CT (2005-2010) and NT (2011-2016)

‡Treatment means for NUE were obtained under CT (2005-2010) and NT (2011-2016).

Table 2.7 Mean N uptake and grain nitrogen use efficiency (NUE) for winter wheat varieties used in the study at Experiment 502, Lahoma and Experiment 222, Stillwater, Oklahoma. 2005 – 2016.

Tillage	Variety	Grain Yield (kg ha^{-1})	N Uptake (kg ha^{-1})	NUE (%)
		Experiment 502		
NT	Iba	2.91^{cb}	63.2^{ba}	56.0^{a}
NT	Bullet	2.40^{cd}	56.1^{ba}	38.6^{bc}
CT	Custer	3.76^{a}	x	X
CT	Overley	3.20^{b}	66.1^{a}	45.1^{ba}
CT	Billings	2.76^{cb}	56.0^{ba}	41.3^{b}
CT	Endurance	2.96^{cb}	52.2^{bc}	39.7^{bc}
CT	Rubylee	1.91^{ed}	42.2^{dc}	31.5^{bc}
CT	Bullet	1.48^{ed}	35.9^{d}	26.9^{c}
		Experiment 222		
NT	Doublstop-CL	2.37^{b}	62.7^{a}	39.2^{a}
NT	Iba	2.88^{a}	54.8^{ba}	26.0^{cb}
NT	Endurance	2.0^{cb}	38.1^{c}	27.8^{b}
NT	Centerfield	1.19^{d}	29.6^{d}	20.1^{dc}
NT	OK9935C	0.72^{e}	17.7^{e}	10.6^{d}
CT	GoLead	2.10^{cb}	53.8^{b}	17.8^{d}
CT	P2174	2.18^{b}	53.2^{b}	18.8^{dc}
CT	OKField	1.74^{c}	27.4^{d}	12.9^{d}
CT	Custer	2.35^{b}	X	X
CT	Endurance	0.63^{e}	16.9^{e}	10.9^{d}

E502, experiment number 502; E222, experiment number 222; N, nitrogen; NUE, nitrogen use efficiency; CT, conventional tillage; NT, no tillage.

Means with different letter superscripts in the same column under each location represent significant differences in grain yield, NUE, and grain N uptake between varieties at the $p < 0.05$ level, Tukey’s HSD test.

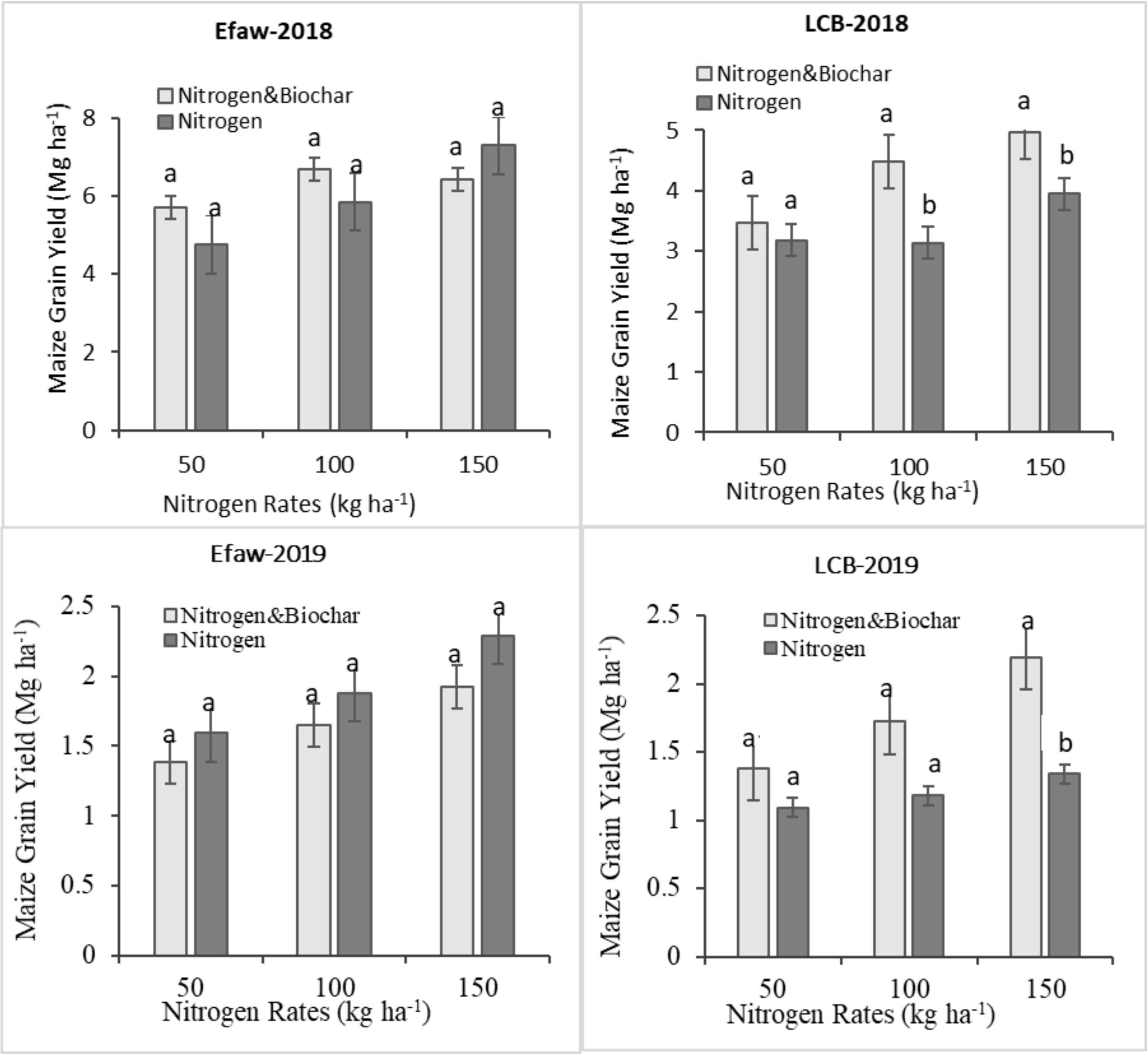

Figure 1.1 Mean maize grain yield for nitrogen (N) and N plus biochar treated plots in 2018 and 2019 at Efaw and Lake Carl Blackwell (LCB), Stillwater, Oklahoma. Biochar rates were 5, 10 and 15 Mg ha^{-1} corresponding to application rate of 50, 100 and 150 kg N ha^{-1}, respectively. Vertical columns with different letters are statistically different at $p < 0.05$; Tukey's HSD test.

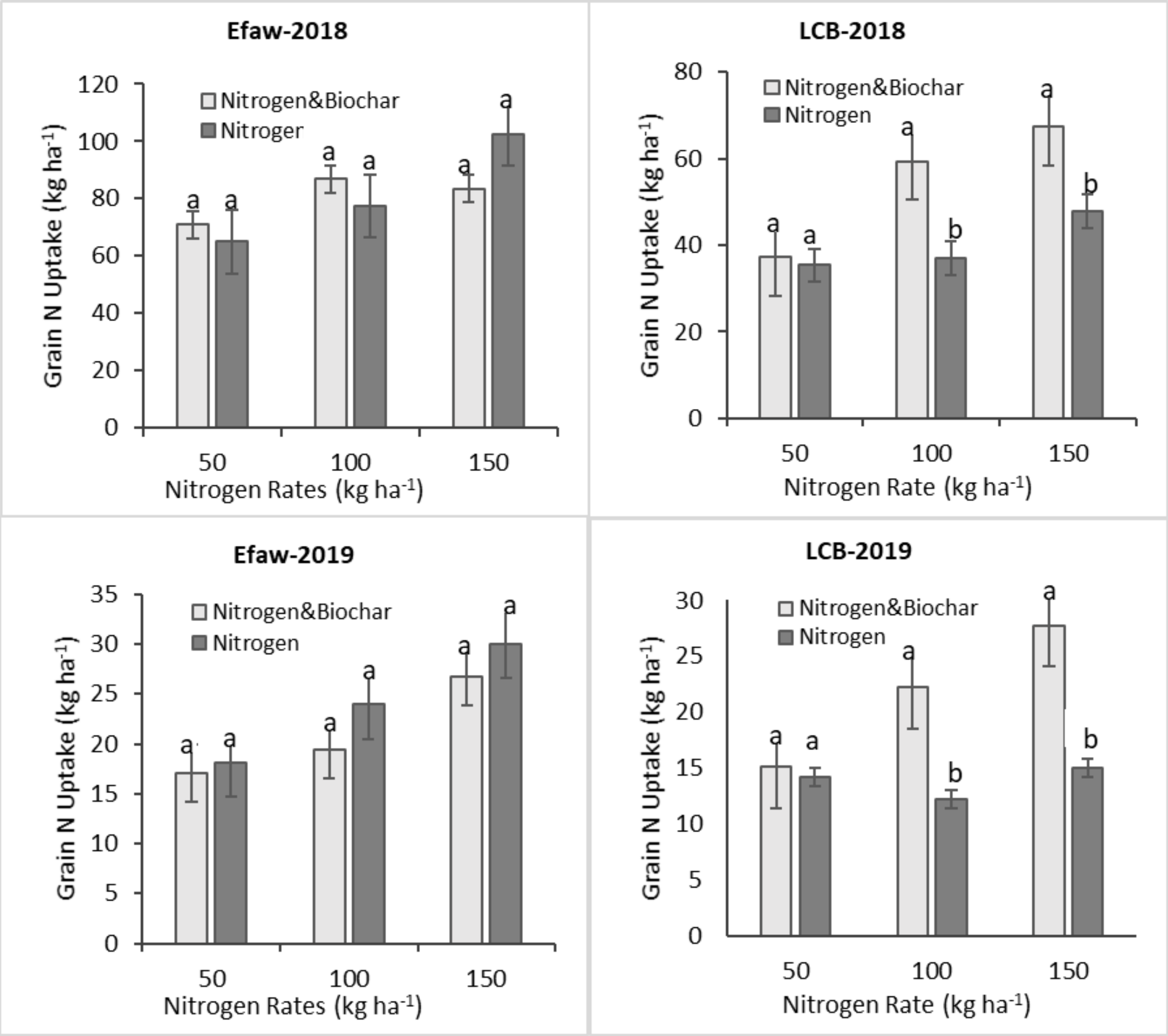

Figure 1.2 Mean maize grain N uptake for N and N plus biochar treated plots in 2018 and 2019 at Efaw and Lake Carl Blackwell (LCB), Stillwater, Oklahoma. Biochar rates were 5, 10 and 15 Mg ha^{-1} corresponding to application rate of 50, 100 and 150 kg N ha^{-1}, respectively. Vertical columns with different letters are statistically different at $p < 0.05$; Tukey's HSD test.

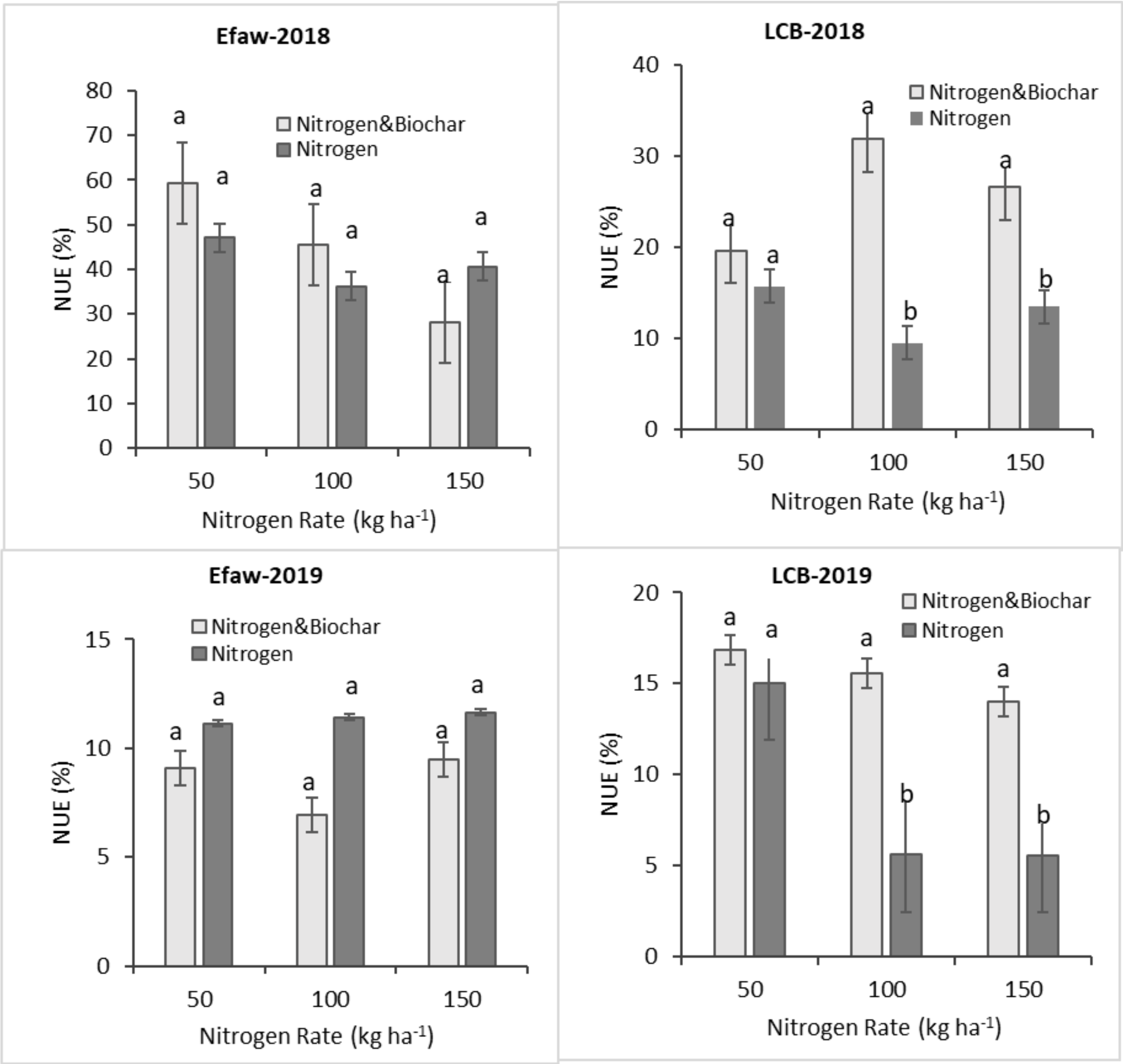

Figure 1.3 Mean grain NUE for N and N plus biochar treated plots in 2018 and 2019 at Efaw and Lake Carl Blackwell (LCB), Stillwater, Oklahoma. Biochar rates were 5, 10 and 15 Mg ha^{-1} corresponding to application rate of 50, 100 and 150 kg N ha^{-1}, respectively. Vertical columns with different letters are statistically different at $p < 0.05$; Tukey's HSD test.

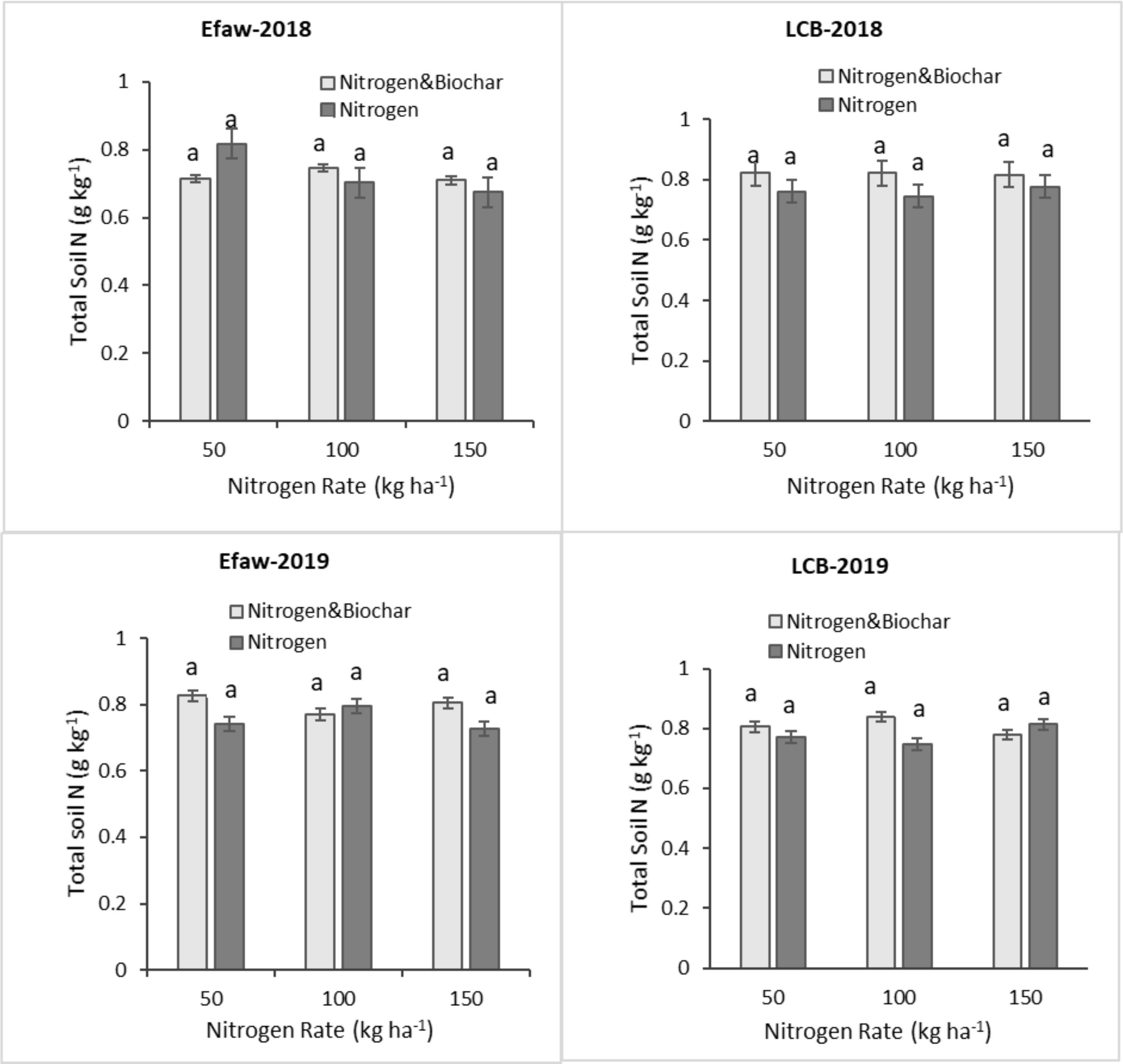

Figure 1.4 Mean total soil N for N and N plus biochar treated plots in 2018 and 2019 at Efaw and Lake Carl Blackwell (LCB), Stillwater, Oklahoma. Biochar rates were 5, 10 and 15 Mg ha^{-1} corresponding to application rate of 50, 100 and 150 kg N ha^{-1}, respectively. Vertical columns with different letters are statistically different at $p < 0.05$; Tukey’s HSD test.

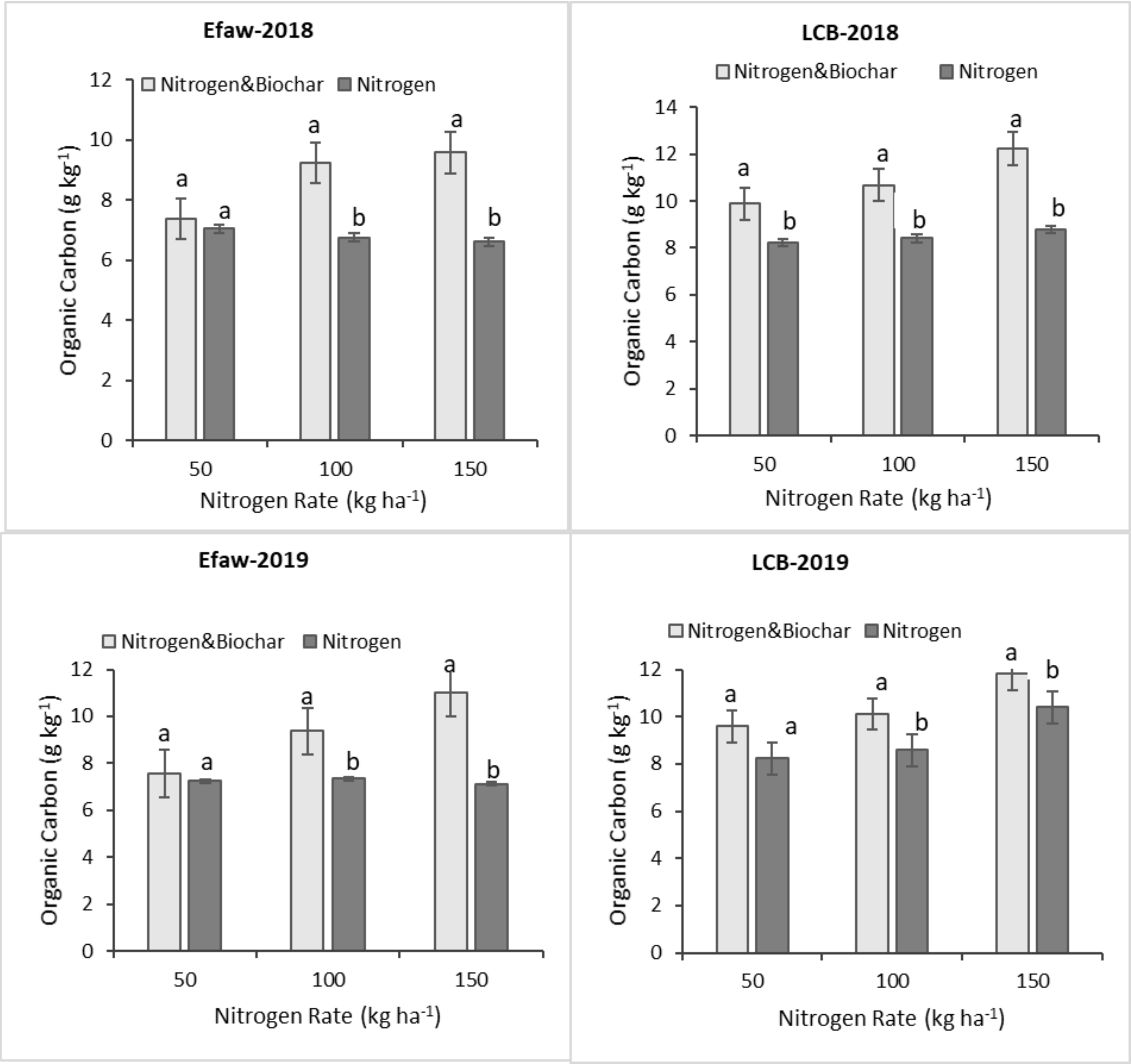

Figure 1.5 Mean soil organic carbon for N and N plus biochar treated plots in 2018 and 2019 at Efaw and Lake Carl Blackwell (LCB), Stillwater, Oklahoma. Biochar rates were 5, 10 and 15 Mg ha^{-1} corresponding to application rate of 50, 100 and 150 kg N ha^{-1}, respectively. Vertical columns with different letters are statistically different at $p < 0.05$; Tukey's HSD test.

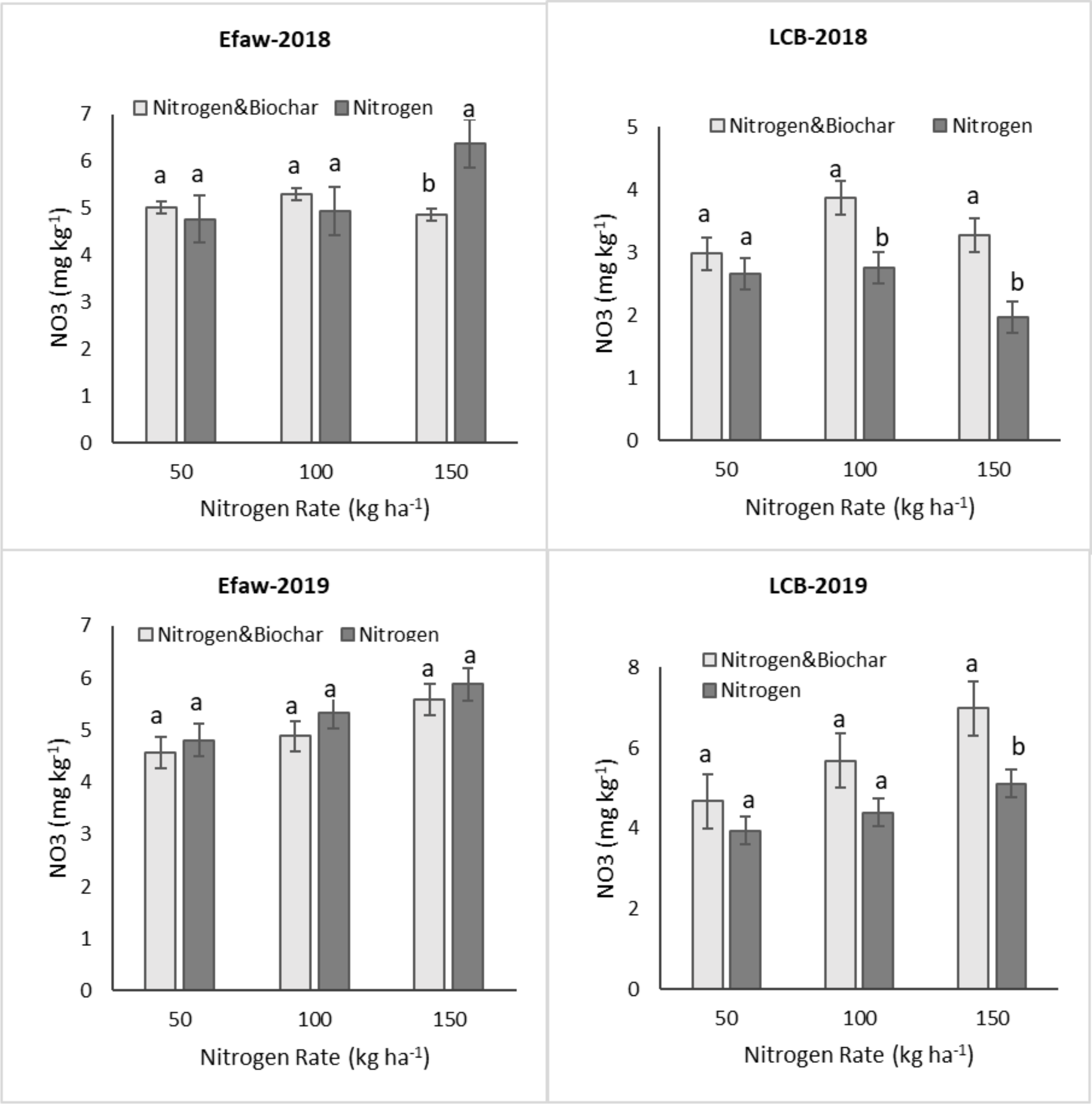

Figure 1.6 Mean soil NO3-N concentration for N and N plus biochar treated plots in 2018 and 2019 at Efaw and Lake Carl Blackwell (LCB), Stillwater, Oklahoma. Biochar rates were 5, 10 and 15 Mg ha-1 corresponding to application rate of 50, 100 and 150 kg N ha^{-1}, respectively. Vertical columns with different letters are statistically different at $p < 0.05$; Tukey's HSD test.

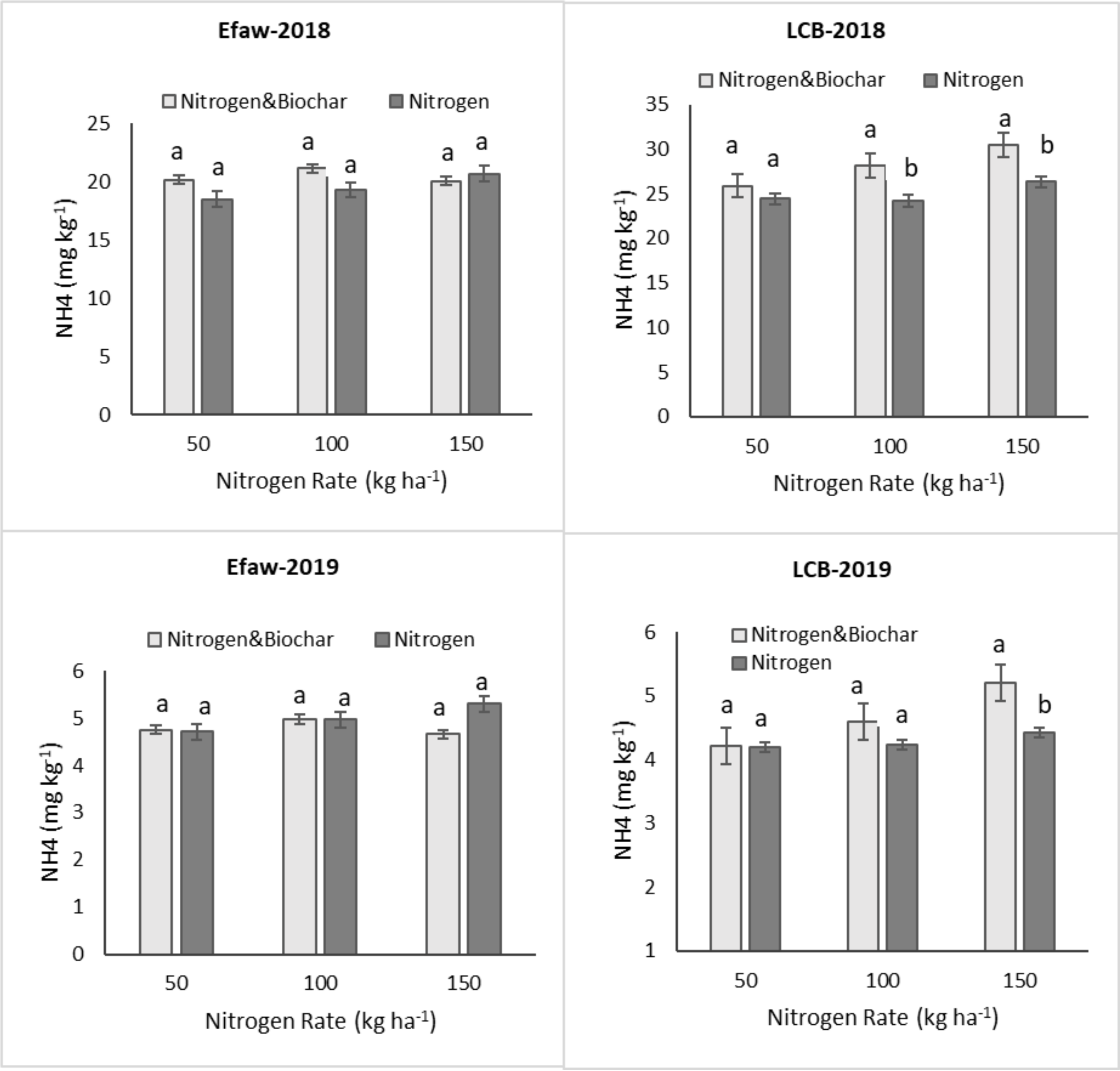

Figure 1.7 Mean soil NH4-N concentration for N and N plus biochar treated plots in 2018 and 2019 at Efaw and Lake Carl Blackwell (LCB), Stillwater, Oklahoma. Biochar rates were 5, 10 and 15 Mg ha^{-1} corresponding to application rate of 50, 100 and 150 kg N ha^{-1}, respectively. Vertical columns with different letters are statistically different at $p < 0.05$; Tukey's HSD test.

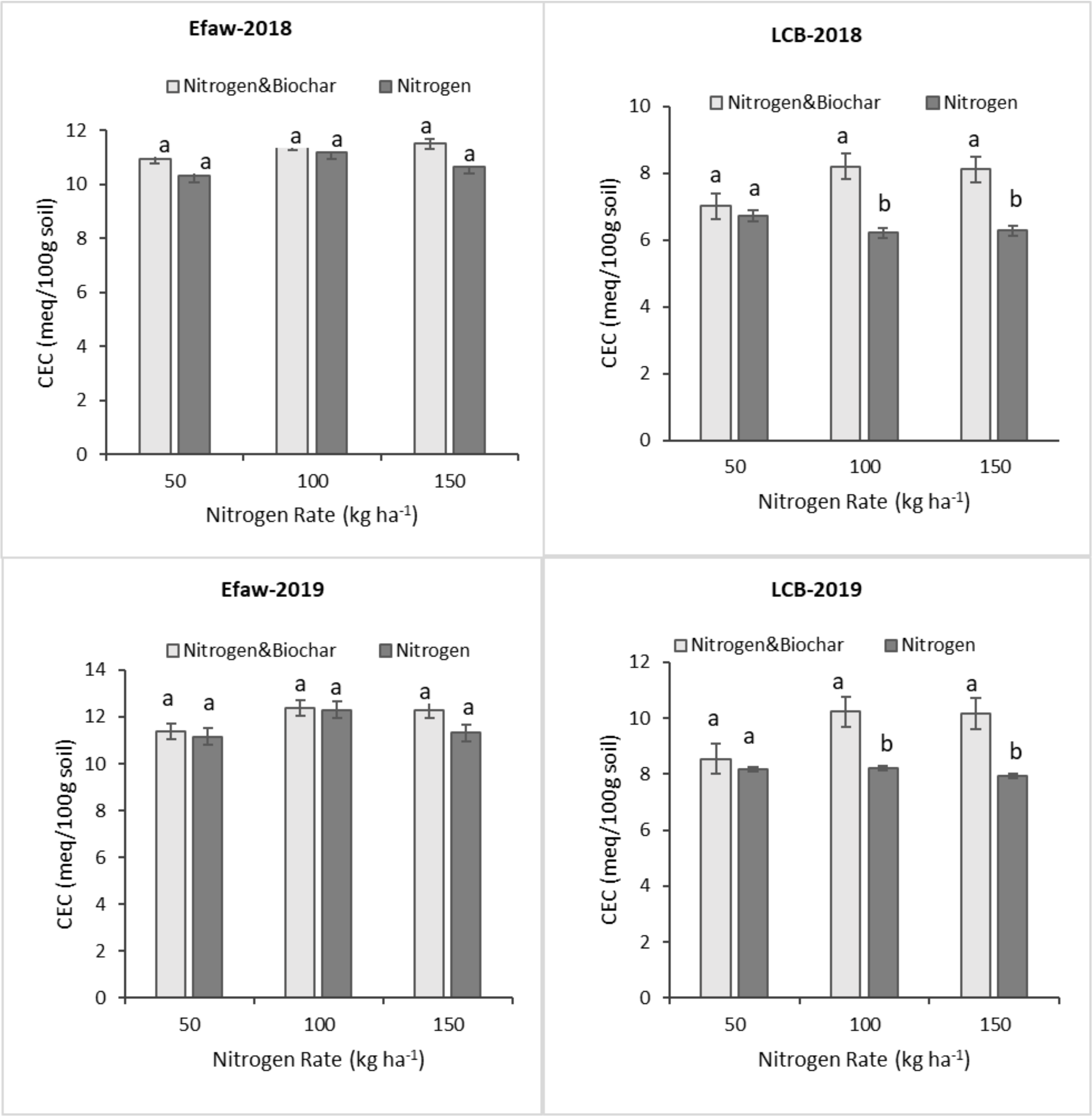

Figure 1.8 Mean CEC for N and N plus biochar treated plots in 2018 and 2019 at Efaw and Lake Carl Blackwell (LCB), Stillwater, Oklahoma. Biochar rates were 5, 10 and 15 Mg ha^{-1} corresponding to application rate of 50, 100 and 150 kg N ha^{-1}, respectively. Vertical columns with different letters are statistically different at $p < 0.05$; Tukey's HSD test.

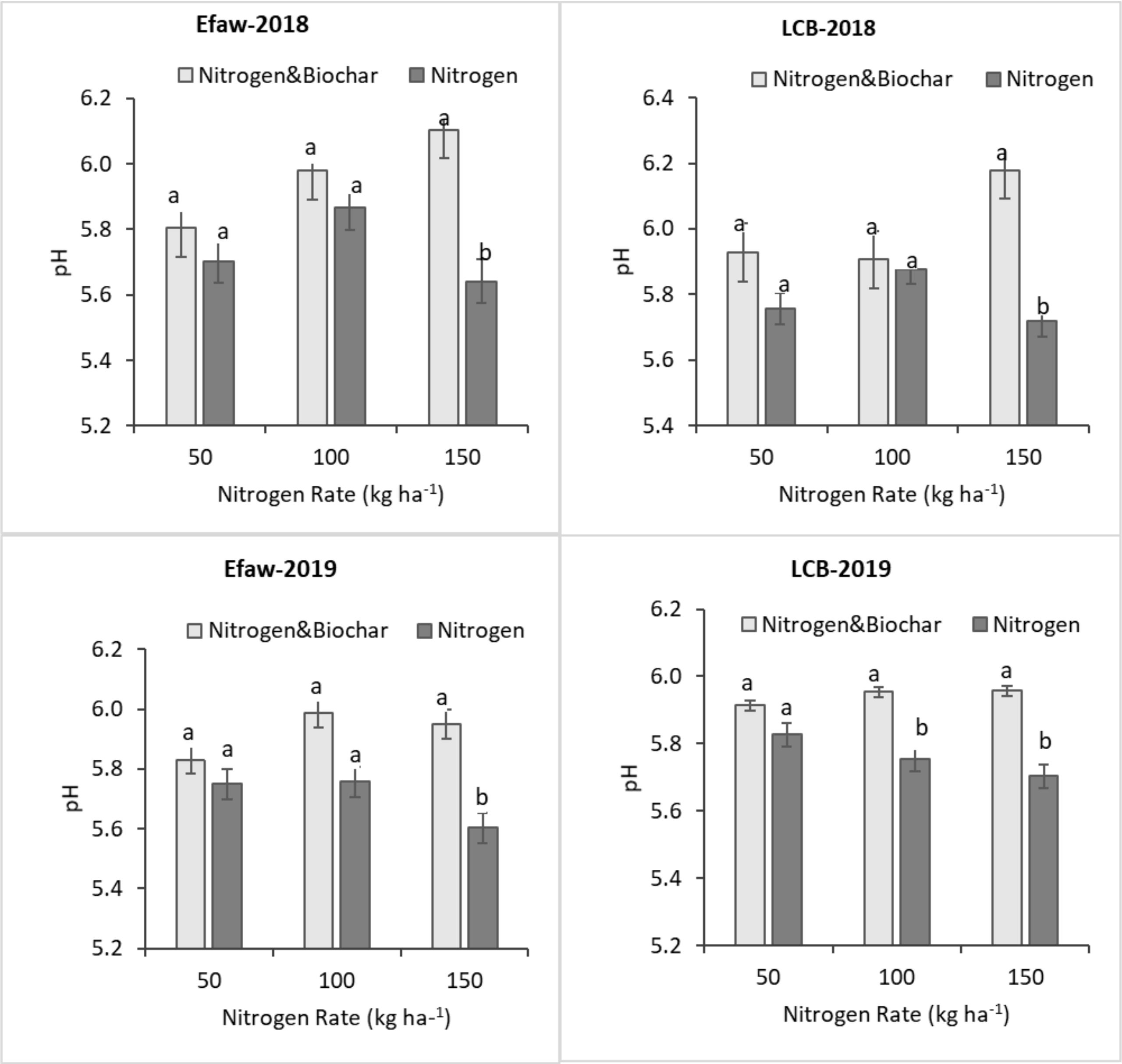

Figure 1.9 Mean pH for N and N plus biochar treated plots in 2018 and 2019 at Efaw and Lake Carl Blackwell (LCB), Stillwater, Oklahoma. Biochar rates were 5, 10 and 15 Mg ha-1 corresponding to application rate of 50, 100 and 150 kg N ha-1, respectively. Vertical columns with different letters are statistically different at $p < 0.05$; Tukey's HSD test.

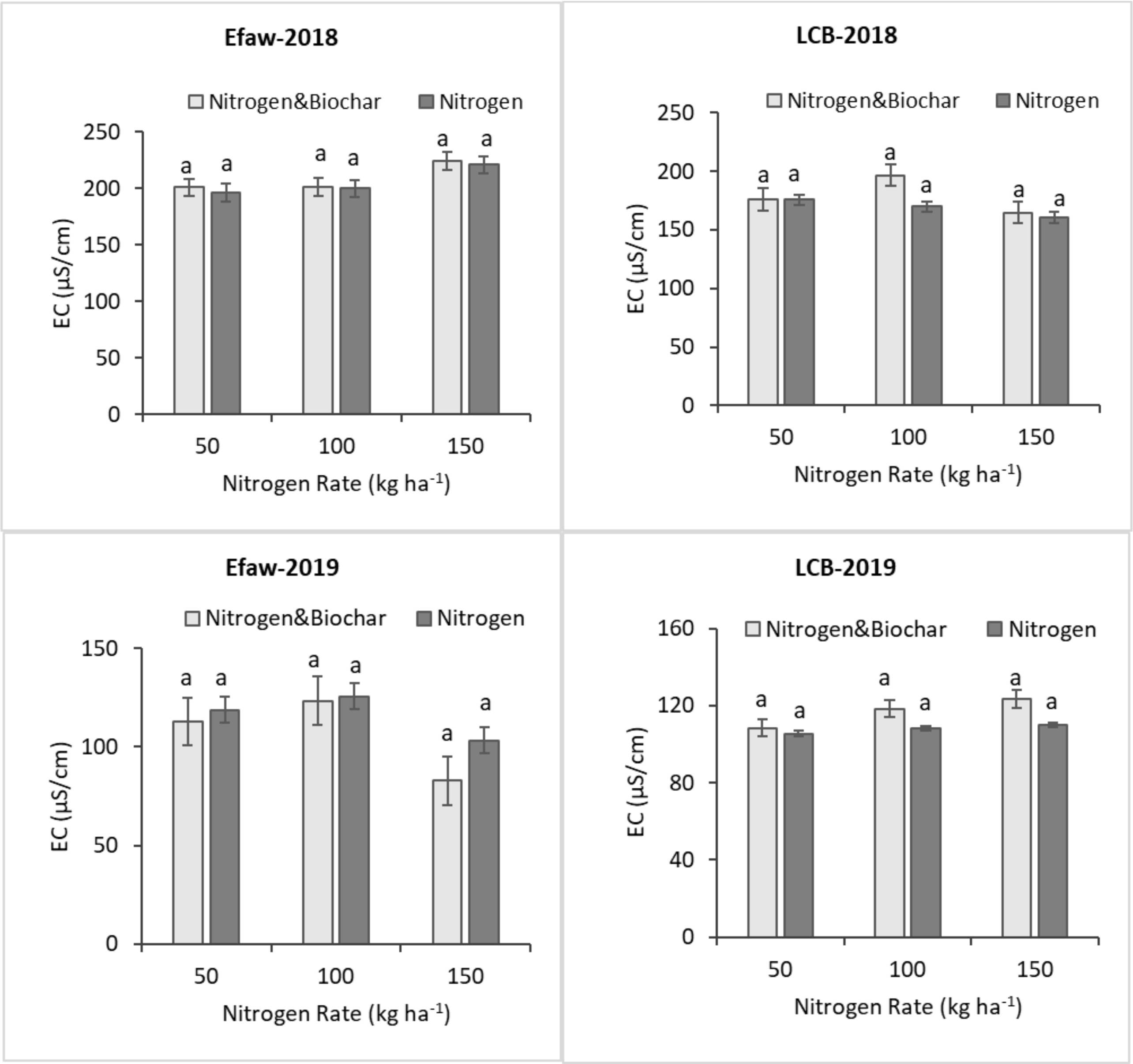

Figure 1.10 Mean Electrical Conductivity for N and N plus biochar treated plots in 2018 and 2019 at Efaw and Lake Carl Blackwell (LCB), Stillwater, Oklahoma. Biochar rates were 5, 10 and 15 Mg ha-1 corresponding to application rate of 50, 100 and 150 kg N ha-1, respectively. Vertical columns with different letters are statistically different at $p < 0.05$; Tukey's HSD test.

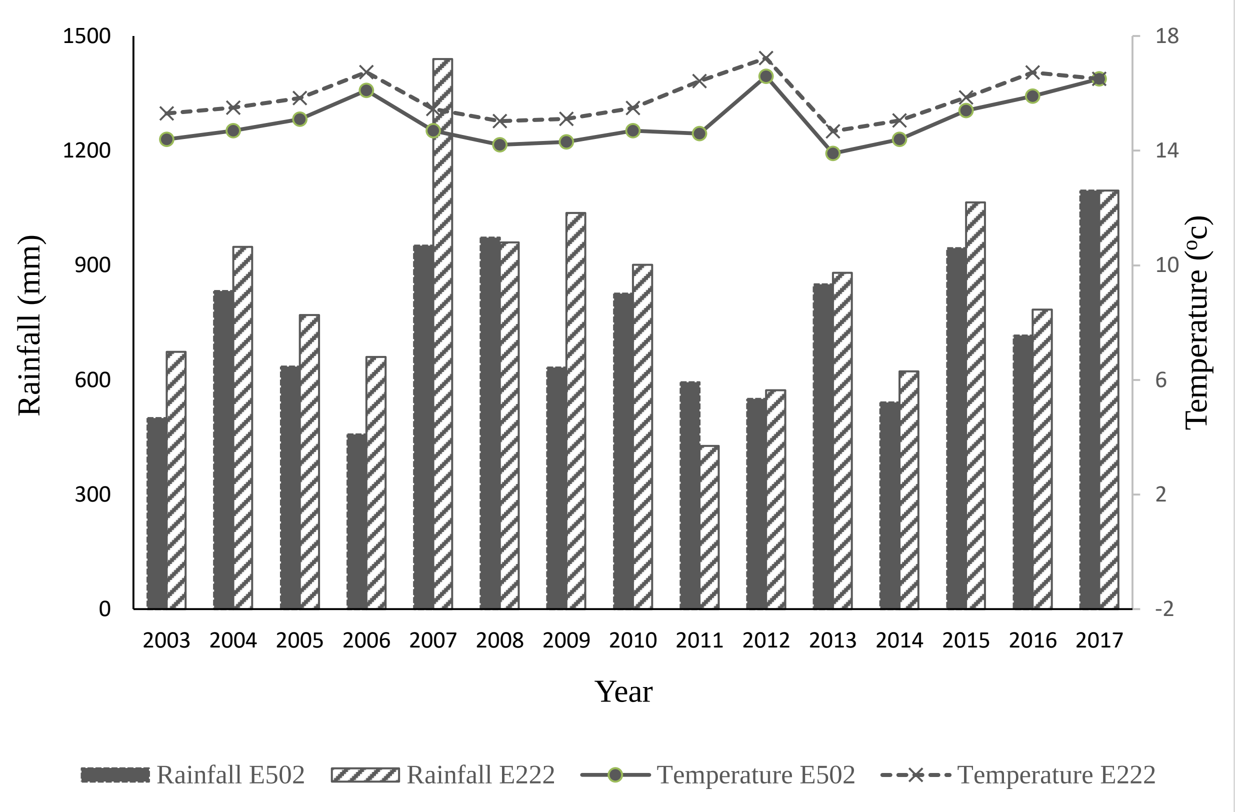

Figure 2.1 Total rainfall (October-June) and average air temperature (October-June) at E222 (Stillwater) and E502 (Lahoma), Oklahoma-USA, 2003-2017.

Figure 2.2 Average wheat grain yield for varieties planted under CT (conventional tillage) and NT (no-tillage) at E222 (Stillwater) and E502 (Lahoma), Oklahoma; different letters indicate significant differences between varieties at each site at $p < 0.05$; Tukey's HSD test.

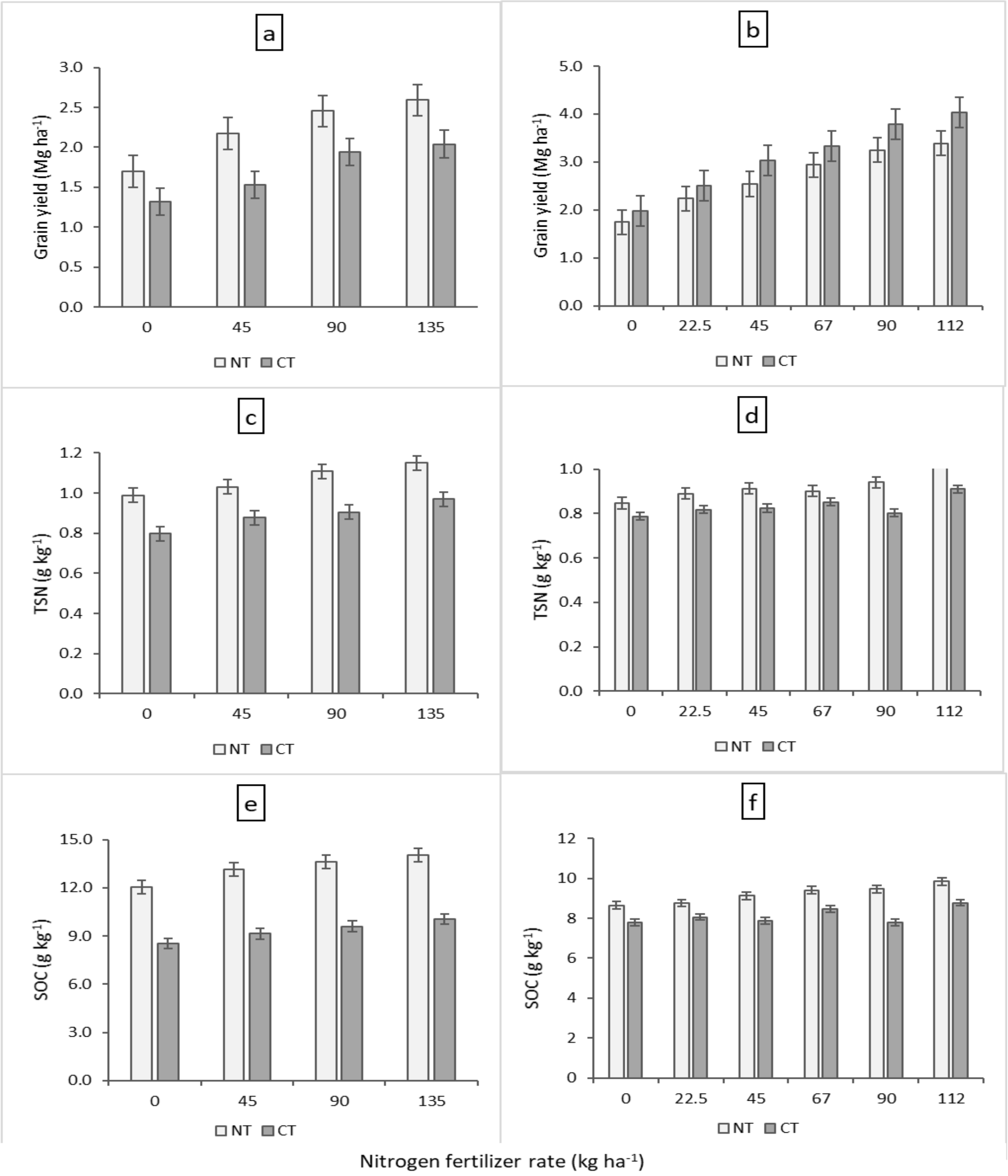

Figure 2.3 Mean grain yield at E222 (a) and E502 (b); TSN at E222 (c) and E502 (d); SOC at E222 (e) and E502 (f) as influenced by different fertilizer rates under NT (no-tillage) and CT (conventional tillage).

VITA

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Candidate for the Degree of

Doctor of Philosophy

Dissertation: IMPROVING NITROGEN USE EFFICIENCY, SOIL PROPERTIES AND GRAIN YIELD OF MAIZE (*Zea mays* L.) AND WINTER WHEAT (*Triticum aestivum* L.) WITH BIOCHAR AND NO-TILLAGE PRACTICE

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