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Nitrous Oxide Emissions from Rice Production on a Silt-loam Soil in Arkansas

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Nitrous Oxide Emissions from Rice Production on a Silt-loam Soil in Arkansas

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Master of Science in Crop, Soil, and Environmental Science

by

Casey Rector
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Abstract

Rice (*Oryza sativa* L.) is a common crop grown in Arkansas under flooded-soil conditions. The saturated to nearly saturated soil makes rice production an ideal environment for the production of potent greenhouse gases, such as nitrous oxide (N_2O). The objectives of this study were to i) evaluate the impact of water management practice (full-season-flood and intermittent-flood) and cultivar (pure-line and hybrid) on N_2O fluxes, season-long N_2O emissions, and global warming potential (GWP; 2016) and ii) evaluate the impact of tillage practice [conventional tillage and no-tillage (NT)] and type of urea fertilizer [N-(n-butyl) thiosphosphoric triamide (NBPT)-coated and non-coated urea] on N_2O fluxes, season-long N_2O emissions and GWP (2017). For both objectives, rice was grown in a direct-seeded, delayed-flood production system. Gas samples were collected from enclosed chambers at 20-min intervals for 1 hr approximately weekly between flood establishment and 4 to 7 days after end-of-season flood release. In 2016, both N_2O fluxes and season-long N_2O emissions were unaffected ($P > 0.1$) by water management or cultivar. However, season-long N_2O emissions ranged from 0.38 to 0.84 kg N_2O-N ha^{-1} $season^{-1}$ from the full-season-flood/hybrid and intermittent-flood/hybrid treatment combinations, respectively. The GWP differed ($P < 0.003$) between cultivars, where the hybrid (XL753; 2272 kg CO_2 eq. ha^{-1} $season^{-1}$) had a substantially lower GWP than the pure-line cultivar (LaKast; 4473 kg CO_2 eq. ha^{-1} $season^{-1}$). In 2017, both N_2O fluxes and season-long N_2O emissions ranged from 0.27 and 0.50 kg N_2O-N ha^{-1} $season^{-1}$ from NT/NPBT-coated urea and NT/non-coated urea, respectively, but were unaffected ($P > 0.1$) by tillage practice or type of urea fertilizer. The NT/non-coated-urea combination (2204 CO_2 eq. ha^{-1} $season^{-1}$) had the numerically largest GWP, but GWP was unaffected ($P > 0.05$) by tillage or fertilizer type. There are limited N_2O emissions studies that have been conducted in rice

production in the US, therefore, it is important to quantify and evaluate N_2O emissions from common rice production practices (full-season-flood and conventional tillage) and their alternatives (intermittent-flood and no-tillage) to estimate the environmental impacts of these practices when rice producers are considering a conversion to more sustainable practices.

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Dedication

I dedicate this thesis to my loving spouse, Ben, for always being by my side, encouraging me to follow my passion, and supporting me emotionally when the days and summers of graduate school seemed too long and arduous. I would also like to dedicate this to my family, friends, and the two most amazing dogs, Bailey and Bowie, because all have supported me in their own ways, and for that I will be eternally grateful.

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INTRODUCTION

Rice (*Oryza sativa* L.) is one of the most important grain crops in the world. The cultivation of rice has been part of the human experience for as far back as 10,000 years ago (Maclean et al., 2013). The importance of rice varies from region to region, but generally, the areas where rice has a large value also contain a large portion of the human population.

Asia is the largest global producer and consumer of rice and, as of 2015, Asia accounted for 60% of the world's human population (UN-DESA 2015; USDA-FAS 2018). Of all rice produced, 85% is consumed by humans and, through being consumed, rice contributes to the biological fitness of the human population (Maclean et al., 2013). By providing 25% of energy created from food consumption, rice is especially important for the segments of the world population defined as poor (Maclean et al., 2013). The significance of rice being a staple food and calorie source is that, as the world population continues to grow, the need for rice will continue to increase.

In comparison to other agronomic grain crops, rice has an unusual characteristic that can be viewed as both beneficial and detrimental to the environment. The main characteristic that makes rice unique is its ability to grow in saturated, flooded-soil conditions. The ability to grow in saturated, flooded conditions is beneficial because lands that might be considered non-arable can be used for rice production. A potentially detrimental environmental aspect of rice production has to do with the saturated, flooded-soil condition in which rice is grown, not the rice plant itself. The saturated, flooded-soil condition causes two separate issues. The first issue is the use of large quantities of freshwater for irrigation purposes. Freshwater irrigation is used for 75% of all rice produced around the globe to maintain the flood in rice fields (Maclean et al., 2013). The second issue is the chemical/biochemical response in the soil, which is altered when soils are flooded for days to months in rice fields or in natural wetlands.

As the oxidation/reduction (redox) potential of the soil decreases, redox reactions occur to specific compounds, such as nitrate (NO_3^-) and carbon dioxide (CO_2), reducing the compounds to potentially environmentally sensitive compounds, such as nitrous oxide (N_2O) and methane (CH_4), respectively. The biochemical modification of compounds that occurs in saturated soils is in response to the lack of oxygen available for cellular respiration in microbes and plants. Microbes and plants use NO_3^- and CO_2 as a terminal electron acceptor, also reducing those compounds to N_2O and CH_4. Nitrous oxide and CH_4 are considered greenhouse gases (GHG) that are both more potent than CO_2 in the atmosphere at trapping out-going infrared radiation within Earth's atmosphere (Cubasch et al., 2013).

In the Lower Mississippi River Delta region of eastern Arkansas, an average of 1,395 mm of water, including irrigation and rainfall, is used for rice production (Henry et al., 2016). Groundwater is the primary source of irrigation water (74%; Hardke, 2017) for rice production in Arkansas (i.e., the Lower Mississippi River Delta region of eastern Arkansas), and the current water-use rate is not sustainable (Holland, 2007). To help mitigate potential impacts of the excessive use of freshwater in the irrigation of rice, research is being conducted to evaluate rice production under different water management practices. One alternative water management practice being evaluated is intermittent flooding, which allows a rice field to naturally drain from evaporation, transpiration, and vertical and lateral seepage to a specific water potential before being re-flooded to restart the cycle. By allowing the soil to dry out, the flux of oxygen into the soil allows oxidation reactions to occur, such as chemical oxidation reactions or reactions facilitated by microbes through nitrification. This wetting and drying cycle has the potential, through microbial nitrification of ammonium (NH_4^+) that was hydrolyzed from urea (synthetic nitrogen fertilizer) and adsorbed to soil colloids after the original flooding event, to increase the amount of NO_3^- available for reduction to N_2O.

Furthermore, the preparation of crop fields, such as conventional tillage before seed planting, can negatively impact the environment. The most notable environmental impact of excessive conventional tillage was the American dustbowl of the 1930s, which was caused by an increase in soil erosion, and resulted in an overall reduction in soil health for the impacted region (Pittelkow et al., 2015). To help mitigate the environmental concerns with conventional tillage, no-tillage was introduced as an alternative. No-tillage practices help reduce soil erosion and support soil health (i.e., soil structure, water infiltration, water retention, etc.). No-tillage also increases soil organic matter (SOM) that provides nutrients to crops, but also supplies an abundance of carbon substrate to microbial communities that mediate the production of N_2O in saturated soil conditions (Liu et al., 2006; Ahmad et al., 2009).

In 2014, agricultural activities (i.e., agricultural soil management, enteric fermentation, manure management, rice cultivation, and field burning of agriculture residue) accounted for 8.3% of all GHG (i.e., CO_2, CH_4, and N_2O) in the US or 573.6 teragrams of CO_2 equivalent (Tg CO_2 Eq.) of N_2O and CH_4 (USEPA, 2016). Nitrous oxide makes up 59% (336.0 Tg CO_2 Eq.) of non-CO_2 GHG (i.e., N_2O, CH_4) emitted from agricultural activities and 95% (318.4 Tg CO_2 Eq.) of N_2O emissions came from soil management practices (i.e., synthetic nitrogen fertilizers, manure/organic fertilizer application, production of nitrogen fixing crops, etc.) (USEPA, 2016). Global non-CO_2 GHG emissions from agriculture are expected to increase by 36% and from rice production alone by 2% by 2030 (Smith et al., 2014). With limited research on N_2O emissions from rice grown under different water management practices or tillage practices in Arkansas, research is needed to quantify N_2O emissions from Arkansas rice to determine what impact alternative water management practices, particularly intermittent flooding, and tillage may have on N_2O emissions.

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CHAPTER ONE

LITERATURE REVIEW

Rice

Worldwide, rice (*Oryza sativa* L.) is one of the most important grain crops used as a staple food crop for a large human population. The cultivation of rice has been part of the human experience for as far back as 10,000 years ago (Maclean et al., 2013). However, there are two cultivated rice species (*Oryza sativa* and *Oryza glaberrima)* that are consumed by the human population. *Oryza sativa* is the most common of those species grown, while *O. glaberrima* is almost exclusively confined to Africa (Maclean et al., 2013). *Oryza sativa* is a rice species with two main sub-species (*indica* and *japonica*) with many varieties, and 75% of cultivated varieties are a direct result of breeding by researchers (Maclean et al., 2013). Rice is grown in a wide array of climatic zones ranging in air temperature (i.e., 17 to 33°C), solar radiation (25 to 95% of potential), elevation (i.e., sea level to 2,600 m above seas level), and rainfall (i.e., 100 to 5100 mm) during the growing season (Maclean et al., 2013).

Rice is a semi-aquatic, perennial grass that grows in flooded-/saturated-soil conditions, but is most often cultivated as an annual crop (Maclean et al., 2013). To compensate for reduced Oxygen (O_2) levels in flooded/saturated soils, rice, through programmed cell death, forms aerenchyma tissue inside the plant to assist in transporting atmospheric O_2 from the leaves to the roots (Counce et al., 2003). With the ability to transport gases, rice plants can also act as a passive conduit for greenhouse gases that are produced in the soil to be transported from the soil to the atmosphere through transpiration (Yu et al., 1997; Yan et al., 2000).

There are abiotic factors other than a flooded field that impact rice production (i.e., sunlight hours and temperature) (Yoshida, 1981). Temperature effects differ depending on growth stage, with the minimum and maximum temperature ranges of 10 to 45°C occurring during germination, and optimal ranges of 20 to 25°C for grain yield occurring during ripening

(Yoshida, 1981). Ripening has critical levels of 12 to 30°C, with sterility of the plant becoming more prominent outside those ranges (Yoshida, 1981). Most rice varieties have an optimum photoperiod (i.e., the length of daylight between sunrise and sunset) of 9 to 10 hours that reduces the number of days required for the plant to flower after being planted (Yoshida, 1981). Some rice varieties may have an optimum range that allows a photoperiod of 12 hours (Yoshida, 1981). The physiological requirements of rice associated with the surrounding environment play a major role in where rice and its different subspecies can be easily grown, where the ease of growing a cereal grain can influence the diet of a local population.

Rice Production

Global Rice Production

For the 2017 growing season, global milled rice production was over 480 million metric tons (MMT) on over 160 million hectares, and rice was grown on all continents except Antarctica (USDA-FAS, 2018). The largest rice-producing region in the world is in Asia, which accounts for around 89% of all rice grown, followed by South America with 3% (USDA-FAS, 2018). Asia also has nine of the top 10 rice-producing countries (Brazil is ranked 8th) with just two countries, China (144 MMT) and India (109 MMT), accounting for over 50% of all milled rice produced (USDA-FAS, 2018). Additionally, Asia accounts for around 85% of all rice consumed (USDA-FAS, 2018).

The most common rice-production practice is growing rice in irrigated lowlands in paddies or bundled fields, which are small plots that have walls/levees that keep the water pooled inside (Maclean et al., 2013). Rice can be planted directly in the soil before flooding (i.e., direct-seeded), or can be planted in dry soil located away from the paddy or bundled field, and after emergence, the rice plants are transplanted to the flooded patties/fields (Maclean et al., 2013). The irrigated lowland rice production systems account for about 75% of all rice produced globally (Maclean et al., 2013). Rice is also diverse enough to be grown in upland areas, areas that are drier than lowland regions, and upland rice production accounts for 4% of total rice production (Maclean et al., 2013). *Indica* and *japonica* are rice sub-species that account for 75 and 8% of the global rice trade, respectively, with *indica* coming from tropical regions of Asia and *japonica* coming from the more temperate regions across the globe (i.e., North America) (Maclean et al., 2013; USDA-ERS, 2016).

US Rice Production

Rice production in the United States (US) began when rice seeds were transported from Madagascar to Charleston, SC by John Thurber and were given to Dr. Henry Woodward for planting in 1685 (Dethloff, 2003). By 1709, the US was producing 680 metric tons of rice per year (Dethloff, 2003). By 2017, the US had increased that production to around 7 MMT of rice per year, which is approximately 1.4% of the global annual rice production, however, the US accounts for 7% of all exported rice (USDA-FAS, 2018).

The US has three main rice-producing regions: Mississippi Delta (AR, LA, MO, and MS), Gulf Coast (TX and southwest LA), and the Sacramento Valley of CA, with AR, CA and LA making up 82% of the national rice production (Maclean et al., 2013). The US specializes in growing long-grain rice, which constitutes 75% of all rice grown in the US, instead of the more common short-grain varieties grown in other countries (Hardke and Wilson, 2013; USDA-ERS, 2016). *Japonica* is the most common rice sub-species grown in the US due to the temperate climate (USDA-ERS, 2016).

Rice producers in the US utilize two common planting methods that differ from region to region and could differ within a state. The two common planting methods in the US are water-seeded and dry-seeded methods. Water-seeded planting requires a prepared seedbed that is flooded, in which pre-germinated rice seeds are aerially released from a plane that is flown over the field (Street and Bollich, 2003). Dry-seeded planting requires a prepared seedbed, in which rice is drill-seeded at a depth of at least 2.5 cm prior to establishing a flood (Street and Bollich, 2003).

Arkansas Rice Production

Rice production in Arkansas can be traced back to as early as 1902, with some reports pushing that date back even further to the American Civil War (Hardke and Wilson, 2013). Arkansas rice production accounts for 47% of all rice produced in the US, making Arkansas the leading rice-producing state in the country (Hardke, 2017). The top five rice-producing counties in Arkansas, in descending order of harvested area, are Poinsett, Jackson, Lawrence, Cross, and Lonoke, which are all located in the eastern part of the state and collectively account for 35% of total harvested area of rice in Arkansas (Hardke, 2017). Arkansas produces 56% of the long-grain rice in the US compared to the second largest rice-producing state, California (< 1% of the long-grain rice production), which grows 71% of the medium-grain rice in the US (Maclean et al., 2013; USDA-NASS, 2018).

Around 80% of Arkansas' rice is planted using the dry-seed method, while California's predominant method of planting rice is the water-seeding method (Hardke and Wilson, 2013; Maclean et al., 2013). Crop rotations that predominate in Arkansas are soybean (*Glycine max* L.)-rice (68%) and rice-rice (20%; Hardke, 2017). Conventional-tillage practices account for

61% of all tillage practices, and silt-loam surface texture is present in 48% of rice fields (Hardke, 2017). The continuous, full-season flood water management practice accounted for 95% of Arkansas' rice fields in the 2016 growing season (Hardke 2017). Rice planting and harvesting dates in Arkansas ranges from March to June and August to November, respectively, in contrast to California, which has planting and harvest times that range from April to June and September to November, respectively (Maclean et al., 2013; Hardke, 2017). Arkansas and other southern states grow more hybrid rice varieties than California, which grows mostly pure-line rice varieties (Maclean et al., 2013).

Even though Arkansas shares several similarities with the other southern rice-growing states, Arkansas does not maintain a year-round average air temperature as warm as that in Louisiana or Texas, which hinders the production of a second rice crop (i.e., a ratoon crop). Therefore, only one rice crop per year is typical in Arkansas, while many places in Texas and Louisiana manage and produce a ratoon crop each year (Maclean et al., 2013). Arkansas' 2017 average long-grain rice yield was 8.4 Mg ha^{-1}, with a total production of 3,248 Mg long-grain rice on an estimated harvested area of 386,000 ha (USDA-NASS, 2018).

Cultivar

Even within a sub-species (i.e., *indica* or *japonica*), rice cultivars are diverse with differing traits. A cultivar may have traits that are desirable for producers, such as disease, insect, lodging, or environmental stress resistance and improved yield, that another cultivar may not possess (McClung, 2003). Through selective breeding practices of rice from the same cultivar for desired traits, an improved cultivar is created and is referred to as a pure-line cultivar. Carolina Gold was one of the original rice cultivars grown in the US and is the parent behind still-used cultivars, such as Dawn and derivations of Dawn (Mackill and McKenzie, 2003). Hybrid rice varieties are first generation (F1) seedlings from the crossing of two pure-line cultivars with different desirable traits (i.e., drought resistance, disease resistance, etc.) resulting in greater yields (Wilson et al., 2013). The hybrid cultivars CLXL745 and CLXL753 are the two most common rice varieties grown in Arkansas, and account for 1/3 of all planted rice area (Hardke, 2017).

Nitrogen Fertilization

Nitrogen (N) is an essential plant macronutrient, and is the one nutrient in which most plants are deficient due to soil deficiencies (Havlin et al., 2014). Nitrogen is a key component of protein synthesis in leaves that allows for increases in leaf size to maximize photosynthesis, and therefore is important in the early stages of rice growth (i.e., S0-S3 and V1-V13 growth stages) (Norman et al., 2003, 2013). Nitrogen is also important during panicle differentiation in the R1 reproductive growth stage that will influence grain yield (Norman et al., 2003).

To assist the rice plant in yielding as much grain as possible, N-fertilizers are being used to supply the plant with more N than the soil alone can provide. The amount of N-fertilizer that will effectivity maximize yield is specific to the rice cultivar, soil texture, and previously grown crop (Norman et al., 2013). Urea (46% N) and N-(n-butyl) thiosphosphoric triamide (NBPT)-coated urea (46% N) are two of the most common N-fertilizers used in rice production because of their large N concentration (Norman et al., 2003, 2012). The NBPT coating is a urease inhibitor that helps reduce the loss of mineral N from ammonia (NH_3) volatilization in different crop production systems [i.e., rice and wheat (*Triticum aestivum* L.)] (Norman et al., 2009; Dillon et al., 2012). The average total N-fertilizer rate for cultivars (i.e., pure-line and hybrid) commonly grown in Arkansas on a silt-loam soil in a soybean-rice crop rotation is 160 kg N ha^{-1} with a two-way split N-fertilizer application (Norman et al., 2013). In a two-way split application of N-fertilizer, 65-75% of the season total (160 kg N ha^{-1}) is applied prior to flooding with the remaining 25-35% applied at either the internode elongation stage (i.e., pure-line cultivars) or at the booting stage (i.e., hybrid cultivars) (Norman et al., 2013).

The two methods currently being used to determine N-fertilizer recommendations in Arkansas are the Standard Method and the N-Soil Test for Rice (N-Star) (Norman et al., 2013). The Standard Method N-fertilizer recommendations are based on cultivar, soil textural class, and previous crop, assuming all soils of the textural class are the same, and the N-Star method recommendations are based on cultivar, soil textural class, and a soil sample (i.e., 46-cm soil depth for silt-loam soil) that is analyzed for N available for plant uptake (Norman et al., 2013).

Tillage

Historically, conventional tillage has been used in agronomic production systems. Conventional tillage is the process of disturbing the topsoil in a field, including organic residue from the previous crop, to a specific depth, which helps with weed suppression and seedbed preparation (Brady and Weil, 2008). Since conventional tillage at least partially incorporates the previous crop's residue, the topsoil is left partially bare. Bare topsoil increases the rate of soil erosion creating possible environmental issues with regards to nutrient and sediment pollution in waterways. To help mitigate the environmental issues, other tillage practices are being used in replace of conventional tillage including: conservation tillage and no-tillage. Conservation tillage and no-tillage practices are distinct from conventional tillage because the plant residue mostly remains on the soil surface allowing for slower decomposition of organic matter (Brady and

Weil, 2008). To be considered conservation tillage, there must be at least 30% residue remaining on the surface, while no-tillage leaves all of the previous crop's residue on the soil surface (Brady and Weil, 2008). Conventional tillage and no-tillage account for 61 and 4%, respectively, of tillage practices used in rice production in Arkansas (Hardke, 2017).

Water Management

Several types of water management practices (i.e., continuous, full-season flood, intermittent flooding, or mid-season drain) are currently used globally for rice production. The most common type, both historically and currently, is the continuous, full-season flood. Another water management practice that is gaining popularity is intermittent flooding, and with no known operational difference is also being described as alternate-wet-and-dry (AWD) flooding (Roberts et al., 2015; LaHue et al., 2016). Intermittent flooding allows the rice field to drain, after establishment of the initial flood, through evapotranspiration and/or percolation into and through the soil profile to a specific soil water potential or volumetric water content (i.e., ~ -20 kPa or ~ 0.35 cm^3 cm^{-3}, respectively), and then be re-flooded, with this cycle continuing throughout the entire growing season without significantly reducing yield (Linquist, 2015; Roberts et al., 2015; LaHue, 2016). However, Linquist et al. (2015) reported some grain reduction in fields that were allowed to periodically drain to 40% of the volumetric water content. As of 2015, the continuous, full-season-flood scheme accounted for 95% of the water management practices used in Arkansas, with intermittent flooding making up 2% (Hardke, 2017). Furrow irrigation of upland rice has increased in Arkansas from < 1% in 2015 to almost 3% in 2016 (Hardke, 2017)

Irrigation Water Sources

In Arkansas, approximately 63% of all water used, whether for commercial, residential, or agricultural use, comes from groundwater, and of that 63% groundwater, 95% comes from the Alluvial Aquifer in the Lower Mississippi River Delta region of eastern Arkansas (ANRC, 2015). The Alluvial Aquifer extends from southeastern Missouri to northern Louisiana, and under the Mississippi River into Tennessee and Mississippi, where 98% of the groundwater withdrawals are used specifically for irrigated agriculture (ANRC, 2015).

Irrigation for crops, pasture land, parks, golf courses, etc. accounts for 92% of groundwater use and 72% of all water sources (i.e., groundwater and surface water) used in Arkansas (Holland, 2007). Groundwater use for irrigation purposes in Arkansas has increased from 3.59 x 10^6 m^3 d^{-1} (949 Mgal d^{-1}) in 1965 to 2.63 x 10^7 m^3 d^{-1} (6942 Mgal d^{-1}) in 2005 (Holland, 2007). A sustainable pumping rate for the Alluvial Aquifer was estimated to be 1.28 x 10^7 m^3 d^{-1} (3374 Mg d^{-1}), but the current pumping rate is 3.04 x 10^7 m^3 d^{-1} (8036 Mg d^{-1}), which results in daily over-pumping of 1.77 x 10^7 m^3 d^{-1} (4662 Mg d^{-1}) (ANRC, 2015). In Arkansas, irrigation for rice accounts for 35% of all groundwater withdrawals and 40% of all water sources used for irrigation (Holland, 2007). In general, rice grown in the southern US requires an estimated 1000 to 2500 m^3 ha^{-1} or an average of 1,395 mm of water, including irrigation and rainfall, to produce an optimal yield (Street and Bollich, 2003; Henry et al., 2016). The amount of water required for rice production is substantially more than other crops commonly grown in Arkansas, such as, cotton [(*Gossypium hirsutum L.*); 516-1300 mm], corn [(*Zea mays* L.); 500-800 mm], soybean (450-700 mm), and wheat (450-650 mm) (Chapagain et al., 2005; UN-FAO, 2015).

Oxidation-Reduction

Oxidation-reduction (redox) reactions occur when a compound's parent element has an increase or decrease in valence charge, and can occur through chemical or biochemical interactions. A chemical redox reaction is the movement of electrons from one compound to another compound, or the acceptance, by a compound, of available electrons in the soil profile (Sposito, 2008). This type of chemical reaction does not occur at any meaningful rate, thus for reduction in the soil to occur, bacteria act as a catalyst in coupling oxidation and reduction reactions, where organic C is oxidized to generate the reduction of specific compounds (i.e., O_2, NO_3^-, CO_2, etc.) through the biochemical process of cellular respiration (Scott et al., 2003).

Oxygen is the first element reduced during cellular respiration, and when all the O_2 has been reduced, the next compound that is reduced is nitrate (NO_3^-) (Scott et al., 2003; Brady and Weil, 2008). Biochemical cellular respiration still occurs when O_2 levels are depleted because facultative anaerobes replace O_2 as their terminal electron acceptor with another compound (i.e., NO_3^-, MnO_2, Fe^{3+}, SO_4^{2-}, or CO_2) and are used for metabolism (van Breeman and Feijtel, 1990; Brady and Weil, 2008). A facultative anaerobe prefers O_2 as its terminal electron acceptor, but, in the absence of O_2, preference changes based on the redox potential [E_h, measured in volts (V) or millivolts (mV)] of the soil (Brady and Weil, 2008). Redox potential (E_h) is the state of the soil in relation to how easily electrons of a compound can be transferred to another compound, and each compound that is donating electrons has an E_h range that promotes reduction [i.e., O_2 (+380 to +320 mV), NO_3^- (+280 to +220 mV), MnO_2 (+220 to +180 mV), Fe^{3+} (+110 to +80 mV), SO_4^{2-} (-140 to -170 mV), and CO_2 (-200 to -280 mV)] (Brady and Weil, 2008) . The reduced forms of O_2, NO_3^-, MnO_2, Fe^{3+}, SO_4^{2-}, CO_2 are as follows: H_2O, N_2, Mn^{2+}, Fe^{2+}, H_2S, and CH_4 (Brady and Weil, 2008).

Arsenic

Some metals, such as arsenic (As), become mobile and plant accessible in reduced soil conditions (Zhao et al., 2010). Arsenic can exist in two forms in the soil, arsenate [As(V)] under oxidized conditions, which is immobile, and arsenite [As (III)] under reducing conditions. The reduced form [As (III)] becomes mobile in anoxic soils, which encourages anaerobic bacteria to use As (V) as their terminal electron acceptor in the absence of O_2 (Zhao et al., 2010). Atmospheric O_2 diffuses into the soil during the dry-down period of an AWD water management practice and the influx of O_2 promotes oxidation of arsenite [As (III)] to arsenate [As(V)] (Linquist et al., 2015). The oxidizing of arsenite [As (III)] helps mitigate As uptake by the rice crop and concentration in rice grain by immobilizing As in the soil as arsenate [As(V)] (Linquist et al., 2015). Consequently, in addition to minimizing irrigation water use, the AWD water management scheme serves a secondary purpose of minimizing As uptake and accumulation in rice grain.

Greenhouse Gas Emissions

Greenhouse gases are chemical compounds that absorb infrared radiation that is reflected off the Earth's surface (Cubasch et al., 2013). The absorption of infrared radiation results in a warming effect in the lower atmosphere and surface of the Earth (Cubasch et al., 2013). Greenhouse gases are compounds that come from naturally occurring sources (i.e., cellular respiration, oxidation/reduction processes, etc.), but can also come from anthropological sources (i.e., fuel combustion, over fertilization in agriculture, energy production, etc.). The most common greenhouse gases are CO_2, CH_4, and N_2O and their concentrations in the atmosphere have steadily increased since the mid-18th century (CO_2 by 40%, CH_4 by 150%, and N_2O by

20%; IPCC, 2014). As of 2005, agricultural lands and production systems produced 54% of all non-CO_2 greenhouse gas emissions (i.e., N_2O and CH_4), and of the non-CO_2 emissions from agriculture, synthetic fertilizers, particularly N-fertilizers, and rice production accounted for 12 and 11%, respectively (USEPA, 2012; Smith et al., 2014). As of 2014, the overall greenhouse gas emissions in the US were approximately 6,870 MMT of CO_2 equivalent (MMT CO_2 Eq.) with rice contributing to 14.7 MMT CO_2 Eq. of CH_4, and overall agriculture soil management (not exclusive to rice) contributing 403.5 MMT CO_2 Eq. of N_2O (USEPA, 2016). Non-CO_2 greenhouse gas emissions from agriculture are expected to increase by 36%, and by 2% from rice production specifically, by 2030 (Smith et al., 2014). As of 2016, the average monthly N_2O and CH_4 concentrations in the atmosphere were ~329 and 1800 ppb, respectively (NOAA-ESRL/GMD, 2017).

Nitrous oxide has a global warming potential (GWP) that is 298 times more than that of CO_2, based on a climate-carbon feedback 100-yr time scale, while CH_4 has a GWP that is only approximately 34 times greater than that of CO_2 (Myhre et al., 2013). The GWP relates the radiative forcing that 1 kg of a greenhouse gas (i.e., N_2O or CH_4) has in the atmosphere compared to the radiative forcing of 1 kg of CO_2 (Shine et al., 1990). To estimate non-CO_2 emissions from specific activities, the Intergovernmental Panel on Climate Change (IPCC) has set the emissions factor from flooded rice fields at 3 g N_2O-N kg N input^{-1}, and the United States Environmental Protection agency (USEPA) has set the CH_4 emissions factor from non-California primary rice crop production at 177 kg CH_4-C ha^{-1} season^{-1} (de Klein et al., 2006; USEPA, 2014).

Methane Emissions from Rice in Arkansas

Methane fluxes and total growing-season emissions have been quantified from rice production in Arkansas for several years (Brye et al., 2013; Rogers et al., 2013, 2014; Smartt et al., 2016 a,b), with different treatments and soil properties, showing rice production is a source of C emissions in the atmosphere. Brye et al. (2013) evaluated soil texture effects on CH_4 fluxes and total season emissions from drill-seeded, delayed flood rice production cropped to a rice-soybean rotation in Arkansas with pure-line cultivar ‘Taggart’. Brye et al. (2013) reported that the largest CH_4 peak flux occurred 51 days after flooding (DAF) in a N-fertilized rice-silt loam treatment (15.6 mg CH_4-C m^{-2} h^{-1}) compared to an N-fertilized rice-clay treatment (4.8 CH_4-C m^{-2} h^{-1}), which did not occur until 60 DAF (Brye et al., 2013). The lowest CH_4 fluxes were reported for the bare-soil treatment, with negligible CH_4 fluxes during the flooded portion of the growing season (Brye et al., 2013). Total season-long, area-scaled CH_4 emissions were largest in a N-fertilized rice-silt-loam treatment (138.6 kg CH_4-C ha^{-1}) compared to an N-fertilized rice-clay treatment (35.0 kg CH_4-C ha^{-1}) (Brye et al., 2013). While the bare-soil treatment had the lowest total season-long, area-scaled CH_4 emissions, with the silt-loam treatment having 5.5 kg CH_4-C ha^{-1} compared the lowest emissions measured in the clay treatment (0.5 kg CH_4-C ha^{-1}) (Brye et al., 2013).

Rogers et al. (2013) evaluated CH_4 fluxes and total season-long emissions from a drill-seeded, delayed flood rice production on a silt-loam soil cropped to a rice-soybean rotation in Arkansas with the pure-line cultivar ‘Wells’. The effects of N-fertilization, chamber placement (i.e., in a rice row or between rows), and vegetation (i.e., rice or bare soil) on CH_4 emissions were investigated (Rogers et al., 2013). Rogers et al. (2013) reported that CH_4 fluxes peaked around 41 DAF, where the largest flux occurred from the rice-in-row (31.9 mg CH_4-C m^{-2} h^{-1})

and the lowest flux occurred from the bare-soil treatment (0.05 mg CH_4-C m^{-2} h^{-1}). Rogers et al. (2013) also reported that N-fertilization had no measurable effect on CH_4 emissions. Measurements from the flood-release to harvest period showed that the largest CH_4 flux occurred 6 days after flood release (DAFR) and after four consecutive days of declining fluxes in the rice-between-row treatment (15.0 mg CH_4-C m^{-2} h^{-1}) (Rogers et al., 2013). By 8 DAFR, all treatments had a CH_4 flux of < 2 mg CH_4-C m^{-2} h^{-1} (Rogers et al., 2013). Treatments with rice plants present had greater total season-long CH_4 emissions (195 kg CH_4-C ha^{-1}) than the bare-soil treatment (55 kg CH_4-C ha^{-1}) and treatments with rice present had the larger post-flood-release emissions (9.5 kg CH_4-C ha^{-1}) than the bare-soil treatment (2.6 kg CH_4-C ha^{-1}) (Rogers, et al., 2013). The rice-present treatments had mean yield-based CH_4 emissions of 31.3 kg CH_4-C (Mg grain)$^{-1}$ (Rogers et al., 2013).

Rogers et al. (2014) evaluated the impacts of previous crop and cultivar on CH_4 fluxes and total season emissions from drill-seeded, delayed flood rice production in Arkansas. Treatment plots were established on a silt-loam soil in Arkansas and seeded with two pure-line cultivars, 'Taggart' and 'Cheniere', and the RiceTec hybrid cultivar 'CLXL745'. Treatments also consisted of rice and soybean as the previous crop. It was shown that 'Taggart'/soybean, 'Taggart'/rice, and 'CLXL745'/rice treatment combinations had the largest CH_4 fluxes (18.7 mg CH_4-C m^{-2} h^{-1}) around 51 DAF and the lowest flux (8.3 mg CH_4-C m^{-2} h^{-1}) by 51 DAF occurred from the 'CLXL745'/soybean treatment combination (Rogers et al., 2014). Averaged across previous crop, the pure-line cultivars 'Taggart' and 'Cheniere' had the largest CH_4 flux (12.7 mg CH_4-C m^{-2} h^{-1}) at 1 DAFR compared to the hybrid 'CLXL745' (4 mg CH_4-C m^{-2} h^{-1}) between 1 and 5 DAFR (Rogers et al., 2014). The pure-line cultivars had the greatest season-long emissions at 186 kg CH_4-C ha^{-1} and 21.9 kg CH_4-C (Mg grain)$^{-1}$ compared to the hybrid cultivar at 111 kg CH_4-C ha^{-1} and 11.1 kg CH_4-C (Mg grain)$^{-1}$ (Rogers et al., 2014).

Smartt et al. (2016a) evaluated CH_4 fluxes and emissions from the pure-line cultivar 'Taggart' grown on a clay soil in Arkansas. It was observed that the N-fertilized/rice-present treatment combination had the largest flux (4.8 mg CH_4-C m^{-2} h^{-1}) at 60 DAF compared to the non-fertilized/rice and bare-soil treatment combinations (< 1 mg CH_4-C m^{-2} h^{-1}) (Smartt et al., 2016a). Season-long, area-scaled and yield-scaled CH_4 emissions were greatest from the N-fertilized/rice-present treatment combination at 35.6 kg CH_4-C ha^{-1} and 3.5 kg CH_4-C (Mg grain)$^{-1}$ compared to the non-fertilized/rice-present and bare-soil treatments at < 8.94 kg CH_4-C ha^{-1} and 1.9 kg CH_4-C (Mg grain)$^{-1}$, respectively (Smartt et al., 2016a). There was no difference in CH_4 fluxes among treatments between the flood-release to harvest period; however, the bare-soil treatment recorded the largest peak flux around 5 DAFR at 2.54 mg CH_4-C m^{-2} h^{-1} (Smartt et al., 2016a). Total post-flood emissions were greater from the bare-soil and non-fertilized/rice-present (1.27 kg CH_4-C ha^{-1}) compared to the N-fertilized/rice-present (0.62 kg CH_4-C ha^{-1}) treatment combination, but the post-flood emissions fraction of the total season emissions was significantly greater in the bare-soil (63.5%) than in the rice-present treatments (8.5%) (Smartt et al., 2016a)

Smartt et al. (2016b) evaluated the effects of previous crop (i.e., rice or soybean) and cultivar [i.e., 'Taggart' (standard-stature pure-line), 'Cheniere' (semi-dwarf pure-line), and 'CLXL745' (hybrid)] on CH_4 fluxes and total season emissions from drill-seeded, delayed flood rice production on a clay soil in Arkansas. Rice as the previous crop had a peak CH_4 flux of 2.15 mg CH_4-C m^{-2} h^{-1} 56 DAF compared to soybean as previous crop, which had a peak flux of 0.81 mg CH_4 Cm^{-2} h^{-1} around 56 DAF (Smartt et al., 2016b). Total season-long, area- and yield-scaled CH_4 emissions were similarly influenced by previous crop. Rice as the previous crop had an average total season-long, area-scaled emissions of 19.6 kg CH_4-C ha^{-1} $season^{-1}$ and an average yield-scaled emissions of 2.05 kg CH_4-C (Mg grain)$^{-1}$, while treatments with soybean as the previous crop had an average season-long emissions of 7.0 kg CH_4-C ha^{-1} $season^{-1}$ and an average yield-scaled emissions of 0.68 kg CH_4-C (Mg grain)$^{-1}$ (Smartt et al., 2016b). Cultivar effects were not as clear as previous crop effects on CH_4 fluxes with 'Taggart' and 'CLXL745' peaking around 56 DAF and 'Cheniere' at 63DAF with all three cultivars (i.e., Taggart, CLXL745, and Cheniere) having peak flux of approximately 1.5 mg CH_4-C m^{-2} h^{-1} (Smartt et al., 2016b). Averaged across previous crop, total season-long, area- and yield-scaled CH_4 emissions were influenced by cultivar, with 'CLXL745' having the lowest average area- (10.2 kg CH_4-C ha^{-1} $season^{-1}$) and yield-scaled emissions [0.99 kg CH_4-C (Mg grain)$^{-1}$], while 'Taggart' and 'Cheniere' had the largest average area- (15.5 kg CH_4-C ha^{-1} $season^{-1}$) and yield-scaled emissions [1.66 kg CH_4-C (Mg grain)$^{-1}$] (Smartt et al., 2016b).

Nitrous Oxide Emissions

Nitrous oxide is a covalently bonded, gaseous compound with a molecular weight of 44.01 g mol^{-1} and a net zero charge. Nitrous oxide is an intermediate byproduct of either a chemical reduction of NO_3^- to atmospheric nitrogen (N_2), the oxidation of ammonia (NH_3) to NO_3^-, or denitrification of NO_3^- to N_2 by microbial cellular respiration (van Breeman and Feijtel, 1990).

Because the strictly chemical oxidation-reduction reactions do not occur at any significant rate, microbial production of N_2O is the main driver in N_2O emissions (Scott et al., 2003). The microbial community can produce N_2O through either through the incomplete oxidation of NH_3 to NO_3^- (i.e., nitrification) or the incomplete reduction of NO_3^- to N_2 (i.e., denitrification; van Breeman and Feijtel, 1990). Since microbes play a significant role in N_2O production, the habitability of the soil by microbes also influences N_2O, therefore soil pH, soil temperature, and soil moisture content have an impact on N_2O emissions (van Breeman and Feijtel, 1990).

Cultivar Effects

Few studies have been conducted to evaluate potential differences in N_2O emissions due to cultivar selection (i.e., hybrid or pure-line). In a 1-yr study, Simmonds et al. (2015) reported no difference in seasonal N_2O emissions between a hybrid (i.e., CLXL745) cultivar and several pure-line cultivars (i.e., Francis, Jupiter, and Sabine) on a silt-loam soil near Stuttgart, AR. The N_2O results were distinctly different from CH_4 emissions, where Simmonds et al. (2015) and Rogers et al. (2014) reported lower seasonal CH_4 emissions from a hybrid (i.e., CLXL745) cultivar compared to several pure-line cultivars (i.e., Francis, Cheniere, and Taggart) in 1-yr studies on a silt-loam soil near Stuttgart, AR. However, Simmonds et al. (2015) did not measure a difference in seasonal CH_4 emissions between CLXL745 and the pure-line cultivars Jupiter and Sabine at the same location and time as the difference between CLXL745 and Francis was measured. The difference in greenhouse gas (GHG) emissions between hybrid and pure-line cultivars is not thoroughly understood, but lower CH_4 emissions measured from hybrid cultivars has been attributed to an increase in CH_4 oxidation in the rhizosphere related to an increase in biomass and strong root systems (Ma et al., 2010; Rogers et al., 2014).

Nitrogen Fertilization Effects

Nitrogen fertilization rates and their impacts on N_2O emissions have been evaluated by several studies, and those studies have generally demonstrated an increase in seasonal N_2O emissions with an increase in N-fertilizer application rate (Zou et al., 2005; Adviento-Borbe et al., 2013; Liang et al., 2013; Pittelkow et al., 2013). Pittelkow et al. (2013) in a 2-yr study in California on a clay soil reported seasonal N_2O emissions that increased by ~400% as N-fertilization rates increased from 0 to 140 kg N ha^{-1}. Adviento-Borbe et al. (2013) measured seasonal N_2O emissions that increased by ~250% from low N-rate applications (i.e., 0 to 100 kg N ha^{-1}) to larger N-rate applications (i.e., 150 to 200 kg N ha^{-1}) in a 1-yr study in California on a clay soil, while also reporting a ~550% increase in seasonal N_2O emissions from below-optimal N-rate applications (i.e., 0 to 112 kg N ha^{-1}) to optimal N-rate applications (i.e., 168 kg N ha^{-1}) in a 1-yr study in Arkansas on a silt-loam soil. Zou et al. (2005) measured seasonal N_2O emissions in a 1-yr study on a silty-clay soil in China that were numerically 0.63 times less for the sub-optimal N-fertilization rate (i.e., 150 kg N ha^{-1}) and 1.3 times larger for the above-optimal N-fertilization rate (i.e., 450 kg N ha^{-1}) when comparted to a regionally adjusted optimal N-fertilization rate of 300 kg N ha^{-1}. Over a 6-year period in China on a clay-loam soil, Liang et al. (2013) reported mean seasonal N_2O emissions that were numerically 0.34 to 0.65 times less between the sub-optimal N-fertilization rates (i.e., 0 and 90 kg N ha^{-1}) and 1.5 times larger for the above-optimal N-fertilization rate (i.e., 270 kg N ha^{-1}) when compared to the optimal N-fertilization rate of 180 kg N ha^{-1}.

Compared to N-fertilization rate, little research has been conducted on the impact that coating urea fertilizers with urease inhibitors [i.e., NBPT and hydroquinone (HQ)] has on N_2O emissions from rice production. Urease inhibitors inhibit the urease enzyme, commonly present in the soil, preventing the hydrolysis of N fertilizer (i.e., urea) during surface application, therefore reducing N volatilization/loss (Havlin et al., 2014). Seasonal N_2O emissions measured numerically lower in several 1-yr studies from HQ-coated N-fertilizers compared to non-coated N-fertilizer, on loam soils in India (Malla et al., 2005) and sandy-loam soils in Belgium (Xu et al, 2002; Boeckx et al., 2005), but no significant difference was shown between the two N-fertilizer treatments. However, Xu et al. (2002) and Boeckx et al. (2005) did report a ~30% reduction in seasonal CH_4 emissions from HQ-coated compared to non-coated N-fertilizers, while Malla et al. (2005) measured no significant difference in seasonal CH_4 emissions between HQ-coated and non-coated N-fertilizers. Xu et al. (2002) and Boeckx et al. (2005) grew rice in planter pots compared to a more typical field experiment used by Malla et al. (2005).

Research on seasonal N_2O emissions that focuses on NBPT-coated urea in rice production is absent, however, studies of seasonal N_2O emissions from NBPT-coated urea have been conducted in corn (Ding et al., 2011; Sanz-Cobena et al., 2012) and grazed pasture land that was fenced off from cattle one year prior to experiment (Dawar et al., 2011). Dawar et al. (2011), Ding et al. (2011) in 1-yr studies measured a 7 and 37% reduction, respectively, in seasonal N_2O emissions from NBPT-coated urea compared to non-coated urea, with Dawar et al. (2001) measuring N_2O emission on a silt-loam soil in New Zealand and Ding et al (2011) measuring N_2O emissions on a sandy-loam soil in China. Sanz-Cobena measured an overall 54% reduction in seasonal N_2O emission in year one of a 2-yr study in Spain on a sandy-clay-loam soil; however, Sanz-Cobena et al. (2012) reported no difference in N_2O emissions between NBPT-coated and non-coated urea in the studies second year.

Tillage Effects

As of 2017, research on the impact of differing tillage practices (i.e., conventional tillage, reduced/conservation tillage, and no-tillage) on seasonal N_2O emissions from row crops [i.e., barley (*Hordeum vulagre* L.), corn, wheat, and rice) has been inconclusive (Venterea et al., 2005; Liu et al., 2006; Chatskikh and Olesen, 2007; Ahmad et al., 2009; Zhang et al., 2015). Ahmad et al. (2009) in a 1-yr study in China on a silty-clay-loam soil measured an approximate 30% increase in seasonal N_2O emissions in rice production from conventional tillage (CT) to no-tillage (NT), while Liu et al (2006) in a 1-yr study in Colorado on a clay-loam soil measured a 300% increase in seasonal N_2O emissions in corn from CT to NT. However, Zang et al. (2015) in a 4-yr wheat-rice rotation study in China on a silty-clay-loam soil and Chatskikh and Olesen (2007) in a 1-yr barley study in Denmark on loamy-sand soil reported no significant difference in seasonal N_2O emissions from CT to reduced tillage (RT). Venterea et al. (2005) reported an increase, decrease, or no difference depending on fertilizer in a corn-soybean rotation in seasonal N_2O emissions from CT to NT or RT in a 1-yr study in Minnesota on a silt-loam soil. The potential impacts of NT on N_2O emissions are not well understood, but one plausible explanation for an increase in GHG emissions from NT is the increase in labile organic matter concentrated near the soil surface to support increased microbial activity (Liu et al., 2006; Ahmad et al., 2009).

Water Management Effects

The traditional, continuous, full-season-flood water management practice is known to increase some GHG emissions, such as CH_4, due to prolonged soil saturation and reducing conditions during the growing season. As for rice fields that are periodically drained throughout the growing season, research has shown reduce seasonal CH_4 emissions (i.e., 60 to 93%) compared to the continuous, full-season flood (Zou et al., 2005; Linquist et al., 2015; LaHue et al., 2016; Peyron et al., 2016). However, the processes associated with periodic draining of rice fields (i.e., increased aeration and increased soil redox potentials) that has resulted in decreases in seasonal CH_4 emissions (Zou et al., 2005; Linquist et al., 2015; LaHue et al., 2016; Peyron et al., 2016) have also been shown to numerically increase seasonal N_2O emissions. Zou et al. (2005) in a 1-yr study in China on a silty-clay soil and LaHue et al. (2016) in a 3-yr study in California on a clay soil reported numerically increased seasonal N_2O emissions from fields under continuous, full-season flood compared to fields that were drained or flushed one to four times during the growing season. Linquist et al. (2015) in a 3-yr study in Arkansas on a silt-loam soil and Peyron et al. (2016) in a 2-yr study in Italy on a loam soil reported significant increases in seasonal N_2O emissions during the growing season that were two to four times greater from intermittently flooded fields than from a continuous, full-season flood. Linquist et al. (2015) and LaHue et al. (2016) measured peak N_2O fluxes in drill-seeded, intermittently flooded rice fields during the first drain or flush period between ~7 to 90 N_2O-N g ha^{-1} d^{-1}, while Zou et al. (2005) during the same periods measured peak N_2O fluxes of ~288 N_2O-N g ha^{-1} d^{-1} in transplanted, intermittently flooded rice fields. However, continuously flooded rice fields either produced negligible N_2O fluxes (LaHue et al., 2016), N_2O fluxes that peaked prior to the onset of the full-season flood (~ 5 to 20 N_2O-N g ha^{-1} d^{-1}; Linquist et al., 2015), or N_2O fluxes that peaked after the release of the full-season flood (~18 to 48 N_2O-N g ha^{-1} d^{-1}; Zou et al., 2005; Linquist et al., 2015).

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CHAPTER TWO

WATER MANAGEMENT PRACTICE AND CULTIVAR EFFECTS ON NITROUS OXIDE EMISSIONS FROM A SILT-LOAM SOIL CROPPED TO RICE

Abstract

Rice (*Oryza sativa* L.) is a crop unlike any of the other commonly grown row crops [i.e., wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), or soybean (*Glycine max* L.)]. Grown most often under flooded-soil conditions, rice production makes an ideal environment for the reduction of nitrate (NO_3^{-1}) and carbon dioxide (CO_2) to greenhouse gases, such as nitrous oxide (N_2O) and methane (CH_4), respectively. The objectives of this study were to evaluate the effects of water management practice (full-season-flood and intermittent-flood) and cultivar (pure-line and hybrid) on N_2O fluxes, season-long N_2O emissions, and the global warming potential (GWP) from rice grown on a silt-loam soil in the direct-seeded, delayed-flood production system in eastern Arkansas. Gas samples were collected from 30-cm-diameter enclosed chambers at 20-min intervals for 1 hr approximately weekly between the establishment of the delayed flood (i.e., 4-5 leaf stage) and several days after end-of-season flood release. Nitrous oxide fluxes differed over time ($P = 0.07$) throughout the 2016 rice growing season, while N_2O emissions ranged from 0.38 to 0.84 kg N_2O-N ha^{-1} $season^{-1}$ from the full-season-flood/hybrid and intermittent-flood/hybrid treatment combinations, but neither water management nor cultivar affected ($P >$ 0.1) N_2O fluxes or season-long emissions. Hybrid rice (XL753; 2272 kg CO_2 eq. ha^{-1} $season^{-1}$) had lower ($P < 0.003$) GWP than the pure-line rice (LaKast; 4473 kg CO_2 eq. ha^{-1} $season^{-1}$), while the intermittent-flood/hybrid combination (2046 kg CO_2 eq. ha^{-1} $season^{-1}$) had the numerically lowest GWP compared to the other three treatment combinations; however, N_2O emissions contribution was minimal. With limited N_2O emissions studies conducted not just in Arkansas, but the US in general, it is important to quantify and evaluate N_2O emissions from rice to determine if changes to common, conventional rice production practices (i.e., full-season-flood water management) have detrimental effects on the environment.

Introduction

The importance of rice (*Oryza sativa* L.) in the 21st century cannot be over-stated, as rice, along with wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.), account for 42% of all calories associated with the current global diet of the human population (Maclean et al., 2013). The Asian continent accounts for roughly 89 and 85% of global rice production and consumption, respectively, while the US contributes ~1.5% to global rice production (USDA-FAS, 2017). At approximately 47% of total production, Arkansas is the leading rice-producing state in the US (Hardke, 2017). Rice is a semi-aquatic plant, therefore, is most frequently agronomically managed by establishing and maintaining a constant flood compared to wheat and corn, which are both grown as upland crops. The rice plant has adapted to living in flooded-/saturated-soil conditions by forming aerenchyma tissue, which facilitates the movement of oxygen (O_2) from the atmosphere to the roots (Counce et al., 2003).

Soil microbial life is influenced by the saturated soil conditions created by the continuously flooded soil profile. Saturated soils are not readily replenished with atmospheric O_2 due to O_2's low diffusion through water and soil. Anaerobic soil conditions that form, due to the absence of O_2, necessitate that facultative anaerobic microbes utilize other compounds as their final electron acceptor during microbial cellular respiration, such as nitrate (NO_3^-). Cellular respiration reduces compounds to other forms of the parent atom, such as NO_3^- is reduced to atmospheric nitrogen (N_2) through the process of denitrification (Smith and Tiedje, 1979). Nitrate is either applied to the soil as fertilizer, or is formed from the oxidation of other nitrogen (N) compounds, such as ammonium (NH_4^+), through the process of nitrification. However, even in O_2 depleted soil conditions, NO_3^- can be created in the rhizosphere of the rice plant then translocated to the reduced soil profile and denitrified by microbes to N_2 (Arth and Frenzel, 2000). Microbes utilized compounds for respiration in a sequential order ($O_2 > NO_3^- > Mn^{4+} > Fe^{3+} > SO_4^{2-} > CO_2$) due to ease and efficiency of reduction. Soil reduction oxidation (redox) potential [Eh (mV)] measures the electron activity of the soil, therefore, inferring which compounds (i.e., O_2, NO_3^-, and CO_2) will be available for microbial respiration (Reddy and DeLaune, 2008). Each compound that is utilized during microbial respiration has an Eh range, which supposes the absence of the previously more reducible compound [i.e., O_2 (+380 to +320 mV), NO_3^- (+280 to +220 mV), and CO_2 (-200 to -280 mV)] (Brady and Weil, 2008).

Nitrous oxide (N_2O) is a by-product of the incomplete reduction (i.e., denitrification) of NO_3^- to N_2 and a potent greenhouse gas (GHG). The most common GHGs, such as carbon dioxide (CO_2), methane (CH_4), and N_2O, have globally increased 40, 150, and 20%, respectively, since the mid-18th century (IPCC, 2014). Nitrous oxide and CH_4 have estimated global warming potentials (GWP) that are 298 and 34 times, respectively, more than that of CO_2, based on a carbon-climate feedback 100-yr time scale (Myhre et al., 2013). The average monthly N_2O and CH_4 concentrations in the atmosphere are ~329 and 1800 $\mu g\ L^{-1}$, respectively (NOAA-ESRL/GMD, 2017). Agriculture accounts for 54% of all non-CO_2 (i.e., N_2O and CH_4) GHG emissions and, of the non-CO_2 emissions from agriculture, synthetic fertilizers, mostly nitrogen (N)-fertilizers, and rice production account for 12 and 11%, respectively (USEPA, 2012; Smith et al., 2014). By the year 2030, global agricultural emissions of non-CO_2 GHGs are predicted to increase by 36%; 2% from rice production alone (Smith et al., 2014).

More than a few water management practices (i.e., continuous, full-season flood, intermittent flooding, and mid-season drain) are used in rice production. The most common water management practice used in Arkansas is the continuous, full-season flood, which accounts for ~ 95% of the total rice area (Hardke, 2017); however, intermittent flooding is being considered as a possible alternative to reduce water consumption (Roberts et al., 2015). In Arkansas, rice production accounts for 35% of groundwater usage (Holland, 2007), and the majority of groundwater (95%) used (i.e., commercial, residential, or agriculture usage) comes from the Alluvial Aquifer (ANRC, 2015). A sustainable pumping rate for Alluvial Aquifer is estimated to be 1.28 x 10^7 m^3 d^{-1}, while the current pumping rate is two times that rate at 3.04 x 10^7 m^3 d^{-1} (ANRC, 2015). Using 451 observations from 38 studies, Carrijo et al. (2017) estimated a 25% water-use reduction for water management practices that utilized some form of intermittent flooding or draining compared to the continuous, full-season flood management practices.

Water management practices are known to influence CH_4 emissions with a conventional, continuous, full-season-flood water management practice increasing emissions compared to alternative water management practices (i.e., intermittent flooding) that utilize varying drainage or reaeration events due to the prolonged soil saturation and reducing conditions during the growing season (LaHue et al., 2016; Linquist et al., 2015; Peyron et al., 2016; Zou et al., 2005). However, these same reaeration events, because of the potential to increase soil Eh, have shown to numerically (LaHue et al., 2016; Linquist et al., 2015; Zou et al., 2005) and significantly (Linquist et al., 2015; Peyron et al., 2016) increase seasonal N_2O emissions.

Cultivar selection is important for many rice farmers, as some cultivars are more tolerant to certain environmental conditions (i.e., drought, pest, or herbicide resistance) than other cultivars. Pure-line and hybrid cultivars are derived using different breeding techniques (i.e., selective breeding of self-pollinating plants or cross breeding of two plants); however, hybrids are known to be more drought resistant and greater yielding than pure-line cultivars (Wilson et al., 2013). In Arkansas, the two most common hybrid cultivars, CLXL745 and CLXL753, account for an estimated 33% of all planted rice (Hardke, 2017).

Few studies have evaluated cultivar effect on N_2O emissions; however, Simmonds et al. (2015) reported no difference in area-scaled, season-long N_2O emissions between a hybrid (i.e., CLXL745) cultivar and multiple pure-line cultivars (i.e., Francis, Jupiter, and Sabine) on a silt-loam soil in east-central Arkansas. In contrast, Rogers et al. (2014) and Simmonds et al. (2015) reported lower area-scaled, season-long CH_4 emissions from a hybrid (i.e., CLXL745) cultivar compared to multiple pure-line cultivars [i.e., Cheniere and Taggart (Rogers et al., 2014), and Francis (Simmonds et al., 2015)] on a silt-loam soil. The cultivar effect on GHG emissions is not fully understood, but lower CH_4 emissions from hybrid cultivars have been credited to CH_4 oxidation within the rhizosphere connected to an increase in biomass and stronger root systems, therefore, increasing O_2 dissemination to the rhizosphere (Ma et al., 2010; Rogers et al., 2014).

There are limited studies that have quantified or evaluated agronomic production effects on N_2O emissions from rice grown in Arkansas, but those studies that have, have all been conducted on a silt-loam soil near Stuttgart, AR (Adviento-Borbe et al., 2013; Linquist et al., 2015; Simmonds et al., 2015). The majority of rice in Arkansas is grown under a continuous, full-season-flood, while an estimated 45% of rice planted is hybrid rice (Hardke, 2017). Conventional, continuous, full-season-flood water management practices increase CH_4 emissions due to extended soil saturation compared to intermittent flooding (LaHue et al., 2016; Linquist et al., 2015; Peyron et al., 2016; Zou et al., 2005). Furthermore, CH_4 emissions account for the majority of the GWP and, in some circumstances (i.e., full-season-flood), as much as 90% or more of the GWP compared to the contributions of N_2O (Adviento-Borbe et al., 2013; Linquist et al., 2015). The objectives of this study were to evaluate the effects of water management practice (full-season-flood and intermittent-flood) and cultivar (pure-line and hybrid) on N_2O fluxes, season-long N_2O emissions, and the GWP from rice grown on a silt-loam soil in the direct-seeded, delayed-flood production system in eastern Arkansas. It was hypothesized that non-zero N_2O fluxes will occur more frequently and with greater magnitude from the intermittent-flood than from the full-season-flood water management scheme, because reaeration events of the soil during periodic drainage can increase soil Eh. It was also hypothesized that area-scaled, season-long N_2O emissions will be greater from the intermittent-flood-hybrid treatment combination than any other water management-cultivar combination, due to the impacts periodic draining of the soil and the hybrid's roots have on keeping soil Eh at an optimal level for N_2O production. In addition, it was hypothesized that the full-season-flood-pure-line treatment combination will produce a greater GWP than any other water management-cultivar combinations, since the soil Eh will be more reduced due to the prolonged soil saturation that prevents oxidation of the soil, therefore, increasing CH_4 production.

Materials and Methods

Site Description

Research was conducted at the University of Arkansas System, Division of Agriculture's Rice Research and Extension Center (RREC) east of Stuttgart in Arkansas County, AR (34.46°N, 91.46°W) from May to October 2016. The study site consisted of an area that had been conventionally tilled and cropped to a rice-soybean rotation for at least the last 15 years on a Dewitt silt-loam (Fine, smectitic, thermic Typic Albaqualfs) soil with < 1% slope (USDA-NRCS, 2013, 2014).

The climate in the region is classified as Humid Subtropical or Cfa by the Koppen Classification System, which consists of warm weather and periodic precipitation all year (Arnfield, 2016). The 30-yr (1981 to 2010; meteorological station ID USC00036920) average monthly air temperature is 16.5°C, with the largest average monthly maximum air temperature of 33.3°C in July and the lowest average monthly minimum of -1.1°C in January (NOAA-NCEI, 2010). The 30-yr mean annual precipitation is 125.6 cm, with the most precipitation occurring in April (13.4 cm) and May (13.0 cm), while the month with the least amount of precipitation is August (6.1 cm) (NOAA-NCEI, 2010). The mean daily air temperature and precipitation for a typical rice growing season in Arkansas (i.e., May through September) is 25.1°C and 43.4 cm, respectively (NOAA-NCEI, 2017), while the mean daily air temperature and precipitation for May through September during the 2016 growing season were 26.2°C and 43.2 cm.

Treatments and Experimental Design

This study was designed to evaluate the effects of two water management practices, the full-season flood as the conventional practice and the intermittent flood as an alternative, water-saving practice, and two rice cultivar selections, a commonly grown pure-line (LaKast) and hybrid (XL753) cultivar. A randomized complete block (RCB) design replicated four times was established with a factorial arrangement of field plots, 1.6-m wide by 4.6-m long and 18-cm row spacing. There were a total of 16 field plots arranged in the RCB design with one replication of each of the four-treatment combinations (i.e., full-season-flood/pure-line, full-season-flood/hybrid, intermittent-flood/pure-line, and intermittent-flood/hybrid) represented in each block. A split-split-plot design was used for the effects of water management, cultivar, time (i.e., measurement date), and their interactions, with water management practice as the whole-plot factor, cultivar as the split-plot factor, and time as the split-split-plot factor to evaluate treatment effects on N_2O fluxes and emissions. To evaluate N_2O emissions, a split-plot design was used for the effects of water management, cultivar, and their interactions, with water management practice as the whole-plot factor and cultivar as the split-plot factor. To facilitate imposition of the full-season-flood or intermittent-flood scheme, separate water management bays were necessarily established adjacent to one another that were separated by a levee. Blocks spanned across both water management bays.

Plot Management

Field tillage (i.e., disking followed by field cultivating and land planing) occurred during February 2016. Pre-plant fertilization of 29.4 kg P ha^{-1} as triple super phosphate, 83.8 kg K ha^{-1} as KCl, and 11.2 kg Zn ha^{-1} as $ZnSO_4$ were applied on 22 March, 2016. Rice was planted on 23 April, 2016 by drill-seeding with 18-cm row spacing. Nine rows of the standard-stature, pure-line cultivar 'LaKast', which was developed at the RREC (Moldenhauer et al., 2014), and the hybrid cultivar 'XL753' from RiceTec, Inc. (Houston, TX) were planted. Both cultivars are considered long-grain rice cultivars. Pre-emergent Command 3ME (FMC Corp., Philadelphia, PA), Facet L (BASF, Research Triangle Park, NC) herbicide mixture was sprayed on 27 April, 2016 and an application of Facet (BASF, Research Triangle Park, NC), Permit Plus (Gowan Co., Yuma, AZ) herbicide mixture was sprayed on 19 May, 2016 for weed control.

Two separate water management bays were constructed with levees established around each bay after planting and 2 to 3 weeks prior to initial flooding. One bay was managed as a delayed, continuous, full-season flood, which is the most common water management practice for rice production in Arkansas, where there was an approximate 10-cm-deep flood kept in the bay between one month after planting (i.e., the 4- to 5-leaf rice stage) until physiological maturity or two weeks before harvest. The other bay was managed with an intermittent flood, where the soil had a delayed-flood established one month after planting to an approximate 10-cm depth to saturate the soil to a soil moisture potential of 0 kPa. Once the soil reached saturation, flood water in the bay was allowed to dissipate and the soil dry down to a soil moisture potential of ~ -20 kPa through evaporation, plant uptake and transpiration, and vertical and/or lateral seepage (Roberts et al., 2015). The soil moisture potential was measured using a 900M datalogger (Irrometer Co., Riverside, CA) with vertically installed 200SS Watermark soil moisture sensors (Irrometer Co, Riverside, CA) at a ~ 10- to 15-cm soil depth and monitored daily. Once the soil reached the ~ -20-kPa soil moisture potential, the bay was re-flooded (i.e., 17 June, 2016, 27 June, 2016, and 14 July, 2016) and the alternate wet-dry sequence began again, except for the last reflood event (i.e., 14 July, 2016). A permeant flood was maintained in the intermittent-flood treatment from 14 July, 2016 until the end-of-season drain (i.e., 23 August, 2016).

Nitrogen (N) fertilization occurred pre-flood and during the middle of the season using N-(n-butyl) thiophosphoric triamade(NBPT)-coated urea (46-0-0) for optimum rice production based on recommended fertilization rates in Arkansas (Norman et al., 2013). Pre-flood fertilization for the pure-line cultivar LaKast consisted of 118 kg N ha^{-1} and 135 kg N ha^{-1} for the hybrid XL753 applied manually to dry soil the day prior to the flood being established (8 June, 2016). The delayed flood was established in both water management treatments on 9 June, 2016. Mid-season fertilization for LaKast consisted of 50.5 kg N ha^{-1} broadcasted manually to the floodwater at the beginning of internode elongation (27 June, 2016), which occurred around 18 days after flooding (DAF). Mid-season fertilization for XL753 consisted of 33.6 kg N ha^{-1} broadcasted manually to the floodwater 26 DAF (5 July, 2016).

Soil Sampling and Initial Physical and Chemical Soil Property Analyses

On 16 May 2016, soil samples were collected from the top 10 cm of each plot prior to fertilization and flooding with a 2.4-cm-radius, stainless steel core chamber and slide hammer for bulk density determinations. Soil samples were dried (70°C, > 48 hr) and weighed. On 28 May 2016, a second set of soil samples was collected from the top 10 cm prior to fertilization and flooding consisting of eight cores per plot obtained with a 2-cm-diameter manual push probe that were mixed to create one composite sample per plot for particle-size and chemical analyses. Soil samples were oven-dried (70°C, > 48 hr), ground, and sieved to pass a 2-mm mesh screen. Soil particle-size analyses were conducted using a modified 12-hr hydrometer method (Gee and Or, 2002). Soil pH and electrical conductivity (EC) were measured potentiometrically on a 1:2 soil mass:water volume suspension. Soil sub-samples were extracted with Mehlich-3 extraction solution and analyzed for extractable nutrients (i.e., P, K, Ca, Mg, Fe, Mn, Na, S, Cu, and Zn) using inductively coupled, argon-plasma spectrophotometry (Tucker, 1992). Soil organic matter (SOM) concentrations were determined by mass-loss-on-ignition after 2 hours at 360^{o}C. Total carbon (TC) and N (TN) concentrations were determined by high-temperature combustion using a VarioMax CN analyzer (Elementar Americas Inc., Mt. Laurel, NJ; Nelson and Sommers, 1996). Soil from the study site did not effervesce upon treatment with dilute hydrochloric acid, thus all measured soil C was assumed to be organic C. Measured elemental concentrations (g kg^{-1}) were converted to contents (kg ha^{-1}) using the measured bulk density per plot and the 10-cm sample depth.

Soil Redox Potential and Temperature

Soil oxidation-reduction (redox, Eh) potential sensors (Model S650KD-ORP, Sensorex, Garden Grove, CA) and thermocouples (Type E, chromel-constantan) were installed in each plot to a depth of 7.5 cm the day of flooding and at a depth of 4 cm the day prior to flooding, respectively. Soil redox sensors were inserted into the soil vertically and thermocouples were placed at depth in the soil horizontally. Both sensors were connected to a CR1000 datalogger (Campbell Scientific, Inc., Logan, UT) to record data at 15-minute intervals and report averaged data at 1-hr intervals throughout the flooded portion of the growing season. There was one datalogger per water-management bay. Soil Eh measurements from the silver/silver-chloride reference electrodes were adjusted by adding 199 mV to each sensor to convert to the standard hydrogen electrode Eh measurement (Patrick et al., 1996). Recorded data were collected weekly, at which time all sensors were checked for proper functioning. Summarized data for soil redox potentials and soil temperatures were determined by using the value output at 0900 hrs on each sampling date, except for 80 and 81 DAF since sensors were removed prior to these dates. In addition to redox data from gas sampling dates, redox data from 0, 1, 75, 76, and 77 DAF were also summarized.

Trace Gas Sampling and Analyses

Similar to recent procedures (Rogers et al., 2014; Smartt et al., 2016 a,b), base collars, 30-cm tall with a 30-cm diameter made of polyvinyl chloride (PVC) and beveled on one end, were installed in each plot after initial fertilization, while the bays were being flooded. The base collars were placed over two rice rows, including an inter-row area of bare soil (Parkin and Venterea, 2010). Base collars had four, 12.5-mm-diameter holes 12 cm from the bottom, beveled end of the collars that were situated right above the soil surface once installed to allow floodwater to flow in and out of the collar. Two sets of extensions, 30 cm in diameter by either 40- or 60-cm long, were used to accommodate the growing rice throughout the season. Extensions were outfitted with a rubber flap cut from tire inner tubes on one end to connect to each other or to the base collar. Extensions were placed on the base collar and around the rice plants the afternoon or evening prior to gas sampling. When a standing flood was not present in the intermittent-flooded bay, then septa were inserted into the base collar holes to prevent air flowing in and out of the collar during sampling. To facilitate minimal soil disturbances during gas sampling, wooden boardwalks were constructed between field plots and over adjacent levees.

On the day of sampling, a 10-cm tall, 30-cm-diameter PVC cap was placed on top of the extension and sealed with a rubber flap to create an enclosed headspace chamber that trapped gases for sampling (Livingston and Hutchinson, 1995). Sampling occurred between 0930 and 1100 hrs, which was comparable timing to previous studies (Adviento-Borbe et al., 2013; Rogers et al., 2014; Smartt et al., 2016 a,b). The cap and extensions were wrapped in reflective aluminum tape (Mylar metallized tape, CS Hyde, Lake Villa, IL) to minimize temperature increases inside the chamber. A 12-mm-diameter hole drilled on top of the cap had a septa inserted so gas samples could be collected using a syringe. A 2.5-cm^2 fan (MagLev GM1202PFV2-8, Sunon Inc., Brea, CA) was mounted on the bottom of the cap and was powered by a 9-V battery to mix the entrapped gas in the headspace during sampling. A 15-cm-long, 0.63-cm-inside-diameter piece of copper refrigerator tubing was mounted on the side of the cap to serve as ventilation and for pressure equilibrium while the chambers were capped during sampling.

Gas samples were collected using a 20-mL syringe with a 0.5- by 25-mm needle [Beckton Dickson and Co (B-D), Franklin Lakes, NJ]. When collecting gas samples, syringes were opened with the needle still inserted into the septa (part #73828A-RB, Voigt Global, Lawrence, KS) of the cap sealed onto the chamber and the plunger was drawn back to fill the syringe with headspace gas. The syringe was then removed from the septa in the chamber cap and the syringe contents were transferred into a pre-capped (20-mm headspace crimp cap; part #5183-4479, Agilent Technologies, Santa Clara, CA) and pre-evacuated, 10-mL glass vial (part #5182-0838, Agilent Technologies). Samples were collected weekly during the flooded portion of growing season in 20-min intervals for 1 hour after sealing the chamber with the cap (i.e., at 0, 20, 40, 60 min after capping). Additional samples were collected 1 d prior to flood release (23 August 2016) and 5 and 6 d after flood release (DAFR). Once gas sampling was completed, the caps and extensions were removed until the next sampling. The air temperature, relative humidity, and barometric pressure were also measured throughout the sampling period (S/N: 182090284, Control Company, Webster, TX). The height of chamber from the top of the floodwater or soil surface, whichever was present, to the top of the cap was measured for accurate chamber volume determinations. Samples of N_2O and CH_4 gas standards (i.e., 0.1, 0.5, 1.0, 5.0, and 20.0 mg L^{-1}) were also collected in the field prior to ending the sampling protocol on each sample date.

Gas samples were stored at room temperature and were analyzed for N_2O and CH_4 concentrations no later than four weeks after collection in the field. Gas samples were analyzed on an Agilent 6890N gas chromatograph (Agilent Technologies), which contained a 19095P-Q04 30M plot, Capillary 30-m by 530-µm by 40-µm column, flame-ionization detector (FID) for CH_4 detection and a micro-electron capture detector (ECD) for N_2O detection. Before field samples were analyzed, N_2O and CH_4 gas standards (i.e., 0.1, 0.5, 1.0, 5.0, and 20.0 mg L^{-1}) were also collected in the laboratory for analysis.

Nitrous oxide and CH_4 fluxes were determined based on the change in concentration in the chamber over the 20-min sampling intervals (i.e., 0, 20, 40, 60 min) similar to previous studies (Parkin and Venterea, 2010; Rogers et al., 2014; Smartt et al., 2016 a,b). The concentration at each interval (mL L^{-1}) was plotted against the time interval (min) to evaluate the change in concentration over time (Rogers et al., 2014; Smartt et al., 2016 a,b). Total growing season (i.e., flood establishment to 6 DAFR) emissions of N_2O and CH_4 were calculated by linear interpolation between each sample date on a chamber-by-chamber basis. Total growing season emissions were converted to CO_2-equivalent GWPs for each treatment combination (i.e., full-season-flood/pure-line, full-season-flood/hybrid, intermittent-flood/pure-line, and intermittent-flood/hybrid) using the climate-carbon feedback 100-yr GWP conversion rates of 298 and 34 for N_2O and CH_4, respectively (Myhre et al., 2013). In addition, all CH_4 GWPs have been adjusted from the conversion rate of 25 to 34 for all comparative studies mentioned henceforth.

To address the limit of detection (LOD) corresponding to the Agilent micro-ECD, a calculated LOD of 0.9 mg L^{-1} for N_2O was first determined by evaluating a series of low standard concentrations (i.e., 0.1, 0.5, and 1.0 mg L^{-1}) and determining which standard consistently reported an area-under-the-curve from the instrument throughout the growing season. The 1.0 mg L^{-1} concentration standard measured an area-under-the-curve on a more consistent basis than the 0.1 or 0.5 mg L^{-1} concentrations, therefore, seven additional 1.0 mg L^{-1} standard samples were analyzed on the Agilent micro-ECD. A standard deviation was calculated among the seven measured concentrations of the 1.0 mg L^{-1} standard concentration and a 0.9 mg L^{-1} LOD was determined in accordance with recognized procedures (USEPA, 2013).

To address the LOD, in relation to a calibration curve, 1.0 and 5.0 mg L^{-1} standard concentrations for the sampling dates between 28 June and 22 August 2016 were applied to N_2O fluxes on all sampling dates. In addition, to most accurately capture the low-end range of N_2O fluxes for any sample time point (i.e., 0, 20, 40, and/or 60 min), where the ECD failed to report an area-under-the-curve value or reported an area-under-the-curve value that resulted in a calculated concentration below the LOD (0.9 mg L^{-1}), a calculated ambient air concentration (i.e., 0-min point) of 0.312 mg L^{-1} was substituted for those impacted time points. The calculated ambient air concentration (i.e., 0-min point) of 0.312 mg L^{-1} was calculated using the mean concentration of 0-min gas samples for each chamber's gas sample analyzed on a Shimadzu GC-2014 gas chromatograph (Shimadzu North America/Shimadzu Scientific Instruments Inc., Columbia, MD) with an LOD of < 0.1 mg L^{-1} for the dates of 22, 28, and 29 August, 2016. These gas samples corresponded to the same gas samples that were analyzed by the Agilent 6890N gas chromatograph, and the calculated ambient air concentration was similar to that reported by the National Oceanic and Atmospheric Administration (0.329 mg L^{-1}; NOAA; NOAA-ESRL/GMD, 2017). Resulting N_2O fluxes from the Agilent 6890N tended to vary somewhat compared to those determined from measurements on the Shimadzu GC-2014, where N_2O fluxes ranged from 18.7 times greater to reporting zero fluxes for nine out of 12 comparisons (Table 1). Lastly, a linear regression among measured concentrations across measurement time points (i.e., 0, 20, 40, and 60 min) for a given chamber that resulted in a negative slope was assigned a flux of zero, such that any potential sink of N_2O was disregarded in this study. Season-long N_2O and CH_4 emissions were divided by the base-collar area, on a chamber-by-chamber basis, to report area-scaled emissions.

Plant Sampling

Aboveground biomass was collected on 29 August, 2016 from within the base collar and from a 1-m length of row adjacent to the collar in each plot by cutting stems at 2 cm above the soil. Biomass was dried at 55°C for 3 weeks then weighed to determine aboveground dry matter. Rice was harvested on 3 October, 2016 using a research-grade plot combine after a growing season (i.e., planting to harvest) of 134 days and with a total of 77 days from flooding to flood release. Grain was collected and cleaned of chaff from the 1-m biomass collection and a sub-sample was dried at 70°C for at least 48 hours. The 1-m biomass collected comprised of rice plants with a growing season (i.e., planting to 6 DAFR) of 129 days. Dry weights of grain from sub-samples were used to determine grain weight in each treatment plot, which were corrected to 12% moisture content for yield (kg ha^{-1}) reporting. Nitrous oxide emissions on a per-unit-grain-yield basis for each treatment combination were determined by dividing season-long emissions by rice grain yield on a chamber-by-chamber basis.

Statistical Analyses

A two-factor analysis of variance (ANOVA) was performed in SAS (version 9.4, SAS Institute, Inc., Cary, NC) using PROC MIXED to determine the effects of pre-assigned water management practice, cultivar, and their interaction on initial soil properties from the top 10 cm. A three-factor ANOVA was performed to evaluate the effects of water management practice, cultivar, time, and their interactions on N_2O fluxes throughout the growing season. A two-factor

ANOVA was performed to determine the effects of water management practice, cultivar, and their interactions on aboveground biomass, yield, area-scaled pre- and post-flood-release N_2O emissions, and season-long yield- and area-scaled N_2O and CH_4 area-scaled emissions and season-long GWP. When main effects or interactions were statistically significant, means were separated by least significant difference (LSD) at the $\alpha = 0.1$ level for N_2O fluxes and area-scaled and yield-scaled N_2O emissions. The 0.1 significance threshold was used due to low expected magnitudes and large expected variability associated with N_2O fluxes and emissions. All other parameter means were separated by LSD at the $\alpha = 0.05$ level.

Results and Discussion

Pre-flooding Soil Physical and Chemical Properties

Pre-flooding soil properties were measured to assess plot uniformity among cultivar and pre-assigned water management treatments. With the exception of soil pH and extractable soil P, Ca, and Mg, all other soil properties measured in the top 10 cm before flooding (i.e., EC, extractable soil K, Fe, Mn, Na, S, Cu, Zn, TN, TC, and SOM, bulk density, sand, silt, and clay) were unaffected ($P > 0.05$) by placement of water management practice (i.e., full-season flood and intermittent flood), placement of cultivar (i.e., pure-line, LaKast and hybrid, XL753), or their combination thereof (Table 2). Pre-flood soil pH was 1.4% greater ($P = 0.04$) in the pre-assigned intermittent-flood (pH = 7.0) than in the full-season-flood treatment (pH = 6.9), which was slightly above the ~ 5.0 to 6.75 pH range for optimal growth in rice (Havlin et al., 2014), while soil pH was unaffected ($P > 0.05$) by cultivar (Table 2). Pre-flood extractable soil P, Ca, and Mg contents were 6, 3, and 4%, respectively, greater for the hybrid (i.e., 102, 2102, and 172 kg ha^{-1}, respectively) than for the pure-line cultivar (96, 2036, and 165 kg ha^{-1}, respectively), while extractable soil P, C, and Mg contents were unaffected ($P > 0.05$) by water management practice (Table 2). Sand, silt, and clay averaged 0.19, 0.73, and 0.08 g g^{-1} in the top 10 cm, confirming a silt-loam soil surface texture (Table 2). Overall mean extractable soil K (135 mg K kg^{-1}) and Zn (8.1 mg Zn kg^{-1}) concentrations in the top 10 cm were within the 'optimum' (131 to 175 mg K kg^{-1} and ≥ 4.1 mg Zn kg^{-1}, respectively) soil-test category for fertilizer recommendations for rice grown in Arkansas (Norman et al., 2013).

Though there were differences in soil P, Ca, and Mg in the top 10 cm between cultivars, extractable soil P concentrations (70 and 73 mg P kg^{-1} for LaKast and XL753, respectively) were both above optimum (≥ 51 mg P kg^{-1}) for rice produced in Arkansas, and extractable soil Ca and Mg concentrations were approximately four times greater than the suboptimal 'Low' soil-test category (i.e., the only category given for soil Ca and Mg concentrations) for row crops in Arkansas (Espinoza et al., 2012; Norman et al., 2013). Therefore, it was assumed that these slight differences had no negative agronomic effects on either rice cultivar. Furthermore, considering only few, minor, non-agronomically significant differences in soil properties existed prior to flooding, it was reasonably assumed that any subsequently measured differences in N_2O fluxes and emissions were due to imposed treatments rather than due to inherent pre-flood differences among plots.

Nitrous Oxide Fluxes

Unlike the somewhat predictable CH_4 flux trends from a silt-loam soil over the rice growing season (Brye et al., 2013; Rogers et al., 2013, 2014), N_2O fluxes over time during the 2016 growing season were much less consistent (Figure 1). Nitrous oxide fluxes were variable over the course of the growing season and were generally low, near zero, on many sample dates, even in the intermittent-flood treatment where it was expected that soil redox conditions would be more prone to N_2O production more frequently than in the continuous-flood treatment. Specifically, mean N_2O fluxes were zero in each of the four treatment combination (i.e., full-season-flood/LaKast, full-season-flood/XL753, intermittent-flood/LaKast, and intermittent-flood/XL753) on six (i.e., 5, 19, 40, 54, 80, and 81 DAF) of the 12 sampling dates (i.e., 5, 12, 19, 27, 32, 40, 47, 54, 61, 74, 80, and 81 DAF; Figure 1). The intermittent-flood/XL753 treatment combination had measurable, non-zero N_2O fluxes that occurred between the boot N application and prior to the soil drying out to the -20 kPa soil water potential mark (i.e., 27 DAF) and immediately prior to the end-of-season flood release (i.e., 74 DAF; Figure 1). The intermittent-flood/LaKast treatment combination had measurable, non-zero N_2O fluxes that occurred prior to the soil reaching the -20 kPa soil water potential mark (i.e., 32 DAF), after 50% heading (i.e., 47 DAF), and immediately prior to the end-of-season flood release (i.e., 74 DAF; Figure 1). The full-season-flood/LaKast treatment combination had measurable, non-zero N_2O fluxes that occurred after mid-season N fertilization (i.e., 27 DAF) and 50% heading (i.e., 47 DAF). The full-season-flood/XL753 treatment combination had measurable, non-zero N_2O fluxes that occurred after internode elongation (i.e., 12 DAF), between 50% heading and the end-of-season flood release at 61 DAF, and immediately prior to the end-of-season flood release at 74 DAF (Figure 1). However, it was expected that there would be no measurable N_2O fluxes weeks after flood establishment in the full-season flood, as the soil would be saturated to such a degree and for an extended amount of time that the soil redox potential (Eh) would be too low to support N_2O production. No measurable N_2O fluxes were recorded after flood release (i.e., 80 and 81 DAF; Figure 1) for any of the four treatment combinations

Nitrous oxide fluxes peaked at various times among the four treatment combinations, including after different growth stages (i.e., beginning internode elongation, 50% heading, and reproduction/grain fill), N fertilization (i.e., mid-season N fertilization for the pure-line cultivar or boot N fertilization for the hybrid cultivar) and after re-flooding events in the intermittent-flood water management practice, with no overall obvious trend. The numerically largest overall mean N_2O flux for the season (i.e., flood establishment to harvest) occurred after mid-season N fertilization (i.e., 27 DAF) from the full-season-flood/LaKast (72.8 g N_2O-N ha^{-1} d^{-1}) treatment combination. In contrast, the numerically largest mean N_2O flux from the intermittent-flood/XL753, intermittent-flood/LaKast, and full-season-flood/XL753 combinations occurred immediately prior to the end-of-season flood release (i.e., 74 DAF), which were 22 (56.5 g N_2O-N ha^{-1} d^{-1}), 63 (26.4 g N_2O-N ha^{-1} d^{-1}), and 74% (18.9 g N_2O-N ha^{-1} d^{-1}), respectively, lower than that from the full-season-flood/LaKast treatment combination.

In contrast to that hypothesized, neither water management practice, cultivar, nor their interaction affected N_2O fluxes from a silt-loam soil during the 2016 rice-growing season ($P >$ 0.10; Table 3). However, averaged across water management and cultivar treatments, N_2O fluxes differed significantly over time ($P = 0.07$; Table 3). Nitrous oxide fluxes measured on 27 and 74 DAF were 5 to 30 times greater than the non-zero fluxes measured on all other sampling dates (i.e., 5, 12,19, 32, 40, 54, 61, 80, and 81 DAF), except for the N_2O flux measured on 47 DAF, which not differ from that measured on either 27 and 74 DAF (Figure 2). However, due to large variability, the N_2O flux measured on 47 DAF also did not differ from that measured on any other sampling date, which included dates where there was no measured N_2O flux (Figure 2). The non-zero N_2O fluxes measured on 27 and 74 DAF occurred during the reproductive and grain filling growth stages and after the split fertilizer-N application (Figure 2). However, delayed-flood rice is known to have large N-uptake efficiency [i.e., > 60% of N uptake for the first N application (pre-flood establishment) and > 70% uptake for the second, mid-season N-fertilization application (post-flood establishment) of fertilizer N] when optimal N-fertilization rates (i.e., 151 to 168 kg N ha^{-1}) are applied to a silt-loam soil (Norman et al., 2003). Consequently, the large, split-application N-uptake efficiency likely reduced the influence of a second, midseason fertilizer-N application on N_2O fluxes. There was no obvious explanation for the significantly large measured N_2O fluxes on 27 and 74 DAF. The weekly gas sampling scheme could have masked potential significant fluxes and/or treatment combination differences that may have occurred at smaller temporal scales, as N_2O fluxes are known to be temporally variable in lowland rice production (LaHue et al., 2016; Simmonds et al., 2015;) and even in upland crop production (i.e., corn; Parkin and Kaspar, 2006; Omonode et al., 2011).

Previous limited research in Arkansas on silt-loam soils have shown N_2O fluxes gradually building up to a maximum peak near heading (~10 g N_2O-N ha^{-1} d^{-1}), with a lower peak at ~5 g N_2O-N ha^{-1} d^{-1} after heading and a similar ~10 g N_2O-N ha^{-1} d^{-1} peak following the end-of-season flood release for a full-season-flood/pure-line treatment combination (Simmonds et al., 2015). Simmonds et al. (2015) had an additional Arkansas site that produced N_2O fluxes that oscillated throughout the season, but never more than 5 g N_2O-N ha^{-1} d^{-1}, until peaking at ~15 g N_2O-N ha^{-1} d^{-1} weeks after heading, with a secondary peak (~10 g N_2O-N ha^{-1} d^{-1}) following the end-of-season flood-release for a full-season-flood/hybrid treatment combination. In addition, similar to the results of this study, Simmonds et al. (2015) did not measure a statistically significant difference in N_2O fluxes between a pure-line and hybrid cultivar.

Similar to the intermittent-flood scheme in this study, other limited studies investigating the alternate-wet-and-dry (AWD) water management scheme in both Arkansas and California reported peak N_2O fluxes prior to the first re-flooding event and lower peaks at the second re-flooding event; however, a non-zero N_2O flux was not always measured at each subsequent re-flooding event beyond the second re-flood event (Linquist et al., 2015; LaHue et al., 2016). Adding to the inconsistent trend of N_2O fluxes from the conventional, full-season-flood water management practice, Adviento-Borbe and Linquist (2016) reported only one non-zero N_2O flux during the growing season from two of three California sites, with the measured N_2O fluxes < 5 g N_2O-N ha^{-1} d^{-1}. Adviento-Borbe et al. (2013) also did not measure any appreciable N_2O fluxes during the 2011 growing season at a site near Stuttgart, AR, but did measure non-zero fluxes several weeks after the end-of-season flood release, with a peak flux of ~50 g N_2O-N ha^{-1} d^{-1} during that time.

Unlike the seemingly unpredictable N_2O flux trends, CH_4 fluxes occur in a more temporally predictable manner. Several studies conducted on a silt-loam soil at the RREC near Stuttgart, AR have shown that CH_4 fluxes in a full-season-flood water management scheme begin to gradually increase several weeks after flood establishment and peak flux around 50 to 60 DAF, which corresponds closely to the 50% heading rice growth stage, then decrease as the season approaches the end-of-season flood-release period, with a final CH_4 spike often occurring between the end-of-season flood release and harvest (Brye et al., 2013; Rogers et al., 2013, 2014).

Aboveground Biomass and Yield

Aboveground biomass measured six days post flood release was unaffected ($P > 0.05$) by water management practice, but differed ($P = 0.03$) between cultivars (Table 4). Aboveground biomass from the hybrid cultivar XL753 (23.1 Mg ha^{-1}) was 20% greater than that from the pure-line cultivar LaKast (19.3 Mg ha^{-1}). A similar study in Arkansas also reported greater aboveground biomass with a hybrid cultivar (i.e., CLXL745) than several pure-line cultivars (i.e., Francis, Jupiter, and Sabine; Simmonds et al., 2015)

Similar to the differences in aboveground biomass, rice grain yield differed ($P = 0.03$) between cultivars, but was unaffected ($P > 0.05$) by water management practice (Table 4). Rice grain yield for XL753 (14.5 Mg grain ha^{-1}) was 29% greater than that for LaKast (11.2 Mg grain ha^{-1}). Rice grain yield for LaKast was 51% numerically greater than the last reported average LaKast yields (7.1 Mg grain ha^{-1}) in 2015, and XL753 had a yield that was 71% numerically greater than the average XL753 yields (8.5 Mg grain ha^{-1}) in 2016 when both cultivars were part of the Arkansas Rice Research Verification Program (Baker et al., 2016, 2017). These results supported the general consensus that hybrid rice yields 5 to 15% greater than pure-line rice cultivars (Maclean et al., 2013).

Nitrous Oxide Emissions

Area-scaled N_2O emissions for the pre-flood-release (i.e., establishment of the delayed flood to end-of-season flood release) segment of the growing season were unaffected ($P > 0.10$) by water management practice or cultivar (Table 3). Though significant differences among treatments or treatment combinations were not identified, even at the $P < 0.1$ level, the full-season-flood/LaKast treatment combination had the numerically largest pre-flood-release, area-scaled N_2O emissions (0.80 kg N_2O-N ha^{-1}), which were 7% larger than that from the intermittent-flood/XL753 (0.75 kg N_2O-N ha^{-1}), 68% larger than that from the intermittent-flood/LaKast (0.48 kg N_2O-N ha^{-1}), and 229% larger than that from the full-season-flood/XL753 (0.35 kg N_2O-N ha^{-1}) treatment combinations (Table 5).

Similar to the pre-flood-release period, post-flood-release (i.e., end-of-season flood release to harvest), area-scaled N_2O emissions were also unaffected (*P* > 0.10) by water management practice or cultivar (Table 3). Though significant differences were not identified, the intermittent-flood/XL753 treatment had the numerically largest post-flood-release, area-scaled N_2O emissions (0.09 kg N_2O-N ha^{-1}), which were 109% larger than that from the intermittent-flood/LaKast (0.04 kg N_2O-N ha^{-1}) and 203% larger than that from the full-season-flood/XL753 (0.03 kg N_2O-N ha^{-1}) treatment combinations (Table 5). In contrast, no N_2O emissions were measured after flood release from the full-season-flood/LaKast treatment combination (Table 5). Post-flood-release, area-scaled N_2O emissions constituted 0, 8, 8, and 11% of the season-long N_2O emissions for the full-season-flood/LaKast, full-season-flood/XL753, intermittent-flood/LaKast, and intermittent-flood/XL753 treatment combinations, respectively (Table 5).

Limited research has differentiated N_2O fluxes between pre- and post-flood-release periods of the rice growing season. However, Zhao et al. (2011) reported that the post-flood-release period constituted 5 to 7% of the seasonal N_2O emissions when a mid-season aeration period occurred. Through three different field studies, Adviento-Borbe et al. (2015) reported the post-flood-release period contributed from 0 to 82% of the season-long N_2O emissions under a full-season flood.

Season-long (i.e., establishment of the delayed flood to harvest), area-scaled N_2O emissions were unaffected (*P* > 0.10) by water management practice or cultivar (Table 3). Despite the lack of significant differences, N_2O emissions from the intermittent-flood (0.68 kg N_2O-N ha^{-1} $season^{-1}$) were 1.1 times numerically greater than that from the full-season-flood treatment (0.59 kg N_2O-N ha^{-1} $season^{-1}$), while N_2O emissions from the pure-line cultivar LaKast

(0.66 kg N_2O-N ha^{-1} season^{-1}) were 8% numerically greater than that from the hybrid cultivar XL753 (0.61 kg N_2O-N ha^{-1} season^{-1}). Season-long N_2O emissions from the intermittent-flood/XL753 averaged 0.84 kg N_2O-N ha^{-1} season^{-1}, which was 5% numerically greater than that from the full-season-flood/LaKast (0.80 kg N_2O-N ha^{-1} season^{-1}), 62% greater than that from the intermittent-flood/LaKast (0.52 kg N_2O-N ha^{-1} season^{-1}), and 121% greater than that from the full-season-flood/XL753 (0.38 kg N_2O-N ha^{-1} season^{-1}) treatment combination (Table 6). Averaged across water management practice and cultivar, mean season-long N_2O emissions were 0.64 kg N_2O-N ha^{-1} season^{-1}, which were 25% numerically greater than the 0.51 kg N_2O-N ha^{-1} season^{-1} expected based on the Intergovernmental Panel on Climate Change's emissions factor from flooded rice fields at 3 g N_2O-N kg N input^{-1} with an N input rate of 168 kg N ha^{-1} (de Klein et al., 2006).

Similar to the results of this study, numerically low season-long, area-scaled N_2O emissions have been reported under a conventional, full-season-flood rice crop in a soybean-rice rotation with similar N-fertilization rates (i.e., 134 to 168 kg N ha^{-1}) with both pure-line (i.e., Francis, Jupiter, and Sabine) and hybrid (i.e., XL745 and CLXP4534) rice cultivars at the RREC near Stuttgart, AR (Linquist et al., 2015; Simmonds et al., 2015). Nitrous oxide emissions ranged from a sink (-0.10 kg N_2O-N ha^{-1} season^{-1}) to a source of 0.17 kg N_2O-N ha^{-1} season^{-1} (Linquist et al., 2015; Simmonds et al., 2015). However, Linquist et al. (2015) also evaluated alternating-wet-and-dry (AWD) management practices (i.e., similar to intermittent flooding) where rice fields were allowed dry to 40 to 60% of the saturated water content and measured low N_2O emissions that ranged from 0.39 to 1.05 kg N_2O-N ha^{-1} season^{-1}, which were similar to the intermittent-flood results of this study (Table 6). Unlike this study, Linquist et al. (2015) reported a significant difference in year 2 of a 2-yr study between a continuously flooded and the AWD treatment combinations, where AWD treatments had an increase in N_2O emissions. Adviento-Borbe et al. (2013) also reported N_2O emissions from the RREC in a water management practice that had several flushes at the beginning of the growing season followed by a continuous flood for the remainder of the season with varying N-fertilization rates (i.e., 0, 112, 168, 224 kg N ha^{-1}). Nitrous oxide emissions of only 0.16 kg N_2O-N ha^{-1} $season^{-1}$ were measured from optimally N fertilized (i.e., 168 kg N ha^{-1}) rice, while emissions from excessively N-fertilized rice (224 kg N ha^{-1}) were more than double, but still relatively low (0.34 kg N_2O-N ha^{-1} $season^{-1}$; Adviento-Borbe et al., 2013).

Limited studies on N_2O emissions in California have results that varied from those documented in previous studies conducted in Arkansas when similar production techniques (i.e., water management practice and seeding method) were used. LaHue et al. (2016) measured relatively low N_2O emissions, ranging between 0.10 to 0.32 kg N_2O-N ha^{-1} $season^{-1}$ in an AWD and direct-seeded rice production system. Additionaly, LaHue et al. (2016) did not report N_2O emissions that differed between an AWD and non-AWD water-seeded, production system (i.e., -0.02 to -0.04 kg N_2O-N ha^{-1} $season^{-1}$), and those measurements indicated that the rice field was a N_2O sink. Water-seeded rice under continuously flooded conditions in other California studies have also exhibited N_2O-sink tendencies (i.e., negative measured N_2O emissions), but did not differ from the relatively small, positive N_2O emissions recorded (0.01 to 0.06 kg N_2O-N ha^{-1} $season^{-1}$) in the same studies (Adviento-Borbe et al., 2016; Simmonds et al., 2015).

Varying season-long N_2O emissions have been reported when water-seeded fields were flushed at the beginning of the season (Adviento-Borbe et al., 2013; Pittelkow et al., 2013). Adviento-Borbe et al. (2013) measured greater N_2O emissions, between 0.86 and 1.9 kg N_2O-N ha^{-1} $season^{-1}$, in fields that were optimally N fertilized (i.e., 100 kg N ha^{-1}) and were flushed multiple times at the beginning of the season. However, Pittelkow et al. (2013) measured N_2O emissions that only ranged from 0.2 to 0.4 kg N_2O-N ha^{-1} $season^{-1}$ in fields that were optimally N fertilized (i.e., 140 to 200 kg N ha^{-1}) and were only flushed one time at the beginning of the season. Overall lower N_2O emissions in California could be a result of more fine-textured soils than those at the RREC, which would be similar to clayey soils in Arkansas emitting less CH_4 than coarser-textured silt-loam soils (Brye et al., 2013).

Similar to season-long, area-scaled N_2O emissions, the yield-scaled N_2O emissions were also unaffected ($P > 0.10$) by water management practice or cultivar (Table 3). The full-season-flood/LaKast treatment combination had the numerically largest yield-scaled N_2O emissions [0.07 kg N_2O-N (Mg $grain)^{-1}$], which was 20% greater than that from the intermittent-flood/XL753 [0.06 kg N_2O-N (Mg $grain)^{-1}$], 51% greater than that from the intermittent-flood/LaKast [0.05 kg N_2O-N (Mg $grain)^{-1}$], and 196% greater than that from the full-season-flood/XL753 [0.02 kg N_2O-N (Mg $grain)^{-1}$; Table 6).

Limited studies have reported yield-scaled N_2O emissions to range from 0 to 0.30 kg N_2O-N (Mg $grain)^{-1}$ from field studies using water management practices similar to an intermittent or a full-season flood (LaHue et al., 2016; Linquist et al., 2015). Linquist et al. (2015) reported lower yields for drill-seeded, delayed-flood rice production systems during the 2013 growing season that were allowed to dry out the most compared to yields in the same year from a full-season flood maintained from reproductive growth to the end-of-season flood release.

Soil Redox and Temperature

Nitrous oxide and CH_4 production generally occur in soils with redox potentials (Eh) readings that range from 220 to 280 and from -200 to -280 mV, respectively (Brady and Weil, 2008). As might be expected, soil Eh, recorded from the hour immediately before N_2O fluxes were measured each week, differed between water management practices over the growing season ($P < 0.01$), but were unaffected ($P > 0.05$) by cultivar (Table 4). Soil redox potentials differed between water management practices only on sampling dates that occurred on or between 19 and 40 DAF, which included the second and third re-flooding events (i.e., 18 and 35 DAF) in the intermittent-flood treatment (Figure 3). The intermittent-flood treatment had soil Eh readings ranging from 24 to 290 mV between 19 and 40 DAF , while the full-season-flood treatment had a more reduced soil environment, with Eh readings ranging from -74 to -219 mV (Figure 3). There were no differences ($P > 0.05$) between Eh readings when Eh readings were > 0 mV for dates that fell between 0 and 40 DAF, except for 12 DAF in the intermittent-flood treatment (Figure 3). Soil redox potentials did not differ ($P > 0.05$) between water management practices prior to 19 DAF or after 40 DAF, and soil Eh in both water management practices tended to become more reduced later in the growing season as the duration of wet to saturated soil conditions increased (Figure 3). The re-flooding events that occurred in the interment-flood treatment clearly allowed the soil to reaerate or oxidize, therefore, increasing soil Eh for a short duration of time surrounding the re-flooding events.

Similar to soil Eh, soil temperature differed between water management practices over the course of the growing season ($P < 0.01$) and was unaffected ($P > 0.05$) by cultivar (Table 4). The soil temperature was warmer in the full-season-flood than the intermittent-flood on many dates (i.e., 0, 5, 12, 27, 32, 47, 54, 61, 74 and 75 DAF), but did not differ by more than 3°C on any given date (Figure 4). Soil temperatures fluctuated throughout the growing season, with the soil temperature starting above 35°C, but immediately decreasing to below 30°C, where the numerically largest (12 DAF) and lowest (32 DAF) soil temperatures recorded for the entire growing season occurred in the intermittent-flood treatment (29 and 24°C, respectively; Figure 4). Though differences between day and nighttime air temperatures were shown to significantly impact CH_4 emissions from silt-loam soils in east-central Arkansas (Brye et al., 2016), it is unclear yet how minor variations in soil temperature between water management practices might impact N_2O emissions.

Seasonal Methane Emissions and Total Global Warming Potential

In contrast to N_2O emissions, season-long, area-scaled CH_4 emissions differed (P = 0.001) between cultivars (Table 3). However, CH_4 emissions were unaffected ($P > 0.05$) by water management practice (Table 3). Season-long, area-scaled CH_4 emissions from the pure-line cultivar LaKast (92.1 kg CH_4-C ha^{-1} season^{-1}) were more than twice the emissions from the hybrid cultivar XL753 (43.9 kg CH_4-C ha^{-1} season^{-1}). The intermittent-flood/LaKast (82.6 kg CH_4-C ha^{-1} season^{-1}) treatment combination had the numerically greatest CH_4 season-long, area-scaled emissions, which were 22, 98, and 178% numerically greater than that from the full-season-flood/LaKast, full-season-flood/XL753, and intermittent-flood/XL753 treatment combinations, respectively (Table 6).

Similar season-long, area-scaled CH_4 emissions have been reported in Arkansas fields cropped with hybrid rice (i.e., CLXL745 and CLXP4534) on a silt-loam soil, ranging from 7.8 (intermittent-flood) to 100 kg CH_4-C ha^{-1} season^{-1} (full-season-flood; Adviento-Borbe et al., 2013; Linquist et al., 2015; Simmonds et al., 2015). However, pure-line cultivars (i.e., Wells and Taggart) consistently had greater CH_4 emissions than hybrid cultivars, ranging from 150 to 220 CH_4-C ha^{-1} season^{-1} (Brye et al., 2013; Rogers et al., 2013). Though CH_4 emissions did not differ between water management practices in this study, Linquist et al. (2015) reported greater CH_4

emissions from a full-season flood than from a water management practice similar to the intermittent-flood scheme used in this study.

In contrast to many previous agriculturally related, trace gas emissions studies, particularly from rice, this study directly measured both CH_4 and N_2O emissions under field conditions. As a result, to better evaluate potential climatic effects and future sustainability, GWP could be quantified and compared among each treatment combination. Similar to CH_4, but in contrast to N_2O emissions, the total GWP differed ($P = 0.003$) between cultivars, but was unaffected ($P > 0.05$) by water management practice (Table 3; Figure 5). The total GWP from the pure-line cultivar LaKast (4473 kg CO_2 eq. ha^{-1} $season^{-1}$) was nearly twice that from the hybrid cultivar XL753 (2272 kg CO_2 eq. ha^{-1} $season^{-1}$; Figure 5). Though not significant, the total GWP was only 4% numerically greater from the intermittent-flood (3441 kg CO_2 eq. ha^{-1} $season^{-1}$) than from the full-season-flood (3303 kg CO_2 eq. ha^{-1} $season^{-1}$) water management practice (Figure 5). The numerically largest GWP was associated with the intermittent-flood/LaKast (4836 kg CO_2 eq. ha^{-1} $season^{-1}$) treatment combination, which was two times greater than the total GWP associated with the intermittent-flood/XL754 (2046 kg CO_2 eq. ha^{-1} $season^{-1}$) treatment combination, which had the lowest total GWP (Table 6). Nitrous oxide season-long emissions accounted between 5 and 19% of total GWP for the four treatment combinations.

In contrast to the results of this study, Linquist et al. (2015) reported greater total GWP from rice produced in Arkansas under a full-season flood than rice grown under an intermittent-flood water management scheme. Linquist et al. (2015) estimated total GWP ranged between 3226 and 4555 kg CO_2-eq ha^{-1} $season^{-1}$ for the full-season-flood water management practice during the 2012 and 2013 growing season, while under a rice-soybean crop rotation. In contrast, Linquist et al. (2015), under the same crop rotation, estimated total GWP ranged between 140 and 2746 kg CO_2-eq ha^{-1} season^{-1} for water management practices that had at least one reaeration event during the 2012 and 2013 growing season. However, the estimated total GWP for water management practices that had reaeration events that occurred during the reproductive growth phase (i.e., BIE through grain fill) were significantly less when compared to the water management scheme that had reaeration events outside reproductive growth stages (Linquist et al., 2015). Similar to the result of this study, Simmonds et al. (2015) also reported a significant difference in total GWP between pure-line cultivars [i.e., Francis (3592 kg CO_2-eq ha^{-1} season^{-1}) and Sabine (3443 kg CO_2-eq ha^{-1} season^{-1})] and a hybrid cultivar [i.e., CLXL745 (2541 kg CO_2-eq ha^{-1} season^{-1})]. Total GWPs for the hybrid XL745 (1626 to 4555 kg CO_2-eq ha^{-1} season^{-1}) have been reported in other Arkansas studies, where early season flushing and at least a continuous flood during the reproductive growth stage with optimal N fertilization (Adviento-Borbe et al., 2013; Linquist et al., 2015) in the same range as were reported in this study. However, significantly lower total GWP (140 to 491 kg CO_2-eq ha^{-1} season^{-1}) was estimated from the hybrid cultivar XL745 when the soil was allowed to dry down multiple times, including during reproductive growth, throughout the growing season (Linquist et al., 2015). The proportion of total GWP associated to N_2O emissions ranged from <0.01 to 58% (Adviento-Borbe et al., 2013; Linquist et al., 2015; Simmonds et al., 2015). Nitrous oxide emissions accounted for the least amount of total GWP when minimal to no drainage events occurred (Adviento-Borbe et al., 2013; Simmonds et al., 2015), and N_2O emissions dominated when there were significant drainage events (Linquist et al., 2015).

Environmental Implications

Averaged across all treatment factors evaluated in this study, CH_4 emissions accounted for 93% of the total GWP associated with rice grown on a silt-loam soil in east-central Arkansas. Similar to other Arkansas studies, CH_4 emissions appear to be the main driver controlling total GWP, while the contribution of N_2O emissions to total GWP was relatively minor for the treatment combinations evaluated in this study (Linquist et al., 2015; Simmonds et al., 2015).

The rice-growing region of Arkansas also relies heavily on groundwater for irrigation. However, water is being withdrawn from the shallow aquifers at unsustainable rates (ANRC, 2015). Consequently, there is growing interest in potential water conservation practices associated with rice production, hence the use of the intermittent-flood-irrigation approach. Furthermore, in order to alleviate potential detrimental effects of reduced water use on pure-line rice cultivars, there may also be an increased need to plant hybrid rice.

As non-CO_2 greenhouse gas emissions are prevalent and generally increasing in agricultural systems (Smith et al., 2014), some large companies are encouraging producers to reduce specific non-CO_2 greenhouse gas emissions, such as N_2O. Therefore, the need for quantifying the effects that current management practices have on N_2O emissions, and understanding the potential effect that migrating to other rice-production systems may have on those same emissions, is vital for making informed decisions for an industry that is important to many local and state economies.

Conclusions

Though the intermittent-flood treatment had three different re-flood events that caused the soil redox potential to increase (i.e., become less reduced) compared to that measured in the full-season-flood treatment and contrary to that hypothesized, neither weekly N_2O fluxes nor season-long emissions (i.e., area- or yield-scaled) were affected by water management practice (full-season-flood or intermittent-flood), cultivar (pure-line LaKast or hybrid XL753), or their interaction from rice grown on a silt-loam soil in 2016 in the direct-seeded, delayed-flood production system in east-central Arkansas. Despite non-zero N_2O fluxes only being measured on six of 12 sample dates, regardless of imposed treatment, N_2O fluxes varied over time throughout the rice growing season, where peak N_2O fluxes generally occurred between beginning internode elongation and 50% heading and immediately prior to the end-of-season flood release.

Contrary to that hypothesized, total GWP was unaffected by water management practice (full-season-flood or intermittent-flood), but, similar to that hypothesized, was greater (i.e., more environmentally undesirable) from the pure-line than from the hybrid cultivar evaluated in this field study. Based on the numeric ranking of total GWP, results indicated that the combination of growing a pure-line rice cultivar with the intermittent-flood water management practice may want to be avoided by rice producers and that the intermittent-flood/hybrid combination evaluated in this study may be the more environmentally desirable. Though this study only took into account one growing season, the field measurements collected add to the limited research of N_2O emissions in the largest US rice-producing state (i.e., Arkansas). An expanding collection of studies on N_2O emissions from rice production can further assist in environmental decision making for the rice industry and agriculture in general.

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Table 1. Comparison of nitrous oxide (N_2O) fluxes (g N_2O-N ha^{-1} d^{-1}) between the Agilent 6890N and Shimadzu GC-2014 gas chromatographs for three dates during the 2016 growing season where gas samples were analyzed on both instruments for water management (i.e., full-season-flood and intermittent flood)-cultivar (i.e., pure-line LaKast and hybrid XL753) treatment combinations (n = 4).

Measurement date/treatment combination	Agilent 6890N (g N_2O-N ha^{-1} d^{-1})	Shimadzu GC-2014 (g N_2O-N ha^{-1} d^{-1})
22 August, 2017		
Full-season-flood/LaKast	0.0	3.18
Full-season-flood /XL753	18.9	5.73
Intermittent-flood/LaKast	26.7	11.3
Intermittent-flood /XL753	56.5	3.12
28 August, 2017		
Full-season-flood /LaKast	0.0	4.05
Full-season-flood /XL753	0.0	0.0
Intermittent-flood /LaKast	0.0	4.45
Intermittent-flood /XL753	0.0	3.10
29 August,2017		
Full-season-flood /LaKast	0.0	12.0
Full-season-flood /XL753	0.0	8.85
Intermittent-flood /LaKast	0.0	0.76
Intermittent-flood /XL753	0.0	10.2

Table 2. Analysis of variance summary of the effects of pre-treatment water management practice [i.e., full-season-flood and intermittent-flood (n = 8)], cultivar [i.e., pure-line LaKast and hybrid XL753 (n = 8)], and their interaction on soil physical [i.e., sand, silt, clay, and bulk density) and chemical properties [i.e., pH, electrical conductivity (EC), extractable soil P, K, Ca, Mg, Fe, Mn, Na, S, Cu, and Zn and total nitrogen (TN), total carbon (TC), and soil organic matter (SOM) contents] from 2016 at the Rice Research and Extension Center near Stuttgart, AR. Also reported are overall mean values (n = 16) for each soil property. Bolded values represent significant effects ($P < 0.05$).

Soil property	Water management	Cultivar	Water management x cultivar	Overall mean
		P		
Sand (g g^{-1})	0.17	0.16	0.21	0.19
Silt (g g^{-1})	0.23	0.11	0.28	0.73
Clay (g g^{-1})	0.52	0.89	0.06	0.08
Bulk density (g cm^{-3})	0.67	0.20	0.41	1.38
pH	**0.04**	0.09	0.78	7.0
EC (dS m^{-1})	0.98	0.72	0.33	0.30
P (kg ha^{-1})	0.57	**0.04**	0.62	99.3
K (kg ha^{-1})	0.20	0.42	0.54	186
Ca (Mg ha^{-1})	0.12	**0.01**	0.16	2.1
Mg (kg ha^{-1})	0.43	**0.04**	0.67	168
S (kg ha^{-1})	0.73	0.81	0.56	20.4
Na (kg ha^{-1})	0.32	0.29	0.36	94.7
Fe (kg ha^{-1})	0.23	0.27	0.56	684
Mn (kg ha^{-1})	0.06	0.49	0.98	303
Zn (kg ha^{-1})	0.57	0.48	0.23	11.2
Cu (kg ha^{-1})	0.96	0.26	0.24	2.66
TN (kg ha^{-1})	0.45	0.51	0.96	691
TC (Mg ha^{-1})	0.40	0.92	0.71	8.51
SOM (Mg ha^{-1})	0.98	0.32	0.62	22.3
C:N	0.22	0.57	0.58	12.4

Table 3. Analysis of variance summary of the effects of water management practice [i.e., full-season-flood and intermittent-flood (n = 8)], cultivar [i.e., pure-line LaKast and hybrid XL753 (n = 8)], days after flooding [DAF (n = 12)], and their interactions on nitrous oxide (N_2O) fluxes, pre- and post-flood-release and season-long, area- and yield-scaled N_2O emissions, season-long, area-scaled methane (CH_4) emissions, and total global warming potential (GWP) from 2016 at the Rice Research and Extension Center near Stuttgart, AR. Bolded values represent significant effects.

Measured property/Treatment effect	*P*
N_2O fluxes	
Water management practice	0.97
Cultivar	0.74
DAF	**0.07**
Water management practice x cultivar	0.31
Water management practice x DAF	0.89
Cultivar x DAF	0.75
Water management practice x cultivar x DAF	0.27
Pre-flood-release N_2O emissions	
Water management practice	0.97
Cultivar	0.80
Water management practice x cultivar	0.32
Post-flood-release N_2O emissions	
Water management practice	0.53
Cultivar	0.22
Water management practice x cultivar	0.77
Season-long, area-scaled N_2O emissions	
Water management practice	0.92
Cultivar	0.89
Water management practice x cultivar	0.32
Season-long, yield-scaled N_2Oemissions	
Water management practice	0.89
Cultivar	0.82
Water management practice x cultivar	0.29
Season-long, area-scaled CH_4 emissions	
Water management practice	0.77
Cultivar	**0.001**
Water management practice x cultivar	0.06
Total GWP	
Water management practice	0.42
Cultivar	**0.003**
Water management practice x cultivar	0.24

Table 4. Analysis of variance summary of the effects of water management practice [i.e., full-season-flood and intermittent-flood (n = 8)], cultivar [i.e., pure-line LaKast and hybrid XL753 (n = 8)], and their interactions on aboveground dry matter, yield, soil oxidation-reduction (redox) potential, and soil temperature from 2016 at the Rice Research and Extension Center near Stuttgart, AR. Bolded values represent significant effects.

Measured property/Treatment effect	*P*
Aboveground dry matter	
Water management practice	0.66
Cultivar	**0.03**
Water management practice x cultivar	0.41
Grain yield	
Water management practice	0.49
Cultivar	**0.03**
Water management practice x cultivar	0.41
Soil redox potential	
Water management practice	0.18
Cultivar	0.15
DAF	< 0.01
Water management practice x cultivar	0.14
Water management practice x DAF	**< 0.01**
Cultivar x DAF	0.69
Water management practice x cultivar x DAF	0.81
Soil temperature	
Water management practice	0.21
Cultivar	0.90
DAF	< 0.01
Water management practice x cultivar	0.07
Water management practice x DAF	**< 0.01**
Cultivar x DAF	0.16
Water management practice x cultivar x DAF	0.76

Table 5. Mean pre- (i.e., establishment of the delayed flood to end-of-season flood release) and post-flood release (i.e., end-of-season flood release to harvest) nitrous oxide (N_2O) emissions among water management (i.e., full-season-flood and intermittent-flood)-cultivar (i.e., pure-line LaKast and hybrid XL753) treatment combinations measured in 2016 at the Rice Research and Extension Center near Stuttgart, AR.

Treatment combination	Pre-flood-release N_2O emissions ($kg\ N_2O\text{-}N\ ha^{-1}\ season^{-1}$)	Post-flood-release N_2O emissions ($kg\ N_2O\text{-}N\ ha^{-1}\ season^{-1}$)
Full-season-flood / LaKast	0.80 A[†],a[‡]	0 A[†],a[‡]
Full-season-flood / XL753	0.35 A,a	0.03 A,a
Intermittent-flood / LaKast	0.48 A,a	0.04 A,a
Intermittent-flood / XL753	0.75 A,a	0.09 A,a

[†] Different capital letters in a column denote significant differences between water management practices ($P < 0.10$)

[‡] Different lower-case letters in a column denote significant differences between cultivars ($P < 0.10$)

Table 6. Mean season-long, area- and yield-scaled nitrous oxide (N_2O) emissions, season-long, area-scaled methane (CH_4) emissions, and total global warming potential (GWP) among water management (i.e., full-season-flood and intermittent-flood)-cultivar (i.e., pure-line LaKast and hybrid XL753) treatment combinations measured in 2016 at the Rice Research and Extension Center near Stuttgart, AR.

Treatment combination	Area-scaled N_2O emissions (kg N_2O-N ha^{-1} season^{-1})	Yield-scaled N_2O emissions [kg N_2O-N (Mg grain)$^{-1}$]	Area-scaled CH_4 emissions (kg CH_4-C ha^{-1} season^{-1})	Total GWP (kg CO_2 equivalent ha^{-1} season^{-1})
Full-season-flood / LaKast	0.80 A†,a‡	0.07 A†,a‡	82.6 A$^{\#}$,a§	4110 A$^{\#}$,a§
Full-season-flood / XL753	0.38 A,a	0.02 A,a	51.3 A,b	2497 A,b
Intermittent-flood / LaKast	0.52 A,a	0.05 A,a	101.6 A,a	4836 A,a
Intermittent-flood / XL753	0.84 A,a	0.06 A,a	36.5 A,b	2046 A,b

[†] Different capital letters in the column denote significant differences between water management practices ($P < 0.10$)

[‡] Different lower-case letters in the column denote significant differences between cultivars ($P < 0.10$)

[#] Different capital letters in the column denote significant differences between water management practices ($P < 0.05$)

[§] Different lower-case letters in the column denote significant differences between cultivars ($P < 0.05$)

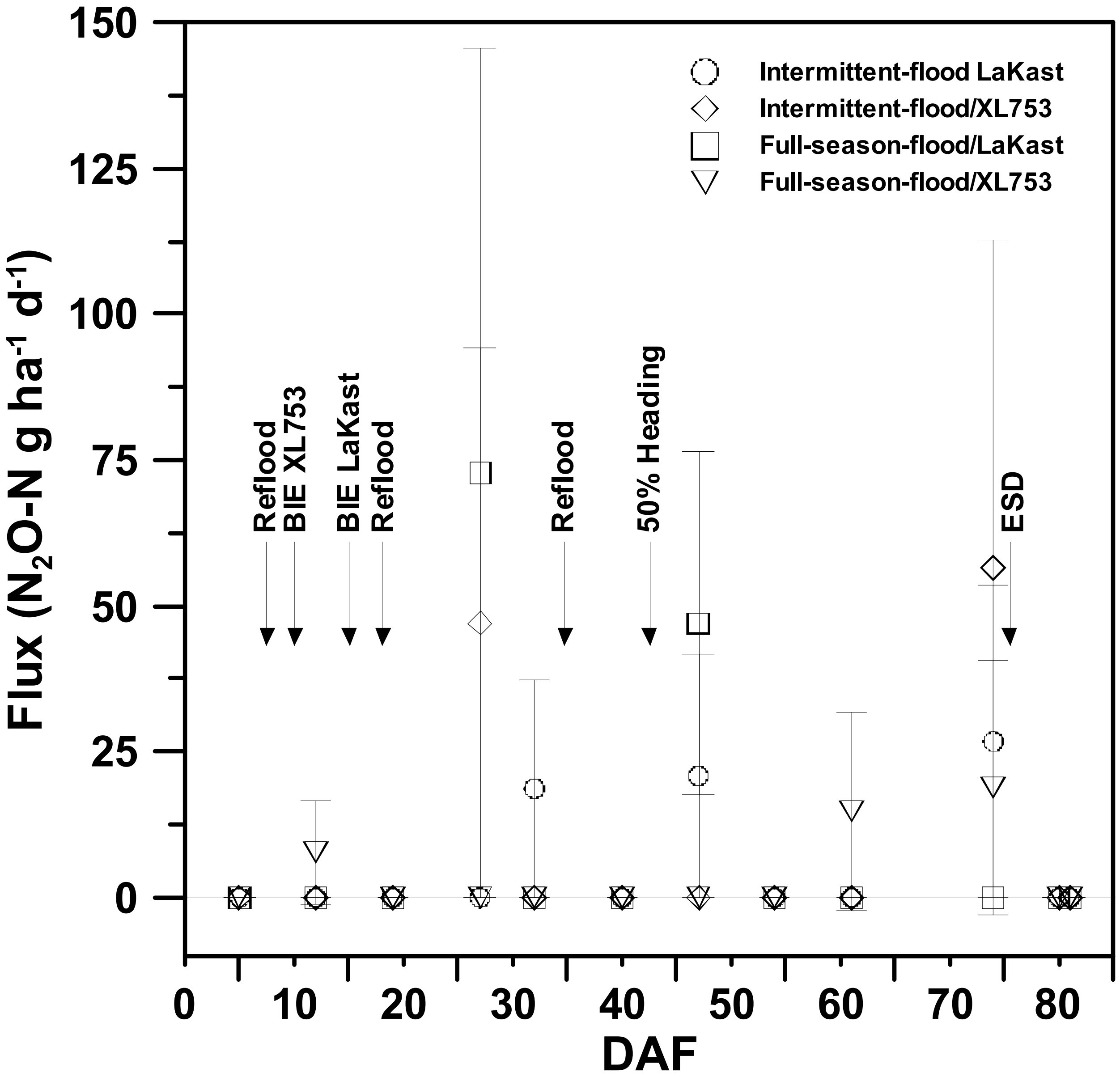

Figure 1. Nitrous oxide (N_2O) fluxes over time during the 2016 rice-growing season at the Rice Research and Extension Center near Stuttgart, AR. Solid vertical lines indicate when re-flooding of the intermittent-flood treatment occurred [i.e., 8, 18, 35 days after flood (DAF)]. Dashed vertical lines represent growth stages [beginning internode elongation (i.e., BIE; LaKast-15 DAF and XL753-10 DAF) and 50% heading (42 DAF)], and end-of-season drain (75 DAF). Mid-season nitrogen (N)-fertilization for the pure-line cultivar LaKast occurred 18 DAF and boot N-fertilizer application for the hybrid cultivar XL753 occurred 26 DAF. Error bars associated with treatment means are standard errors (n = 4). Least significant difference (LSD) at the α = 0.1.

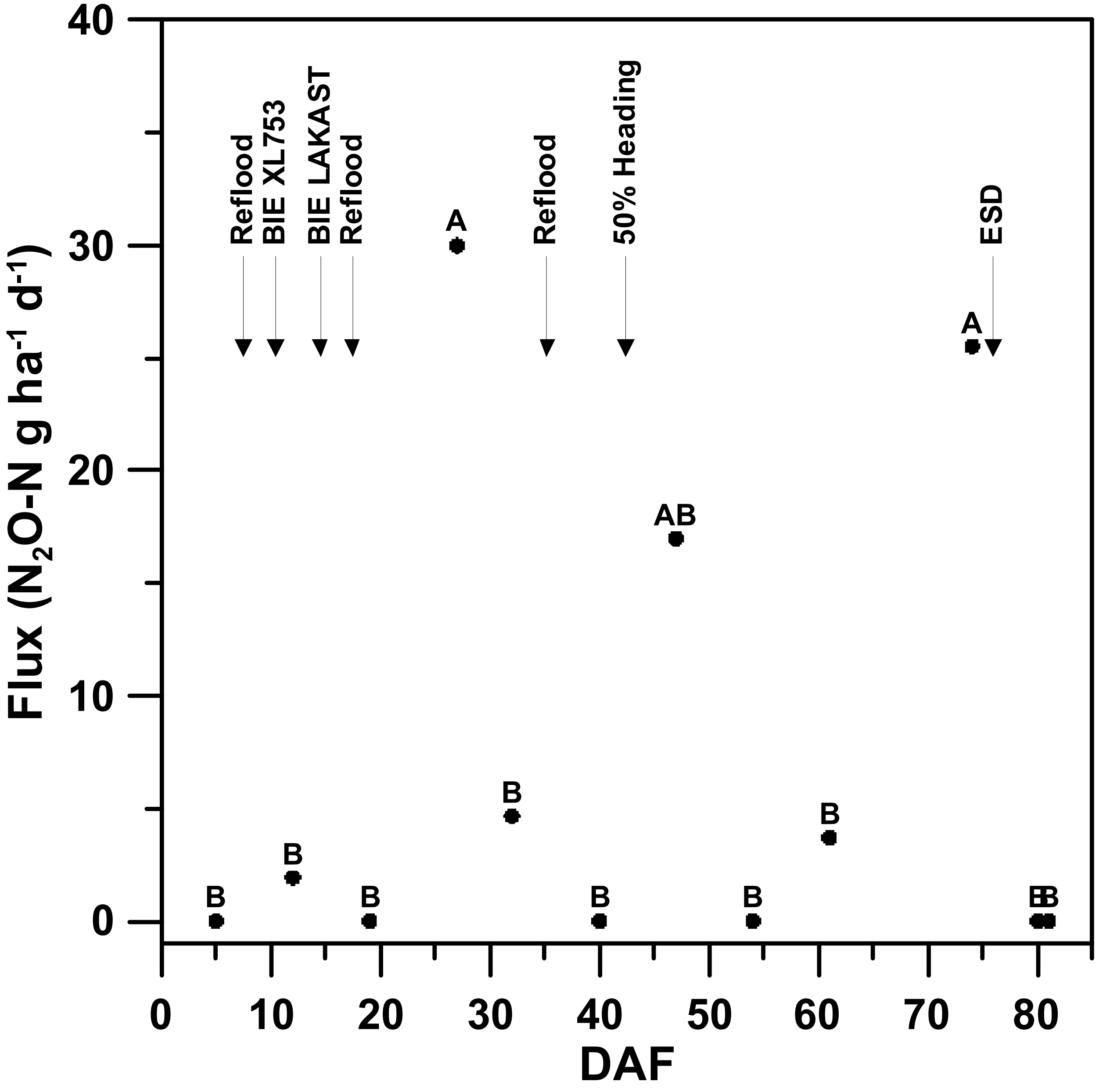

Figure 2. Mean (n = 16) nitrous oxide (N_2O) fluxes, averaged across water management practice and cultivar, over time during the 2016 rice-growing season at the Rice Research and Extension Center near Stuttgart, AR. Solid vertical lines indicate when re-flooding of the intermittent-flood treatment occurred [i.e., 8, 18, 35 days after flood (DAF)]. Dashed vertical lines represent growth stages [internode elongation (i.e., LaKast, 15 DAF and XL753, 10 DAF) and 50% heading (42 DAF)], and end-of-season drain (75 DAF). Mid-season nitrogen (N)-fertilization for the pure-line cultivar LaKast occurred 18 DAF, and boot N-fertilizer application for the hybrid cultivar XL753 occurred 26 DAF. Different letters indicate a significant difference ($P < 0.10$) among sample dates.

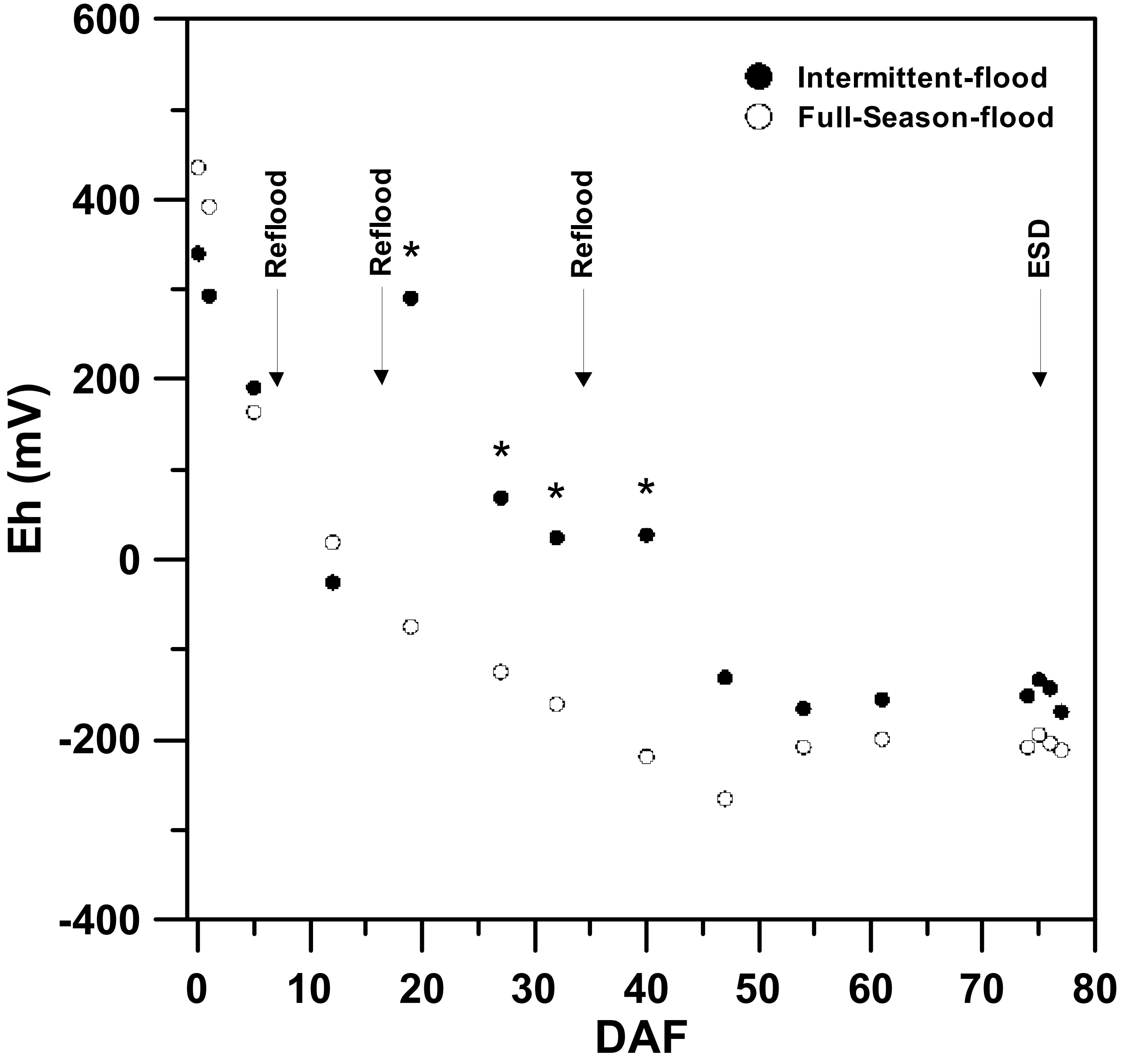

Figure 3. Soil redox potential (Eh) over time during the 2016 rice-growing season at the Rice Research and Extension Center near Stuttgart, AR. Arrows (↓) denote re-flooding of the intermittent-flood treatment [i.e., 8, 18, 35 days after flood (DAF)] and end-of-season drain (ESD; 75 DAF). An asterisks (*) represents a significant difference ($P < 0.05$) between water management practices on that date.

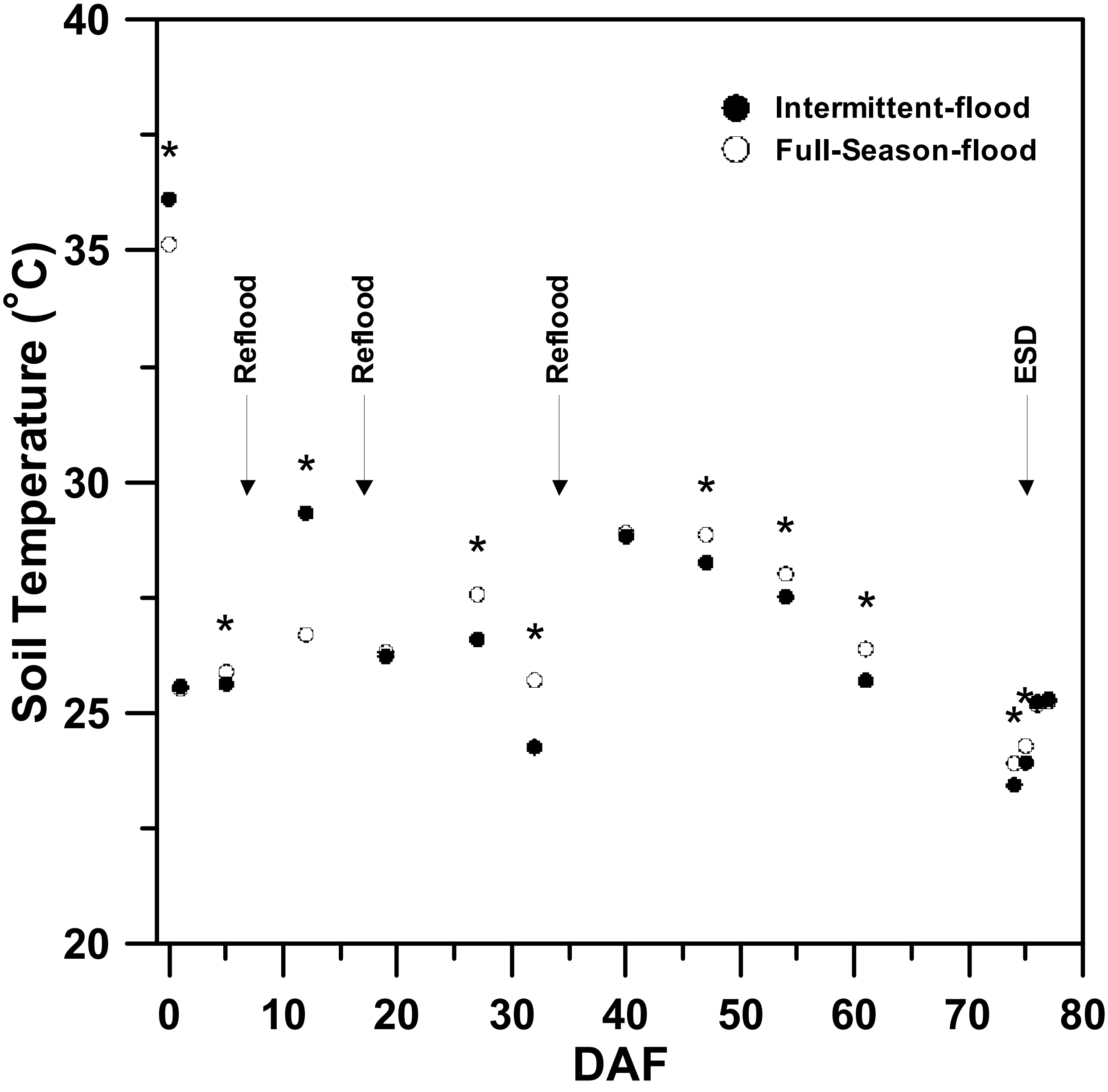

Figure 4. Soil temperature (°C) over time during the 2016 rice-growing season at the Rice Research and Extension Center near Stuttgart, AR. Arrows (↓) denote re-flooding of the intermittent-flood treatment [i.e., 8, 18, 35 days after flood (DAF)] and end-of-season drain (ESD; 75 DAF). An asterisks (*) represents a significant difference (*P* < 0.05) between water management practices on that date.

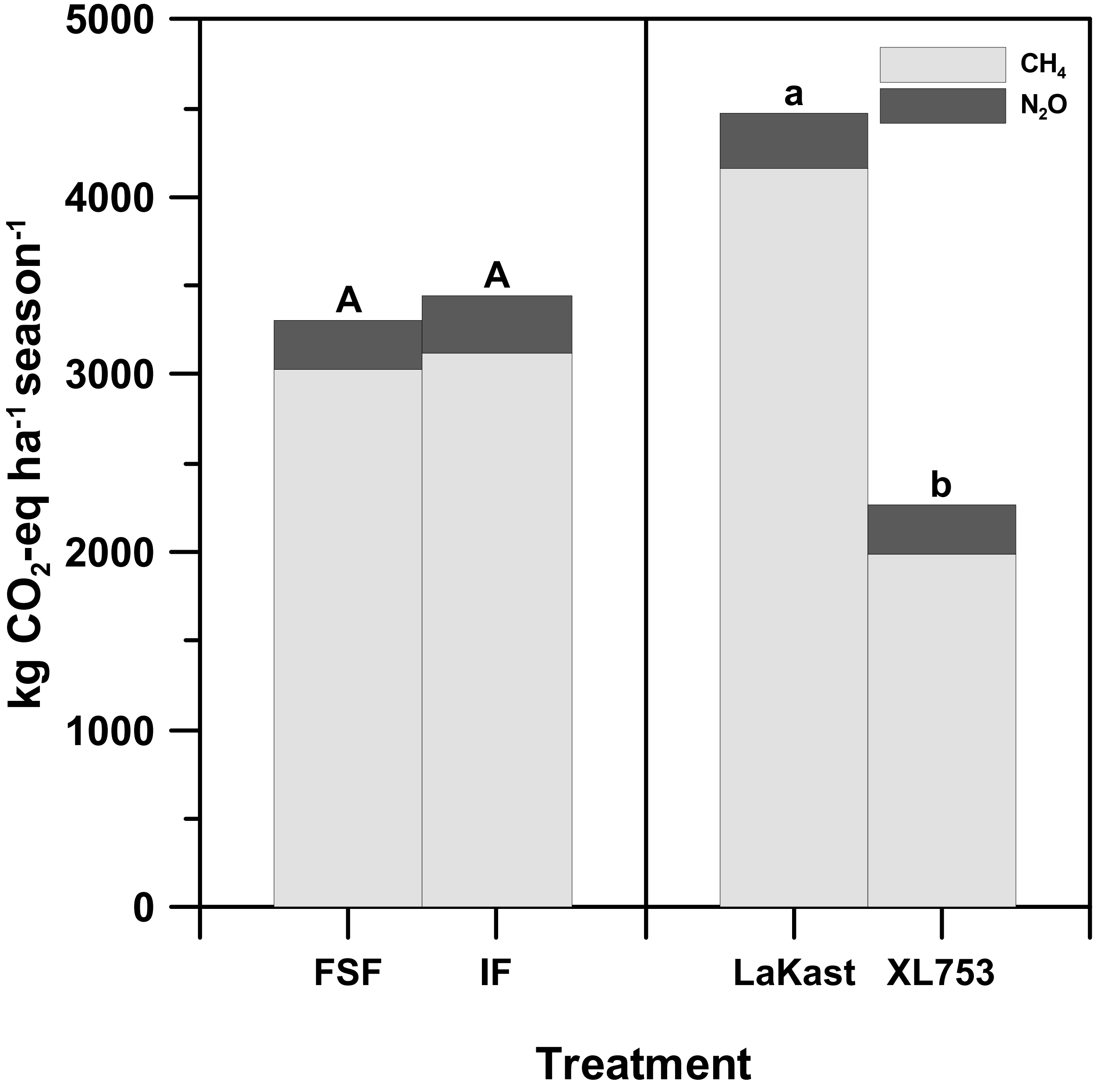

Figure 5. Total global warming potential (GWP), reported as carbon dioxide equivalents (CO_2-eq) for nitrous oxide (N_2O) and methane (CH_4) emissions, estimated for water management practice [i.e., full-season-flood (FSF) and intermittent-flood (IF)] and cultivars (LaKast and XL753) from the 2016 rice-growing season at the Rice Research and Extension Center near Stuttgart, AR. Different capital letters in the column denote significant differences between water management practices (n = 8; $P < 0.05$). Different lower-case letters in the column denote significant differences between cultivars (n = 8; $P < 0.05$).

CHAPTER THREE

TILLAGE PRACTICE AND COATED-UREA EFFECTS ON NITROUS OXIDE EMISSIONS FROM RICE PRODUCTION IN ARKANSAS

Abstract

Rice (*Oryza sativa* L.) is a key component of the diet of billions of humans, thus rice is a main agricultural product in many regions, particularly in eastern Arkansas. Rice production is known to be a source of greenhouse gases, namely methane (CH_4), but, under certain conditions, nitrous oxide (N_2O) as well. The main objective of this study was to evaluate the effects of tillage practice [conventional tillage (CT) and no-tillage (NT)] and type of urea fertilizer [NBPT (N-(n-butyl) thiophosphoric triamide)-coated and non-coated urea] on N_2O fluxes, season-long N_2O emissions, and the global warming potential (GWP) from rice grown in eastern Arkansas in a direct-seeded, delayed-flood production system on a silt-loam soil. Gas samples were collected from enclosed chambers at 20-min intervals for 1 hr on a weekly basis between establishment of the full-season flood and four days after end-of-season flood release. Nitrous oxide fluxes were unaffected ($P > 0.1$) by tillage practice, urea fertilizer type, or time throughout the 2017 rice growing season. Nitrous oxide emissions ranged from 0.27 to 0.50 kg N_2O-N ha^{-1} $season^{-1}$ from the NT/NBPT-coated urea and NT/non-coated urea treatment combinations, but were unaffected ($P > 0.1$) by tillage practice or fertilizer type. Total global warming potential (GWP) ranged from 1324 to 2204 kg CO_2-equivalent ha^{-1} $season^{-1}$ from the CT/NBPT-coated urea and NT/non-coated urea treatment combinations, but was also unaffected ($P > 0.05$) by tillage practice or urea fertilizer type. With limited studies in Arkansas evaluating the impacts of tillage practice or urea fertilizer type on N_2O emissions, it is important to quantify and evaluate potential agronomic factors affecting N_2O emissions from rice production to properly determine if changing to alternative management practices for improved soil health (i.e., no-tillage) or to limit ammonia volatilization (i.e., NBPT-coated urea) will impact N_2O emissions.

Introduction

Rice (*Oryza sativa* L.) is a cereal grain that accounts for 25% of all energy created by food consumption and is especially important to the diets of poorer populations (Maclean et al., 2013). The world's population is expected to increase by over 2 billion people by 2050, with the largest increases coming from lesser-developed countries (UN-DESA, 2017). The need for rice as a staple food will only increase as the human population increases.

Arkansas leads the United States (US) in rice production, where 47% of all US rice was grown in Arkansas in 2016, and Arkansas annually exports $147 million worth of rice abroad (Hardke, 2017; USCB, 2017). The uncommon use of a flooded field during the growing season for rice production, compared to upland grain crops [i.e., soybean (*Glycine max* L.), corn (*Zea mays* L.), and wheat (*Triticum aestivum* L.)], can be viewed as both beneficial and detrimental to the environment. Flooded-soil conditions in flood irrigated rice production can increase soil nutrient availability and facilitate weed management, but at the same time can lead to the unintended production of greenhouse gases (GHG), such as methane (CH_4) and nitrous oxide (N_2O).

Near-saturated to saturated soils, induced by flooding, rapidly become oxygen (O_2) depleted, therefore rice plants have developed aerenchyma tissue that facilitates the movement of atmospheric O_2 through the plant to the roots (Counce et al., 2003). However, as long as the soil is saturated, the soil profile will continue to be depleted of O_2, which impacts the soil microbial community. When there is an absence of O_2, facultative anaerobic microbes will switch from using O_2 as their final electron acceptor to other compounds to meet that need, such as nitrate (NO_3^-; Smith and Tiedje, 1979). As NO_3^- becomes the preferred final electron acceptor, NO_3^- is reduced to dinitrogen (N_2) gas through denitrification (Smith and Tiedje, 1979). In some cases, the denitrification process is incomplete and N_2O gas is released as a by-product. Nitrate can be introduced to the soil through nitrate-based N fertilizers or created through the aerobic process of nitrification. However, nitrification of ammonium (NH_4^+) to NO_3^- has been observed in reduced soils associated with rice production (Arth and Frenzel, 2000). The movement of O_2 through the aerenchyma tissue to the rhizosphere facilitates nitrification of NH_4^+ that is adsorbed to nearby soil colloids and NO_3^- that is not taken up by the plant is translocated to the underlying reduced soil profile where the NO_3^- can also be denitrified to either N_2O or N_2 (Arth and Frenzel, 2000).

Nitrous oxide, along with CH_4, is a common and potent GHG directly emitted from rice production. Between 1700 and the present, atmospheric N_2O and CH_4 concentrations have increased globally by 20 and 150%, respectively (IPCC, 2014). It is expected that, from rice production alone, non-carbon-dioxide (CO_2) emissions (i.e., N_2O and CH_4) will increase 2% by 2030 (Smith et al., 2014). Nitrous oxide and CH_4 are more potent in the atmosphere than CO_2, with a global warming potential (GWP) that is 298 and 34 times, respectively, greater than that of CO_2 (Myhre et al., 2013). As of 2017, the average monthly atmospheric N_2O concentration was 329 $\mu g\ L^{-1}$, and the most recent measurements from 2016 have the average monthly atmospheric concentration of CH_4 between 1800 and 1900 $\mu g\ L^{-1}$ (NOAA-ESRL/GMD, 2018).

Tillage is a frequent soil management practice in many crops and is used extensively in rice production. However, the preparation of crop fields with conventional tillage (CT) prior to planting can lead to detrimental effects on the environment because CT removes residue from the soil surface, leaving a bare soil surface to potentially increase soil erosion (Pittelkow et al., 2015). Other tillage practices, such as conservation tillage and no-tillage (NT) that have been utilized to reduce soil erosion. No-tillage practices minimize soil erosion and support soil health by improving soil structure and increasing water infiltration and retention (Seta et al., 1993;

Turmel et al., 2014). No-tillage increases soil organic matter (SOM), which not only provides nutrients to crops, but also supplies an increased amount of carbon (C) substrate to microbial communities that are known to facilitate the production of N_2O in partially saturated-soil conditions (Liu et al., 2006; Ahmad et al., 2009).

Research studies evaluating the impacts of differing tillage practices (i.e., CT, reduced/conservation tillage, and/or NT) on N_2O fluxes and/or emissions from row crops [i.e., barley (*Hordeum vulagre* L.), corn, wheat, and rice) have been inconclusive. A few studies have reported a significant difference between CT and NT (Liu et al., 2006; Ahmad et al., 2009), while others reported no effect of tillage practice on N_2O emissions (Chatskikh and Olesen, 2007; Zhang et al., 2015). The potential effects that tillage practices have on N_2O emissions are inconsistent, but, when a significant difference has been reported, N_2O emissions tend to be greater from NT compared to CT practices. Methane emissions as affected by tillage have also been inconsistent, where Liu et al. (2006) and Ahmad et al. (2009) reported significant increases in CH_4 emissions from CT compared to NT, but Zhang et al. (2015) reported significant decreases in CH_4 emissions from CT compared to NT. In addition to extensive CT being a common pre-plant agronomic activity associated with rice production, N management is also a careful consideration for optimal rice production.

Nitrogen is an essential plant macronutrient that most crops become deficient with due to many soils' limited N-mineralization and N-supplying capacity relative to N requirements for optimal production (Havlin et al., 2014). For rice specifically, sufficient N is most important during panicle differentiation in the R1 reproductive growth stage, which ultimately influences grain yield (Norman et al., 2003). To compensate for N deficiencies in soils, synthetic N-fertilizers are used. The two most regularly used N-fertilizers in rice production are uncoated urea (46% N) and N-(n-butyl) thiosphosphoric triamide (NBPT)-coated urea (46% N) because of their large N concentration (Norman et al., 2003, 2013).

Urea has two amine groups, instead of nitrate groups, which help reduce N loss through denitrification. However, when urea is applied to a dry soil surface and not flooded within a day or two to limit aerobic conditions (i.e., nitrification), significant loss of mineral N through ammonia (NH_3) volatilization can occur (Norman et al., 2009; Dillon et al., 2012). Urease enzymes, which commonly exist in the soil, are the catalyst for NH_3 volatilization, therefore inhibitors are used to limit activity of the urease enzyme and reduce N volatilization losses (Havlin et al., 2014). The compound NBPT is a urease inhibitor that has been reported to reduce NH_3 volatilization by as much as 30% (Norman et al., 2013). If N is not lost as NH_3, the N is hydrolyzed to ammonium (NH_4^+) and is either taken up by the plant or is adsorbed to the surrounding soil colloids.

Limited research has been conducted evaluating the impacts of urea fertilizers coated with urease inhibitors [i.e., NBPT or hydroquinone (HQ)] on N_2O emissions from rice production. In several studies, seasonal N_2O emissions were only numerically lower from HQ-coated compared to non-coated N fertilizers (Xu et al, 2002; Malla et al., 2005; Boeckx et al., 2005). However, CH_4 emissions as affected by coated or uncoated N fertilizer have been inconsistent. Xu et al. (2002) and Boeckx et al. (2005) reported an ~30% reduction in seasonal CH_4 emissions from HQ-coated compared to non-coated N-fertilizers, while Malla et al. (2005) reported a numerical 12% increase in seasonal CH_4 emissions from HQ-coated compared to non-coated N fertilizers.

Field studies evaluating NBPT-coated-urea effects on N_2O emissions from rice production are absent, however, studies of seasonal N_2O emissions from NBPT-coated urea have been conducted in corn (*Zea mays* L.) and pasture land, where seasonal N_2O emissions either increased from non-coated urea compared to NBPT-coated urea (Dawar et al., 2011; Ding et al., 2011) or no difference was reported (Sanz-Cobena et al., 2012). The general trend of increased N_2O emissions from non-coated urea is likely related to the ability of urea to hydrolyze more in a wet to nearly saturated soil profile. However, N-fertilization rates and their impacts on N_2O emissions have been evaluated in several studies, the results of which have generally confirmed an increase in seasonal N_2O emissions with an increase in N-fertilizer application rate (Adviento-Borbe et al., 2013; Pittelkow et al., 2013).

There are no known studies evaluating effects of tillage practice and NBPT coating of urea on N_2O emissions in Arkansas. Therefore, the main objective of this study was to evaluate the effects of tillage practice (i.e., NT and CT) and urea fertilizer type (NBPT-coated and non-coated) on N_2O fluxes, season-long N_2O emissions, and GWP (i.e., N_2O and CH_4 combined) from rice grown on a silt-loam soil from a drill-seeded, delayed-full-season-flood production system in Arkansas. A secondary objective of this study was to evaluate the effects of N-fertilizer type (i.e., NBPT-coated and non-coated urea) compared to a non-fertilized control on season-long N_2O emissions and GWP from CT rice grown on a silt-loam soil from a drill-seeded, delayed-full-season-flood production system in Arkansas. It was hypothesized that N_2O fluxes, season-long N_2O emissions, and GWP would be greater from the NT/non-coated-urea treatment combination than from any other tillage/fertilizer-type treatment combination because NT will increase the C concentration near the soil surface more than CT, therefore increasing microbial activity and the non-coated urea will supply a more labile form of N. It was also hypothesized that season-long N_2O emissions and GWP would be greater from N-fertilized rice than unfertilized rice because N fertilizer will increase the N source for soil microbial activity in a wet to nearly saturated soil, thus increasing N_2O production.

Materials and Methods

Site Description

Research was conducted between May and October 2017 at the University of Arkansas Division of Agriculture's Rice Research and Extension Center (RREC) east of Stuttgart in Arkansas County in east-central AR (34.46°N, 91.46°W). A Dewitt silt-loam (fine, smectitic, thermic Typic Albaqualfs) soil with < 1% slope was present throughout the research site (USDA-NRCS, 2013, 2014). Replicate, large research plots under long-term NT management for at least 10 years (Slaton et al., 2017) and an adjacent area that has been under CT management for over 75 years were used for this study. The NT plots used in this study were sub-areas of larger NT plots that were part of an on-going, long-term NT phosphorous (P) and potassium (K) fertilization study (Slaton et al., 2017).

The area surrounding Stuttgart, AR is classified as humid subtropical, which includes warm weather with periodic precipitation year-round (Arnfield, 2016). The average monthly air temperature is 16.5°C, ranging from a minimum of -1.1°C in January to a maximum of 33.3°C in July, and annual precipitation is 125.6 cm (NOAA-NCEI, 2010). April (13.4 cm) and May (13.0 cm) are the wettest months of the year, while August (6.1 cm) is the driest month (NOAA-NCEI, 2010). The 2017 growing season (i.e., May-September) had an average daily temperature of 25.0°C, which was similar to the 30-year (i.e., 1981 to 2010) average of 25.1°C for the same months (NOAA-NCEI, 2017). However, precipitation during the 2017 growing season was 55.0 cm, which was1.3 times larger than the 30-year average of 43 cm (NOAA-NCEI, 2017).

Treatments and Experimental Design

For the main objective of this study, a randomized complete block (RCB) design replicated four times was used with a factorial arrangement of each tillage (CT and NT)-fertilizer type [NBPT-coated urea (NBPT-U) and non-coated urea (NC-U)] treatment combination. Two long-term NT plots, 4.57-m wide by 7.62-m long, were used with the placement of two, 30-cm-diameter, gas sampling chamber base collars (described in more detail below) fertilized with NBPT-U and two for NC-U in each of two large NT plots. Conventional tillage plots, 1.6-m wide by 4.6-m long with 18-cm row spacing, established immediately adjacent to the long-term NT plots, had one gas sampling chamber base collar placed per plot, with four chamber base collars associated with the NBPT-U and four chamber base collars associated with the NC-U treatment. No-tillage and CT plots were situated in two full-season-flood bays that were immediately adjacent to one another and separated by a levee. There was a total of 16 field plots for each of the four tillage-fertilizer-type treatment combinations (i.e., NT/NBPT-U, NT/NC-U, CT/NBPT-U, CT/NC-U).

The tillage and fertilizer-type treatments were arranged as a split-plot, where tillage was the whole-plot factor and fertilizer type was the split-plot factor, while time (i.e., gas measurement date) was a split-split-plot factor for gas flux analyses. For measured parameters without a time component, a split-plot design was used, with tillage as the whole-plot factor and fertilizer type as the split-plot factor.

For the secondary objective, only the CT plots under full-season-flood water management were used. In addition to four randomized plots for each of the NBPT-U and NC-U treatments, four extra CT plots, with one gas sampling chamber per plot, were established to serve as an untreated control (UTC). For measured parameters without a time component, a split-plot design was used, with tillage as the whole-plot factor and fertilizer type as the split-plot factor.

Plot Management

Conventionally tilled plots were disked with one pass then floated (i.e., smoothed to prepare for planting) with two passes on 20 November, 2016 and 25 April, 2017, respectively. Pre-plant fertilization of 29.4 kg P ha^{-1} as P_2O_5, 83.8 kg K ha^{-1} as K_2O, and 11.2 kg Zn ha^{-1} as elemental Zn were applied to CT plots on 22 March, 2016. No-tillage plots were pre-plant fertilized only with 83.8 kg K ha^{-1} as K_2O on 22 March, 2016 and seeds were pretreated with Zn. No-tillage plots were cropped to soybean, while the CT plot area was left fallow during the 2016 growing season. The pure-line cultivar 'CL172', bred by the University of Arkansas, which is a long-grain, semi-dwarf cultivar, was planted on 9 May in the NT plots and on 11 May, 2017 in the CT plots. An Obey (FMC Corp., Philadelphia, PA) and Permit Plus (Gowan Co., Yuma, AZ) herbicide mixture was sprayed pre-emergence on 9 May, 2017 for weed control, while no additional herbicide applications were made the remainder of the season.

Two separate bays for full-season-flood water management were created with a levee that was established around the NT and CT plot areas after planting and two to three weeks prior to flooding. A recommended single, pre-flood N application at the rate of 118 kg N ha^{-1}, determined according to the N-Soil Test for Rice (N-STaR; Norman et al., 2013) in the NT portion of the study area, was broadcast manually within each gas sampling chamber to dry soil in both CT and NT plots on 12 June, 2017. The N-STaR fertilizer-N recommendation scheme was based on soil samples to a depth of 46 cm and refined based on cultivar selection and soil textural class (Norman et al., 2013). The delayed, full-season-flood was established at the 4- to

5-leaf rice stage on 13 June, 2017, after which the flood was maintained at a 10-cm depth with periodic water additions made on an as-needed basis until two weeks prior to harvest when the flood was released.

Soil Sampling and Analyses

On 30 May 2017, two week before flood establishment, soil samples were collected from the top 10 cm near each chamber base collar prior to N fertilization and flooding. Soil samples were collected for bulk density determinations using a 4.8-cm-diameter, stainless-steel core chamber and slide hammer. Eight additional soil samples per chamber base collar were collected from the top 10 cm prior to N fertilization and flooding using a 2-cm-diameter, stainless-steel push probe that were used for particle-size and chemical analyses. Soil samples were dried at 70°C for at least 48 hr and weighed. Dried soil samples were sieved to pass a 2-mm mesh screen for particle-size and chemical analysis. A modified 12-hr hydrometer method was used to determine particle-size distribution (Gee and Or, 2002). A 1:2 soil mass:water volume suspension was used to determine soil pH and electrical conductivity (EC) potentiometrically. Mehlich-3 extractable nutrients (i.e., P, K, Ca, Mg, Fe, Mn, Na, S, Cu, and Zn) were determined using inductivity coupled, argon-plasma spectrophotometry after extraction in a 1:10 soil mass-to-solution-volume ratio (Tucker, 1992). Total carbon (TC) and nitrogen (TN) were determined by high-temperature combustion with a VarioMax CN analyzer (Elementar Americas Inc., Mt. Laurel, NJ; Nelson and Sommers, 1996). Soil organic matter (SOM) was determined by weight-loss-on-ignition after 2 hours at 360°C. Using the measured bulk density and 10-cm sample depth, measured elemental concentrations (g kg^{-1}) were converted to contents (kg ha^{-1}) on a chamber-by-chamber basis.

Soil Redox Potential and Temperature

Soil oxidation-reduction (redox, Eh) potential sensors (Model S650KD-ORP, Sensorex, Garden Grove, CA) and thermocouples (Type E, chromel-constantan) were installed adjacent to two NT/NBPT-U and two NT/NC-U gas sampling chambers in the NT plots and adjacent to two chambers in the CT/NBPT-U, two in the CT/NC-U, and two in the CT/UTC plots at a depth of 7.5 cm the day of flooding and at a depth of 4 cm a day prior to flooding, respectively. The flood bays were oriented east-to-west with the prevailing slope, with three sets of sensors positioned (i.e., CT/NBPT-U, CT/NC-U, and CT/UTC) on the east end and three sensors on the west end of the CT bay. Soil Eh sensors and thermocouples were placed at depth in the soil vertically and horizontally, respectively. Each sensor was connected to a CR1000 datalogger (Campbell Scientific, Inc., Logan, UT) to record data at 15-minute intervals and output averaged data at 1-hr intervals throughout the flooded portion of the growing season and for several additional days after the flood was released to prepare for harvest. There was one datalogger in the NT bay and two in the CT bay to accommodate the length of the bay. Soil Eh measurements from the silver/silver-chloride reference electrodes were adjusted by adding 199 mV to each sensor to convert to the standard hydrogen electrode Eh measurement (Patrick et al., 1996). Recorded sensor data were collected weekly, at which time all sensors were checked for proper functioning. Soil Eh and soil temperature data were summarized based on the values recorded at 0900 hrs on each gas sampling date, except for 89 days after flooding (DAF) since sensors had been removed prior to that date.

Trace Gas Sampling and Analyses

Similar to Rogers et al. (2014) and Smartt et al. (2016 a,b), 30-cm-tall by 30-cm-diameter, polyvinyl chloride (PVC) base collars (Parkin and Venterea, 2010) were installed in both NT and CT plots prior to pre-flood fertilization to minimize the impact of N fertilization of the NT bay for the larger NT study. Each base collar was installed over two rice rows and an inter-row area of bare soil prior to flood establishment. Base collars were beveled at the bottom with four, 12.5-mm-diameter holes 12 cm above the beveled end to facilitate water flow into and out of the collars after flooding. Base collars were manually pounded into place using a hammer and wooden block. Chamber extensions, 30 cm in diameter by either 40- or 60 cm in length made out of PVC, were used to accommodate the growing rice throughout the season. Extensions were outfitted with a rubber flap to connect to the base collar or each other. Wooden boardwalks were constructed between field plots and over adjacent levees to limit soil disturbance next to the chambers during gas sampling.

A 10-cm-tall, 30-cm-diameter PVC cap was placed on top of the upper-most extension immediately prior to sampling and sealed with a rubber flap to create an enclosed headspace chamber that traps gases for sampling (Livingston and Hutchinson, 1995). Sampling occurred between 0930 and 1030 hours (i.e., a comparable time to previous studies; Adviento-Borbe et al., 2013; Rogers et al., 2014; Smartt et al., 2016 a,b). To minimize temperature increases that could occur in the enclosed chamber, the cap and extensions were covered in reflective aluminum tape (Mylar metallized tape, CS Hyde, Lake Villa, IL). A 2.5-cm^2 fan (MagLev GM1202PFV2-8, Sunon Inc., Brea, CA), powered by a 9-V battery, was installed on the bottom side of the cap and used to circulate the entrapped gas in the headspace during sampling. Ventilation and pressure equilibrium during sampling was accomplished by installing a 15-cm-long, 0.63-cm-inside-diameter piece of copper refrigerator tubing on the side of the cap.

Gas sample collection was accomplished by inserting a 20-mL syringe with a 0.5- x 25-mm needle [Beckton Dickson and Co (B-D), Franklin Lakes, NJ] into a septa (part #73828A-RB, Voigt Global, Lawrence, KS) that was fitted around a 12-mm hole on top of the sealed cap. The gas sample was transferred from the syringe into a pre-capped (20-mm headspace crimp cap; part #700-181, SUN-SRi, Rockwood, TN) and pre-evacuated, 10-mL glass vial (part #405-134, SUN-SRi, Rockwood, TN). Samples were collected in 20-min intervals for 1 hr (i.e., at 0, 20, 40, 60 min) once the caps were placed over the chambers. Sampling occurred on a weekly basis from after the establishment of the full-season flood until four days after flood release at the end of the season in preparation for harvest. Extensions were removed at the end of each sampling date. Air temperature, relative humidity, and barometric pressure were recorded adjacent to the chamber at the time of sampling. Chamber height was measured from the top of the floodwater, or soil surface if no standing flood was present, to the bottom of the cap for chamber volume determinations. Nitrous oxide (i.e., 0.1, 0.5, 1.0, 5.0, and 10 mg L^{-1}) and CH_4 (2, 5, 10, 20, and 50 mg L^{-1}) standards were collected in the field at the end of each sample date to evaluate potential leakage during sample transport from the field.

Gas samples were stored at room temperature and analyzed as soon after collection in the field as possible. Gas samples were analyzed on a Shimadzu GC-2014 gas chromatograph (Shimadzu North America/Shimadzu Scientific Instruments Inc., Columbia, MD) using a flame-ionization detector (FID) for CH_4 detection and an electron capture detector (ECD) for N_2O. Samples of N_2O (i.e., 0.1, 0.5, 1.0, 5.0, and 10 mg L^{-1}) and CH_4 (2, 5, 10, 20, 50 mg L^{-1})

standards were collected again in the laboratory and analyzed along with field samples for quality control.

Nitrous oxide and CH_4 fluxes were determined based on the change in concentration in a chamber over the 20-min sampling intervals (i.e., 0, 20, 40, and 60 min), which was similar to previous studies (Rogers et al., 2014; Smartt et al., 2016 a,b). The concentration at each interval (mL L^{-1}) was plotted against the time interval (min) and fitted with a linear regression equation to determine the change in concentration over time (i.e., slope of the regression line; Rogers et al., 2014; Smartt et al., 2016 a,b). The slope of the best-fit line was multiplied by the measured volume (L) of the chamber and divided by the inside surface area (m^2) of the chamber to determine the flux (µL m^{-2} min^{-1}; Parkin and Venterea, 2010). Total seasonal N_2O and CH_4 emissions were calculated by linear interpolation between consecutive sample dates on a chamber-by-chamber basis. Total seasonal emissions were also converted to CO_2-equivalent global warming potential (GWP) for each treatment combination (i.e., NT/NBPT-U, NT/NC-U, CT/NBPT-U, CT/NC-U, and CT/UTC) by using the climate-carbon-feedback, 100-yr GWP conversion rates of 298 and 34 for N_2O and CH_4, respectively. Hereafter, all comparative studies have had GWP conversion rates for CH_4 adjusted from 25 to 34.

Plant Sampling

Aboveground biomass in each base collar was collected by harvesting rice plants 2-cm above the soil surface on 10 September, 2017 (i.e., four days after flood release). Biomass samples were dried at 55°C for 3 weeks and weighed to determine aboveground dry matter. Yield was determined by clipping panicles on a chamber-by-chamber basis, then weighed, and adjusted to 20% grain moisture. Nitrous oxide emissions on a per-unit-grain-yield-basis for each treatment combination (i.e., NT/NBPT-U, NT/NC-U, CT/NBPT-U, CT/NC-U, and CT/UTC) were determined by dividing season-long emissions by rice panicle yield on a chamber-by-chamber basis.

Statistical Analyses

A two-factor analysis of variance (ANOVA) was performed using SAS 9.4 (SAS Institute, Inc., Cary, NC) to determine the effects of field treatments (i.e., tillage practice, pre-assigned N-fertilization type, and their interaction) on initial soil properties in the top 10 cm. A three-factor ANOVA was performed to evaluate the effects of tillage, N-fertilizer type, time, and their interactions on N_2O fluxes. A two-factor ANOVA was performed to evaluate the effects of tillage practice, N-fertilizer type, and their interaction on panicle yield, pre- and post-flood-release, season-long N_2O emissions, area- and yield-scaled, season-long N_2O emissions, and GWP. A one-factor ANOVA was performed to determine the effects of urea fertilization in CT on panicle yield and area- and yield-scaled N_2O emissions. When appropriate, means were separated by least significant difference (LSD) at the $\alpha = 0.1$ level for N_2O fluxes and emissions due to the low expected magnitudes and large expected variability associated with N_2O fluxes and emissions. All other data sets had means that were separated by LSD at the $\alpha = 0.05$ level.

Results and Discussion

Pre-flooding Soil Physical and Chemical Properties

Pre-flooding soil properties were measured to evaluate field plot uniformity among pre-assigned urea-fertilizer [i.e., NBPT-coated (NBPT-U) and non-coated (NC-U)] and tillage [i.e., no-till (NT) and conventional till (CT)] treatment combinations. Soil bulk density and extractable soil K differed ($P < 0.05$) among tillage-fertilizer treatment combinations, while soil pH and extractable soil P, Mg, Na, Fe, Mn, and Zn differed ($P < 0.05$) between tillage treatments (Table 1). All other soil properties measured in the top 10 cm before flooding (i.e., sand, silt, and clay; EC; extractable soil Ca, S, and Cu; TN, TC, C:N ratio; and SOM) were unaffected ($P > 0.05$) by tillage or fertilizer treatment (Table 1).

Pre-flood soil bulk density did not differ between fertilizer treatments under CT; however, bulk density in the CT/NBPT-U and CT/NC-U treatment combinations (1.38 and 1.37 g cm^{-3}, respectively) were 11 and 19% greater ($P < 0.05$) than bulk density in the NT/NBPT-U and NT/NC-U treatment combinations (1.23 and 1.15 g cm^{-3}, respectively), where bulk density in the NT/NBPT-U was 7% greater than that in the NT/NC-U treatment combination. However, all treatment combinations fall within an acceptable, common bulk density range of 0.9 to 1.5 g cm^{-3} for a clay or silt-loam soil under cultivation (Brady and Weil, 008; Table 1). Pre-flood extractable soil K content only differed between NT/NBPT-U (156 kg ha^{-1}) and NT/NC-U (135 kg ha^{-1}) treatment combinations and did not differ between fertilizer treatments under CT (143 kg ha^{-1}). However, all treatment combinations had extractable soil K concentrations in the top 10 cm of soil that fell within the "Medium' (91 to 130 mg K kg^{-1}) soil-test category for fertilizer recommendations for rice grown in Arkansas, with any additional K fertilizer having a minimal effect on the health of the rice (Norman et al., 2013).

Pre-flood soil pH was 13% greater in the CT (pH = 6.1) than in the NT treatment (pH = 5.4), but soil pH in both tillage treatments were within the optimal pH range for rice production (~ 5.0 to 6.75; Havlin et al., 2014; Table 1). Pre-flood extractable soil P, Mg, Na, Mn, and B contents were 12, 60, 45, 24, and 18%, respectively, greater under CT than under NT, while extractable soil Fe and Zn contents were 1.2 and 2.1 times, respectively, greater under NT than under CT (Table 1). Extractable soil Zn concentrations were 2.1 and 5.1 mg kg^{-1} under CT and NT, respectively, with CT having a soil-test category of “Low” and NT “Optimum”; however, neither Zn concentrations required additional Zn fertilizer for rice grown on a silt-loam soil in Arkansas (Norman et al., 2013). Unlike extractable soil K and Zn, the extractable soil P concentration under both tillage treatments were in the “Very Low” (i.e., $\leq$ 15 mg kg^{-1}) soil-test category, for which additional P fertilizer would have been recommended to overcome potential negative impacts to plant growth and productivity (Norman et al., 2013). However, the NT study plots were part of a long-term K and P study, which superseded the adjusting soil-test P to a more optimum level. Mean sand, silt, and clay fractions (0.14, 0.71, and 0.15 g g^{-1}, respectively) in the top 10 cm confirmed a silt-loam soil surface texture for both tillage treatments (Table 1). Though several soil physical and chemical properties differed prior to flooding, differences were relatively minor and generally non-agronomically significant, and it was reasonably assumed that any measured differences in N_2O fluxes and/or emissions were the result of imposed treatment effects rather than due to large, inherent differences among plots prior to flooding.

Nitrous Oxide Fluxes

Unlike previous reports for CH_4 (Rogers et al., 2014; Smartt et al., 2016 a, b), N_2O fluxes during the 2017 growing season (i.e., establishment of full-season flood to four days after end-of-season flood release) did not show any discernable trend over time. Mean N_2O fluxes did not exceed 15 N_2O-N g ha^{-1} d^{-1} at all during the 2017 growing season, with peak numeric N_2O fluxes not occurring until 62 (14.5 g N_2O-N ha^{-1} d^{-1} from the CT/NC-U treatment combination) and 85 (14.6 g N_2O-N ha^{-1} d^{-1} from the NT/NC-U treatment combination) DAF (Figure 1). All treatment combinations had peak numeric N_2O fluxes that occurred after 50% heading. However, the

NT/NC-U, CT/NC-U, and NT/NBPT-U (5.1 g N_2O-N ha^{-1} d^{-1}) treatment combinations had peak numeric N_2O fluxes that occurred prior to the end-of-season drain, while the CT/NBPT-U (9.5 g N_2O-N ha^{-1} d^{-1}) treatment combination had a peak numeric flux after the end-of-season drain.

In contrast to that hypothesized, neither tillage practice nor fertilizer type affected ($P >$ 0.1) N_2O fluxes throughout the 2017 growing season (Table 2). Similarly, averaged across field treatments, N_2O fluxes did not differ over time (i.e., DAF) throughout the 2017 growing season (Table 2). A multi-week gap occurred between 6 and 41 DAF where no N_2O fluxes were measured due to analytical difficulties, which may have impacted the ability to ascertain field treatment and/or time effects on N_2O fluxes. However, though non-significant due to large variability associated with flux measurements, N_2O fluxes from non-coated-urea treatment combinations tended to be numerically greater than fluxes from NBPT-coated urea treatment combinations (Figure 1). It was somewhat expected that there was no significant difference in N_2O fluxes over time because there was no split N-fertilizer application. Rice plants are known to take up available N efficiently (i.e., > 60% of pre-flood N-fertilizer application; Norman et al., 2013). Furthermore, both tillage treatments had a full-season flood that minimized fluctuations of soil Eh that would have promoted N_2O production and release.

Limited research has been conducted to evaluate individual or combined effects of tillage practice and urease-inhibiter-coated urea on N_2O fluxes. Studies investigating NT and/or CT effects on N_2O fluxes are few and inconclusive. Based on a 3-yr, wheat-rice rotation study in China on a silty-clay-loam soil, Zhang et al. (2015) documented no numerical trends or difference in N_2O fluxes among tillage practice [i.e., NT or reduced tillage (RT) and CT] in rice production. In contrast, based on a 1-yr study in China on a silty-clay-loam soil, Ahmed et al. (2009) reported NT produced greater peak N_2O fluxes than CT, with peaks occurring after application of N fertilizer. Zhang et al. (2015) measured a peak flux at ~24 g N_2O-N ha^{-1} d^{-1}, while Ahmad et al. (2009) measured a peak N_2O flux at 240 g N_2O-N ha^{-1} d^{-1}, with both peak N_2O fluxes 1.6 to 16 times greater than the peak flux measured in this study (14.6 g N_2O-N ha^{-1} d^{-1}). Liu et al. (2006) conducted a 1-yr corn study in Colorado on a clay-loam soil, while Chatskikh and Olesen (2007) conducted a 1-yr barley study in Denmark on loamy-sand soil, with both study results supporting a numerical trend of NT producing greater N_2O fluxes than CT.

The limited research on NBPT-coated urea and its effect on N_2O fluxes are more consistent, where generally lower numeric peak N_2O fluxes have been reported from treatments using urease inhibitors (i.e., NBPT; Dawar et al., 2011; Ding et al., 2011; Sanz-Cobena et al., 2012). Ding et al. (2011) conducted a 1-yr study in corn on a sandy-loam soil in China and reported a peak N_2O flux (120 g N_2O-N ha^{-1} d^{-1}) that was 1.5 times greater from a NC-U than from a NBPT-U treatment, where both treatments had peak fluxes after N-fertilizer application. Sanz-Cobena et al. (2012) conducted a 2-yr study, also in corn, on a sandy-clay-loam soil in Spain and reported peak N_2O fluxes from a NC-U treatment that ranged from 80 to 160 g N_2O-N ha^{-1} d^{-1}, which were 60% greater than peak N_2O fluxes from a NBPT-U treatment. Dawar et al. (2011) conducted a 1-yr study in New Zealand, mainly in silt-loam soils, under grazed pasture landuse that excluded cattle one year prior to initiating the study and reported a peak N_2O flux (20 g N_2O-N ha^{-1} d^{-1}) from a NC-U treatment that was two times greater than the peak N_2O flux from a NBPT-U treatment, where all peak fluxes occurred during large rainfall or irrigation events.

Aboveground Biomass and Yield

Aboveground biomass for CL172 was unaffected (*P* = 0.61) by fertilizer treatment, but was affected by tillage practice (*P* 0.01; Table 3). Aboveground biomass was 18% greater in CT (19.4 Mg ha^{-1}) than in NT (16.5 Mg ha^{-1}). No-tillage had a lower initial soil-test P than CT and did not receive additional P fertilizer, which could have impacted biomass production.

Similar to aboveground biomass, rice grain yield for CL172 was unaffected (*P* = 0.54) by fertilizer treatment but differed (*P* = 0.01) between tillage practice (Table 3). Grain yield was 15% greater from CT (8.9 Mg grain ha^{-1}) than from NT (7.8 Mg grain ha^{-1}). Rice yields measured in this study were slightly lower than the multi-location mean yield for CL172 (9.2 Mg grain ha^{-1}) based on Arkansas yield trials (Hardke et al., 2014). However, through a global meta-analysis, Pittelkow et al. (2015) determined that NT had no significant effect on rice yield compared to CT. In this study, the same quantity of fertilizer N was applied to plots in both tillage treatments, but, unlike CT, the NT treatment was not fertilized with additional P due to the long-term nature of P-fertilization treatments the NT plots were a part of that were used in this study. Based on visual observations over the course of the growing season, rice yield could have been impacted by false smut (*Ustilaginoidea virens*), which is a fungal disease that occurred in both tillage treatments.

N-fertilization Effects on Rice Yield under CT Only

Rice grain yield from CL172 differed between fertilizer treatment [i.e., NBPT-U, NC-U, and UTC; *P* < 0.01] under CT management only (Table 4). Treatments with N applied as urea (8.9 Mg grain ha^{-1}) had yields that were 78% greater than the UTC (5.10 Mg grain ha^{-1}). Several studies evaluating GHG emissions have reported a significant increase in yield with N fertilization (Brye et al., 2013; Pittelkow et al., 2013; Smartt et al., 2016a).

Nitrous Oxide Emissions

Area-scaled N_2O emissions for the pre-flood-release (i.e., establishment of flood to end-of-season drain) portion of the 2017 growing season ranged from 0.26 kg N_2O-N ha^{-1} $period^{-1}$ in the NT/NBPT-U to 0.49 kg N_2O-N ha^{-1} $period^{-1}$ in the NT/NC-U treatment (Table 5). However, area-scaled N_2O emissions for the pre-flood-release portion of the 2017 growing season were unaffected ($P > 0.10$) by tillage practice () or fertilizer treatment (Table 2). There was also no discernable trend in pre-flood-release N_2O emissions among treatment combinations (Table 5). Though not significant, treatments with NBPT-U (0.47 kg N_2O-N ha^{-1}) had pre-flood-release, area-scaled N_2O emissions that were nearly twice that from the NC-U treatments (0.28 kg N_2O-N ha^{-1}, Table 5).

Area-scaled N_2O emissions for the post-flood-release (i.e., end-of-season drain to harvest) portion of the 2017 growing season ranged from < 0.01 kg N_2O-N ha^{-1} $period^{-1}$ in the NT/NBPT-U to 0.02 kg N_2O-N ha^{-1} $period^{-1}$ in the CT/NBPT-U treatment (Table 5). However, area-scaled N_2O emissions for the post-flood-release portion of the 2017 growing season were also unaffected ($P > 0.10$) by tillage practice or fertilizer treatment (Table 2). Similar to pre-flood-release emissions, there was no discernable trend in post-flood-release N_2O emissions among treatment combinations (Table 5). Post-flood-release N_2O emissions accounted for less than 7% of total season-long emissions across all treatment combinations (Table 5). No known studies have reported differences between pre- and post-flood-release N_2O emissions among tillage treatments or among differing urea-fertilizer treatments. However, Zhao et al. (2011), who evaluated the effects of water management practice on N_2O emissions, and Adviento-Borbe et al. (2015), who evaluated the effects of N-fertilizer rate on N_2O emissions, determined that emissions during the post-flood-release period could contribute between 0 and 82% of total season-long N_2O emissions.

Season-long, area-scaled N_2O emissions ranged from 0.27 kg N_2O-N ha^{-1} $season^{-1}$ in the NT/NBPT-U to 0.500.27 kg N_2O-N ha^{-1} $season^{-1}$ in the NT/NC-U treatment (Table 6). However, similar to pre- and post-flood-release N_2O emissions, season-long, area-scaled N_2O emissions were unaffected ($P > 0.10$) by tillage practice or fertilizer treatment (Table 2). Nitrous oxide emissions averaged 0.39 kg N_2O-N ha^{-1} $season^{-1}$ across all tillage-fertilizer treatment combinations, which was 11% greater than the expected 0.35 kg N_2O-N ha^{-1} $season^{-1}$ based on the Intergovernmental Panel on Climate Change's N_2O emissions factor of 3 g N_2O-N (kg N-input)$^{-1}$ for a N inputs of 118 kg ha^{-1} $season^{-1}$ (de Klein., 2006).

Few studies have evaluated the effect of tillage practice and urease-inhibitor-coated urea, such as NPBT, on season-long N_2O emissions. However, studies investigating NT and/or CT practices in rice either reported significantly greater N_2O emissions from NT than from CT (Venterea et al., 2005; Ahmed et al., 2009) or reported only a numerical difference (Liu et al., 2006; Zhang et al., 2015). Ahmad et al. (2009) reported a 32% increase in season-long N_2O emissions from NT (7.4 kg N_2O-N ha^{-1}) compared to CT (5.6 kg N_2O-N ha^{-1}) from rice. Venterea et al. (2005) conducted a 2-yr corn study in Minnesota on a silt-loam soil and reported greater N_2O emissions from NT than from CT. Liu et al. (2006) reported N_2O emissions that were more than two times numerically greater from NT (0.90 kg N_2O-N ha^{-1}) than from CT (0.44 kg N_2O-N ha^{-1}). During a 3-yr wheat-rice rotation study, Zhang et al. (2015) reported numerically greater season-long N_2O emissions from CT (0.15 kg N_2O-N ha^{-1}) than from NT (0.12 kg N_2O-N ha^{-1}) during rice production.

In contrast to tillage effects, the few studies evaluating NBPT-coated urea and its effect on N_2O emissions were more consistent, with NBPT-coated urea resulting in significantly lower N_2O emissions than non-coated urea from corn production (Dawar et al., 2011; Sanz-Cobena et al., 2012) and from pastureland (Ding et al., 2011). During a 2-yr study, Sanz-Cobena et al. (2012) reported N_2O emissions that were two times greater from NC-U than from NBPT-U; however, there was no difference in N_2O emissions between NC-U and NBPT-U treatments in one of two years. Similarly, Ding et al. (2011) also reported greater N_2O emissions from NC-U than from NBPT-U, while Dawar et al. (2011) measured an 8% increase in N_2O emissions from NC-U than from NBPT-U.

Similar to season-long, area-scaled N_2O emissions, yield-scaled N_2O emissions were also unaffected ($P > 0.10$) by tillage practice or fertilizer treatment (Table 2). Yield-scaled N_2O emissions averaged 0.05 kg N_2O-N (Mg grain)$^{-1}$ across all tillage-fertilizer treatment combinations (Table 6). Sanz-Cobena et al. (2012) report yield-scaled N_2O emissions did not differ between NBPT-U and NC-U treatments.

N-fertilization Effects on N_2O Emissions under CT Only

Similar to area- and yield-scaled N_2O emissions between tillage-fertilizer treatment combinations, area- and yield-scaled N_2O emissions were unaffected ($P > 0.10$) by N-fertilizer application under CT only (Table 4). Despite the lack of a significant effect, mean N_2O area-scaled emissions tended to be numerically larger from the NC-U (0.47 kg N_2O-N ha^{-1} $season^{-1}$) than from the NBPT-U and UTC treatments (0.32 kg N_2O-N ha^{-1} $season^{-1}$; Table 7). Yield-scaled

N_2O emissions from the UTC [0.07 kg N_2O-N (Mg grain)$^{-1}$] tended to be numerically greater than from the NC-U [0.06 kg N_2O-N (Mg grain)$^{-1}$] and NBPT-C [0.04 kg N_2O-N (Mg grain)$^{-1}$] treatments (Table 7). In contrast to the results of this study, N_2O emissions have been shown to increase with the addition of N fertilizer under grazed pastureland (Dawar et al., 2011), corn (Sanz-Cobena et al., 2012), and rice (Adviento-Borbe et al., 2013; Pittelkow et al., 2013). However, less fertilizer N (118 kg ha^{-1}) was applied in this study, to maintain consistency for the larger long-term study, than what is typically suggested for the hybrid CL172 grown on a silt-loam soil (168 kg ha^{-1}), which may have impacted the amount of gaseous N loss.

Soil Eh and Temperature

The reduction of NO_3^- occurs efficiently when soil reduction-oxidation (redox) potential (Eh) ranges from 220 to 280 mV, therefore increasing the likely of N_2O production (Brady and Weil, 2008). Soil Eh, recorded from the hour immediately before N_2O fluxes were measured each week, at the 7.5-cm depth differed between tillage practice over the growing season ($P < 0.01$) and differed between tillage-fertilizer treatment combinations ($P < 0.01$; Table 3). However, means separation could not specifically identify which sample dates soil Eh differed between tillage treatments, but differences in soil Eh between tillage treatments tended to be greater early than late in the growing season (Figure 2). Optimal (246 mV) or near optimal (195 mV) soil Eh for NO_3^- reduction was only measured at 1 and 2 DAF in NT, while there were no sample dates under CT that were within or near the optimal soil Eh range for NO_3^- reduction. Soil Eh fell below 0 mV between 13 and 24 DAF and did not increase above 0 mV throughout the remainder of the rice growing season (Figure 2). Average over time, soil Eh among tillage-fertilizer treatment combinations [NT/NC-U (-55.6 mV), NT/NBPT-U (-340 mV), CT/NC-U (-

199 mV), and CT/NBPT-U (-183 mV)] were variable, but specific differences were also unable to be identified with means separation.

Soil temperatures at the 7.5-cm depth fluctuated throughout the growing season, where soil temperature started around 26°C, increased to around 28°C mid-season (41 DAF), and decreased to below 20°C after the end-of-season drain (86-88 DAF; Figure 3). The numerically largest soil temperature occurred under CT at 41 DAF, while the numerically lowest soil temperature occurred under NT at 87 DAF (Figure 3). Similar to soil Eh, soil temperature at the 7.5-cm depth differed between tillage practices throughout the season ($P < 0.01$) and differed between tillage-fertilizer treatment combinations ($P = 0.03$; Table 3). The soil temperature was significantly greater under CT than under NT on numerous dates during the middle of the flooded portion of the growing season (i.e., 34, 41, 48, 55, 62, and 70 DAF), but did not differ by more than 2°C on any given date (Figure 3). Averaged across measurement dates, the mean soil temperature was significantly warmer in the CT/NBPT-U (24.5°C) and CT/NC-U (23.8°C), which did not differ, than in the NT/NBPT-U (23.5°C) and NT/NC-U (23.6°C) treatment combinations, which did not differ. Brye et al. (2016) documented an impact of day and nighttime air temperatures on CH_4 emissions from silt-loam soils in Arkansas, but there is currently no known study that has evaluated the potential impact of day and/or nighttime air temperatures on N_2O emissions.

Total Global Warming Potential

Total GWP (i.e., the combination of CO_2-equivlent CH_4 and N_2O emissions) during the 2017 growing season (i.e., flood establishment to harvest) ranged from 1324 kg CO_2 equivalent ha^{-1} $season^{-1}$ from the CT/NBPT-U to 2204 kg CO_2 equivalent ha^{-1} $season^{-1}$ from the NT/NC-U treatment combination (Table 6). However, total GWP was unaffected ($P > 0.05$) by tillage practice or fertilizer treatment (Table 2). Nitrous oxide accounted for ≤ 12% of the total GWP between all treatments (Figure 4).

Few studies have reported total GWP of non-CO_2 emissions (i.e., $N_2O + CH_4$) among tillage practices. It has been reported that CH_4 emissions from rice under a full-season-flood can contribute over 90% of the total GWP (Adviento-Borbe et al., 2013; Simmonds et al., 2015). Ahmed et al. (2009) reported a significant difference in CH_4 emissions in rice between CT (180 kg CH_4-C ha^{-1}) and NT (140 kg CH_4-C ha^{-1}) tillage practices, consequently, explaining the significantly greater total GWP in CT (18161 kg CO_2 equivalent ha^{-1}) than NT (15130 kg CO_2 equivalent ha^{-1}) despite N_2O emissions being greater from NT (4.9 kg N_2O-N ha^{-1}) than from CT (3.6 kg N_2O-N ha^{-1}). However, Zhang et al. (2015) reported greater CH_4 emissions from NT than from CT, which could be inferred that an increase in CH_4 emissions could result in an increase in total GWP, since it is commonly understood that CH_4 emissions are the dominant driver of GWP for non-CO_2 emissions.

Considering only few studies have evaluated the effects of NBPT-coated urea on N_2O emissions, there are no known studies that have evaluated NBPT-coated urea effects on non-CO_2 total GWP. Malla et al. (2005) evaluated the impact of the urease inhibiter HQ (hydroquinone) and reported no change in GWP from rice production when HQ was used with urea compared to urea not used with a urease inhibiter. Unlike Malla et al. (2005), Xu et al. (2002) reported a significant decrease in CH_4 emissions from urea mixed with HQ compared to non-treated urea for rice production.

N-fertilization Effects on Total GWP under CT Only

Total GWP ranged from 907 kg CO_2 equivalent ha^{-1} $season^{-1}$ from the UTC to 1612 kg CO_2 equivalent ha^{-1} $season^{-1}$ from the NC-U treatment under CT only (Table 7). However, similar to tillage-fertilizer treatment combination effects, total GWP was unaffected ($P > 0.05$) by N-fertilization treatment under CT only (Table 4). Nitrous oxide accounted for less than 20% of the total GWP across all fertilizer treatments under CT only. In contrast, Adviento-Borbe et al. (2013) and Pittelkow et al. (2013) reported lower total GWP in non-N-fertilized than in N-fertilized rice treatments. Nitrous oxide constituted less than 22 and 10% of total GWP in Adviento-Borbe et al. (2013) and Pittelkow et al. (2013), respectively. Both Adviento-Borbe et al. (2013) and Pittelkow et al. (2013) measured differences in N_2O emissions among differing fertilizer-N rates, but did not measure any differences in CH_4 emissions among fertilizer-N rates, further supporting that total GWP is driven primarily by CH_4 emissions.

Environmental Implications

Averaged across all treatment combinations, N_2O accounted for only 10% of the total GWP, with the remainder of the total GWP was due to CH_4. Methane as the key driver of GWP for rice production is supported by other studies evaluating GHG emissions from rice grown on silt-loam soils in the Lower Mississippi River Delta region of eastern Arkansas (Linquist et al., 2015; Simmonds et al., 2015).

To improve fertilizer-N efficiency and reduce nutrient pollution, such as ammonia (NH_3) volatilization, urease inhibitors (i.e., NBPT coating) are of great interest in rice production, which relies heavily on fertilizer-N additions for optimal production. Furthermore, as another option to alleviate soil erosion and therefore improve soil fertility and soil health, NT helps keep the soil covered during period of non-production months and protected from wind and water erosion.

Nitrous oxide emissions, in combination with CH_4, from agricultural sources are expected to rise through the next decade and beyond (Smith et al., 2014). Even more concerning is that N_2O and CH_4 are more potent as GHGs than CO_2 in the atmosphere. Therefore, in order to make responsible decisions regarding crop production, N_2O emissions need to be quantified and the effects of traditional and alternative production practices on N_2O emissions need to be evaluated. Expanding research on N_2O emissions is of increasing importance because the human population continues to grow, which will require similar increase in crop production, especially commonly consumed grains such as rice. A proper understanding of N_2O emissions can help mitigate or offset detrimental environmental impacts resulting from increased crop production.

Conclusions

Contrary to that hypothesized, neither N_2O fluxes nor season-long emissions (i.e., area- or yield-scaled) ($P > 0.1$) or total GWP were affected ($P > 0.05$) by tillage practice (CT or NT) or type of urea fertilizer (i.e., NBPT-coated and non-coated) from rice grown under a direct-seeded, delayed-flood production system during the 2017 growing season on a silt-loam soil eastern Arkansas. Nitrous oxide fluxes, season-long emissions, and total GWP were also unaffected by N fertilization under CT only.

Despite the lack of significant findings, this study added to the limited knowledge of N_2O emissions from rice production. The global importance of rice production makes it imperative to quantify GHG emissions and evaluate potential traditional and alternative agronomic and environmental factors that may affect N_2O production and emission.

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Table 1. Analysis of variance summary of the effects of tillage practice [i.e., conventional and no-tillage (n = 8)], pre-assigned urea fertilizer type [i.e., N-(n-butyl) thiosphosphoric triamide (NBPT)-coated and non-coated urea (n = 8)], and their interaction on soil physical [i.e., sand, silt, clay, and bulk density) and chemical properties [i.e., pH, electrical conductivity (EC), extractable soil P, K, Ca, Mg, Fe, Mn, Na, S, Cu, and Zn and total nitrogen (TN), total carbon (TC), and soil organic matter (SOM) contents] from 2017 at the Rice Research and Extension Center near Stuttgart, AR. Also reported are overall mean values (n = 16) for each soil property. Bolded values represent significant effects ($P < 0.05$).

Soil property	Tillage	Fertilizer	Tillage x fertilizer	Overall mean (NT)	Overall mean (CT)
	———————*P*———————				
Sand (g g^{-1})	0.38	0.24	0.24	0.15a	0.13a
Silt (g g^{-1})	0.76	0.18	0.30	0.71a	0.71a
Clay (g g^{-1})	0.24	0.99	0.45	0.14a	0.16a
Bulk density (g cm^{-3})	< 0.01	0.02	**0.04**	1.19	1.38
pH	**0.03**	0.08	0.38	5.43b	6.09a
EC (dS m^{-1})	0.38	0.93	0.25	0.19a	0.21a
P (kg ha^{-1})	**0.04**	0.48	0.70	15.9b	18a
K (kg ha^{-1})	0.80	0.02	**0.03**	146	143
Ca (Mg ha^{-1})	0.10	0.38	0.22	1.16a	1.49a
Mg (kg ha^{-1})	**0.04**	0.91	0.30	162	260a
S (kg ha^{-1})	0.69	0.76	0.78	15.1a	14.6a
Na (kg ha^{-1})	**< 0.01**	0.40	0.28	52b	97.4a
Fe (kg ha^{-1})	**0.02**	0.54	0.66	507a	424b
Mn (kg ha^{-1})	**< 0.01**	0.67	0.33	219b	289a
Zn (kg ha^{-1})	**< 0.01**	0.79	0.64	6.09a	2.91b
Cu (kg ha^{-1})	0.16	0.91	0.98	1.41a	1.62a
TN (kg ha^{-1})	0.66	0.22	0.35	903a	853a
TC (Mg ha^{-1})	0.53	0.20	0.21	9.23a	8.49a
SOM (Mg ha^{-1})	0.70	0.27	0.17	23.1a	23.6a
C:N ratio	0.23	0.68	0.34	10.20a	9.97a

Table 2. Analysis of variance summary of the effects of tillage practice [i.e., conventional and no-tillage (n = 8)], urea fertilizer type [i.e., N-(n-butyl) thiosphosphoric triamide (NBPT)-coated and non-coated urea (n = 8)], days after flooding [DAF (n = 12)], and their interactions on nitrous oxide (N_2O) fluxes, pre- and post-flood-release and season-long, area- and yield-scaled N_2O emissions, and total global warming potential (GWP) from 2017 at the Rice Research and Extension Center near Stuttgart, AR. Least significant difference (LSD) at the α = 0.05.

Measured property/Treatment effect	*P*
N_2O fluxes	
Tillage practice	0.86
Fertilizer	0.13
DAF	0.97
Tillage practice x fertilizer	0.35
Tillage practice x DAF	0.82
Fertilizer x DAF	0.51
Tillage practice x fertilizer x DAF	0.22
Pre-flood-release N_2O emissions	
Tillage practice	0.99
Fertilizer	0.26
Tillage practice x fertilizer	0.81
Post-flood-release N_2O emissions	
Tillage practice	0.30
Fertilizer	0.93
Tillage practice x fertilizer	0.43
Season-long, area-scaled N_2O emissions	
Tillage practice	0.96
Fertilizer	0.27
Tillage practice x fertilizer	0.79
Season-long, yield-scaled N_2Oemissions	
Tillage practice	0.87
Fertilizer	0.22
Tillage practice x fertilizer	0.70
Total GWP	
Tillage practice	0.19
Fertilizer	0.17
Tillage practice x fertilizer	0.87

Table 3. Analysis of variance summary of the effects of tillage practice [i.e., conventional and no-tillage (n = 8)], urea fertilizer type [i.e., N-(n-butyl) thiosphosphoric triamide (NBPT)-coated and non-coated urea (n = 8)], and their interactions on aboveground dry matter, yield, soil oxidation-reduction (redox) potential, and soil temperature from 2017 at the Rice Research and Extension Center near Stuttgart, AR. Bolded values represent significant effects ($P < 0.05$).

Measured property/Treatment effect	*P*
Aboveground dry matter	
Tillage practice	**0.01**
Fertilizer	0.61
Tillage practice x fertilizer	0.48
Grain yield	
Tillage practice	**0.01**
Fertilizer	0.54
Tillage practice x fertilizer	0.41
Soil redox potential	
Tillage practice	0.96
Fertilizer	0.48
DAF	< 0.01
Tillage practice x fertilizer	**< 0.01**
Tillage practice x DAF	**< 0.01**
Fertilizer x DAF	0.95
Tillage practice x fertilizer x DAF	0.94
Soil temperature	
Tillage practice	0.53
Fertilizer	0.22
DAF	< 0.01
Tillage practice x fertilizer	**0.03**
Tillage practice x DAF	**< 0.01**
Fertilizer x DAF	0.65
Tillage practice x fertilizer x DAF	0.67

Table 4. Analysis of variance summary of the effects of urea fertilization [i.e., N-(n-butyl) thiosphosphoric triamide (NBPT)-coated (n = 4), non-coated urea (n = 4), untreated control (n = 4)], and their interactions on season-long, area- and yield-scaled nitrous oxide (N_2O) emissions, total global warming potential (GWP), and grain yield from conventional tillage (CT) only during 2017 at the Rice Research and Extension Center near Stuttgart, AR. Bolded values represent significant effects ($P < 0.05$).

Measured property/Treatment effect	*P*
Season-long, area-scaled N_2O emissions	
Fertilizer	0.68
Season-long, yield-scaled N_2Oemissions	
Fertilizer	0.47
Total GWP	
Fertilizer	0.06
Grain yield	
Fertilizer	**< 0.01**

Table 5. Mean pre- (i.e., establishment of the delayed flood to end-of-season flood release) and post-flood-release (i.e., end-of-season flood release to harvest) nitrous oxide (N_2O) emissions and post-flood-release fraction of season-long N_2O emissions among tillage practice [i.e., conventional tillage (CT) and no-tillage (NT; n = 8)]- urea fertilizer type [i.e., N-(n-butyl) thiosphosphoric triamide (NBPT)-coated and non-coated urea (n = 8)] treatment combinations measured in 2017 at the Rice Research and Extension Center near Stuttgart, AR.

Treatment combination	Pre-flood-release N_2O emissions (kg N_2O-N ha^{-1} $period^{-1}$)	Post-flood-release N_2O emissions (kg N_2O-N ha^{-1} $period^{-1}$)	Percent (%) post-flood-release N_2O emissions (kg N_2O-N ha^{-1} $season^{-1}$)
NT/Non-coated urea	0.49	0.016	3.1
NT/NBPT-coated urea	0.26	0.009	3.4
CT/Non-coated urea	0.45	0.014	3.1
CT/ NBPT-coated urea	0.30	0.020	6.2

Table 6. Mean season-long, area- and yield-scaled nitrous oxide (N_2O) emissions and total global warming potential (GWP) among tillage practice [i.e., conventional tillage (CT) and no-tillage (NT; n = 8)]-urea fertilizer type [i.e., N-(n-butyl) thiosphosphoric triamide (NBPT)-coated and non-coated urea (n = 8)] treatment combinations measured in 2017 at the Rice Research and Extension Center near Stuttgart, AR.

Treatment combination	Area-scaled N_2O emissions (kg N_2O-N ha^{-1} $season^{-1}$)	Yield-scaled N_2O emissions [kg N_2O-N (Mg $grain)^{-1}$]	Total GWP (kg CO_2 equivalent ha^{-1} $season^{-1}$)
NT/Non-coated urea	0.50	0.06	2204
NT/NBPT-coated urea	0.27	0.04	1972
CT/Non-coated urea	0.47	0.06	1612
CT/ NBPT-coated urea	0.32	0.04	1324

Table 7. Mean season-long, area- and yield-scaled nitrous oxide (N_2O) emissions and total global warming potential (GWP) among fertilization treatments [i.e., N-(n-butyl) thiosphosphoric triamide (NBPT)-coated (n = 4), non-coated urea (n = 4), untreated control (n = 4)] under conventional tillage measured in 2017 at the Rice Research and Extension Center near Stuttgart, AR.

Fertilizer treatment	Area-scaled N_2O emissions (kg N_2O-N ha^{-1} season^{-1})	Yield-scaled N_2O emissions [kg N_2O-N (Mg grain)$^{-1}$]	Total GWP (kg CO_2 equivalent ha^{-1} season^{-1})
Untreated control	0.32	0.07	907
Urea	0.47	0.06	1612
Urea + NBPT	0.32	0.04	1324

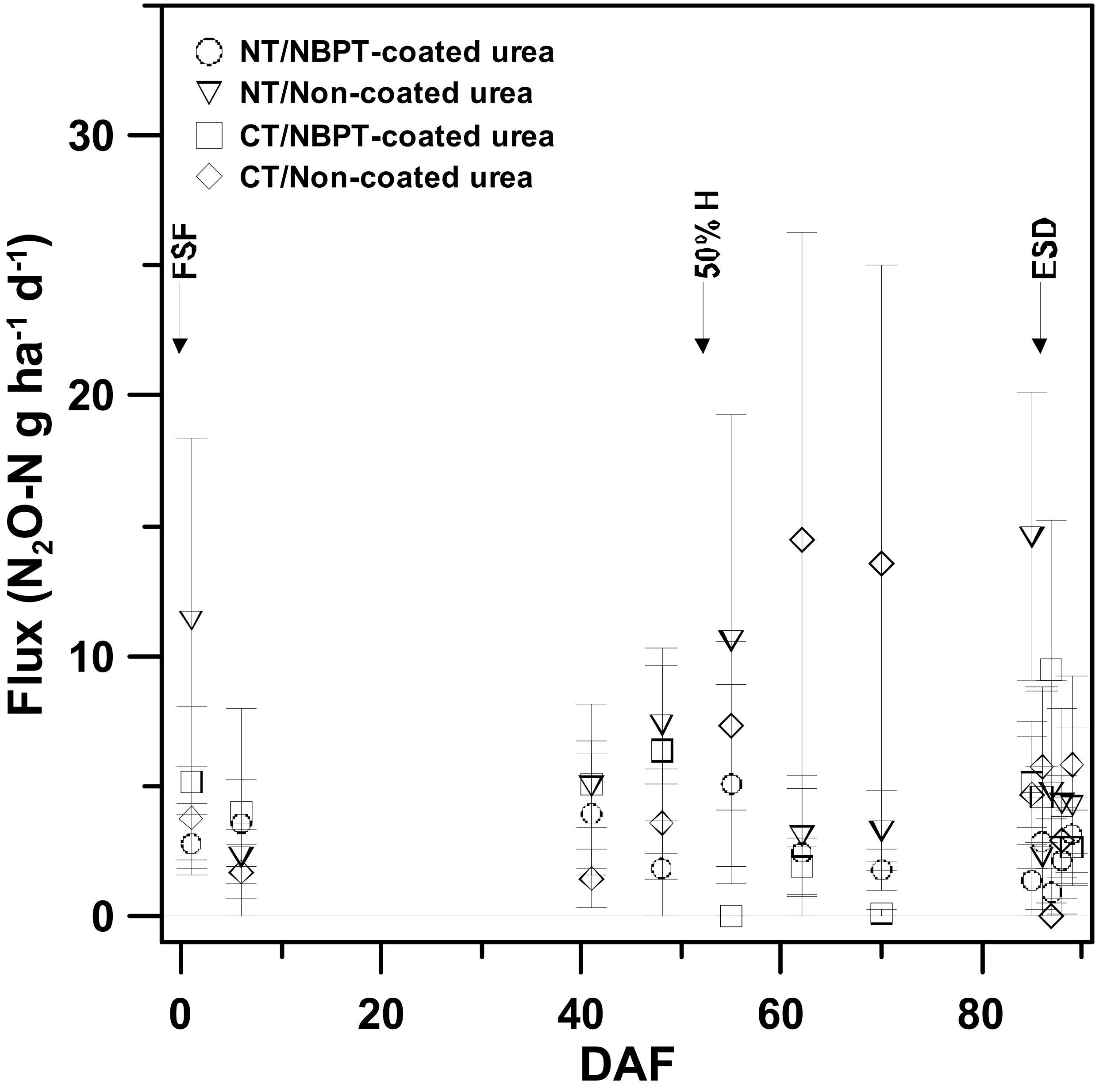

Figure 1. Nitrous oxide (N_2O) fluxes over time during the 2017 rice-growing season at the Rice Research and Extension Center near Stuttgart, AR among tillage practice [i.e., conventional (CT) and no-tillage (NT; n = 8)]-urea fertilizer type [i.e., N-(n-butyl) thiosphosphoric triamide (NBPT)-coated and non-coated urea (n = 8)] treatment combinations. Arrows (↓) indicate establishment of the full-season-flood [FSF; 0 days-after-flood (DAF)], growth stages [50% heading (50% H; 53 DAF)], and end-of-season drain (ESD; 85 DAF). Error bars associated with treatment means are standard errors (n = 4). Least significant difference (LSD) at the $\alpha = 0.1$.

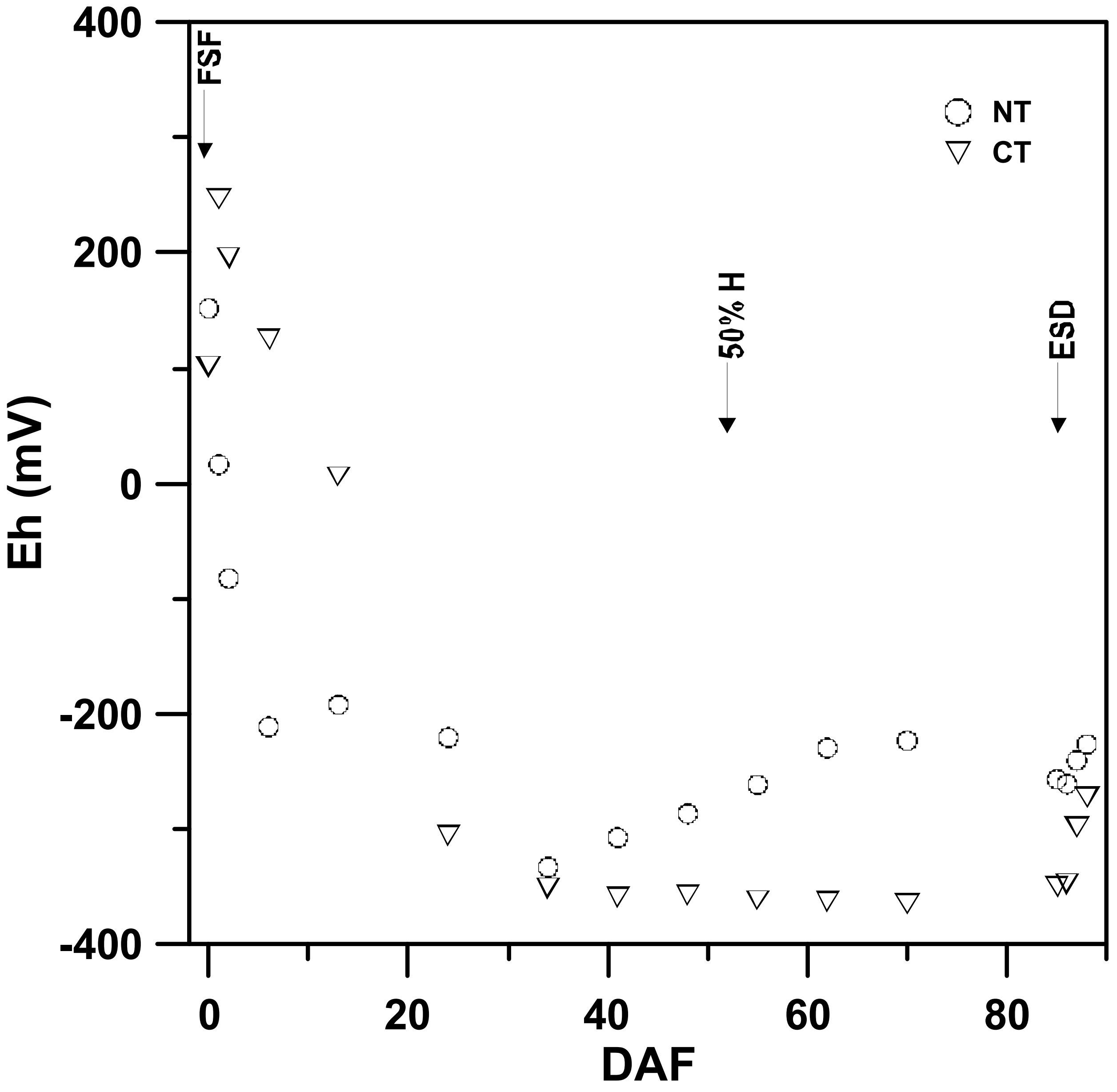

Figure 2. Soil redox potential (Eh) over time during the 2017 rice-growing season at the Rice Research and Extension Center near Stuttgart, AR for conventional tillage (CT) and no-tillage (NT) treatments average across fertilizer treatments. Arrows (↓) indicate establishment of the full-season flood [FSF; 0 days-after-flood (DAF)], growth stages [50% heading (50% H; 53 DAF)], and end-of-season drain (ESD; 85 DAF). Least significant difference (LSD) at the α = 0.05.

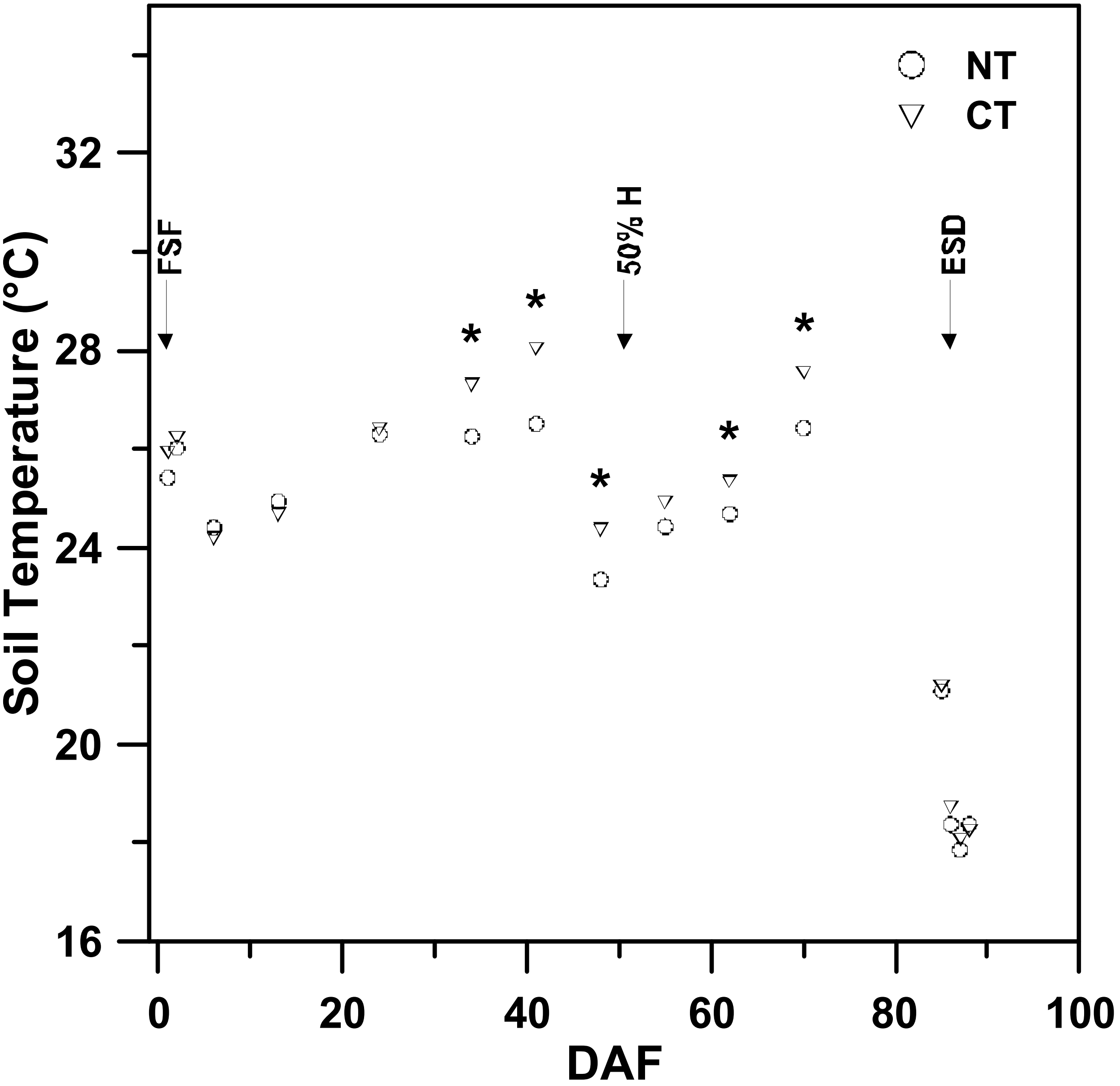

Figure 3. Soil temperature (°C) over time during the 2017 rice-growing season at the Rice Research and Extension Center near Stuttgart, AR for conventional tillage (CT) and no-tillage (NT) treatments average across fertilizer treatments. Arrows (↓) indicate establishment of the full-season flood [FSF; 0 days-after-flood (DAF)], growth stages [50% heading (50% H; 53 DAF)], and end-of-season drain (ESD; 85 DAF). An asterisks (*) represents a significant difference ($P < 0.05$) between water management practices on that date.

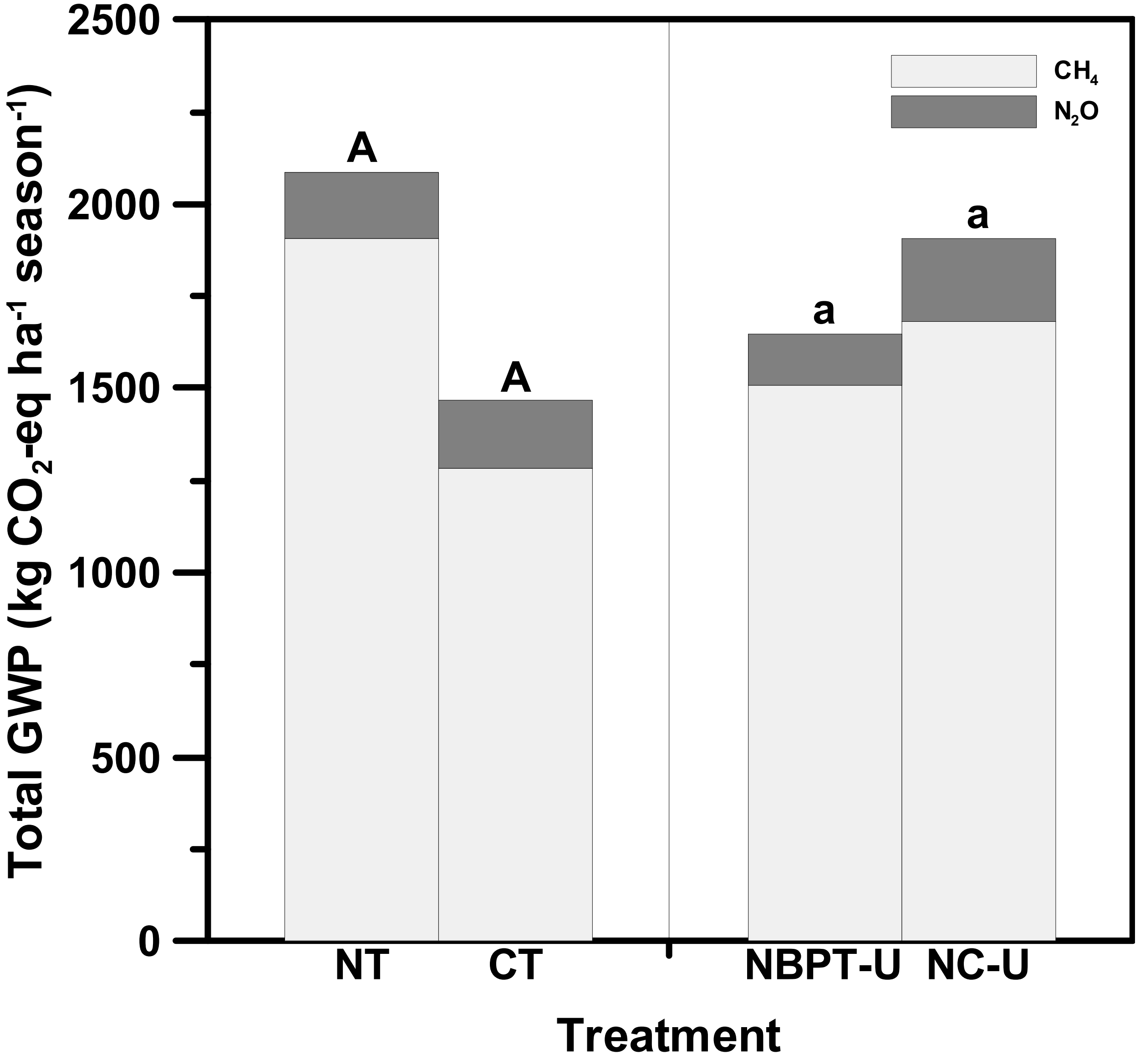

Figure 4. Total global warming potential (GWP), reported as carbon dioxide equivalents (CO_2-eq), for nitrous oxide (N_2O) and methane (CH_4) for tillage practices [i.e., conventional (CT) and no-tillage (NT; n = 8)] and urea fertilizer type [i.e., N-(n-butyl) thiosphosphoric triamide (NBPT)-coated (NBPT-U) and non-coated urea (NC-U; n = 8)] from the 2017 rice growing season at the Rice Research and Extension Center near Stuttgart, AR. Different capital letters atop bars denote significant differences between water management practices (n = 8; $P < 0.05$). Different lower-case letters atop bars denote significant differences between cultivars (n = 8; $P < 0.05$).

Thesis Conclusion

The rice-growing region of Arkansas relies heavily on groundwater for irrigation, and water is being withdrawn from the shallow aquifers at unsustainable rates. Consequently, there is growing interest in potential water conservation practices associated with rice production, hence the use of the intermittent-flood-irrigation approach. Furthermore, to alleviate potential detrimental effects of reduced water use on pure-line rice cultivars, there may also be an increased need to plant hybrid rice.

In addition, urease inhibitors (i.e., NBPT coating) are of great interest in rice production because they may improve N-fertilizer efficiency and reduce nutrient loss, such as by ammonia (NH_3) volatilization. Interest in tillage practices is a result of trying to alleviate soil erosion from the field and to improve soil fertility and health. No-tillage and similar practices (i.e., reduced tillage) keep residual crop cover on soil during non-production months from wind and water erosion. Soil erosion of agricultural fields has been known to contain excess nutrients, therefore, having the potential to cause detrimental effects on waterways (i.e., eutrophication).

In 2016, this study reported that the intermittent-flood treatment had three different re-flood events that caused the soil redox potential to increase (i.e., become less reduced) compared to that measured in the full-season-flood treatment and, contrary to that hypothesized, neither weekly N_2O fluxes nor season-long emissions (i.e., area- or yield-scaled) were affected by water management practice (full-season-flood or intermittent-flood) or cultivar (pure-line LaKast or hybrid XL753) from rice grown on a silt-loam soil in the direct-seeded, delayed-flood production system in east-central Arkansas. Despite non-zero N_2O fluxes only being measured on six of 12 sample dates, regardless of imposed treatment, N_2O fluxes varied over time throughout the rice growing season, where peak N_2O fluxes generally occurred between internode elongation and

50% heading and immediately prior to the end-of-season flood release. In 2017, results were contrary to what was hypothesized because neither N_2O fluxes nor season-long emissions (i.e., area- or yield-scaled) were affected ($P > 0.1$) by tillage practice (conventional-tillage and no-tillage), type of urea fertilizer (i.e., NBPT-coated and non-coated), or the use of urea fertilizer in a conventionally tilled field (i.e., urea-fertilized and non-fertilized control) from rice grown under a direct-seeded, delayed-flood production system, on a silt-loam soil eastern Arkansas.

In 2016, contrary to that hypothesized, total GWP was unaffected ($P > 0.05$) by water management practice (full-season-flood or intermittent-flood), but, similar to that hypothesized, the pure-line cultivar had a greater (i.e., more environmentally undesirable; $P < 0.05$) GWP than the hybrid cultivar that was evaluated in this field study. Based on the numeric ranking of total GWP, results clearly indicated that the combination of growing a pure-line rice cultivar with the intermittent-flood water management practice should be avoided by rice producers and that the intermittent-flood/hybrid combination evaluated in this study may be more environmentally desirable. However, in 2017, also in contrast to that hypothesized, total GWP was unaffected ($P > 0.05$) by tillage practice, type of urea fertilizer, or the common use of N-fertilization in a conventionally-tilled field.

In 2016, averaged across all treatment factors evaluated in this study, CH_4 and N_2O emissions accounted for 93 and 7%, respectively, of the total GWP. In 2017, N_2O emissions, as a component of GWP, was averaged across all treatment combinations and accounted for 10% of the total GWP, which was similar to that in 2016, with the remainder of the total GWP attributed to CH_4 emissions. Likewise, CH_4 was the key driver of GWP for rice production. Both field seasons supported what few Arkansas studies evaluating CH_4 and N_2O emissions have reported, which was that CH_4 is the driving force behind total GWP for non-CO_2 emissions and N_2O emissions are relatively minor.

Nitrous oxide emissions, in combination with CH_4 emissions, from agricultural settings are expected to rise through the next decade and beyond, which is concerning because N_2O and CH_4 are more potent GHGs than CO_2 in the atmosphere. Greenhouse gas emission studies are of increasing importance because the world's human population continues to grow, which will require similar increases in crop production, especially commonly consumed grains such as rice. Therefore, a proper understanding of N_2O emissions from more sustainable agricultural practices that are used to potentially mitigate or offset environmental degradation is vital to help industry leaders, and local, state, and federal agencies make responsible decisions regarding crop production.

Appendices

Appendix 1. Example of SAS program for evaluating N_2O fluxes between water management practices and cultivar for the 2016 season.

```
title 'Nitrous Field Study 2016 - Casey Rector';
title2 'Nitrous Fluxes 2016 ANOVA';
data nitrous2016;
  infile 'N2OFluxMDL.prn' firstobs=2;
  input ID DAF Block water $ cultivar $ flux;
 run;

proc sort data=nitrous2016; by  DAF;
quit;

title3 'Initial Data Listing and Data Plot';
Proc print data=nitrous2016 noobs;by DAF;
id DAF;
var water cultivar flux;
run;

proc sort; by Treatment var DAF;
proc means;
class water DAF;
var flux;
quit;

proc sort; by Treatment var DAF;
proc means;
class cultivar DAF;
var flux;
quit;


proc mixed data=nitrous2016 method=type3;
class  cultivar water DAF block;
model flux = cultivar water cultivar*water DAF DAF*cultivar DAF*water DAF* cultivar*water
/ ddfm=kr ;
random  Block block*water block*cultivar ;
ods exclude FitStatistics Tests3 IterHistory ;
lsmeans DAF  / diff alpha=0.10;
quit;
```

Appendix 2. Example of SAS program for evaluating season, long, area-and yield-scaled, and pre- and post-flood-release N_2O emissions between water management practices and cultivar for the 2016 season.

```
title 'Nitrous Field Study 2016 - Casey Rector';
title2 'Emission Nitrous 2016 ANOVA';
data nitrous2016;
  infile 'N2OEmissionsMDL.prn' firstobs=2;
  input ID Block water $ cultivar $ Emission;
 run;

proc sort data=nitrous2016; by cultivar water;
quit;

title3 'INITIAL DATA LISTING AND DATA PLOT';

proc print data=nitrous2016 noobs; by cultivar;
  id ;
  var water Emission;
  run;

proc sort; by water cultivar ;
proc means;
class water ;
var Emission;
quit;

proc sort; by water cultivar ;
proc means;
class cultivar ;
var Emission;
quit;


proc mixed data=nitrous2016 method=type3;
class  cultivar water block;
model emission = cultivar water cultivar*water  / ddfm=kr  ;
random   Block  block*water ;
ods exclude FitStatistics Tests3 IterHistory   ;
*lsmeans cultivar water cultivar*water  / diff alpha=0.10;
quit;
```

Appendix 3. Example of SAS program for evaluating season, long, area-scaled CH_4 emissions, global warming potential (GWP), yield, aboveground biomass, soil redox potential, and soil temperature between water management practices and cultivar for the 2016 season.

```
title 'Nitrous Field Study 2016 - Casey Rector';
title2 'Emission Nitrous 2016 ANOVA';
data nitrous2016;
  infile 'N2OGWP.prn' firstobs=2;
  input ID Block water $ cultivar $ GWP;
 run;

proc sort data=nitrous2016; by cultivar water;
quit;

title3 'INITIAL DATA LISTING AND DATA PLOT';

proc print data=nitrous2016 noobs; by cultivar;
  id ;
  var water GWP;
  run;

proc sort; by water cultivar ;
proc means;
class water ;
var GWP;
quit;

proc sort; by water cultivar ;
proc means;
class cultivar ;
var GWP;
quit;


proc mixed data=nitrous2016 method=type3;
class  cultivar water block;
model GWP = cultivar water cultivar*water  / ddfm=kr  ;
random   Block  block*water ;
ods exclude FitStatistics Tests3 IterHistory   ;
*lsmeans cultivar water cultivar*water  / diff alpha=0.05;
quit;
```

Appendix 4. Example of SAS program data for evaluating soil properties between water management practices and cultivar for the 2016 season.

```
title 'Nitrous Oxide Field Study - Initial Soil Sample Analysis 2016 -  Casey Rector';
title2 'Soil Data N2O 2016 ANOVA';
data soildata2016;
  infile 'Soil Properties.prn' firstobs=2;
  input id block  water $ cultivar $ ph ec p k ca mg su na fe mn zn cu N C LOI CN ;
 run;

proc sort data=soildata2016; by water cultivar;
quit;

title3 'INITIAL DATA LISTING AND DATA PLOT';

proc print data=soildata2016 noobs; by cultivar;
  id ;
  var cultivar block water ph ec p k ca mg su na fe mn zn cu N C LOI CN ;
  run;
quit;


title3 'pH ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model ph =  water cultivar water*cultivar / ddfm=kr ;
random block block*water;
ods exclude FitStatistics Tests3 IterHistory;
lsmeans water  / diff ;
quit;

title3 'Electrical Conductivity ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model ec = water cultivar water*cultivar / ddfm=kr ;
random block block* water;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans water / diff ;
quit;

title3 'Phosphorus ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model p = water cultivar water*cultivar / ddfm=kr ;
random block block* water;
ods exclude FitStatistics Tests3 IterHistory;
```

```
lsmeans cultivar / diff  ;
quit;

title3 'Potassium ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model k = water cultivar water*cultivar / ddfm=kr ;
random block block* water;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans water  / diff;
quit;

title3 'Calcium ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model ca = water cultivar water*cultivar / ddfm=kr ;
random block block* water;
ods exclude FitStatistics Tests3 IterHistory;
lsmeans cultivar  / diff ;
quit;

title3 'Magnesium ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model mg = water cultivar water*cultivar / ddfm=kr ;
random block block* water;
ods exclude FitStatistics Tests3 IterHistory;
lsmeans cultivar  / diff  ;
quit;

title3 'Sulfur ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model su = water cultivar water*cultivar / ddfm=kr ;
random block block* water;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans water / diff;
quit;

title3 'Sodium ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model na = water cultivar water*cultivar / ddfm=kr ;
random block block* water;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans water  / diff ;
```

```
quit;

title3 'Iron ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model fe = water cultivar water*cultivar / ddfm=kr ;
random block block*water;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans water  / diff ;
quit;

title3 'Manganese ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model mn = water cultivar water*cultivar / ddfm=kr ;
random block block* water;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans water  / diff ;
quit;

title3 'Zinc ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model zn = water cultivar water*cultivar / ddfm=kr ;
random block block* water;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans water  / diff ;
quit;

title3 'Copper ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model cu = water cultivar water*cultivar / ddfm=kr ;
random block block* water;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans water / diff;
quit;


title3 'Total Nitrogen ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model N = water cultivar water*cultivar / ddfm=kr ;
random block block* water ;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans water  / diff ;
```

```
quit;

title3 'Total Carbon ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model C = water cultivar water*cultivar / ddfm=kr ;
random block block* water;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans water / diff;
quit;

title3 'LOI ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model LOI = water cultivar water*cultivar / ddfm=kr ;
random block block* water;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans water  / diff ;
quit;

title3 'CN ANALYSIS OF VARIANCE';
proc mixed data=soildata2016 method=type3 ;
class block cultivar water;
model CN = water cultivar water*cultivar / ddfm=kr ;
random block block* water;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans water / diff;
quit;
```

Appendix 5. Example of SAS program for evaluating N_2O fluxes between tillage practices and type of urea fertilizer for the 2017 season.

```
title 'Nitrous Field Study 2017 - Casey Rector';
title2 'Nitrous Fluxes 2017 ANOVA';
data nitrous2017;
  infile 'N2OFlux.prn' firstobs=2;
  input ID DAF Block tillage $ fert $ flux;
 run;

proc sort data=nitrous2017; by  DAF;
quit;

title3 'Initial Data Listing and Data Plot';
Proc print data=nitrous2017 noobs;by DAF;
id DAF;
var tillage fert flux;
run;

proc sort; by tillage fert DAF;
proc means;
class tillage DAF;
var flux;
quit;

proc sort; by Treatment var DAF;
proc means;
class fert DAF;
var flux;
quit;


proc mixed data=nitrous2017 method=type3;
class  cultivar tillage fert block;
model flux = tillage fert tillage*fert DAF DAF*fert DAF*tillage DAF* tillage*fert / ddfm=kr ;
random  Block block*tillage block*fert ;
ods exclude FitStatistics Tests3 IterHistory ;
lsmeans DAF  / diff alpha=0.10;
quit;
```

Appendix 6. Example of SAS program for evaluating season, long, area-and yield-scaled, and pre- and post-flood-release N_2O emissions between tillage practices and type of urea fertilizer for the 2017 season.

```
title 'Nitrous Field Study 2017 - Casey Rector';
title2 'Emission Nitrous 2017 ANOVA';
data nitrous2017;
  infile 'N2OEmissions.prn' firstobs=2;
  input ID Block tillage $ fert $ Emission;
 run;

proc sort data=nitrous2017; by tillage fert;
quit;

title3 'INITIAL DATA LISTING AND DATA PLOT';

proc print data=nitrous2017 noobs; by fert;
  id ;
  var tillage Emission;
  run;

proc sort; by tillage fert ;
proc means;
class tillage ;
var Emission;
quit;

proc sort; by tillage fert;
proc means;
class fert ;
var Emission;
quit;


proc mixed data=nitrous2017 method=type3;
class  fert tillage block;
model emission = tillage fert tillage*fert  / ddfm=kr  ;
random   Block  block*tillage ;
ods exclude FitStatistics Tests3 IterHistory   ;
*lsmeans tillage  / diff alpha=0.10;
quit;
```

Appendix 7. Example of SAS program for evaluating season, long, area-scaled CH_4 emissions, global warming potential (GWP), yield, aboveground biomass, soil redox potential, and soil temperature between tillage practices and type of urea fertilizer for the 2017 season.

```
title 'Nitrous Field Study 2017 - Casey Rector';
title2 'Emission Nitrous 2017 ANOVA';
data nitrous2017;
  infile 'N2OGWP.prn' firstobs=2;
  input ID Block tillage $ fert $ GWP;
 run;

proc sort data=nitrous2017; by tillage fert;
quit;

title3 'INITIAL DATA LISTING AND DATA PLOT';

proc print data=nitrous2017 noobs; by fert;
  id ;
  var tillage GWP;
  run;

proc sort; by tillage fert ;
proc means;
class tillage ;
var GWP;
quit;

proc sort; by tillage fert;
proc means;
class fert ;
var GWP;
quit;


proc mixed data=nitrous2017 method=type3;
class  fert tillage block;
model GWP = tillage fert tillage*fert  / ddfm=kr  ;
random   Block  block*tillage ;
ods exclude FitStatistics Tests3 IterHistory   ;
*lsmeans tillage  / diff alpha=0.10;
quit;
```

Appendix 8. Example of SAS program data for evaluating soil properties between tillage practices and type of urea fertilizer for the 2017 season.

```
title 'Nitrous Oxide Field Study - Initial Soil Sample Analysis 2017 -  Casey Rector';
title2 'Soil Data N2O 2017 ANOVA';
data soildata2017;
  infile 'Soil Properties.prn' firstobs=2;
  input id block  tillage $ fert $ ph ec p k ca mg su na fe mn zn cu N C LOI CN ;
 run;

proc sort data=soildata2017; by tillage fert;
quit;

title3 'INITIAL DATA LISTING AND DATA PLOT';

proc print data=soildata2017 noobs; by fert;
  id ;
  var fert block tillage ph ec p k ca mg su na fe mn zn cu N C LOI CN ;
  run;
quit;


title3 'pH ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model ph =  fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
lsmeans tillage  / diff ;
quit;

title3 'Electrical Conductivity ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model ec = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans tillage / diff;
quit;

title3 'Phosphorus ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model p = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
```

```
lsmeans tillage / diff  ;
quit;

title3 'Potassium ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model k = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
lsmeans tillage*fert  / diff;
quit;

title3 'Calcium ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model ca = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans fert/ diff ;
quit;

title3 'Magnesium ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model mg = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
lsmeans tillage  / diff  ;
quit;

title3 'Sulfur ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model su = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans tillage/ diff ;
quit;

title3 'Sodium ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model na = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
lsmeans tillage  / diff ;
```

```
quit;

title3 'Iron ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model fe = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
lsmeans tillage / diff ;
quit;

title3 'Manganese ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model mn = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
lsmeans tillage  / diff ;
quit;

title3 'Zinc ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model zn = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
lsmeans tillage / diff ;
quit;

title3 'Copper ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model cu = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans tillage / diff ;
quit;


title3 'Total Nitrogen ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model N = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans tillage diff ;
```

```
quit;

title3 'Total Carbon ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model C = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans tillage / diff;
quit;

title3 'LOI ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model LOI = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans tillage / diff ;
quit;

title3 'CN ANALYSIS OF VARIANCE';
proc mixed data=soildata2017 method=type3 ;
class block fert tillage;
model CN = fert tillage fert*tillage / ddfm=kr ;
random block block*tillage;
ods exclude FitStatistics Tests3 IterHistory;
*lsmeans tillage / diff ;
quit;
```

Appendix 8. Example of SAS program for evaluating season, long, area- and yield-scaled N_2O emissions between fertilization rates utilizing a conventional tillage practice for the 2017 season.

```
title 'Nitrous Field Study 2017 - Casey Rector';
title2 'Emission Nitrous CT 2017 ANOVA';
data nitrous2017;
  infile 'N2OEmissions2017CT.prn' firstobs=2;
  input ID Block Tillage $ Fert $ Emissions;
 run;

proc sort data=nitrous2017; by  Fert Tillage;
quit;

title3 'INITIAL DATA LISTING AND DATA PLOT';

proc print data=nitrous2017 noobs; by Fert;
  id ;
  var Tillage Emissions;
  run;

proc sort; by Tillage Fert ;
proc means;
class Tillage ;
var Emissions;

quit;
proc sort; by Tillage Fert ;
proc means;
class Fert ;
var Emissions;

quit;


proc mixed data=nitrous2017 method=type3;
class  Fert block;
model emissions = Fert  / ddfm=kr  ;
random   Block  ;
ods exclude FitStatistics Tests3 IterHistory   ;
*lsmeans Fert / diff;
quit;
```

Appendix 9. Example of SAS program for the total global warming potential (GWP) and yield between fertilization rates utilizing a conventional tillage practice for the 2017 season.

```
title 'Nitrous Field Study 2017 - Casey Rector';
title2 'Emission Nitrous CT 2017 ANOVA';
data nitrous2017;
  infile 'GWP2017CT.prn' firstobs=2;
  input ID Block Tillage $ Fert $ GWP;
 run;

proc sort data=nitrous2017; by  Fert Tillage ;
quit;

title3 'INITIAL DATA LISTING AND DATA PLOT';

proc print data=nitrous2017 noobs; by Fert;
  id ;
  var Tillage GWP;
  run;

proc sort; by Treatment Fert ;
proc means;
class Tillage ;
var GWP;

quit;
proc sort; by Tillage Fert ;
proc means;
class Fert ;
var GWP;

quit;


proc mixed data=nitrous2017 method=type3;
class  Fert block;
model GWP = Fert  / ddfm=kr  ;
random   Block  ;
ods exclude FitStatistics Tests3 IterHistory   ;
*lsmeans Fert / diff;
quit;
```