Evaluation of Nitrous Oxide Emissions from Furrow-irrigated Rice on a Silt-loam Soil in Arkansas

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Evaluation of Nitrous Oxide Emissions from Furrow-irrigated Rice on a Silt-loam Soil in Arkansas

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Abstract

As the number one rice (*Oryza sativa*)-producing state in the United States, Arkansas also ranks fourth as the largest user of groundwater. Recently, due to the development of drought-resistant hybrid cultivars, the furrow-irrigated rice production system has become an increasingly popular alternative to traditional flood-irrigated production with respect to conserving groundwater and maintaining yield. However, other environmental parameters, like greenhouse gas emissions, specifically nitrous oxide (N_2O), have yet to be evaluated under furrow-irrigated rice. The objectives of this study were to i) evaluate the effects of site position (i.e., up-, mid-, and down-slope) and tillage treatment [i.e., conventional tillage (CT) and no-tillage NT)] on N_2O fluxes and season-long emissions from a furrow-irrigated rice production system on a silt-loam soil in east-central Arkansas, and ii) to evaluate the effects of nitrogen (N)-fertilization amount and timing [i.e., 100% of the early season optimum N rate plus one split application (OPOS), 50% of the early season optimum N rate plus two split applications (HOPTS), 100% of the early season plus two split applications (OPTS), and an unamended control (UC)] on N_2O fluxes and season-long emissions in a greenhouse trial simulating a furrow-irrigated rice production system. Gas collection occurred weekly over the 2018 and 2019 rice growing seasons for the field study and during 2020 growing season for the greenhouse trial. In 2018, N_2O emissions differed ($P <$ 0.1) among site positions and differed between tillage treatments, while 2019 emissions differed ($P < 0.1$) only between tillage treatments. Nitrous oxide emissions in 2018 were greatest at the down-slope position (3.34 kg N_2O ha^{-1} $season^{-1}$) compared to both the mid- (2.78 kg N_2O ha^{-1} $season^{-1}$) and up-slope (2.74 kg N_2O ha^{-1} $season^{-1}$) positions, which did not differ. For both growing seasons, CT produced greater ($P < 0.1$) N_2O emissions than NT, where mean annual emissions from CT were 3.15 and 2.58 kg N_2O ha^{-1} $season^{-1}$ for the 2018 and 2019 seasons,

respectively. In 2020, N_2O fluxes differed among fertilizer-N treatments over time ($P < 0.01$), yet there was no consistent trend between mid-season fertilizer-N application timing and the timing of peak N_2O fluxes. Nitrous oxide emissions numerically ranged from 0.42 kg N_2O ha^{-1} $season^{-1}$ from the UC to 0.65 kg N_2O ha^{-1} $season^{-1}$ from the OPOS treatment, but unlike fluxes, did not differ ($P = 0.60$) among N-fertilizer treatments. Results of these studies highlight the importance of soil management practices and water regimes in regulating N_2O production and release from rice fields. The evaluation of N_2O fluxes and emissions from furrow-irrigated rice is essential to understanding the environmental impact of furrow-irrigation as an alternative water management scheme for rice production.

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Dedication

I am dedicating this work to my younger self who had no idea that she was capable of such a feat.

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Introduction

Greenhouse gas (GHG) concentrations in the atmosphere, many of which are exacerbated by anthropogenic actions, are contributing largely to the global crisis of climate change. From 1750 to 2017, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) concentrations increased 45, 164, and 22%, respectively (EPA, 2019). In 2010, the total annual anthropogenic GHG emissions were 49 Gt CO_2-equivalents (Eq) yr^{-1}, with 76% of the emissions from CO_2, 16% from CH_4, and 6.2% from N_2O (IPCC, 2014). It was estimated that, from 2000 to 2010, GHG emissions increased an average of 2.2% each year (IPCC, 2014). Due to radiative forcing from increased GHG concentrations, global air temperatures have risen ~ 0.8°C (~1.4°F) since 1880, which have affected weather patterns, ocean chemistry, animal migration, and plant lifecycles, to name a few (NASA, 2010). Human activities have contributed roughly 50 to 65% of the CH_4 emissions from natural gas/petroleum consumption and from enteric fermentation from livestock agriculture and other anaerobic processes, such as rice (*Oryza sativa*) agriculture. Nitrous oxide, a by-product of the nitrogen (N) cycle from partial denitrification, is sourced mainly from poor agricultural soil management, which accounts for nearly 74% of total N_2O emissions (EPA, 2019). Nitrous oxide is especially potent because N_2O depletes stratospheric ozone (Li et al., 2011). Although CO_2 emissions are greater than that of CH_4 and N_2O, the global warming potential (GWP) of CO_2 is less than the other gases, such that, even though CH_4 and N_2O are not as abundant in the atmosphere, the ability of CH_4 and N_2O to trap heat in the atmosphere is significantly greater than that of CO_2.

The demand for rice is projected to increase in direct correlation with the population of developing countries that rely on rice, which will account for 83% of the world population by 2028 (USDA, 2019). Currently, rice production is the largest, single use of land for producing food, with 160,586,000 ha of harvested rice world-wide (Maclean et al., 2013, USDA-FAS, 2020). Within the United States (US), six states produce rice: Arkansas, California, Louisiana, Missouri, Texas, and Mississippi, with Arkansas being the largest rice-producing state in the US. In 2019, Arkansas harvested 455,676 ha of rice constituting about 46% of the total rice production in the US (USDA-ERS, 2020). Among the best management practices in rice production systems, tillage, water regime, and fertilizer type and timing represent the main factors controlling and influencing production and release of N_2O.

In Arkansas, approximately 60% of rice is conventionally tilled (CT) with the remaining rice produced using stale-seedbed (30.1%) or no-tillage (6%; NT) systems (Hardke, 2016). Conventional tillage is achieved by incorporating the previous growing season's stubble into the soil often using multiple passes over the same area with rollers, field cultivators, and disks (UA-DA-CES, 2019). In so doing, the top 10 to 15 cm of soil is disturbed, thus severely disrupting soil aggregates, soil macroporosity, microbial communities, organic matter, and soil nutrients. The organic matter from the incorporated crop residues serve as sources of nutrients for the up-coming rice crop and the disrupted seed bed allows for easier planting. However, NT management for rice in Arkansas is increasing due to the previously reported reduced labor cost, better long-term aggregate stability, sustained soil structure, and decreased methane emissions (Ahmad et al., 2009; Chatskikh and Olesen, 2007; Humphreys, 2018; Rector et al., 2018; Zhang et al., 2013). No-tillage involves keeping the previous season's stubble intact during the current growing season. Consequently, there is a slower release of nutrients from the crop residues and often greater water-holding capacity compared to CT (Six et al., 2002).

The production and release of N_2O are heavily influenced by the soil water content and the chosen irrigation practice. A known benefit of flood-irrigation is decreased N_2O emissions due to the extended anaerobic conditions that disrupt the nitrification/denitrification processes.

Furrow-irrigation is an irrigation style that includes shallow raised beds and furrows on a slightly sloping field. Irrigation water is presented upslope and is allowed to flow horizontally and vertically down the field furrows by gravity. Not uncommonly, the down slope portion of the field can contain a tail levee to retain any tail water that is collected at the end of the field. Not until the last few years has furrow-irrigation become a viable option for rice production. Although furrow-irrigation is commonly used to grow corn (*Zea mays*), soybean (*Glycine max*), and cotton (*Gossypium*), several early studies showed that furrow-irrigation for rice production was problematic. In the 1990s and early 2000s, grain yields from furrow-irrigated rice were significantly lower than yields from traditional flooding (Borell et al., 1997; Ockerby and Fukai, 2001; Kukal et al., 2005). The decrease in yields was attributed to the lack of weed suppression from a permanent flood and rice cultivars that could not sustain aerobic or semi-aerobic conditions.

Furrow-irrigated rice is a relatively new practice in Arkansas with 47,753 ha (118,000 acres), approximately 10.5%, of furrow-irrigated rice grown in Arkansas in 2019 (Hardke, 2020). Recent developments in hybrid rice cultivars have generated new drought-tolerant varieties that can withstand alternative irrigation methods without compromising yield. At present, furrow-irrigation in Arkansas is used on severely sloping land and soil with high leaching potentials where levees, which are constructed to contain the flood water under the flooded-rice production practices, are not as practical. Although furrow-irrigated rice faces new challenges, the paramount benefits of furrow-irrigation, including increased water use efficiency and reduced labor and maintenance costs, are motivating factors for furrow-irrigation to be an alternative rice production system (Hefner and Tracy, 1991).

Urea is the most common N-fertilizer used in Arkansas due to the large N concentration and lower cost compared to the other N fertilizers (UA-DA-CES, 2019). However, a drawback to urea is the potential for large ammonia (NH_3) volatilization losses if not properly managed (UA-DA-CES, 2019). If urea is not incorporated into the soil via tillage or irrigation, urease, an enzyme present in the soil, will break down the urea too quickly and release NH_3 (Rogers, 2014). Typically, urea is used in flooded production systems. Urea is highly soluble and volatilizable and should be applied to a dry soil surface. The field is then flooded to allow the urea to incorporate into the soil through infiltration, and thus, regulate volatilization losses (Rogers, 2014). For alternative rice production systems like furrow-irrigation, N-(n-butyl) thiophosphoric triamide (NBPT)-coated urea is preferred (UA-DA-CES, 2019). Although more costly compared to uncoated urea, NBPT-coated urea, with the aid of a urease inhibitor, is able to retard the breakdown of urea until the fertilizer can be incorporated into the soil, while still being able to provide the same N concentration as uncoated urea (UA-DA-CES, 2019).

In furrow-irrigated systems, more N_2O is produced due to the incomplete denitrification from alternating wet and dry cycles and there are moments where the soil-air interface is available for diffusion to occur more rapidly. Thus, gas diffusion of N_2O under furrow-irrigation is the most prevalent mechanism in which N_2O emissions are released into the atmosphere. To date, only a few studies in the US have focused on the characterizing the environmental impact of furrow-irrigated rice production systems, in combination with best management practices like tillage, water regimes, and fertilizer application timing. Consequently, continued research is necessary to evaluate N_2O production and release in furrow-irrigated rice production systems.

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Chapter 1

Literature Review

Greenhouse Gases

The phrase 'greenhouse gases' refers to atmospheric gases that retain heat energy from solar radiation, thereby increasing the ambient, atmospheric air temperature on Earth. The most abundant greenhouse gases (GHG) in the Earth's atmosphere, in no particular order, are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water (H_2O) (EPA, 2019). Although GHG are produced from biological processes, increasing GHG concentrations in the atmosphere, many of which are exacerbated by anthropogenic actions, are contributing largely to the global crisis of climate change. From 1750 to 2017, CO_2, CH_4, and N_2O concentrations increased 45, 164, and 22%, respectively (EPA, 2019). In 2010, the total annual anthropogenic GHG emissions were 49 Gt CO_2-equivalents (Eq) yr^{-1}, with 76% of the emissions from CO_2, 16% from CH_4, and 6.2% from N_2O (IPCC, 2014). It was estimated that, from 2000 to 2010, GHG emissions increased an average of 2.2% each year (IPCC, 2014). Due to radiative forcing from increased GHG concentrations, global air temperatures have risen ~ 0.8°C (~1.4°F) since 1880, which have affected weather patterns, ocean chemistry, animal migration, and plant lifecycles, to name a few (NASA, 2010).

The main source of CO_2 comes from the combustion of fossil fuels needed for transportation and energy production. Carbon dioxide is prevalent in many of Earth's processes, such as respiration by animals, uptake by plants, storage in soil, and adsorption in water bodies through the C cycle, but the manipulation of these processes by humans has disrupted the balance (Bloom et al., 2016; EPA, 2019). Hakkarainen et al. (2016) used remote sensing to locate global anomalies of CO_2, which correlated to increased anthropogenic activities, such as fossil fuel burning and large CO_2 respiration rates in densely populated areas. Human activities have contributed roughly 50 to 65% of the CH_4 emissions from natural gas/petroleum consumption and from enteric fermentation from livestock agriculture and other anaerobic processes, such as rice (*Oryza sativa*) agriculture. Nitrous oxide, a by-product of the nitrogen (N) cycle from partial denitrification, is sourced mainly from poor agricultural soil management, which accounts for nearly 74% of total N_2O emissions (EPA, 2019). Nitrous oxide is especially potent because N_2O depletes stratospheric ozone (Li et al., 2011).

Although CO_2 emissions are greater than that of CH_4 and N_2O, the global warming potential (GWP) of CO_2 is less than the other gases, such that, even though CH_4 and N_2O are not as abundant in the atmosphere, the ability of CH_4 and N_2O to trap heat in the atmosphere is significantly greater than that of CO_2. Global warming potential is an index, developed by the Intergovernmental Panel on Climate Change (IPCC), to standardize GHG in terms of CO_2 equivalents (IPCC, 2014). The GWP of a particular GHG is defined as the ability of 1 kg of the gas to trap heat relative to CO_2 during a given timeframe, usually 100 years (EPA, 2012). Non-CO_2 gas emissions are then converted to a CO_2-equivalent basis, most often in the form of million metric tons of CO_2 equivalent (MMT CO_2 Eq). At present, the GWP for CO_2, CH_4, and N_2O are 1, 25, and 298, respectively (EPA, 2019). Agriculture accounts for 54% of global non-CO_2 emissions, making agriculture the largest sector of CH_4 and N_2O production compared to the energy, industrial, and waste sectors (EPA, 2012). Considering their GWP, an increase in CH_4 and N_2O emissions suggests that attention and research should be focused on agricultural practices to seek potential sources of GHG mitigation.

General Nitrogen Cycle

Nitrogen (N) is present in many compounds in the environment, both inorganic and organic. The movement of N from one form to another through the environment is known as the nitrogen cycle. The various N transformation processes include nitrification, denitrification, mineralization, immobilization, and N fixation. Organic N is present in amine groups, and other, more sophisticated biological structures in living organisms, such as vegetation and microbes, and therefore is present in decomposing organic matter, typically with a C:N ratio of ~10:1. Inorganic N exists in gaseous and soluble forms. The gaseous N compounds include dinitrogen gas (N_2), nitrogen monoxide (NO), (N_2O), and ammonia (NH_3). Dinitrogen gas is the largest reservoir for N in the N cycle, constituting roughly 79% of the atmosphere (Fernandez and Kaiser, 2018). The inorganic, soluble-N compounds are nitrite (NO_2^-), nitrate (NO_3^-), and ammonium (NH_4^+). The majority of the N in terrestrial ecosystems is located in the soil, with 95 to 99% of the N in an organic form (Brady and Weil, 2008). Therefore, for the sake of this thesis, focus will be directed mainly towards the N cycle with respect to soil.

Dinitrogen gas and inorganic N compounds can be fixed in the soil through two major processes: biological N fixation by legumes and abiotic NH_4^+ fixation between inner clay layers. Symbiotic N fixation from legumes and rhizobia bacteria are responsible for approximately 60% of soil-fixed N_2 (Zahran, 1999). However, other free-living bacteria and archaea, specifically methanogens, have been shown to have N-fixing capabilities in the soil. Ammonium ions are positively charged; therefore, the ions are attracted to negatively charged clay surfaces, more specifically vermiculite. Ammonium ions can be trapped between crystalline clay layers and become protected from plant uptake and leaching (Brady and Weil, 2008). Mineralization is the conversion of organic N to inorganic N in a two-step process with the use of soil bacteria and fungi. The first step, aminization, is the process of breaking down proteins into simpler amine groups. The second step, ammonification, involves hydrolyzing the product of the aminization process to form NH_3, which is then further hydrolyzed to form NH_4^+. Ammonium and NO_3^-, both inorganic and soluble forms of N, are the forms most suitable for plant uptake. The reverse process of mineralization is immobilization, where inorganic N is converted to organic N by microbial activity. Soil microbes take in NH_4^+ and NO_3^- and use these compounds for building proteins. Mineralization and immobilization occur simultaneously in the soil, but one process may be favored over the other depending on the soil C:N ratio, microbial biomass, microbial N content, and microbial respiration and adenosine triphosphate (ATP) content (Bengtsson et al., 2003). Nitrification is a two-step process, where NH_4^+ is oxidized into NO_3^-. Two autotrophic bacteria, nitrosomonas and nitrobacter, facilitate the oxidation process. Optimal conditions for nitrification include a pH of 7-8, warmer temperatures from 25°C (77°F) to 30°C (86°F), and non-oxygen-limited environments (EPA, 2002). More recently, scientists recognized the significant role of archaea in the ammonia-oxidation process that, in addition to bacteria, can also contribute to nitrification in the soil due to different enzymes. Furthermore, archaea may be more abundant in the environment than bacteria. Metagenome studies determined the potential ecosystem function of mesophilic crenarchaea in the first step of the nitrification process (Prosser and Nicol, 2008). However, studies in semi-arid agricultural soils reported ammonia-oxidizing bacteria may be more dominant than archaea in the nitrification process (Banning et al., 2015).

Denitrification is the reduction of NO_3^- to N_2 gas, with NO^- and N_2O as intermediate compounds, therefore N_2O is a by-product of incomplete denitrification. Denitrification occurs with the use of facultative heterotrophs, thereby the process does not require oxygen. However, denitrification can be stopped from the beginning because of a lack of NO_3^- in the soil due to inadequate N fertilization to provide a source of NO_3^- or minimal source material for nitrification from natural SOM mineralization. Denitrification can also be interrupted during the reduction process by the addition of oxygen to the system. Just like the relationship between mineralization and immobilization, nitrification and denitrification can occur simultaneously. Special attention is placed on these two processes with regards to rice production and subsequent alternative irrigation techniques due to the N_2O gas that is produced and emitted into the atmosphere.

Rice Production

Rice cultivation dates back 10,000 years, and rice is cultivated on every continent, excluding Antarctica (Maclean et al., 2013). Rice is a staple food for the largest number of people on Earth, including those countries with the greatest populations, such as India and China (Maclean et al., 2013). The demand for rice is projected to increase in direct correlation with the population of developing countries that rely on rice, which will account for 83% of the world population by 2028 (USDA, 2019). Currently, rice production is the largest, single use of land for producing food, with 160,586,000 ha of harvested rice world-wide (Maclean et al., 2013, USDA-FAS, 2020). Globally, China cultivates the largest amount of rice, where 148.5 million metric tons were produced in the 2018/2019 growing season (Shahbandeh, 2020). Within the United States (US), six states produce rice: Arkansas, California, Louisiana, Missouri, Texas, and Mississippi, with Arkansas being the largest rice-producing state in the US. In 2019, Arkansas harvested 455,676 ha (1,126,000 acres) of rice constituting about 46% of the total rice production in the US (USDA-ERS, 2020).

Rice is a semi-perennial, semi-aquatic grass. Globally, rice is typically grown under four general cultural practices: lowland, deep-water, floating, and upland, with several variations within each general practice. Lowland, deep-water, and floating rice are grown under flooded or saturated soil conditions during the growing season, whereas upland rice experiences periods of unsaturated soil.

Traditionally, rice is grown under flooded-soil conditions, with the majority of production coming from the lowland-rice cultural practice. The purpose of flooding is to inhibit weed growth, to aid in the uptake of N, and to dilute the salt concentration in the soil. However, continuing rice production under flooded conditions is not sustainable. More than 90% of global rice is irrigated or rainfed lowland rice (Maclean et al., 2013). In some cases, groundwater needed for irrigation is not being renewed at an equal rate as application, resulting in aquifer levels declining. Arkansas is the fourth largest user of ground water in the US and withdrawals from the Mississippi River Valley Alluvial Aquifer have caused cones of depression up to 30m deep (USGS, 2005). Droughts in some historically rainfed regions have led to parched soils and decreased crop yields. In addition, the flooded conditions of rice production create an anaerobic environment, from which methane (CH_4) is abundantly produced and emitted.

Methane is the primary GHG released during rice production under saturated, flooded-soil conditions. While ebullition and diffusion through the water column can be mechanisms of CH_4 release from the soil to the atmosphere, more than 90% of CH_4 emissions from a rice field occur through the rice plants themselves by transport through the aerenchyma tissue of the rice stems (Neue, 1993; Peyron et al., 2016; Rosenberry et al., 2003). The plant-mediated transport is the reason that rice is the leading CH_4-producing cereal crop. Paddy rice cultivation accounts for 9 to 11% of agricultural CH_4 production globally and CH_4 emissions from rice cultivation are predicted to increase 2% by 2030 (EPA, 2012; IPCC, 2014).

Due to the unsustainable nature of current water management practices for rice production, the large production of CH_4 from flooded rice systems, and the large demand for rice in human diets, alternative rice production systems are being investigated to replace the traditional, full-season-flood production system. Delayed flood, mid-season aeration, alternate wetting and drying, and, more recently, furrow irrigation (i.e., row rice) are a few of the alternative rice production systems that could potentially replace traditional flooding. The majority of rice grown in Arkansas is delayed flood. For delayed flood rice production in Arkansas, 85% of rice is direct-seeded and the field is flooded once the rice plants reach the 4- to 5-leaf stage (UA-DA-CES, 2019). The flood is maintained on the field for the rest of the growing season until the field is drained to prepare for harvest, about two weeks prior to harvest. Mid-season aeration involves draining the flooded field around mid- to late-tillering and allowing the soil to re-aerate over 10 to 14 days (Troldahl and Fowler, 2016). Alternate wetting and drying consists of cycles between flooding a zero-grade field to a depth of 10 to 25 cm (4 to 10 in) and then letting the ponded water retreat to the soil surface through infiltration and/or evapotranspiration (UA-DA-CES, 2019). Furrow-irrigated rice does not utilize flooding in the field, but instead involves planting rice in rows on a slightly inclined, raised-bed field to allow irrigation water to overlap the top of the beds and gravity flow in the furrows down the length of the field.

The development and testing of new production systems will bring a new set of challenges. The main environmental goals for the future of rice production include increasing water-use efficiency, while maintaining yields and decreasing CH_4 and N_2O emissions, thus decreasing the overall GWP of rice production systems. In the case of the alternative production methods, less water is applied during the growing season, such that the rice is not under a continuous flood. Research has shown decreased CH_4 emissions from rice grown in unsaturated field conditions, verifying the fact that the methanogenic process is favored by anaerobic environments and disfavored by oxidizing conditions (Peyron et al., 2016). However, the relationships among soil water content and production of CH_4 and N_2O are complex. While tackling the goal of better water-use efficiency and reducing CH_4 emissions, studies have shown that introducing aeration to the soil, by means of periodic wet and dry cycles, may stimulate N_2O production, thus increase N_2O emissions over what is produced and emitted from the full-season-flood system.

Nitrogen Cycle in Rice

Additions

Nitrogen is one of the most difficult elements to manage in agricultural systems due to the various oxidation states that N can possess and the necessity of N as a macronutrient for plants and other organisms. Additions of N to rice fields include biological N_2 fixation, decomposing organic matter, and N fertilizers. In Arkansas, many rice producers practice rotational cropping between rice one year and soybean (*Glycine max*) the next year. The leguminous soybean plant increases soil-test N. As organic matter decomposes, as facilitated by soil microbes, organic N is added to the soil system. The magnitude of N addition from organic matter into an agricultural system via decomposition ranges widely based on vegetation, temperature, soil water content, soil health, and tillage practice. Nitrogen fertilizer amendments to the soil are common in rice, where the amount and type of fertilizer applied varies depending on the specific cultivar type (i.e., pureline or hybrid), soil texture (i.e., loamy or clayey), precipitation, cultural practice, the presence of existing soil organic matter (SOM), and whether the organic matter has been incorporated (i.e., tilled) into the soil.

Removals

Various forms of N can be lost in rice cultivation, including NH_3 volatilization, NO_3^- leaching/runoff from the soil, harvested biomass, and N gases produced by denitrification. In traditional paddy rice cultivation, N loss can be minimal if the soil is properly managed, but there are many points in the N cycle that can be compromised. A common N fertilizer used in Arkansas rice production is urea (46-0-0). However, if not applied properly, the urea provides a substrate (NH_4^+) for gaseous N loss by NH_3 volatilization. Previous studies report N losses from rice paddies to range from10 to 60% from NH_3 volatilization alone (Xu et al., 2012). Fertilizers containing NO_3^- are typically avoided in flooded rice systems because NO_3^- is easily leached from the soil due to its negative charge, which will not adsorb to the negatively charged clay particles, and nitrate's solubility in water (Brady and Weil, 2008). During the vegetative stages of the rice growing season, N is taken up by the plant roots in the form of NO_3^- and NH_4^+. The Nthat ends up in the plant is used in many important plant components and processes, including amino acids, nucleic acids, chlorophyll, and plumpness of cereal grains (Brady and Weil, 2008). Once harvested, plant N, particularly in the grain, is also removed from the field, potentially leading to N-deficient soil if not replenished. The lack of oxygen in the soil during continuous flood irrigation reduces the nitrification/denitrification process, therefore decreasing N loss in theform of N_2O. In furrow-irrigation, re-introducing oxygen to the system periodically induces the nitrification/denitrification process. The fluctuating wet and dry cycles do not allow for completion of the cycle, resulting in the release of N_2O.

Transformations

As N is added to the soil, various processes take place that may dictate where the N goes. A common transformation in rice is the hydrolysis of NH_4^+ to NH_3 through volatilization. Urea, a common N fertilizer for rice, contains NH_4^+ and, if added to rice with a flood on, most of the NH_4^+ will hydrolyze into NH_3 gas.

The processes of mineralization and immobilization are other common forms of N transformations in the soil. Soil microbes are capable of decomposing N-containing organic compounds, such as amine groups, and transforming the N into inorganic, plant-available N forms, such as NH_4^+ and NO_3^-. Conversely, when inorganic forms of N are taken up by plants and soil microbes, those forms of N become incorporated into the matrix of living tissue and thereby transform into immobile, organic forms of N.

The processes of nitrification and denitrification in the soil can facilitate further N transformations. During nitrification, NH_4^+ is transformed to NO_3^- during a two-step process that utilizes aerobic, autotrophic bacteria and/or archaea. Denitrification relies on anaerobic, heterotrophic bacteria that reduce NO_3^- to various gases, such as NO, N_2O, and N_2, depending how complete the nitrification process proceeds.

Transports

Nitrogen is very dynamic in the soil environment, constantly moving and/or changing through the soil system. A major N transport medium is soil water. Both NH_4^+ and NO_3^- are soluble in water, therefore these ions percolate through the soil along with the water. Sometimes, when precipitation or irrigation becomes excessive, water drains to the groundwater or runs off of the field, carrying soluble nutrients along with the water. However, the dissolved ions are also able to be easily taken up by plants. Nitrogen gases can also be present in the water and are subject to transport. Another N transport mechanism in soil involves the abiotic fixation of NH_4^+ to the negative outer layers of clay particles. Once adsorbed to the surface of clays, NH_4^+ ions become stable and are transported during pedogenic processes, such as clay translocation (i.e., illuviation). The soil column is also a mode of transport for gaseous forms of N. The air-filled pore space in the soil column provides channels through the soil matrix from which N-containing gases can travel and potentially reach the atmosphere. The rhizosphere, where the root zone interacts with the soil, allows an interface for plants to obtain N from the soil.

N_2O Emissions from Rice

Gas Diffusion

The diffusion of N_2O in a rice field is a natural process driven by the concentration gradient between N_2O concentrations in the soil and in the atmosphere. As N_2O is produced in the soil, the concentration of N_2O increases. In order to establish an equilibrium between the soil-air interface, the gas diffuses through the soil, where there is a greater concentration, to the immediate atmosphere, where there is a lower concentration, or vice versa if the N_2O concentration is greater in the atmosphere than in the soil. In flooded rice, not only do the anaerobic conditions limit N_2O production, but the presence of standing water also decelerates the diffusion process (Simmonds et al., 2015). In furrow-irrigated systems, more N_2O is produced due to the incomplete denitrification from alternating wet and dry cycles and there are moments where the soil-air interface is available for diffusion to occur more rapidly. Thus, gas diffusion of N_2O under furrow-irrigation is the most prevalent mechanism in which N_2O emissions are released into the atmosphere.

Tillage

In Arkansas, approximately 60% of rice is conventionally tilled (CT) with the remaining rice produced using stale-seedbed (30.1%) or no-tillage (6%; NT) systems (Hardke, 2016). Conventional tillage is achieved by incorporating the previous growing season's stubble into the soil often using multiple passes over the same area with rollers, field cultivators, and disks (UA-DA-CES, 2019). In so doing, the top 10 to 15 cm of soil is disturbed, thus severely disrupting soil aggregates, soil macroporosity, microbial communities, organic matter, and soil nutrients. The organic matter from the incorporated crop residues serve as sources of nutrients for the up-coming rice crop and the disrupted seed bed allows for easier planting. However, NT management for rice in Arkansas is increasing due to the previously reported reduced labor cost, better long-term aggregate stability, sustained soil structure, and decreased methane emissions (Ahmad et al., 2009; Chatskikh and Olesen, 2007; Humphreys, 2018; Rector et al., 2018; Zhang et al., 2013). No-tillage involves keeping the previous season's stubble intact during the current growing season. Consequently, there is a slower release of nutrients from the crop residues and often greater water-holding capacity compared to CT (Six et al., 2002).

In both flooded-rice and in row-crop systems [i.e., corn (*Zea mays*), barley (*Hordeum vulgare*), soybean (*Glycine max*), and wheat (*Triticum*)], the effect of tillage treatment on N_2O emissions is indeterminate (Ahmad et al., 2009; Chatskikh and Olesen, 2007; Venterea et al., 2005; Zhang et al., 2013). Venterea et al. (2005) conducted a study in 2003 and 2004 evaluating tillage and fertilizer effects on N_2O and CH_4 emissions in row crops on a silt-loam soil (fine-silty over skeletal mixed, super-active, mesic Typic Hapludoll) in Rosemount, MN. The study resulted in greater N_2O emissions in the NT systems compared to CT when broadcast-fertilized with urea. However, N_2O emissions were greater in the CT when fertilized with anhydrous ammonia and no difference in emissions occurred with respect to tillage when fertilized with urea ammonium nitrate (Venterea et al., 2005). Chatskikh and Olesen conducted a study in 2004 evaluating tillage effects on CO_2 and N_2O emissions from barley grown in a loamy sand (Typic Hapludult) in Denmark. The study reported greater N_2O emissions from the CT system compared to a reduced-tillage system (Chatskikh and Olesen, 2007). In contrast, a study conducted in 2004 investigating the impact of N placement and tillage on NO, N_2O, CH_4, and CO_2 fluxes from corn on a clay loam (fine-loamy, mixed, super-active, mesic Aridic Haplustalf) in northeastern Colorado reported greater N_2O emissions in the NT system compared to the CT system (Liu et al., 2005).

Regarding rice production systems, Ahmad et al. (2009) conducted a study in 2008 evaluating tillage effects on GHG emissions in a direct-seeded rice paddy field in central China. The study included four tillage treatments: no-tillage without fertilizer, conventional tillage without fertilizer, no-tillage with compound fertilizer, and conventional tillage with compound fertilizer and reported no difference in N_2O emissions between tillage treatments (Ahmad et al., 2009). Another study, conducted in southern China between 2005 and 2008, evaluated tillage effects on CH_4 and N_2O emissions in a double-cropped paddy field (Zhang et al., 2013). The study reported large variations in N_2O emissions from NT compared to CT; however, the mean GWP from N_2O emissions was lower for NT compared to CT (Zhang et al., 2013). Rector et al. conducted a study in eastern Arkansas evaluating tillage and fertilizer effects on N_2O emissions in a delayed-flood rice production system on a silt-loam soil (Typic Albaqualf). Similar to result of Ahmad et al. (2009), Rector et al. (2018) reported no difference in N_2O emissions between NT and CT. However, there is no known research on N_2O fluxes and emissions with respect to tillage practice from a FI-rice-production system.

Nitrogen Fertilization

The three most recommended N-fertilizers in Arkansas for rice production are ammonium sulfate [$(NH_4)_2SO_4$], urea, and N-(n-butyl) thiophosphoric triamide (NBPT)-coated urea (UA-DA-CES, 2019). The choice of fertilizer depends on many environmental factors involved in a particular growing season, such as water management, cultivar, and soil physical and chemical properties. Ammonium is the preferred N-containing molecule for rice fertilization because NO_3^- is easily leached, or lost through denitrification, from flooded or frequently irrigated systems. Though the least recommended of the three, $(NH_4)_2SO_4$ is most often used in fields that have low amounts of sulfur (S), like sandy soils (UA-DA-CES, 2019).

Urea is the most common N-fertilizer used in Arkansas due to the large N concentration and lower cost compared to the other N fertilizers (UA-DA-CES, 2019). However, a drawback to urea is the potential for large NH_3 volatilization losses if not properly managed (UA-DA-CES, 2019). If urea is not incorporated into the soil via tillage or irrigation, urease, an enzyme present in the soil, will break down the urea too quickly and release NH_3 (Rogers, 2014). Typically, urea is used in flooded production systems. Urea is highly soluble and volatilizable and should be applied to a dry soil surface. The field is then flooded to allow the urea to incorporate into the soil through infiltration, and thus, regulate volatilization losses (Rogers, 2014).

For alternative rice production systems like furrow-irrigation, NBPT-coated urea is preferred (UA-DA-CES, 2019). Although more costly compared to uncoated urea, NBPT-coated urea, with the aid of a urease inhibitor, is able to retard the breakdown of urea until the fertilizer can be incorporated into the soil, while still being able to provide the same N concentration as uncoated urea (UA-DA-CES, 2019). Rector et al. (2018) reported no difference in N_2O emissions from a full-season flood rice production system on a silt-loam soil in eastern Arkansas under different tillage (conventional tillage and no-tillage) and fertilizer (NBPT-coated and uncoated urea) treatments. However, the effect of NBPT-coated urea on N_2O emissions in furrow-irrigated rice has yet to be investigated.

In addition to N-fertilizer source, the relationship between fertilizer application time on N_2O emissions in rice has also been evaluated, but the results are still unclear, especially with respect to furrow-irrigation (Feng et al., 2018). In a comparative meta-analysis of 49 studies conducted in seven countries (i.e., USA, Mexico, Brazil, Philippines, China, Japan, and Spain), a split N application did not affect N_2O emissions in upland and lowland rice production systems regardless of the management practices (i.e., crop-rotation, residue management, irrigation, and tillage duration; Feng et al., 2018).

Water Management Systems

The production and release of N_2O are heavily influenced by the soil water content and the chosen irrigation practice. A known benefit of flood-irrigation is decreased N_2O emissions due to the extended anaerobic conditions that disrupt the nitrification/denitrification processes. In contrast, alternate wetting and drying and mid-season aeration generally have greater N_2O emissions because of the reintroduced oxygen to the soil during the growing season (Peyron et al., 2016). A study conducted in 2014 at an experimental farm in Hubei Province, China compared GHG emissions from rice grown in a continuous flood to that of flooded-and-dry-intermittent irrigation (FDI; Xu et al., 2014). While the rice under FDI conditions had a 104% increase in N_2O emissions, the overall GWP decreased 29% compared to continuous flood (Xu et al., 2014). A 2012-2013 study at the Italian Rice Research Centre in Castello d’Agogna also reported greater N_2O emissions from intermittent-flood irrigation than continuous flood, but the

GWP of the intermittent-flood irrigation decreased 73 to 90% compared to continuous flood (Peyron et al., 2016).

<u>Furrow-irrigation</u>

Furrow irrigation is an irrigation style that includes shallow raised beds and furrows on a slightly sloping field. Irrigation water is presented upslope and is allowed to flow horizontally and vertically down the field furrows by gravity. Not uncommonly, the down slope portion of the field can contain a tail levee to retain any tail water that is collected at the end of the field. Not until the last few years has furrow-irrigation become a viable option for rice production. Although furrow-irrigation is commonly used to grow corn, soybean, and cotton (*Gossypium*), several early studies showed that furrow-irrigation for rice production was problematic. In the 1990's and early 2000's, grain yields from furrow-irrigated rice were significantly lower than yields from traditional flooding (Borell et al., 1997; Ockerby and Fukai, 2001; Kukal et al., 2005). The decrease in yields was attributed to the lack of weed suppression from a permanent flood and rice cultivars that could not sustain aerobic or semi-aerobic conditions. However, in the last decade, new drought and herbicide-resistant hybrid cultivars have been created and have shown to be a promising alternative to traditional flooding (Bryant et al., 2010; Kandpal and Henry, 2017; Xu et al., 2014). He (2010) and Abdallah et al. (2018) both reported greater grain yield in furrow-irrigated rice production systems than in traditional flooding. Even studies reporting lower yields from furrow-irrigation still had no significant difference in yield between the two production systems (Bagavathiannan, 2011).

Furrow-irrigated rice is a relatively new practice in Arkansas with 47,753 ha (118,000 acres), approximately 10.5%, of furrow-irrigated rice grown in Arkansas in 2019 (Hardke, 2020).

Recent developments in hybrid rice cultivars have generated new drought-tolerant varieties that can withstand alternative irrigation methods without compromising yield. At present, furrow-irrigation in Arkansas is used on severely sloping land and soil with high leaching potentials where levees, which are constructed to contain the flood water under the flooded-rice production practices, are not as practical. Beginning in 2020, congress allowed for insurance coverage for furrow-irrigated rice thus promoting the increase in furrow-irrigated rice production (Hardke, 2020). Although furrow-irrigated rice faces new challenges, the paramount benefits of furrow-irrigation including increased water use efficiency and reduced labor and maintenance costs are motivating factors for furrow-irrigation to be an alternative rice production system (Hefner and Tracy, 1991; Henry et al., 2020a,b).

Della Lunga (2020) reported on correlations between environmental factors (i.e., soil volumetric water content, soil temperature, and oxidation-reduction potential) and weekly GHG fluxes (i.e., N_2O, CH_4, and CO_2) and between various initial soil properties and season-long GHG emissions measured over two consecutive growing seasons from furrow-irrigated rice on a silt-loam soil (Typic Albaqualf) in east-central Arkansas. However, environmental impacts of furrow-irrigated rice have yet to be fully investigated.

Weeds

A common drawback presented with furrow-irrigation is the lack of weed suppression. Weed control is a known benefit of traditional flooding because the ponded water prevents most terrestrial weed growth. While aquatic weed control becomes obsolete in roughly two-thirds of a furrow-irrigated rice field, studies show an increase in grass and broadleaf weed control under furrow-irrigation compared to flooded-rice production (Bagavathiannan et al., 2011; Gealy et al., 2014; UA-DA-CES, 2019). Common weeds that emerge in furrow-irrigation rice include palmer amaranth (*Amaranthus palmeri*), pitted morningglory (*Ipomoea lacunosa*), barnyardgrass (*Echinochloa crus-galli*), and broadleaf signalgrass (*Urochloa platyphylla*; Norsworthy et al., 2008). Although there are no certified weed treatments for rice under furrow-irrigation in Arkansas yet, it is recommended to make multiple, residual herbicide applications later in the growing season (UA-DA-CES, 2019).

The stale-seed-bed technique has also shown some promise as an additional form of weed suppression for FI (Safdar et al., 2011). The stale-seed-bed technique involves tilling and/or irrigating the field before the growing season begins, often the previous fall after harvesting the previous year's crop, to induce weed growth. Once the weeds emerge, a subsequent herbicide application is made prior to seeding (Rathore et al., 2013).

Water-use efficiency

One major benefit of furrow-irrigation is increased water-use efficiency (WUE). Most studies show a substantial increase in WUE in furrow-irrigated rice compared to flooded rice (Abdallah et al., 2018; Bouman et al., 2005; He, 2010; Bagavathiannan et al., 2011). In 2003, 22 million ha of dry-season-irrigated rice in south and south-east Asia already fell in the 'economic water scarcity zone' and groundwater tables dropped on average 1 to 3 m yr^{-1} (3.3 to 10 ft yr^{-1}) in the North China Plain and 0.5 to 0.7 m yr^{-1} (1.6 to 2.3 ft yr^{-1}) in parts of India. By the year 2025, it is predicted that 13 million ha of wet-season-irrigated rice will experience physical water scarcity globally (Tuong and Bouman, 2003). In Arkansas, approximately 83% of rice fields rely on groundwater or aquifers for irrigation and the annual decline of the Mississippi Alluvial

Aquifer is estimated to be 0.15 m yr^{-1} (0.5 ft yr^{-1}; USGS, 2010). Consequently, farmers are looking for alternative irrigation styles that will not compromise yield.

Justification

The lack of research conducted on N_2O emissions from furrow-irrigated rice production needs to be addressed. Ample research on other alternative rice-irrigation techniques has been conducted, but the potential for decreased GWP, cheaper labor costs, and water conservation using furrow-irrigation could be beneficial to the anticipated areas of expanded rice production that will be needed to feed the predicted, future population growth.

Objective and Hypotheses

The overall goal of this study was to quantify N_2O emissions from furrow-irrigated rice production. The specific objectives of this study were i) to evaluate the effects of site position (i.e., up-slope, mid-slope, and down-slope) and tillage treatment [i.e., conventional tillage (CT) and no-tillage NT)] on N_2O fluxes and season-long emissions in the field from a furrow-irrigated rice production system on a silt-loam soil in east-central Arkansas, and ii) to evaluate the effects of N-fertilization amount and timing [i.e., 100% of the early season optimum N rate plus one split application (optimum plus one split, OPOS), 50% of the early season optimum N rate plus two split applications (half optimum plus two splits, HOPTS), 100% of the early season plus two split applications (optimum plus two splits, OPTS), and an unamended control (UC)] on N_2O fluxes and season-long emissions and plant response from a silt-loam soil in a greenhouse trial simulating a furrow-irrigated rice production system.

For Objective 1, it was hypothesized that season-long N_2O emissions will be greater from NT and from the up- and mid-slope positions of the field than from CT and the down-slope position, respectively. The likely greater soil C content under NT will induce greater microbial activity, thus producing more N_2O. The up- and mid-slope positions are subjected to frequently alternating aerobic and anaerobic conditions, driving the processes of nitrification and denitrification and releasing more N_2O than the often purely anaerobic down-slope position.

For Objective 2, it was hypothesized that i) treatments receiving 100% of the early season optimum application (OPOS and OPTS) will have earlier peak N_2O fluxes than when half of the early season optimum is applied (HOPTS), ii) greater N_2O emissions will come from the two-split treatments (HOPTS and OPTS) due to the greater frequency of N substrate input to induce nitrification followed by denitrification, and iii) plants under the two-split treatments will have greater total N uptake in the plant tissue due to the greater frequency of N substrate during the vegetative phase, but plants under OPOS and HOPTS will have greater grain-N uptake due to the greater amount of N added during the last fertilizer application.

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Chapter 2

Site position and tillage treatment effects on nitrous oxide emissions from furrow-irrigated rice on a silt-loam soil

Abstract

The development of drought-resistant hybrid rice (*Oryza sativa*) cultivars has allowed furrow-irrigated rice production systems to become an increasingly popular alternative to traditional flood-irrigation. However, potential environmental implications, such as greenhouse gas emissions, specifically nitrous oxide (N_2O), have yet to be evaluated. The objective of this study was to evaluate the effects of site position (i.e., up-, mid-, and down-slope) and tillage treatment [i.e., conventional tillage (CT) and no-tillage (NT)] on N_2O fluxes and season-long emissions from a furrow-irrigated rice field on a silt-loam soil (Typic Albaqualfs) in east-central Arkansas. Gas collection from closed-chambers occurred weekly over the 2018 and 2019 growing seasons. Nitrous oxide fluxes differed ($P < 0.001$) among site position-tillage treatment combinations in both the 2018 and 2019 growing seasons. In 2018, numeric flux maxima for all site position-tillage treatment combinations occurred at 33 days after planting (DAP). In 2018, N_2O emissions differed ($P < 0.1$) among site positions and differed between tillage treatments, while 2019 emissions differed ($P < 0.1$) only between tillage treatments. Nitrous oxide emissions in 2018 were greatest at the down-slope (3.34 kg N_2O ha^{-1} season^{-1}) compared to both the mid- (2.78 kg N_2O ha^{-1} season^{-1}) and up-slope (2.74 kg N_2O ha^{-1} season^{-1}), which did not differ. For both growing seasons, CT produced greater ($P < 0.1$) N_2O emissions than NT, where mean annual emissions from CT were 3.15 and 2.58 kg N_2O ha^{-1} season^{-1} for the 2018 and 2019 seasons, respectively. The evaluation of N_2O fluxes and emissions from furrow-irrigated rice is essential to understanding the potential environmental impacts of furrow-irrigation as an alternative water management scheme for rice production.

Introduction

The demand for rice (*Oryza sativa*), a staple food for millions of humans globally, is projected to increase in direct correlation with the population increase of developing countries that rely on rice, which will account for 83% of the world population by 2028 (USDA, 2019). Within the United States (US), rice production occurs primarily in six states, Arkansas, California, Louisiana, Missouri, Texas, and Mississippi, with Arkansas being the largest rice-producing state in the US (USDA-ERS, 2020). In 2019, Arkansas harvested 455,676 ha of rice, which constituted about 46% of the total rice production in the US (USDA-ERS, 2020). Historically, rice has been grown under flooded-soil conditions in Arkansas, where the purpose of flooding is to inhibit weed growth and aid in N uptake. However, continuing rice production under flooded conditions is likely not sustainable due to the large freshwater demand. Arkansas is the fourth largest user of groundwater in the US, where ~ 83% of rice fields rely on groundwater aquifers for irrigation and the annual decline of the Mississippi Alluvial Aquifer is estimated to be 0.15 m yr^{-1} (USGS, 2010). In addition, the flooded conditions of rice production create an anaerobic soil environment, from which methane (CH_4) is abundantly produced and emitted. Consequently, CH_4 is the primary greenhouse gas (GHG) released from flood-irrigated rice production, CH_4 is ~ 30 times more potent than carbon dioxide (CO_2; EPA, 2021). Flood-irrigated (i.e., paddy) rice cultivation only accounts for 9 to 11% of agricultural CH_4 production globally, whereas CH_4 emissions from rice cultivation are predicted to increase 2% by 2030 (EPA, 2012; IPCC, 2014).

Due to the unsustainable nature of current water management practices for flood-irrigated rice production, the large production of CH_4 from flooded rice systems, and the large demand for rice in human diets, alternative rice production systems have been developed as options to the traditional, full-season-flood production system. Delayed flood, mid-season aeration, alternate wetting and drying, and, more recently, furrow irrigation (i.e., row rice) are a few of the alternative water management schemes for rice production that could potentially replace traditional full-season-flood irrigation. In Arkansas, the majority of rice is grown using the delayed flood system, in which 85% of rice is direct-seeded and the field is flooded once the rice plants reach the 4- to 5-leaf stage (UA-DA-CES, 2019). The flood is maintained on the field for the rest of the growing season (~ 3 months) until the field is drained about two weeks prior to harvest. Furrow-irrigated rice is gaining in popularity in Arkansas and elsewhere and does not utilize flooding in the field, but instead involves planting rice in rows on raised beds to allow irrigation water to overlap the top of the beds and flow in the furrows down the length of the field via gravity. Drought-resistant hybrid rice cultivars have been developed to withstand alternative water management schemes and have been shown to perform better under furrow-irrigation than pure-line varieties (Kandpal et al., 2016; Kandpal and Henry, 2017). While improving water-use efficiency and reducing CH_4 emissions, studies have shown that introducing a greater frequency of soil aeration events to the soil, by means of periodic wet and dry cycles, may stimulate greater N_2O production, thus increasing N_2O emissions over what is typically produced and emitted from the full-season-flood system. The concern lies in the potency of N_2O as a GHG, which is ~300 times more potent than CO_2 and ~ 10 times more potent than CH_4.

In addition to delayed flood water management, approximately 60% of rice grown in Arkansas is conventionally tilled (CT), with the remaining rice produced using a stale-seedbed (30.1%) or no-tillage (6%; NT) approach (Hardke, 2016). Conventional tillage is typically achieved by incorporating the previous growing season's stubble into the soil, often using multiple passes over the same area with rollers, field cultivators, and disks (UA-DA-CES, 2019). However, NT management for rice in Arkansas is increasing due to the previously reported reduced labor cost, increased long-term soil aggregate stability, sustained soil structure, and decreased CH_4 emissions (Ahmad et al., 2009; Chatskikh and Olesen, 2007; Humphreys et al., 2018b; Zhang et al., 2013). No-tillage management typically involves keeping the previous season's stubble intact during the subsequent growing season. Consequently, there is a slower release of nutrients, including potentially reducible carbon (C) and denitrifiable N, from the crop residues and often greater water-holding capacity compared to CT (Six et al., 2002).

In both lowland flooded-rice and upland row-crop systems [i.e., corn (*Zea mays*), barley (*Hordeum vulgare*), soybean (*Glycine max*), and wheat (*Triticum aestivum*)], the effect of tillage treatment on N_2O emissions has been inconclusive (Ahmad et al., 2009; Chatskikh and Olesen, 2007; Venterea et al., 2005; Zhang et al., 2013). Ahmad et al. (2009) conducted a study in 2008 evaluating tillage effects on GHG emissions in a direct-seeded rice paddy in central China. The study included four tillage treatments, NT without fertilizer, CT without fertilizer, NT with compound fertilizer, and CT with compound fertilizer, and reported no difference in N_2O emissions between tillage treatments (Ahmad et al., 2009). Another study, conducted in southern China between 2005 and 2008, evaluated tillage effects on CH_4 and N_2O emissions in a double-cropped paddy rice field (Zhang et al., 2013). The study reported large variations in N_2O emissions from NT compared to CT; however, the mean global warming potential (GWP) from N_2O emissions was lower for NT compared to CT (Zhang et al., 2013). Rector et al. (2018b) conducted a study in east-central Arkansas evaluating tillage and fertilizer-N effects on N_2O emissions from delayed flood rice production on a silt-loam soil (Typic Albaqualf). Similar to result of Ahmad et al. (2009), Rector et al. (2018b) reported no difference in N_2O emissions between NT and CT. However, to our knowledge, no research has been conducted on N_2O fluxes and emissions with respect to tillage practice from furrow-irrigated rice production.

The lack of research on the potential environmental consequences, namely N_2O emissions, from furrow-irrigated rice production needs to be addressed in areas of concentrated production. Ample research on alternative irrigation techniques has been conducted, but the potential for decreased GWP, cheaper labor costs, and water conservation using furrow-irrigation could be beneficial to the anticipated areas of expanded rice production that will be needed to feed the predicted, future population growth. The objective of this field study was to evaluate the effects of site position (i.e., up-, mid-, and down-slope) and tillage treatment [i.e., conventional tillage (CT) and no-tillage NT)] on N_2O fluxes and season-long emissions from a FI rice production system on a silt-loam soil in east-central Arkansas. The up- and mid-slope positions are subjected to frequently alternating aerobic and anaerobic conditions, driving the processes of nitrification and denitrification and releasing more N_2O than the often purely anaerobic down-slope position (Della Lunga et al., 2020). Therefore, it was hypothesized that N_2O fluxes will be unaffected by tillage treatment, but that greater fluxes will occur from the up- and mid-slope positions than from the down-slope position. It was also hypothesized that season-long N_2O emissions will be greater from NT and from the up- and mid-slope positions than from CT and the down-slope position, respectively, due to greater near-surface soil C content under NT (Della Lunga et al., 2021a) likely simulating greater microbial activity, thus resulting in greater N_2O production.

Materials and Methods

Site Description

Research was conducted at the University of Arkansas Rice Research and Extension Center (RREC) in Arkansas County near Stuttgart, AR (34.46°N, -91.46°W) between May and September 2018 and 2019. The study area was mapped as a Dewitt silt loam (fine, smectitic, thermic Typic Albaqualfs; USDA-NRCS, 2014) derived from silty alluvium from the Mississippi River (USDA-NRCS, 2019). Dewitt soils are located on Arkansas' Grand Prairie as part of the terraces from the Lower Mississippi Valley. The Dewitt silt loam has a typical profile horizon sequence of Ap-Eg1-Eg2-Btg1-Btg2-Btg3-Btg4 (USDA-NRCS, 2014). The Dewitt silt loam series is conducive to rice production due to low concentrations of salts, limited internal drainage, large water-holding capacity, and a slope between 0 and 1% (USDA-NRCS, 2019). The low-grade slope, coupled with flood irrigation, leads to saturated soil conditions that are not prone to runoff. The large clay content, roughly 32.2% based on a weighted average of the top 2 m of soil, provides for the limited internal drainage and the large water-holding capacity characteristics of the Dewitt series (USDA-NRCS, 2019).

The 30-year mean annual minimum and maximum air temperatures for the study area, based on the 1981 to 2010 climate normals, are 10.5°C and 16.5°C, respectively (NCDC, 2019). The 30-year mean annual precipitation for the study area is 125.6 cm (49.4 in; NCDC, 2019).

Treatments and Experimental Design

The study area was approximately 400 m long and 12 m wide, with an average slope of 2% in the north-south direction, which was part of a 16.2-ha field that has been managed under furrow-irrigated rice production for at least the last six years. Three site positions, up-, mid-, and down-slope, were established along the 400-m length of the study area. The up-slope position was located 91 m from the highest-elevation end of the field. The mid-slope position was located 91 m down-slope from the up-slope position, while the down-slope position was 240 m down-slope from the mid-slope position and 9 m from the lowest-elevation end of the field. The slope between the up- and mid-slope positions was ~ 2.5% and was ~ 1.8% between the mid- and down-slope positions. In addition to the three site positions, the 12-m width of the study area was divided into two tillage strips, CT and NT, to constitute a split-strip-plot experimental design (Figure 1).

Within each tillage treatment, there were six raised beds for a total of 12 raised beds spanning the long length of the study area. Six gas sampling chambers were installed at each site position. Chambers were installed atop alternating raised beds so that both tillage treatment areas at each site position contained three gas sampling chambers. Thus, six treatment combinations were established with three replicates of each (i.e., CT/up-slope, CT/mid-slope, CT/down-slope, NT/up-slope, NT/mid-slope, and NT/down-slope) for a total of 18 experimental units (Figure 1). Within the study area, the distances between the centers of the raised beds, the planted rice rows, and between the rice plants themselves were 76 cm, 19.5 cm, and 9 cm, respectively. Each raised bed was approximately 15 cm in height by 30 cm in width across the flattened bed top.

Study Area Management

2018

On May 5, 2018, a 6-m wide strip, constituting half of the study area, was conventionally tilled along the long length of the study area. The field was disked twice to a depth of 15 to 20 cm. A field cultivator was used once to a depth of 10 to 15 cm to break up soil clods. An ~ 76-cm-row-spaced bedder roller was used once to prepare and flatten the tops of the raised beds. The other half of the study area was left untilled and was passed once with a NT furrow-runner implement (Perkins Sales Inc., Bernie, MO) so that the prior years' beds were left intact, but the furrows between the beds were cleaned out.

On May 17, 2018, the study area was direct-seeded to non-flooded soil with the hybrid cultivar 'CL7311' (RiceTec, Inc., Alvin, TX) at a rate of 28 kg seed ha^{-1} and 19 cm row spacing. The study area was broadcast-amended with 101 kg ha^{-1} of potassium (K) as muriate of potash and 67 kg ha^{-1} of phosphorus (P) as diammonium phosphate on June 5, 2018. On June 13, 2018, the study area was broadcast-amended with 168 kg ha^{-1} of N as N-(n-butyl) thiophosphoric triamide (NBPT)-coated urea (46% N).

Weeds were carefully controlled throughout the study area. On May 18, 2018, the study area was treated with an herbicide solution containing 2.3 L glyphosate (Roundup), 0.59 L clomazone (Command), 0.05 L imazosulfuron (League), and 0.05 L safufenacil (Sharpen) per hectare that was ground-sprayed at a rate of 93 L ha^{-1}. On June 11, 2018, the study area was ground-sprayed with a solution composed of 2.7 L of thibencarb (Ricebeux) and 0.02 L of halosulfuron (PermitPlus) per hectare at a rate of 75 L ha^{-1}. On June 19, 2018, the study area was sprayed via airplane with 0.49 L of fenoxaprop (Ricestar) and 0.94 L of pendimethalin (Prowl) per hectare at a rate of 187 L ha^{-1}. On June 28, 2018, a treatment of 0.49 L of cyhalofop (Clincher) and 0.62 L of quinclorac (Facet) per hectare were sprayed via airplane at a rate of 187 L ha^{-1}. On July 2, 2018, the study area was sprayed via airplane with a solution composed of 0.59 L ha^{-1} cyhalopfop (Clincher) at a rate of 187 L ha^{-1}. On both July 10 and July 11, 2018, 0.15 L ha^{-1} of imazamox (Beyond) were applied via airplane at a rate of 187 L ha^{-1}. Lastly, on August 27, 2018, the study area was sprayed via airplane with 0.12 L ha^{-1} pirethrid (Mustang Max) at a rate of 187 L ha^{-1}.

The study area was furrow-irrigated approximately once a week from June 5 to September 12, 2018. A 30-cm-diameter, lay-flat polyethylene pipe (i.e., poly pipe) delivered water from the high-elevation end of the field, down each furrow from a rain-fed, surface reservoir adjacent to the study area. Once the water reached the down-slope position, a variable-flow, tailwater-recovery pump at the down-slope position recirculated water back to the high-elevation end of the field by means of a surface pipe that ran the length of the study area (Kandpal, 2018). This type of furrow-irrigation system, where water was continuously recirculated from the low- to the high-end of the field, differed from a typical furrow-irrigated field that a producer would manage. More commonly, furrow-irrigation would be sourced from a groundwater riser and the tail water would be stored in the field itself by establishing levees at the down-slope end of the field such that excess furrow-irrigation water would pond at the down-slope end of the field.

2019

Field management practices in 2019 were similar to those in 2018. Between April 16 and April 20, 2019, half of the study area was conventionally tilled in the same manner as in 2018. The other half of the study area was again left intact and passed with a NT furrow-runner implement to constitute the NT section of the field.

On April 30, 2019, the study area was direct-seeded to a non-flooded soil with the hybrid rice cultivar '214-Gemini' (RiceTec, Inc., Alvin, TX) at a rate of 21 kg seed ha^{-1} and 19 cm row spacing. On May 16, 2019, the field was broadcast-amended with 67 kg ha^{-1} of K as muriate of potash, 67 kg ha^{-1} of P as triple superphosphate, 11 kg ha^{-1} of zinc (Zn) as Zinc 20, and 23 kg ha^{-1} of N and 27 kg ha^{-1} of sulfur (S) applied as ammonium sulfate. Once the rice had reached the 3-

to 4-leaf stage on June 3, 2019, the field was broadcast-amended with 168 kg ha^{-1} of N as NBPT-coated urea. Furrow irrigation occurred approximately once a week, or more frequently as needed, starting on June 13, 2019 and continuing until September 4, 2019, using the same irrigation methods as in 2018.

A spring-burndown herbicide, paraquat (Gramoxone), was applied on April 24, 2019 at a rate of 140 L ha^{-1} in the amount of 2.34 L ha^{-1} of active ingredient. Pre-plant herbicides were applied on April 30, 2019 using a ground sprayer at the rate of 140 L ha^{-1}. The solution consisted of imazethapyr (Newpath), safufenacil (Sharpen), clomazone (Command), and glyphosphate (Roundup) in the amounts of 0.44, 0.15, 1.17, and 2.34 L ha^{-1} of active ingredients, respectively. On May 16, 2019, pendimenthalin (Prowl) and quinclorac (Facet) were also ground-sprayed at a rate of 140 L ha^{-1} and both in the amounts of 2.34 L ha^{-1} of active ingredients. On May 24, 2019, imazamox (Beyond), halosulfuron (Permit Plus), and cyhalofop (Clincher) were ground-sprayed at a rate of 140 L ha^{-1} and in the amounts of 0.37, 0.01, and 2.19 L ha^{-1} of active ingredients, respectively. On June 12, 2019, 0.37 L ha^{-1} of imazethapyr (Newpath) were ground-sprayed at a rate of 140 L ha^{-1}. On June 27, 2019, 0.07 L ha^{-1} of halosulfuron (Permit Plus) were applied via airplane at a rate of 140 to 187 L ha^{-1}. On July 9, 2019, bentazone (Basagran), propanil, and imazamox (Beyond) were ground-sprayed at a rate of 98.5 L ha^{-1} and in the amounts of 1.75, 4.68, and 0.37 L ha^{-1} of active ingredients, respectively.

Gas Sampling Chamber Installation

On May 16, 2019, polyvinyl chloride (PVC) base collars, 30 cm in diameter and 30 cm tall with the bottom end beveled, were installed in triplicate in each site position-tillage treatment combination throughout the study area. Collars were tamped 12 cm deep into the middle atop alternating raised beds and positioned to contain portions of two rice rows. The collars had four, equally spaced, 12.5-mm holes drilled 12 cm up from the bottom that were left open to maintain unrestricted water movement into and out of the collar during irrigation events. Collars were set such that the four holes were just above the soil surface when installation was complete

N_2O Sampling and Analyses

In 2018, a total of 16 gas sampling dates were conducted approximately weekly from rice planting, which occurred on May 17, 2018, to harvest [i.e., 20, 27, 33, 40, 47, 54, 61, 68, 75, 82, 89, 96, 101, 108, 115, and 122 days after planting (DAP)]. Similar to the 2018 growing season, a total of 16 gas sampling dates were conducted approximately weekly from rice planting on 30 April 2019, to harvest [i.e. 21, 28, 35, 42, 49, 56, 63, 70, 77, 84, 91, 98, 105, 112, 118, and 125 days after planting (DAP)].

Gas sampling occurred between 0800 and 0900 hours on a given sample date. Before sampling, the four drilled holes at the bottom of the base collars were sealed with 1.3-cm-diameter rubber stoppers (part #73828A-RB, Voigt Global, Lawrence, KS). A 30 cm-diameter, 10-cm tall PVC cap was then placed on top of each base collar and sealed with a rubber flap to create a sealed, closed-headspace chamber. Two sets of PVC collar extensions, 40- and 60-cm tall, were used as needed during the growing season to facilitate containment of the rice plants once they began growing taller than the base collar. The extensions were attached using the same method as the PVC cap. The underside of the cap had a 2.5-cm^2 fan (MagLev GM1202PFV2-8, Sunon Inc., Brea, CA) to circulate the air in the headspace chamber. A 9-V battery was installed on the top of the cap and connected to the fan by battery straps and wires that passed through the cap without compromising the sealed headspace. Each cap had a 15-cm long, 0.63-cm-inner-diameter copper refrigerator tube mounted horizontally within and on the side of the cap to equilibrate pressure between the headspace chamber and the ambient air. Caps were also equipped with a septum (part #73828A-RB, Voigt Global, Lawrence, KS) inserted into a 12.5-mm-diameter, drilled hole on the top of the cap. One cap had an additional septum where a thermometer was used to document the temperature inside the sealed chamber during sampling. Collars, caps, and extenders were covered with reflective aluminum tape (Mylar metallized tape, CS Hyde, Lake Villa, IL) to reduce temperature increases or fluctuations inside the chamber during sampling.

Similar to the procedures used recently by Rector et al. (2018a,b) and Della Lunga (2020), gas samples were collected at 20-minute intervals (i.e. 0, 20, 40, 60 minutes). A 20-mL syringe, equipped with a 0.5-mm-diameter, 25-mm long needle [Beckton Dickson and Co (B-D), Franklin Lakes, NJ], was inserted into the septa to collect 20 mL of headspace gas at each time interval. To allow for an even distribution of gas within the syringe, the syringe was held open for five seconds and then transferred to a pre-capped (20-mm headspace crimp cap; part #5183-4479, Agilent Technologies, Santa Clara, CA), pre-evacuated, 10-mL glass vial (part #5182-0838, Agilent Technologies). At the beginning of each time interval, the air temperature, relative humidity, and barometric pressure were measured with a portable meteorological station (S/N: 182090284, Control Company, Webster, TX). The height of each chamber (collar + cap) was measured from the soil surface or from the top of the ponded water, if present, to determine the volume of the chamber. After each sampling, the caps, extenders, and rubber stoppers were removed from the base collars until the next gas sampling date.

Sample-containing gas vials were stored at room temperature and analyzed within 48 hours of gas collection. Gas samples were analyzed with a Shimadzu GC-2014 ATFSPL 115V gas chromatograph (GC; Shimadzu North America/Shimadzu Scientific Instruments Inc., Columbia, MD). Two sets of gas standards were collected, one set in the field and the other set in the laboratory, for quality control. Each set of standards included concentrations of 0.1, 0.5, 1, 5, and 20 mg N_2O L^{-1}. Nitrous oxide concentrations were measured with an electron capture detector (ECD). Argon gas was used as the reference gas for the ECD and helium gas was used as the carrier gas for sample analysis.

Similar to recent, previous rice studies conducted in Arkansas (Della Lunga et al., 2020; Humphreys et al., 2018a,b, 2019; Rector et al., 2018b; Rogers et al., 2014; Smartt et al., 2016), the N_2O fluxes (mg m^{-2} hr^{-2}) for each gas chamber were determined using the change in gas concentrations over the four, 20-min (0, 20, 40, and 60 min) gas sampling intervals. The flux for each chamber was calculated by multiplying the slope of the linear regression best-fit line between the time intervals by the volume of the chamber and then dividing by the surface area of the chamber. Utilizing linear interpolation between fluxes, seasonal emissions (kg ha^{-1} $season^{-1}$) per chamber were calculated and summed for the whole growing season. On a chamber-by-chamber basis, season-long N_2O emissions were divided by rice grain yields reported in Della Lunga et al (2021b) for both the 2018 and 2019 rice growing season to calculate yield-scaled N_2O emissions (i.e., emissions intensity.

Statistical Analyses

Based on a strip-plot design, where tillage was stripped through site positions, a three-factor analysis of variance (ANOVA) was conducted using the PROC GLIMMIX procedure in SAS (version 9.4, SAS Institute, Inc., Cary, NC) to evaluate the effects of site position, tillage treatment, sample date, and their interactions on N_2O fluxes over the growing season. Due to differences in rainfall and cultivars planted between the two years, flux data were analyzed separately by year. When appropriate, least significant difference at the $P < 0.05$ level was used to separate treatment means for N_2O flux results. A separate two-factor ANOVA was conducted using the PROC GLIMMIX procedure in SAS to evaluate the effects of site position, tillage treatment, and their interactions on season-long N_2O emissions and emissions intensity, separately by year, and the 2-yr cumulative N_2O emissions. Due to large anticipated spatial variability and a small sample size (n =18), when appropriate, least significant difference at the $P < 0.1$ level was used to separate treatment means for N_2O emissions-related results.

Results and Discussion

Initial Soil Properties

As part of another related field study, Della Lunga et al. (2021a) soil sampled the top 10 cm of all tillage-site position treatment combinations associated with the current field study on May 31, 2018, to characterize soil physical and chemical properties throughout the study area prior to beginning N_2O sampling. The surface soil texture was confirmed to be silt loam. However, soil organic matter (SOM), total nitrogen (TN), total carbon (TC), pH, and Mehlich-3 extractable soil nutrients (i.e., P, K, Na, Fe, Mn, and Zn) varied inherently among site positions and tillage treatments (Della Lunga et al., 2021a).

Initial TC and TN contents differed among site position, where TC and TN contents were both greatest at the down-slope position (10.6 and 1.15 Mg ha^{-1}, respectively) and lowest at the up- and mid-slope positions (8.5 and 1.0 Mg ha^{-1}, respectively; Della Lunga et al., 2021a). All TC and TN content maxima and minima occurred under NT, while none of the soil properties differed solely between tillage treatments.

Initial SOM and extractable soil K, Na, Fe, and Mn contents differed among site positions and differed between tillage treatments (Della Lunga et al., 2021a). Initial SOM and extractable Na, Fe, and Mn contents were generally numerically greater under NT than CT. Averaged across site position-tillage treatment combinations, SOM, soil Na, Fe, and Mn contents ranged from 27.1, 0.13, 0.88, and 0.41 Mg ha^{-1} to 23.7, 0.03, 0.29, 0.17 Mg ha^{-1}, respectively, where all maxima occurred under NT and all minima occurred under CT. Soil K contents were generally numerically greater under NT than CT. Both SOM and soil K contents were greatest in the down-slope position (27.1 and 0.24 Mg ha^{-1}, respectively) and lowest in the mid-slope position (23.7 and 0.17 Mg ha^{-1}, respectively). Both soil Na and Mn contents were numerically greatest in the up-slope position (0.13 and 0.41 Mg ha^{-1}, respectively) and lowest in the down-slope position (0.03 and 0.17 Mg ha^{-1}, respectively). Soil Fe contents were numerically lowest in the up-slope position (0.29 Mg ha^{-1}) and greatest in the down-slope position (0.88 Mg ha^{-1}).

Initial soil pH and extractable soil P and Zn differed among site position-tillage treatment combinations (Della Lunga et al., 2021a). The lowest soil pH was 4.75 in down-/CT and differed from the down-/NT treatment combination (4.94), which was the lowest pH under NT. The largest soil pH for both tillage treatments occurred in the up-slope position with pH of 5.49 under CT and 5.57 under NT, which did not differ. The greatest extractable soil P content was in the up-/CT (0.05 Mg ha^{-1}), which did not differ from that in the down-/CT or down-/NT treatment combinations, while soil P in the other three site position-tillage treatment combinations (mid-/CT, up-/NT, and mid-/NT) did not differ and averaged 0.02 Mg ha^{-1}. Initial soil Zn contents were greatest in down-/NT (0.03 Mg ha^{-1}) and did not differ from that in the down-/CT and up-/CT combinations, while soil Zn in the other three site position-tillage treatment combinations (mid-/CT, up-/NT, and mid-/NT) did not differ and averaged 0.01 Mg ha^{-1}.

Despite some differences in initial soil properties among site positions and tillage treatments, differences were generally not large. Therefore, the relatively small inherent differences in soil properties among experimental factors throughout the study area were considered agronomically non-significant, such that negative effects on subsequent plant growth were not expected. Consequently, any identified treatment effects on N_2O fluxes and season-long emissions were considered the result of the actual imposed field treatments rather than due to large, inherent differences in soil properties in the top 10 cm among replicate measurement areas comprising the site position and tillage treatment experimental factors.

N_2O Fluxes

General Trends

Based on visual assessment, across all site position-tillage combinations, N_2O fluxes did not follow a clear temporal pattern over time in 2018 or 2019 from furrow-irrigated rice growing in a silt-loam soil (Figure 2). With the exception of 3 out of 16 sample dates in 2018 and 4 out of 16 sample dates in 2019, N_2O fluxes from all treatment combinations did not exceed 1.75 mg m^{-2} hr^{-1}, where 11 samples dates in both 2018 and 2019 did not exceed 1.0 mg m^{-2} hr^{-1} (Figure 2). Within the first eight weeks of the 2018 growing season (i.e., the first seven measurement dates), the down-slope/CT treatment combination produced the largest numeric N_2O flux on a given sample date (Figure 2). Numeric flux maxima for all site position-tillage treatment combinations occurred at 33 DAP in 2018, just five days after the field was broadcast-fertilized with 168 kg ha^{-1} of N as NBPT-coated urea (Figure 2). On 19 June 2018 (i.e., 33 DAP), numerically largest N_2O fluxes averaged 5.9, 4.0, 3.2, 7.2, 9.7, and 7.7 mg m^{-2} hr^{-1} from the up-slope/CT, up-/NT, mid-/CT, mid-/NT, down-/CT, and down-/NT, respectively (Figure 2). In contrast to the beginning of the growing season, during the last eight weeks of the 2018 rice growing season, the majority of largest numeric N_2O fluxes on a given sampling date were from the mid-/CT treatment combination (Figure 2).

Nitrous oxide flux trends over time in 2019 followed a somewhat different trend than in 2018 (Figure 2). However, similar to 2018, the down-/CT treatment combination in 2019 had the numerically largest fluxes for six of the first eight weeks of the growing season. In contrast to the 2018 growing season, numeric flux maxima for the mid-/NT combination (0.4 mg m^{-2} hr^{-1}) occurred at 21 DAP, while that for the up-/CT, up-/NT, and down-/CT combinations occurred at 56 DAP and averaged 5.8, 1.4, and 4.4 mg m^{-2} hr^{-1}, respectively (Figure 2). Numeric flux maxima for the mid-/CT combination (3.0 mg m^{-2} hr^{-1}) occurred at 77 DAP, while that for the down-/CT combination (1.7 mg m^{-2} hr^{-1}) occurred at 84 DAP (Figure 2). During the second eight weeks of the 2019 growing season, five of the six site position–tillage treatment combinations experienced their numerically smallest N_2O fluxes of the season. Similar to the 2018 growing season, the majority of sample dates during the second half of the 2019 growing season had the largest numeric fluxes from the mid-/CT treatment combination (Figure 2).

2018 Differences

Nitrous oxide fluxes differed ($P < 0.001$) among site position-tillage treatment combinations over time throughout the 2018 rice growing season (Table 1). Of the 96 total site position-tillage-DAP treatment combination mean N_2O fluxes in 2018, only 16 were greater ($P < 0.05$) than a mean flux of zero (Table 2). Nitrous oxide fluxes differed among site position-tillage treatment combinations on 14 of the 16 samples dates in 2018 (i.e., 20, 27, 40, 47, 54, 61, 68, 75, 82, 89, 96, 101, 108, and 115 DAP; Figure 2). In contrast, on 2 of the 16 samples dates in

2018 (i.e., 33 and 122 DAP), N_2O fluxes did not differ among site position-tillage treatment combinations (Figure 2).

At 33 DAP in the 2018 growing season, approximately one week after N-fertilization, numeric peak N_2O fluxes occurred for all site position–tillage treatment combinations (Figure 2). A similar temporal trend in peak N_2O fluxes was measured in 2019 from furrow-irrigated rice with cover crops from a Sharkey silty-clay soil (very-fine, smectitic, thermic Chromic Epiaquerts; USDA-NRCS, 2013) in northeast Arkansas, where peak N_2O fluxes occurred approximately one week after mid-season N fertilization for the up- and down-slope positions that did not have a cover crop (Karki et al., 2021). Karki et al. (2021) reported a peak N_2O flux of 3.4 mg m^{-2} hr^{-1} from the up-slope position, which was 1.7 and 1.2 times lower than the peak flux from CT and NT, respectively, from the up-slope position in the 2018 growing season of the current study. At the down-slope position, Karki et al. (2021) also reported a peak flux of 0.6 mg m^{-2} hr^{-1}, which was 16.5 and 13.1 times lower than the peak flux from CT and NT, respectively, in the 2018 growing season of the current study.

Although N_2O fluxes were numerically greater in the first eight weeks of the growing season, the frequency of flux differences among the site position–tillage treatment combinations were greater during the second eight weeks of the 2018 growing season. For example, during the first eight weeks of the 2018 growing season, the down-/CT combination had the largest N_2O flux on both 40 (5.4 mg m^{-2} hr^{-1}) and 61 DAP (6.14 mg m^{-2} hr^{-1}), where the 40-DAP flux was 9.3 times greater than the lowest flux on that date and the 61-DAP flux was 64.7 times greater than the lowest flux on that date, both of which occurred from the up-/NT treatment combination (Table 2). During the second eight weeks, the up-/CT combination had largest N_2O flux and largest difference among treatment combinations on both 96 (0.71 mg m^{-2} hr^{-1}) and 108 (0.47 mg

m^{-2} hr^{-1}) DAP, where the 96-DAP flux was 710 times greater than the lowest flux (< 0.001 mg m^{-2} hr^{-1} from the up-/NT combination) and the 108-DAP flux was 470 times greater than the lowest flux (< 0.001 mg m^{-2} hr^{-1} from the down-/NT combination; Table 2). Thus, although the majority of N_2O fluxes were numerically greater during the first half of the 2018 growing season, the variability in fluxes among treatment combinations was also greater, which explains why, at 33 DAP, at which flux maxima for all site position–tillage treatment combinations occurred, N_2O fluxes did not differ among treatments (Figure 2). The lowest N_2O flux difference among treatment combinations occurred at 40 DAP, with the largest flux (5.40 mg m^{-2} hr^{-1}) from the down-/CT being 9.3 times greater than the lowest flux (0.58 mg m^{-2} hr^{-1}) from the up-/NT treatment combination (Figure 2). In contrast to the first 8 weeks of the 2018 growing season, N2O fluxes from all treatment combinations were generally numerically lower, but also had lower variability with treatment combinations, such that more differences among treatment combinations occurred during the second eight weeks of the 2018 growing season (Figure 2).

2019 Differences

Similar to 2018, N_2O fluxes also differed (P < 0.001) among site position-tillage treatment combinations over time throughout the 2019 rice growing season (Table 3). Similar to 2018, of the 96 total site position-tillage-DAP treatment combination mean N_2O fluxes in 2019, 10 samples dates had measured N_2O fluxes that were greater (P < 0.05) than a mean flux of zero (Table 2). Nitrous oxide fluxes differed among site position-tillage treatment combinations on 15 of the 16 samples dates in 2019 (i.e., 21, 28, 35, 49, 56, 63, 70, 77, 84, 91, 98, 105, 112, 118, and 125 DAP; Table 2). In contrast, on 1 of the 16 samples dates in 2019 (42 DAP), N_2O fluxes did not differ among site position-tillage treatment combinations (Table 2).

In 2019, N fertilization occurred at 34 DAP and, unlike the N_2O flux trends 2018 and those reported by Karki et al. (2021), numeric peak N_2O fluxes occurred throughout the growing season, with the mid-/NT combination peak flux occurring at 21 DAP, the up-/CT, up-/NT, and down-/CT combinations occurring at 56 DAP, the mid-/CT combination occurring at 77 DAP, and the down-/CT combination occurring at 84 DAP (Figure 2). Karki et al. (2021) reported a peak N_2O flux from the up-slope position in 2019 (3.4 mg m^{-2} hr^{-1}) that was 1.7 times lower than the peak flux from CT and 2.4 times larger than the peak flux from NT at the up-slope position in the 2019 growing season of the current study. The peak flux from the down-slope position (0.6 mg m^{-2} hr^{-1}; Karki et al., 2021) was 7.4 and 2.9 times lower than the peak flux from CT and NT, respectively, at the down-slope position in the 2019 growing season of the current study. Unlike the 2018 growing season, trends in N_2O flux differences among site position–tillage treatment combinations in 2019 were less clear. The two largest flux differences among treatment combinations occurred at 84 and 118 DAP (Table 3). At 84 DAP, the largest flux (1.70 mg m^{-2} hr^{-1}) occurred from the down-/NT combination, which was more than 1700 times greater than the lowest flux (< 0.001 mg m^{-2} hr^{-1}) from the mid-/NT treatment combination. At 118 DAP, the largest flux occurred from the mid-/CT (2.78 mg m^{-2} hr^{-1}) treatment combination and was more than 2780 times greater than the lowest flux from the down-/CT (< 0.001 mg m^{-2} hr^{-1}) treatment combination (Table 3). In both instances, the lowest flux was < 0.001, which exacerbated the magnitude of the flux differences. The lowest N_2O flux difference among treatment combinations occurred at 70 DAP, with the largest flux from the mid-/CT (0.14 mg m^{-2} hr^{-1}) being 3.6 times greater than the lowest flux from the up-/CT (0.04 mg m^{-2} hr^{-1}) treatment combination (Table 3). The largest N_2O flux during the 2019 growing season occurred at 56 DAP from the up-/CT (5.8 mg m^{-2} hr^{-1}) treatment combination, which was 1.9 and 2.1 times greater than the next largest fluxes, on a given sample date, that occurred at 77 (3.0 mg m^{-2} hr^{-1}) and 118 DAP (2.8 mg m^{-2} hr^{-1}) from the mid-/CT treatment combination (Table 3). In comparison, the largest N_2O flux during the 2018 growing season occurred at 33 DAP in the down-/CT (9.7 mg m^{-2} hr^{-1}) treatment combination, which was 1.8 and 1.6 times greater than the next largest fluxes, on a given sample date, that occurred at 40 (5.4 mg m^{-2} hr^{-1}) and 61 DAP (6.1 mg m^{-2} hr^{-1}) from the down-/CT treatment combination (Table 2). Based on 2018 and 2019 measurements, it appears that N_2O fluxes are often, at least numerically, greater from CT than NT, but there is no clear effect of site position in a production-scale furrow-irrigated rice field (Figure 2).

In both the 2018 and 2019 growing seasons, N_2O fluxes were consistently low, except at 118 DAP in 2019 (Figure 2). It is likely that the active plant-N uptake needed during the significant vegetative growth stages minimized the available nitrate in the soil that could be denitrified, therefore reducing N_2O production and release.

In contrast to the tillage effect and substantially larger magnitude of N_2O fluxes measured in the current study, Rector et al. (2018b) reported no effect of tillage (CT and NT) on N_2O fluxes or season-long emissions from a pure-line rice cultivar grown under flood-irrigation at the RREC in the same Dewitt silt-loam soil as used for the current study. Rector et al. (2018b) measured N_2O fluxes ranging from 0 mg N_2O m^{-2} hr^{-1} on two mid-season dates (89 and 104 DAP) to 0.062 mg N_2O m^{-2} hr^{-1} at the end of the growing season (121 DAP) under CT and ranging from 0.01 mg N_2O m^{-2} hr^{-1} at the end of the season (121 DAP) to 0.033 mg N_2O m^{-2} hr^{-1} on one mid-season date (89 DAP) under NT. Rector et al. (2018b) attributed the rather low and minimally varying N_2O fluxes between tillage treatments to the presence of the consistent flood that prevented the release of N_2O through the flood water, which has been reported in other studies (Ahmad et al., 2009; Zhang et al., 2013), whereas, under the furrow-irrigated conditions of the current study, N_2O can immediately escape to the atmosphere without having to diffuse through standing water throughout most of the field.

Season-long N_2O Emissions

Nitrous oxide emissions for the 2018 and 2019 growing seasons and the 2-year cumulative emissions differed ($P < 0.087$) between tillage treatments, while N_2O emissions for the 2018 growing season also differed among site positions ($P = 0.088$; Table 4). Averaged across site position, N_2O emissions for the 2018 and 2019 growing seasons and the 2-year cumulative emissions were 1.5, 3.7, and 1.9 times greater from CT than from NT, respectively (Table 5). The CT treatment experienced a greater number of wet/dry cycles and greater soil redox potential (Eh) fluctuations compared to the NT treatment in both growing seasons (Della Lunga et al., 2020). The greater frequency of soil moisture and Eh oscillations under CT facilitated increased nitrification and denitrification by allowing for reaeration of the soil and increasing the opportunity for incomplete denitrification. Della Lunga et al. (2020) also reported consistently lower Eh values from NT compared to CT meaning that the soil under NT achieved a reduced state below the optimum range for denitrification, thus minimizing the opportunity for N_2O production. Furthermore, soil bulk density in the top 10 cm early in the growing season was significantly lower under CT than NT (Della Lunga et al., 2021b). The greater porosity present under CT likely increased the ability for the soil under CT to achieve a more optimal soil water content and Eh for N_2O production and release compared to the soil under NT that was denser and had lower porosity. Furthermore, the SOM and nutrients from decomposing crop residues at the surface under NT were likely less readily available for microbial metabolic activities compared to under CT, where SOM and nutrient were mixed into the top 10 cm and in more physical contact for microbial processes.

In 2018, averaged across tillage, the largest season-long N_2O emissions was from the down-slope (28.7 kg N_2O ha^{-1} $season^{-1}$) position and was at least 1.7 times greater than from both the mid- and up-slope positions, which did not differ (Table 5). In addition, though non-significant, the 2-year cumulative N_2O emissions were numerically greater in the down-slope than in the other two site positions (Table 5). Della Lunga et al. (2020) reported six Eh fluctuations between aerobic and oxygen-limited conditions for the down-slope position in 2018 compared to just one during the 2019 growing season. There was also 60 to 80% less rainfall in the early months (May through July) of the 2018 growing season compared to the same time period in 2019 and 20 to 77% less rainfall for the same months than the 30-year average monthly rainfall (Table 6). Due to the drier season, the down-slope position in 2018 experienced more optimal conditions for N_2O production and release, while season-long N_2O emissions in 2019 were > 33% lower for each site position compared to 2018 and did not differ among site positions in 2019 (Table 5). However, placement of the base collars on top of the raised beds, which only occupied at most 50% of the field area, in combination with the variable movement of the wetting front from furrows to the top of the raised beds could have resulted in an over-estimation of the area-scaled, season-long emissions.

At the beginning of the 2018 growing season, Della Lunga et al. (2021b) reported a greater TN soil concentration at the down-slope position compared to the mid- and up-slope positions. The greater TN in the soil would provide a larger pool of potentially nitrifiable N for subsequent possible denitrification, leading to greater emissions from the down-slope position in

2018, which also had soil moisture conditions that were more conducive for N_2O emissions than at the other two site positions (Della Lunga et al. (2020).

Though not formally compared on account of different rice cultivars planted between years, averaged across both treatments, N_2O emissions in the wetter 2018 were more than 2.2 times numerically greater than in the drier 2019 growing season (Table 5). More specifically, averaged across site positions, N_2O emissions in 2018 form NT were 4.2 times numerically greater than in 2019, while N_2O emissions from CT were 1.7 times numerically greater in 2018 than in 2019 (Table 5).

Unlike the current study, Rector et al. (2018b) reported no effect of tillage on season-long N_2O emissions from a pure-line rice cultivar grown under flood-irrigation at the RREC in the same DeWitt silt-loam soil as used for the current study. In addition, season-long N_2O emissions were substantially lower from flood-irrigation than from furrow-irrigated management used in the current study (Rector et al., 2018b). Under CT and flood-irrigation, Rector et al. (2018b) reported season-long N_2O emissions of 0.4 kg N_2O ha^{-1} $season^{-1}$, which were 7.5 and 6.1 times lower than the season-long N_2O emissions from CT in the 2018 and 2019 growing seasons, respectively, measured in the current study under furrow-irrigated management. Similarly, under NT and flood-irrigation, Rector et al. (2018b) reported season-long N_2O emissions of 0.5 kg N_2O ha^{-1} $season^{-1}$, which were 5.5 and 2.6 times lower than the season-long N_2O emissions from NT in the 2018 and 2019 growing seasons, respectively, measured in the current study under furrow-irrigated management. Similarly, a multi-site experiment, conducted in Nanjing, China, evaluated GHG emissions from rice agriculture and reported 30% more N_2O emissions from irrigation regimes that diverged from conventional flood-irrigation systems (Khalil et al., 2009).

Karki et al. (2021) reported season-long N_2O emissions at the down-slope position (2.4 kg N_2O ha^{-1} $season^{-1}$) that were similar to the those measured in 2018 and 2019 at the down-slope position in the current study. However, in contrast, up-slope N_2O emissions (11.6 kg N_2O ha^{-1} $season^{-1}$) reported by Karki et al. (2021) were 4.2 and 5.1 greater than those measured in 2018 and 2091, respectively, at the up-slope in the current study.

The National Research Council (2010) reported approximately 3 to 5% of the N applied in fertilizer is lost as N_2O due to soil microbial processes. Furthermore, between the 1950s and the 21st century, Maraseni et al. (2009) reported that the global use of N fertilizers increased by 23 times, which has led to a greater potential for gaseous N losses from agricultural landuses. In the current study, averaged across tillage treatment, the annual proportion of fertilizer-N applied that was lost as N_2O-N ranged from 6.0% in the up- to 10.9% from the down-slope position in 2018 and ranged from 2.1% from the mid- to 3.8% from the up-slope position in 2019 (Table 5).

While the US Environmental Protection Agency (EPA) has not formally summarized N_2O emissions from rice cultivation, as has been done with methane emissions, the EPA has reported that the greatest N_2O emissions in the US originate from poorly managed agricultural fields and croplands (EPA, 2021). However, the depletion of groundwater will continue to push rice producers towards alternative rice production systems. Consequently, it will become increasingly important to focus on the proper management of rice fields moving forward to mitigate potential increases in N_2O production and release in regions of concentrated rice production and globally.

Dry Matter Production, Yield, and Emissions Intensity

For both the 2018 and 2019 growing seasons, there was no effect of tillage treatment or site position on aboveground rice dry matter or yield (Della Lunga et al., 2021b). In 2018, the aboveground dry matter and yield averaged 10.1 and 4.5 Mg ha^{-1}, respectively and in 2019 averaged 12.9 and 7.3 Mg ha^{-1}, respectively, across all treatment combinations. Along with the development of hybrid rice cultivars, yields under furrow-irrigation have increased. Yields from a recent study conducted on a silt-loam soil in Arkansas reported up to 9 Mg ha^{-1} from furrow-irrigated management (Hardke, 2020). In 2018, the study area experienced an uncharacteristically dry growing season (Table 6) and a large concentration of weeds due to low herbicide effectiveness, which likely contributed to a lower-than-typical average rice yield. The 2019 growing season was wetter than 2018 (Table 6), which allowed for greater weed suppression from more optimal herbicide effectiveness, especially at the down-slope position, thus the greater yield in 2019 reflected the change in environmental parameters between the two growing seasons. It was also reported in Della Lunga et al. (2021a) reported no correlation between season-long N_2O emissions and aboveground rice dry matter or yield for either growing season.

In contrast to season-long emissions, N_2O emissions intensity (i.e., season-long emissions divided by the measured rice yield) differed ($P < 0.1$) among site position–tillage treatment combinations in 2018 and (Table 4). In 2018, the numerically largest emissions intensity occurred in the down-/CT treatment combination (10.3 kg N_2O Mg $yield^{-1}$), which did not differ from the up-/CT and mid-/NT treatment combinations (Figure 3). The numerically lowest emissions intensity in 2018 occurred in the down-/NT treatment combination (2.3 kg N_2O Mg $yield^{-1}$), which did not differ from the up-/NT, mid-/CT, and mid-NT treatment combinations (Figure 3). In 2019, the numerically largest emissions intensity occurred in the mid-/CT treatment combination (2.4 kg N_2O Mg yield^{-1}), which did not differ from both the up-/CT and down-/CT treatment combinations (Figure 3). The numerically lowest emissions intensity in 2019 occurred in the mid-/NT treatment combination (0.3 kg N_2O Mg yield^{-1}), which did not differ from the down-NT treatment combination (Figure 3). Though not formally compared, averaged across all treatment combinations, N_2O emissions intensity was 4.3 times numerically greater in the wetter 2018 compared to in the drier 2019 growing season (Figure 3).

Similar to season-long emissions, the 2-year cumulative emissions intensity also differed (P = 0.002) between tillage treatments and was unaffected (P > 0.1) by site position (Table 4). Averaged across site positions, the 2-year cumulative emissions intensity was 2.1 times greater from CT than from NT (Table 5).

Implications

Considering little field research exists regarding N_2O emissions from rice grown under furrow-irrigation, the current study represents one of the first to quantify and report furrow-irrigation impacts on season-long N_2O fluxes and emissions. While N_2O fluxes and emissions from the current study were numerically greater from furrow-irrigation compared to flood-irrigated rice production, further manipulation of the furrow-irrigation system could narrow the N_2O emissions difference between FI and flood-irrigated rice. For example, Della Lunga et al. (2020) speculated that decreasing the number of soil moisture fluctuations within the field, which could be accomplished by more frequent irrigations to maintain a more consistent soil water content, could limit provocation of the nitrification and denitrification processes. Results of the current study also suggest that practicing NT rather than CT could be a management practice option to lower N_2O emissions from furrow-irrigated rice, thus lowering negative environmental consequences of furrow-irrigated rice. Since mismanaged agricultural soils are the leading cause of N_2O emissions in the US, it is essential to practice proper N fertilization and irrigation practices. For example, fertilizer-N (i.e., urea) can be applied coated with a nitrification inhibitor to minimize the soil nitrate concentration to potentially be denitrified and/or fertilizer-N can be applied in one or more split applications compared to a single application to minimize the opportunity for nitrification and maximize the opportunity for plant uptake.

The delicate balance between soil N, soil water content, and soil Eh is the driving force behind N_2O production via the nitrification and denitrification processes (Della Lunga et al., 2021a; Linquist et al., 2018; Butterbach-Bahl et al., 2013). However, furrow-irrigation creates increased variability within and among soil and environmental parameters, and several others (i.e., soil temperature, soil nutrients, the influence of rainfall), due to the greater number of wet-dry cycles compared to the more stable soil moisture regime created by flood-irrigation. Additional investigation and evaluation of environmental parameters and their effects on N_2O production in furrow-irrigated rice production systems will be critical to finding the optimal conditions in which N_2O production can be disrupted and minimized.

Conclusions

Nitrous oxide fluxes were measured and season-long emissions were estimated from the up-, mid-, and down-slope positions under NT and CT management over the 2018 and 2019 growing seasons from a production-scale, furrow-irrigated rice field on a silt-loam soil in east-central Arkansas. In contrast to that hypothesized, N_2O fluxes differed between tillage treatments over time in both growing seasons, with CT having consistently numerically greater fluxes than NT. Though N_2O fluxes were hypothesized to be greater from the up- and mid- compared to the down-slope position, N_2O fluxes differed among site position-tillage treatment combinations over time in both growing seasons and fluxes were often numerically larger from the down-slope position in the drier 2018 growing season, but often numerically larger from the up- and mid-slope positions in the wetter 2019 growing season. Thus, in contrast to tillage treatment, there was little consistent effect of site position on N_2O fluxes over the furrow-irrigated rice growing season.

In contrast to that hypothesized, season-long N_2O emissions were consistently at least numerically greater from CT than from NT. Although it was hypothesized that the mid- and up-slope positions would be greater, season-long N_2O emissions were greater from the down-slope position in the drier 2018 growing season but were unaffected by site position in the wetter 2019 growing season.

Nitrous oxide fluxes and emissions are notoriously challenging to accurately quantify in agricultural settings because of the many environmental factors that influence the nitrification and denitrification processes and their large temporal and spatial variabilities. However, N_2O's greater potency as a GHG relative to CO_2 and CH_4 substantiates the critical need to quantify trace gas emissions and their impacts on the GWP of various production systems that occupy large areas in many agricultural regions. Consequently, further investigation is still required to achieve the most accurate representation of the long-term implications and environmental sustainability and to better understand the agronomic, climatic, and soil- and plant-property effects on N_2O fluxes and emissions in the emerging FI water management system in areas of concentrated rice production, such as in the Lower Mississippi River Valley.

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Tables and Figures

Table 1. Analysis of variance summary of the effects of tillage treatment (conventional and no-tillage), site position (up-, mid-, and down-slope), days after planting (DAP), and their interactions on nitrous oxide fluxes from the 2018 and 2019 rice growing seasons at the Rice Research and Extension Center near Stuttgart, AR.

Source of Variation	2018	2019
	P	
Tillage	< 0.001	0.003
Position	< 0.001	< 0.001
Tillage x Position	0.087	< 0.001
DAP	< 0.001	< 0.001
Tillage x DAP	< 0.001	< 0.001
Position x DAP	< 0.001	< 0.001
Tillage x Position x DAP	< 0.001	< 0.001

Table 2. Summary of nitrous oxide flux means among tillage [conventional (CT) and no-tillage (NT)]-site position (up-, mid-, and down-slope)-days after planting (DAP) treatment combinations from the 2018 rice growing seasons at the Rice Research and Extension Center near Stuttgart, AR.

	Site Position					
	Up-slope		Mid-slope		Down-slope	
DAP	CT	NT	CT	NT	CT	NT
	mg N_2O m^{-2} hr^{-1}					
20	0.02 c-g†	0.03 X-g	0.02 d-g	< 0.01 i	0.03 a-g	< 0.01 i
27	0.13 M-X	0.02 b-g	0.02 e-g	0.21 K-S	0.09 O-c	0.02 c-g
33	5.86 A-C	3.99 A-D	3.23 A-D	7.23 AB	9.71 A	7.68 AB
40	2.90 A-E	0.58 F-L*	1.89 B-G*	1.98 B-F*	5.40 A-C	1.64 C-H*
47	1.24 D-I*	0.27 J-Q	0.75 E-K*	0.54 F-L*	0.66 F-L*	0.04 W-g
54	0.27 J-Q	0.19 K-U	0.29 J-P	0.21 K-T	1.11 D-J*	0.06 R-f
61	0.68 F-L*	0.09 N-c	0.17 L-W	0.17 L-W	6.14 A-C	2.91 A-E
68	0.25 K-R	0.37 I-O*	0.40 H-N*	0.09 P-c	0.03 X-g	< 0.01 j
75	0.11 M-Z	0.12 M-Y	0.54 F-L*	0.05 U-f	0.04 X-g	0.05 T-f
82	0.08 P-c	0.05 S-f	0.19 K-V	< 0.01 j	0.09 P-c	< 0.01 hi
89	0.07 Q-e	< 0.01 hi	0.07 Q-d	0.02 b-g	0.03 Z-g	< 0.01 j
96	0.71 E-K*	< 0.01 j	0.58 F-L*	< 0.01 i	< 0.01 i	0.04 W-f
101	0.22 K-S	< 0.01 j	0.24 K-R	0.05 S-f	0.02 d-g	0.02 Z-g
108	0.47 G-M*	0.03 X-g	0.12 M-Y	0.10 N-b	0.06 S-f	< 0.01 j
115	0.11 N-a	0.05 V-f	0.07 P-d	0.03 X-f	0.02 fg	0.01 gh
122	0.03 b-g	0.02 c-g	0.07 P-d	0.08 P-c	0.02 c-g	0.02 Y-g

* An asterisk denotes a mean nitrous oxide flux that differed from zero (*P* < 0.05)
† Means followed by a letter with the same case do not differ (*P* > 0.05)

Table 3. Summary of nitrous oxide flux means among tillage [conventional (CT) and no-tillage (NT)]-site position (up-, mid-, and down-slope)-days after planting (DAP) treatment combinations from the 2019 rice growing seasons at the Rice Research and Extension Center near Stuttgart, AR.

	Site Position					
	Up-slope		Mid-slope		Down-slope	
DAP	CT	NT	CT	NT	CT	NT
	mg N_2O m^{-2} hr^{-1}					
21	0.21I-P	0.08M-a	1.03C-F*	0.40F-K	0.50E-J*	0.16J-T
28	0.03Y-h	0.01hi	0.04W-g	0.02c-h	0.20I-Q	0.10M-X
35	0.03a-h	0.04V-f	0.07P-c	0.05R-d	0.18I-R	0.05P-c
42	0.08N-b	0.05S-e	0.13K-V	0.07O-c	0.21I-P	0.12L-X
49	0.06P-c	0.05R-d	0.10M-Z	0.06P-c	0.20I-Q	0.10M-X
56	5.80A	1.44B-E*	1.02C-F*	0.27G-M	4.35AB	0.04U-f
63	0.16J-T	0.08N-b	0.17I-S	0.08M-b	0.55E-I*	0.02e-h
70	0.04X-g	0.04U-e	0.14K-U	0.05U-e	0.13K-W	0.10M-Y
77	2.35A-D*	0.75D-H*	3.01A-C	0.12K-X	0.05T-e	0.03Z-h
84	0.10M-X	0.03a-h	0.11L-X	0.00j	0.20I-Q	1.70B-E*
91	0.06P-c	0.03a-h	0.60Q-c	0.01hi	0.01hi	0.00i
98	0.02c-h	0.02b-h	0.02d-h	0.03a-h	0.00j	0.07P-c
105	0.06R-d	0.10M-X	0.25G-N	0.05S-e	0.00j	0.09M-Z
112	0.35F-L	0.10M-X	0.17I-S	0.03a-h	0.04U-e	0.08N-b
118	1.06C-F*	0.78D-G*	2.78A-C	0.23H-O	0.00j	0.01hi
125	0.14K-U	0.13K-U	0.28G-M	0.02c-h	0.04U-e	0.01f-i

* An asterisk denotes a mean nitrous oxide flux that differed from zero ($P < 0.05$)
† Means followed by a letter with the same case do not differ ($P > 0.05$)

Table 4. Analysis of variance summary of the effect of tillage (conventional and no-tillage), site position (up-, mid-, and down-slope), and their interaction on nitrous oxide emissions and emissions intensity for the 2018 and 2019 rice growing seasons and the 2-year cumulative (Cum) emissions and emissions intensity at the Rice Research and Extension Center near Stuttgart, AR.

	Emissions			Emissions Intensity		
Source of Variation	2018	2019	2-Yr Cum	2018	2019	2-Yr Cum
	P					
Tillage	0.087	< 0.001	0.004	0.022	< 0.001	0.002
Site Position	0.080	0.200	0.231	0.957	0.288	0.522
Tillage x Site Position	0.206	0.248	0.517	0.054	0.094	0.497

Table 5. Summary of nitrous oxide (N_2O) emissions and emissions intensity means among tillage [conventional (CT) and no-tillage (NT)]-site position (up-, mid-, and down-slope) treatment combinations from the 2018 and 2019 rice growing seasons and the 2-year cumulative (Cum) emissions and emissions intensity at the Rice Research and Extension Center near Stuttgart, AR.

	Emissions			Emissions Intensity		
Treatment Effect	2018	2019	2-Yr Cum	2018	2019	2-Yr Cum
	kg N_2O ha^{-1} $season^{-1}$			kg N_2O (Mg yield)$^{-1}$		
Tillage						
NT	15.9 B†	3.8 B	20.5 B	3.3 A	0.5 A	1.6 B
CT	24.0 A	13.9 A	39.2 A	6.6 A	2.0 A	3.4 A
Site Position						
Up	15.9 B	10.1 A	26.1 A	4.5 A	1.3 A	2.2 A
Mid	16.4 B	5.6 A	24.5 A	4.5 A	0.8 A	2.1 A
Down	28.7 A	6.9 A	35.6 A	4.9 A	0.9 A	2.7 A

†Means in a column within a treatment effect followed by the same letter do not differ ($P > 0.1$)

Table 6. Monthly weather and irrigation data summary for the 2018 and 2019 rice growing seasons at the Rice Research and Extension Center near Stuttgart, AR. Thirty-year (1981-2010) mean monthly rainfall and air temperature data are also reported for comparison.

Year/ Weather variable	May	June	July	August	September	Growing-season totals
2018						
Rainfall (cm)	3.1	2.7	7.0	13.2	18.3	44.3
Air temperature (°C)	25.3	27.5	27.5	26.0	24.3	-
Irrigation (cm ha^{-1})	0	8.6	2.2	4.6	0	15.4
2019						
Rainfall (cm)	10.3	10.3	17.3	7.3	0.9	46.1
Air temperature (°C)	22.9	25.2	26.6	26.9	27.1	-
Irrigation (cm ha^{-1})	0	1.7	5.7	3.8	0	11.2
30-year normals						
Rainfall (cm)	13.0	8.9	8.7	6.1	6.7	43.4
Air temperature (°C)	21.6	25.9	27.6	27.0	23.1	-

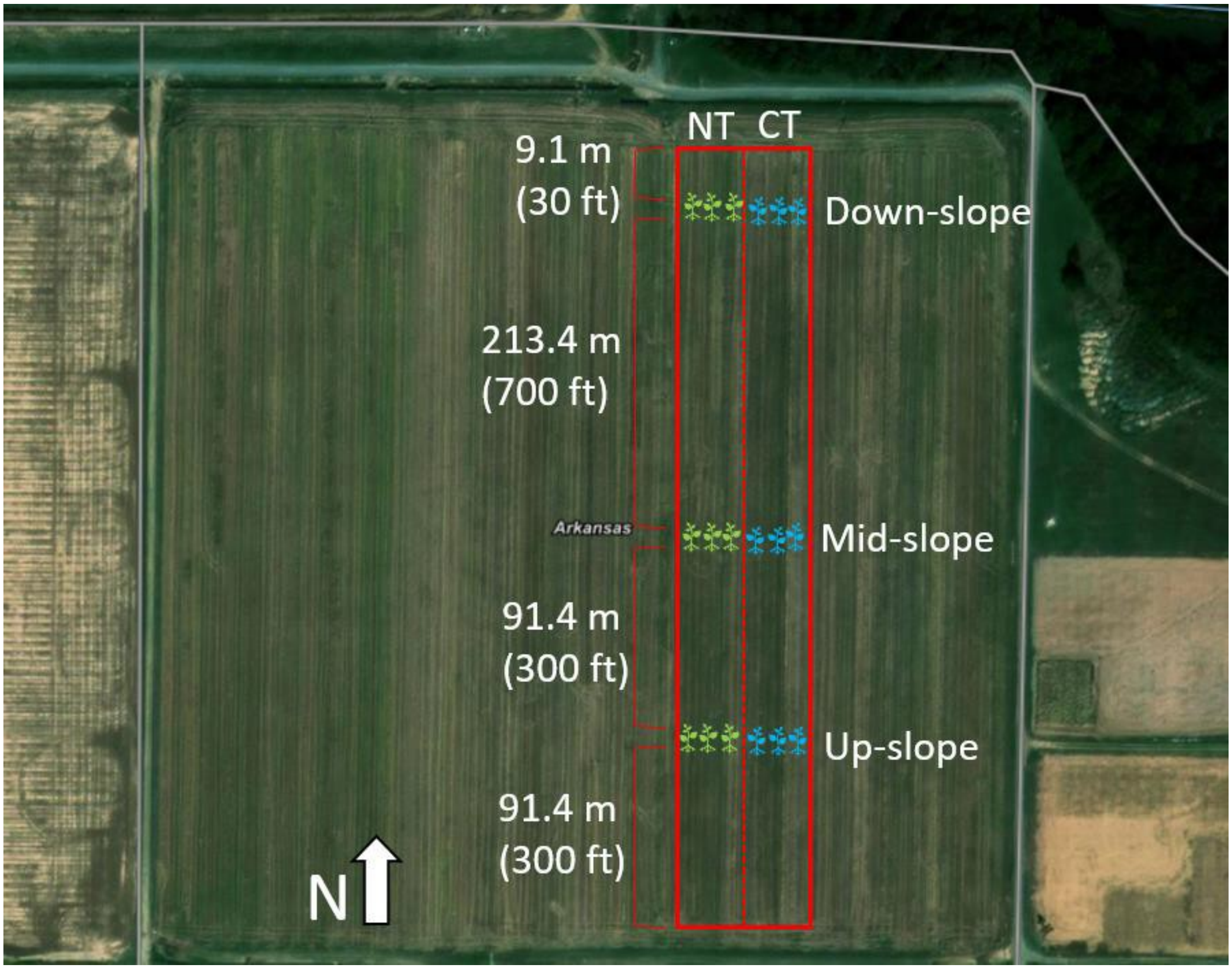

Figure 1. Aerial photo of study field for the 2018 and 2019 rice growing seasons showing the positions and distances between site position (up-, mid-, and down-slope), tillage treatment [conventional (CT) and no-tillage (NT)], and the placement of the 18 total gas sampling chambers at the Rice Research and Extension Center near Stuttgart, AR.

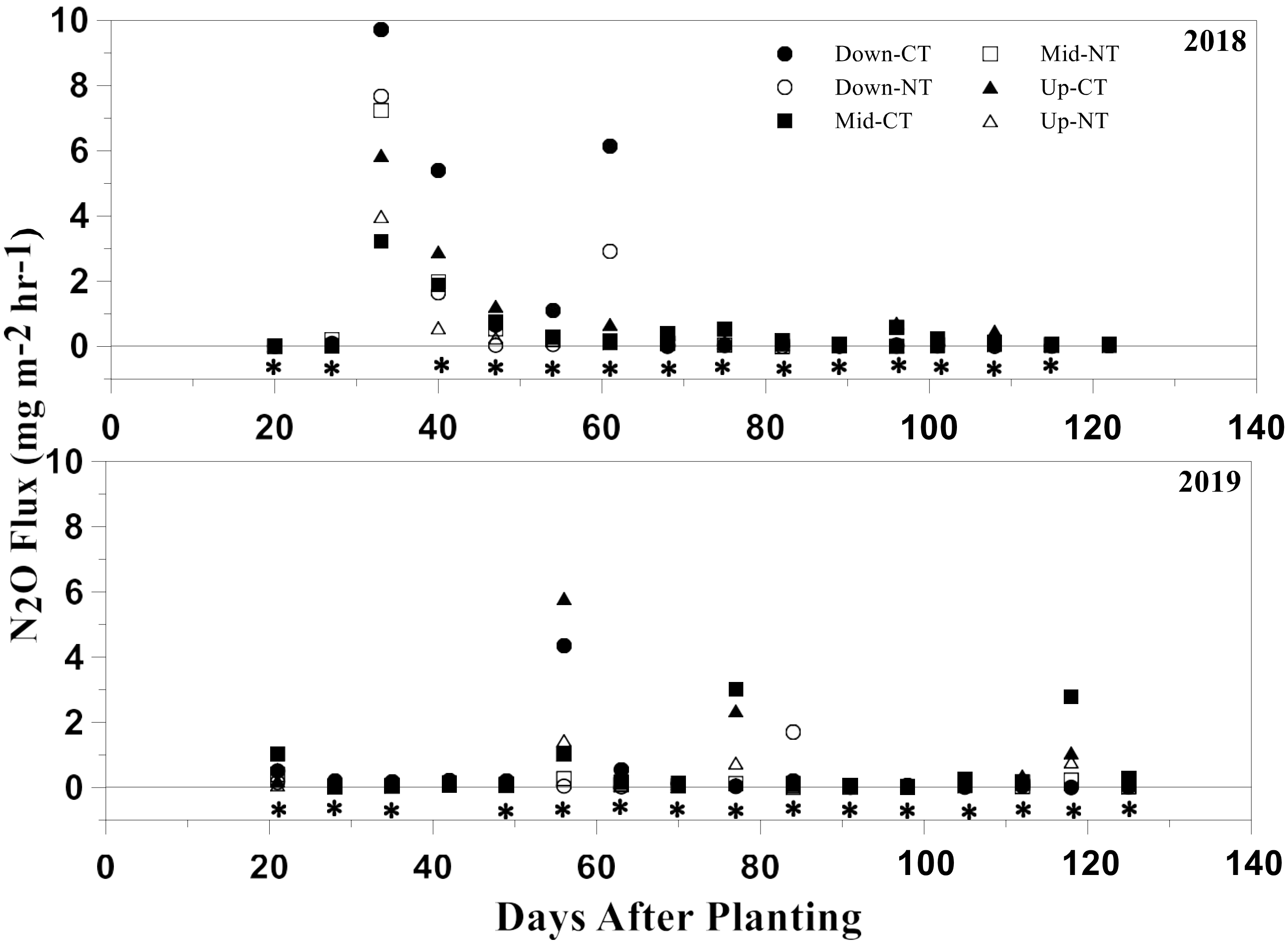

Figure 2. Nitrous oxide (N_2O) fluxes among six site position (up-, mid-, and downslope)-tillage [conventional tillage (CT) and no-tillage (NT)] treatment combinations over time during the 2018 and 2019 rice growing seasons at the Rice Research and Extension Center near Stuttgart, AR. Asterisks below the zero-flux line denotes measurement dates when a significant ($P < 0.05$) treatment difference exists. Nitrogen fertilization occurred at 27 and 34 days after planting in 2018 and 2019, respectively.

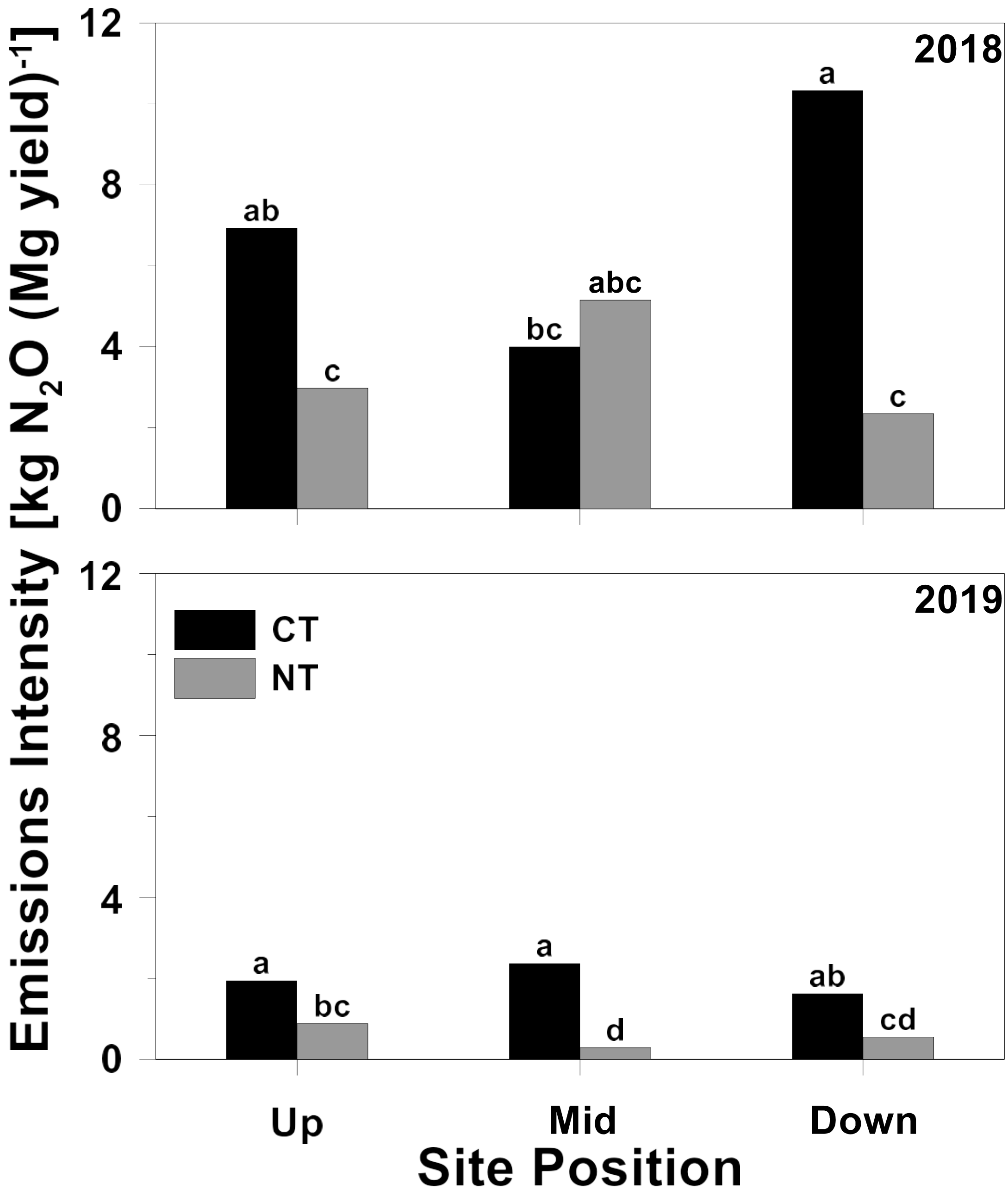

Figure 3. Nitrous oxide (N_2O) emissions intensity among six site position (up-, mid-, and down-slope)-tillage [conventional tillage (CT) and no-tillage (NT)] treatment combinations for both the 2018 and 2019 rice growing seasons at the Rice Research and Extension Center near Stuttgart, AR. Bars within a panel with different letters are different at $P < 0.1$.

Chapter 3

Nitrogen fertilizer application timing effects on nitrous oxide emissions from furrow-irrigated rice on a silt-loam soil

Abstract

Furrow-irrigation represents a growing alternative water management strategy for rice (*Oryza sativa*) production in Arkansas. However, optimal nitrogen fertilization rates and timing for furrow-irrigated rice are still in question. Furthermore, though methane production and release may be minimized with a prolonged flood, concern exists that furrow-irrigated rice may exacerbate nitrous oxide (N_2O) production and release from frequent alternating wet and dry soil conditions. The objective of this study was to evaluate the effects of N-fertilization amount and timing [i.e., 100% of the early season optimum N rate plus one split application (OPOS), 50% of the early season optimum N rate plus two split applications (HOPTS), 100% of the early season plus two split applications (OPTS), and an unamended control (UC)] on N_2O fluxes and season-long emissions in a greenhouse trial simulating a furrow-irrigated rice production system. Gas sampling occurred approximately weekly throughout the 2020 growing season using the closed-chamber approach. Nitrous oxide fluxes differed among fertilizer-N treatments over time ($P <$ 0.01), yet there was no consistent relationship between mid-season fertilizer-N application timing and the timing of peak N_2O fluxes. Nitrous oxide emissions numerically ranged from 0.42 kg N_2O ha^{-1} season^{-1} from the UC to 0.65 kg N_2O ha^{-1} season^{-1} from the OPOS treatment, but, in contrast to N_2O fluxes, did not differ (P = 0.60) among fertilizer-N treatments. Results indicated that the timing of fertilizer-N application was less influencing on season-long N_2O emissions than the total amount of fertilizer-N added. This study contributed to the continuing research into the environmental sustainability of rice production in Arkansas.

Introduction

Rice (*Oryza sativa*) is a staple food for the largest number of people on Earth, including those countries with the greatest populations, such as India and China (Maclean et al., 2013) and demand for rice is expected to increase (USDA, 2019). Rice production is the largest, single use of land for producing food world-wide (Maclean et al., 2013; USDA-FAS, 2020). Globally, China cultivates the largest amount of rice (Shahbandeh, 2020). In the United States (US), Arkansas is the largest rice-producing state, where rice production also occurs in California, Louisiana, Missouri, Texas, and Mississippi (USDA-ERS, 2020).

Rice is a semi-aquatic grass that is traditionally grown under flooded-soil conditions. Consequently, flood-irrigated rice requires a tremendously large amount of water each growing season and surface water or groundwater are the main water sources. In some cases, such as in Arkansas, groundwater needed for irrigation is not being renewed at an equal rate as application, resulting in aquifer levels declining. Arkansas is a large user of groundwater in the US and withdrawals from the Mississippi River Valley Alluvial Aquifer have caused cones of depression up to 30 m deep (USGS, 2005).

In addition to using large quantities of water, flood-irrigated rice is a primary agricultural source of methane (CH_4) emissions. While ebullition and diffusion through the water column can be mechanisms of CH_4 release from the soil to the atmosphere, more than 90% of CH_4 emissions from a rice field occur through the rice plants themselves by transport through the aerenchyma tissue of the rice stems (Neue, 1993; Peyron et al., 2016; Rosenberry et al., 2003). The plant-mediated transport has caused rice to be the leading CH_4-producing cereal crop. Paddy rice cultivation accounts for 9 to 11% of agricultural CH_4 production globally and CH_4 emissions from rice cultivation are predicted to increase 2% by 2030 (EPA, 2012; IPCC, 2014).

The unsustainable nature of current water management practices for rice production in many areas, such as in eastern Arkansas, coupled with the potential environmental implications of CH_4 emissions, have caused that need for alternative water management schemes to be developed for rice production to potentially replace the traditional, full-season-flood approach. Furrow-irrigation is one such relatively new, alternative water management practice being used (Hardke and Chlapecka, 2020; Hefner and Tracy, 1991). In furrow-irrigated rice, water flows down furrows by gravity next to raised beds where the rice is planted and overlaps the top of the beds to water the rice (Hardke and Chlapecka, 2020). Furrow-irrigation avoids purposeful flooding. However, the downslope end of a field will often pond water after some time and behave as if it was flood-irrigated, including stimulating CH_4 production and release from prolonged saturated to flooded-soil conditions (Hardke and Chlapecka, 2020).

The development and testing of new production systems will bring a new set of challenges. The main environmental goals for the future of rice production include increasing water-use efficiency, while maintaining yields and decreasing CH_4 and nitrous oxide (N_2O) emissions, thus decreasing the overall global warming potential (GWP) of rice production systems. In the case of the alternative production methods, less water is applied during the growing season, such that the rice is not under a continuous flood. Research has shown decreased CH_4 emissions from rice grown in unsaturated field conditions (Xu et al., 2014), verifying the fact that the methanogenic process is favored by anaerobic environments and disfavored by oxidizing conditions (Peyron et al., 2016). However, the relationships among soil water content and production of CH_4 and N_2O are complex. While tackling the goal of better water-use efficiency and reducing CH_4 emissions, studies have also shown that introducing aeration to the soil, by means of periodic wet and dry cycles from implementing furrow-irrigation, may stimulate N_2O production (Della Lunga et al., 2020b), thus potentially increasing N_2O emissions over what is produced and emitted from a full-season-flood system. Consequently, the implications of amount and timing of fertilizer-N additions to rice, which are essential for maximum production (Hefner and Tracy, 1991), will be critical to understanding how best to manage furrow-irrigated rice for optimal production as well as minimal greenhouse gas (GHG) emissions.

Urea is the most common fertilizer-N source used in Arkansas due to the large N concentration (46%) and lower cost compared to the other N fertilizers (UA-DA-CES, 2019). However, a drawback to urea is the potential for large NH_3 volatilization losses if not properly managed (UA-DA-CES, 2019). If urea is not incorporated into the soil via tillage or irrigation, urease, an enzyme present in the soil, will break down the urea too quickly and release NH_3 (Rogers, 2014). Urea is commonly used in flooded production systems, as urea is highly soluble, but urea is also readily volatilizable, thus should be applied to a dry soil surface. The field is then flooded to allow the urea to be incorporated into the soil through infiltration, and thus, regulate volatilization losses (Rogers, 2014). For alternative rice production systems like furrow-irrigation, N-(n-butyl) thiophosphoric triamide (NBPT)-coated urea is preferred (UA-DA-CES, 2019). Although more costly compared to uncoated urea, NBPT-coated urea, with the aid of a urease inhibitor, is able to retard the breakdown of urea until the fertilizer can be incorporated into the soil, while still being able to provide the same N concentration as uncoated urea (UA-DA-CES, 2019). In addition to fertilizer-N source, the relationship between fertilizer-N application timing on N_2O emissions in rice has also been evaluated, but the results are still unclear, especially with respect to furrow-irrigation (Feng et al., 2018).

Considering the potential for increased N_2O emissions from furrow-irrigated compared to flood-irrigated rice from the greater frequency of wet-dry cycles, varying the amount and/or timing of fertilizer-N additions may provide a means to minimize N_2O emissions from furrow-irrigated rice. Therefore, the objective of this study was to evaluate the effects of N-fertilization amount and timing [i.e., 100% of the early season optimum N rate plus one split application (optimum plus one split, OPOS), 50% of the early season optimum N rate plus two split applications (half optimum plus two splits, HOPTS), 100% of the early season plus two split applications (optimum plus two splits, OPTS), and an unamended control (UC)] on N_2O fluxes and season-long emissions and plant response from a silt-loam soil in a greenhouse trial simulating a furrow-irrigated rice production system. It was hypothesized that i) treatments receiving 100% of the early season optimum application (OPOS and OPTS) will have earlier peak N_2O fluxes than when half of the early season optimum is applied (HOPTS), ii) greater N_2O emissions will come from the two-split treatments (HOPTS and OPTS) due to the greater frequency of N substrate input to induce nitrification followed by denitrification, and iii) plants under the two-split treatments will have greater total N uptake in the plant tissue due to the greater frequency of N substrate during the vegetative phase, but plants under OPOS and HOPTS will have greater total N grain uptake due to the greater amount of N added during the last fertilizer application.

Materials and Methods

Soil Collection, Processing, and Analyses

On March 8, 2020, 15, 19-L (5-gal) buckets of soil were collected from the top 10 cm of Dewitt silt loam (fine, smectitic, thermic Typic Albaqualfs; USDA-NRCS, 2014) in a field managed for at least the previous five years in a furrow-irrigated rice production system at the Rice Research and Extension Center near Stuttgart, AR. The soil was moist-sieved through a 5-mm mesh screen to simulate conventional tillage (CT), cleaned of any residual vegetation (i.e., roots and crop residue), and air-dried for seven days. Five random sub-samples of the soil were collected for physical and chemical analyses. Air-dried soil was then placed back into the buckets until the soil was ready to be placed in the tubs to prepare for the greenhouse experiment.

Soil sub-samples were oven-dried at 70°C for 48 hours, crushed, and sieved through a 2-mm mesh screen. Particle-size analyses were conducted using a modified 12-hr hydrometer method (Gee and Or, 2002). Soil was prepared in a 1:2 soil mass:water volume suspension for potentiometric measurements of pH and electrical conductivity (EC). Weight-loss-on-ignition after combustion for 2 hr at 360°C was used to determine soil organic matter (SOM) concentration. High-temperature combustion in a VarioMax CN analyzer (Elementar Americas Inc., Mt. Laurel, NJ; Nelson and Sommers, 1996) was used to determine total carbon (TC) and total N (TN) concentrations. All measured soil C was considered to be organic, as soil did not effervesce upon treatment with dilute hydrochloric acid. Extractable soil nutrients (i.e., P, K, Ca, Mg, Fe, Mn, Na, S, Cu, and Zn) were determined by inductively coupled, argon-plasma spectrophotometry after extraction with Mehlich-3 extraction solution in a 1:10 soil mass:solution volume suspension (Tucker, 1992). Measured TC and TN concentrations were used to calculate the soil C:N ratio. Measured soil nutrient, SOM, TC, and TN concentrations were converted to contents (kg or Mg ha^{-1}) using a 10-cm soil depth and an estimated soil bulk density of 1.11 g cm^{-3} (described below). Mean initial soil properties and their variabilities are summarized in Table 1.

Treatments and Experimental Design

Four fertilizer-N amount and timing treatments were evaluated, including: i) 100% of the total optimum N recommendation (146 kg N ha^{-1}; UA-DA-CES, 2017) applied at the 4- to 5-leaf stage, followed by 100% of the recommended mid-season N rate (112 kg N ha^{-1}) applied three weeks after the first application (optimum plus one split, OPOS), ii) 50% of the total optimum N recommendation (78 kg N ha^{-1}) applied at the 4- to 5-leaf stage, followed by 50% two weeks after, followed by 100% of the recommended mid-season N rate applied three weeks after the first application (half optimum plus two splits, HOPTS), iii) 100% of the total optimum N recommendation applied at the 4- to 5-leaf stage, followed by 50% of the recommended mid-season N rate (56 kg N ha^{-1}) two weeks after, followed by 50% of the recommended mid-season N rate applied three weeks after the first application (optimum plus two splits, OPTS), and iv) an unamended control (UC) that received no fertilizer-N addition at any time (Table 2). Each fertilized treatment received a total N application of 258 kg N ha^{-1} according to current recommendations at the time this study was conducted. Recommendations were based on recent results from field and greenhouse trials conducted in Arkansas (Hardke, 2020). However, because plants were in containers and restricted to an approximate 10-cm soil depth, fertilizer amounts added per tub at each timing were increased by 20% (Bouman and Tuong, 2001; Craswell and Vlek, 1979) for an equivalent total-N application of 310 kg N ha^{-1}. In addition, since the beginning of this study, recommended fertilizer-N rates for furrow-irrigated rice production on a silt-loam soil in Arkansas have decreased as more field research data have been obtained (Hardke et al., 2021).

Three soil tubs (i.e., replications) of each of the four treatments were prepared, for a total of 12 tubs. Tubs were arranged on a single greenhouse bench in a randomized complete block design, where each block contained one replication of each of the four treatments randomly organized on the greenhouse bench.

Soil Tub Preparation

On May 16, 2020, air-dried, sieved soil (~ 23,260 g) was evenly distributed, by weight, to a depth of ~ 10 cm into 12 plastic tubs 61.0-cm long by 42.7-cm wide by 19.8-cm tall. Soil in the tubs was then wetted and left to settle for 24 hours. The initial soil bulk density was estimated using the approximate mass of soil in each tub dividing by the approximate volume the soil occupied in the tub (21,000 cm^3), which resulted in approximately 1.11 g cm^{-3}.

On May 18, 2020, tubs were manually seeded at a depth of 0.64 cm with the hybrid rice variety 'RT7311CL' (RiceTec, Inc., Alvin, TX). Using the recommended seeding rate for flood-irrigated, hybrid rice (UA-DA-CES, 2019), a total of 30 seeds were evenly planted in each tub. At the time this experiment was conducted, the recommended seeding rate for furrow-irrigated, hybrid rice was the same for flood-irrigated, hybrid rice (UA-DA-CES, 2019). Within each tub, three rows of 10 seeds were planted along the long length of the tub with 3-cm spacing from the long border of the tub, 8-cm spacing from the short border of the tub, 17-cm spacing between rows, and 4.3-cm spacing between seeds within a row.

Tubs were arranged in a randomized complete block design on a metal bench 4.6-m long by 1.2-m wide by 1.1-m tall in the middle of a greenhouse. The metal framing of the bench was slightly concave in the center, therefore six wooden planks 2.4-m long by 0.18-m wide by 0.04-m thick were placed on the bench for the tubs to be placed on to ensure a level grade. Two planks were placed along the length of the left outer edge of the bench, two planks were placed in the center of the bench, and two planks were placed along the length of the right outer edge of the bench. The greenhouse air temperature was set to be maintained at 29°C. Neither lights nor heat lamps were used for this greenhouse study.

On May 30, 2020, all tubs were fertilized with triple superphosphate (TSP) at a rate of 19.5 kg TSP ha^{-1} (2.68 g TSP tub^{-1}) based on the recommended fertilizer-phosphorus (P) rate for hybrid rice grown in a silt-loam soil and using the measured soil-test P concentration (UA-DA-CES, 2019). On June 17, 2020, potassium (K) was added as muriate of potash [i.e., potassium chloride (KCl)] at a rate of 72.4 kg KCl ha^{-1} (1.94 g KCl tub^{-1}) based on the recommended fertilizer-K rate for hybrid rice grown in a silt-loam soil and using the measured soil-test K concentration (UA-DA-CES, 2019). On July 1, 2020, zinc sulfate ($ZnSO_4$) was applied to the plants via a hand-held, spray bottle with a 1:15 ($ZnSO_4$ mass to water volume) solution. Each tub received five sprays. Weeds were manually removed as needed throughout the duration of the greenhouse experiment.

On June 14, 2020, the first fertilizer-N application was made when the rice was at the 4- to 5-leaf stage, approximately 27 days after planting (DAP; Table 2). On June 28, 2020, the first split application was added to the HOPTS and OPTS treatments (Table 2). On July 5, 2020, the single split application was added to the OPOS treatment, while the HOPTS and OPTS treatments received their second split application (Table 2). No fertilizer N was applied throughout the duration of the experiment for the unamended control.

Base Collar Installation

On June 1, 2020, 14 DAP when the plants were at the ~ 3- to 4-leaf stage, one 30-cm-diameter by 30-cm-tall polyvinyl chloride (PVC) base collar was manually installed in each soil tub to a depth of 10 cm, which was roughly the bottom of the soil layer in the tub. Base collars were beveled at the bottom to facilitate installation. Base collars were set in the tubs to contain three rice rows with approximately seven rice plants total in each collar.

Water Content Measurements

The soil volumetric water content (VWC) within the tubs and base collars was measured daily using a Theta Probe (SM 150, Delta-T Devices Ltd, Cambridge, UK). Two measurements were made within the collar and one was made outside the collar. Based on Della Lunga et al. (2020b), who reported that soil water contents and redox potential had a greater effect on N_2O production than other environmental variables (i.e., soil temperature), an optimal VWC of 0.56 cm^3 cm^{-3} was used as the target VWC for each tub, which was just below saturation of the silt-loam soil used in this study. This nearly saturated water content was specifically used to minimize N_2O emissions by keeping the soil redox potential above the point where nitrate-N would be reduced. The three VWC measurements were averaged and the resulting VWC was converted to a gravimetric water content using the estimated initial soil bulk density (1.11 g cm^{-3}). If the measured water content was lower than optimum, the difference between the target and measured water content was converted to a water volume (mL), which was then measured out in a graduated cylinder and applied to the tub.

N_2O Sampling and Analyses

Gas sampling began on June 9, 2020 and occurred approximately weekly throughout the growing season [i.e., 22, 29, 36, 43, 50, 57, 63, 69, 78, 85, 92, 99, 106, 113, and 120 days after planting (DAP)]. Gas sampling occurred between 0800 and 0900 hours on a given sample date. A 30 cm-diameter, 10-cm tall PVC cap was placed on top of each base collar and the seam covered with a rubber flap to create a sealed, closed-headspace chamber. Two sets of PVC collar extensions, 40- and 60-cm tall, were used as needed during the growing season to facilitate containment of the rice plants once they began growing taller than the base collar. The extensions were attached using the same method as the PVC cap. The underside of the cap had a 2.5-cm^2 fan (MagLev GM1202PFV2-8, Sunon Inc., Brea, CA) to circulate the air in the headspace chamber. A 9-V battery was installed on the top of the cap and connected to the fan by battery straps and wires that passed through the cap without compromising the sealed chamber. Each cap had a 15-cm long, 0.63-cm-inner-diameter copper refrigerator tube mounted horizontally within and on the side of the cap to equilibrate pressure between the headspace chamber and the ambient air. Caps were also equipped with a septum (part #73828A-RB, Voigt Global, Lawrence, KS) inserted into a 12.5-mm-diameter, drilled hole on the top of the cap. One cap had an additional septum where a thermometer was used to document the temperature inside the sealed chamber during sampling. Collars, caps, and extenders were covered with reflective aluminum tape (Mylar metallized tape, CS Hyde, Lake Villa, IL) to reduce temperature fluctuations inside the chamber during sampling.

On each sampling day, gas samples were collected at 0-, 30-, and 60-minute time intervals over the course of 1 hour while the caps sealed the sampling chambers. A 20-mL syringe, equipped with a 0.5-mm-diameter, 25-mm long needle [Beckton Dickson and Co (B-D), Franklin Lakes, NJ], was inserted into the septa to collect 20 mL of headspace gas at each time interval. To allow for an even distribution of gas within the syringe, the syringe was held open for five seconds and then transferred to a pre-capped (20-mm headspace crimp cap; part #5183-4479, Agilent Technologies, Santa Clara, CA), pre-evacuated, 10-mL glass vial (part #5182-0838, Agilent Technologies).

At the beginning of each time interval, the air temperature, relative humidity, and barometric pressure was measured with a portable meteorological station (S/N: 182090284, Control Company, Webster, TX). The height of each chamber (collar plus cap) was also measured from the soil surface or from the top of any temporarily ponded water, if present, to determine the volume of the chamber. After each sampling, the caps, extenders, and rubber stoppers were removed from the base collars until the next gas sampling date.

Vials with collected gas samples were stored at room temperature and analyzed within 48 hours of gas collection. The gas samples were analyzed with a Shimadzu GC-2014 ATFSPL 115V gas chromatograph (GC; Shimadzu North America/Shimadzu Scientific Instruments Inc., Columbia, MD). One set of gas standards was collected in the greenhouse and analyzed for quality control. Each set of standards included concentrations of 0.1, 0.5, 1, 5, and 20 mg N_2O L^{-1}. Nitrous oxide concentrations were measured with an electron capture detector (ECD). Argon gas was used as the reference gas for the ECD and helium gas was used as the carrier gas for sample analysis.

Nitrous oxide fluxes (mg m^{-2} hr^{-2}) for each gas chamber were determined using the change in gas concentrations over the three, 30-min gas sampling intervals (0, 30, and 60 min) as had been done in recent, previous rice studies conducted in Arkansas (Della Lunga et al., 2020b; Humphreys, 2018; Rector et al., 2018a,b; Rogers et al., 2014; Smartt et al., 2016). To calculate the flux for each chamber, the volume of the chamber was multiplied by the slope of the linear regression best-fit line between the gas concentrations and time intervals and then divided by the surface area of the chamber. Using linear interpolation between fluxes, seasonal emissions (kg ha^{-1} $season^{-1}$) were calculated on a chamber-by-chamber basis.

Plant Sampling and Analyses

At the end of the growing season, all rice plants within the base collar were cut to within 2 cm of the soil surface and bagged. The plant roots from each tub were manually separated by washing soil from the roots. All plant matter samples were dried at 55°C for five days and weighed to determine above- and belowground dry matter. The grain from each aboveground dry matter sample was manually separated and weighed to determine yield over-dry yield. A subsample of the grain was pulverized to a powder and analyzed for TN concentration by high-temperature combustion using a VarioMax CN analyzer. Once rice grains were removed, a subsample of the rest of the aboveground dry matter sample as well as a subsample of the belowground dry matter sample were ground and sieved through a 2-mm mesh screen and analyzed for TN concentration by high-temperature combustion using a VarioMax CN analyzer. Nitrogen uptake was calculated separately for the above- and belowground plant and oven-dried grain tissue as the product of the dry matter times the measured tissue N concentration on a chamber-by-chamber basis. Total plant dry matter was calculated as the sum of the dry matter from the above- and belowground plant material plus the grain. Total plant N uptake was calculated as the sum of the N uptake from the above- and belowground plant material plus the grain. Grain yield was corrected to a moisture content of 12% for reporting. Nitrous oxide emissions intensity was also calculated by dividing the season-long N_2O emissions by the moisture-adjusted grain yield on a chamber-by-chamber basis.

Statistical Analyses

Based on a randomized complete block design, a two-factor analysis of variance (ANOVA) was conducted using the PROC GLIMMIX procedure in SAS (version 9.4, SAS

Institute, Inc., Cary, NC) to evaluate the effects of fertilizer-N treatment, sample date, and their interaction on N_2O fluxes over the growing season. A one-factor ANOVA was conducted using the PROC GLIMMIX procedure in SAS to evaluate the effects of fertilizer-N treatment on season-long N_2O emissions, above- and belowground dry matter, N concentration, and N uptake, moisture-adjusted grain yield, grain N concentration, grain N uptake, total plant dry matter and N uptake, and emissions intensity. A beta distribution was used for above- and belowground and grain N concentrations, while all other parameters were analyzed with a gamma distribution. Significance was judged at $P < 0.05$, thus, when appropriate, treatment means were separated by least significant difference at the 0.05 level.

Results and Discussion

N_2O Fluxes

General Trends

In contrast to Slayden et al. (2021), who quantified N_2O fluxes in the field during two consecutive years from furrow-irrigated rice grown on a silt-loam soil in a production-scale field in east-central Arkansas, and Rector et al. (2018a,b), several visual temporal trends in N_2O fluxes occurred among fertilizer-N treatments throughout the 2020 growing season (Figure 1). Both the OPOS and HOPTS treatments had low N_2O fluxes at the beginning, fluxes numerically increased during the middle, and had low fluxes again at the end of the growing season (Figure 1). Nitrous oxide fluxes from the OPTS treatment fluctuated during the season, with numerically greater fluxes primarily in the first half compared to the second half of the season (Figure 1). In contrast, the UC treatment experienced low N_2O fluxes in the beginning and generally numerically increasing fluxes towards the end of the growing season (Figure 1). Of the 60 total measured fluxes, 11 fluxes were greater than 1 mg m^{-2} hr^{-1} and only two fluxes were greater than 2 mg m^{-2} hr^{-1} (Figure 1).

Fertilizer-N Treatment Effects

Nitrous oxide fluxes differed among fertilizer-N treatments over time ($P < 0.01$; Table 3). Of the 60 total measured N_2O fluxes, 42 fluxes differed from a mean flux of zero (Table 4). Peak N_2O fluxes for OPOS, HOPTS, OPTS, and UC were 2.3, 2.1, 2.1, and 1.5 mg m^{-2} hr^{-1}, respectively, which did not differ from one another (Table 4), and occurred at 63, 69, 36, and 92 DAP, respectively (Figure 1). There was no identifiable trend between mid-season fertilizer-N application timing and the timing of peak N_2O fluxes. The lowest N_2O fluxes for all four treatments occurred later in the growing season than the timing of peak fluxes (Figure 1). The lowest N_2O fluxes (< 0.01 mg m^{-2} hr^{-1}) occurred at 106 DAP for the UC treatment was and at 99 and 120 DAP for the OPTS treatment (Figure 1). The lowest N_2O fluxes for the OPOS and HOPTS occurred on the last sampling day (120 DAP) and measured < 0.01 and 0.10 mg m^{-2} hr^{-1}, respectively (Figure 1).

Across the 15 sampling dates, N_2O fluxes differed significantly ($P < 0.05$) among treatments on eight dates (i.e., 22, 36, 63, 69, 85, 99, 106, and 120 DAP; Figure 1, Table 4). At 22 DAP, the mean N_2O flux was numerically largest from the OPTS, which did not differ from that from the OPOS and HOPTS, and was 14 times greater than that from the UC treatment, which did not differ from that from the OPOS and HOPTS treatments (Figure 1, Table 4). At 36 DAP, the mean N_2O flux was also numerically largest from the OPTS, which did not differ from that from the OPOS and HOPTS, and was 11.1 times greater than that from the UC treatment, which did not differ from that from the HOPTS treatment (Figure 1, Table 4). At 63 DAP, the mean N_2O flux was numerically largest from the OPOS, which did not differ from that from the OPTS and HOPTS, and was 8.3 times greater than that from the UC treatment, which did not differ from that from the HOPTS and OPTS treatments (Figure 1, Table 4). At 69 DAP, the mean N_2O flux was numerically largest from the HOPTS, which did not differ from that from the OPOS, and was at least 16.5 times greater than that from the UC and OPTS treatments, which did not differ (Figure 1, Table 4). At 85 DAP, the mean N_2O flux was numerically largest from the OPOS, which did not differ from that from the HOPTS and UC, and was 21 times greater than that from the OPTS treatment (Figure 1, Table 4). In stark contrast to the other sample dates, at 99 DAP, the mean N_2O flux was numerically largest from the UC, which did not differ from that from the OPOS and HOPTS, and was at least 54 times greater than that from the OPTS treatment (Figure 1, Table 4). At 106 DAP, the mean N_2O flux was numerically largest from the HOPTS, which did not differ from that from the OPOS and OPTS, and was at least 42 times greater than that from the UC treatment (Figure 1, Table 4). Similar to at 99 DAP, at 120 DAP, the mean N_2O flux was numerically largest from the UC and was at least 13.5 times greater than that from the OPOS, HOPTS, and OPTS treatments, which did not differ (Figure 1, Table 4).

Within the first nine sample dates, the OPTS treatment had the numerically largest N_2O flux five times among the three N-fertilized treatments, while the HOPTS treatment had the numerically lowest flux four times (Figure 1, Table 4). The OPOS treatment was also numerically greater than the HOPTS five times out of the first nine sampling dates. By increasing the N applied to a tub, the amount of usable substrate for nitrification and denitrification also increased. Therefore, because the OPTS had twice as much N applied as the HOPTS treatment for the first fertilizer application, the OPTS treatment began with a greater amount of N substrate for N_2O production that could be available throughout the first half of the growing season. Subsequently, the OPOS and HOPTS treatments had greater fluxes than the OPTS treatment for the last six sampling dates likely due to the greater N application (7.6 and 7.5 g urea tub^{-1}, respectively) added to the two treatments at the latest fertilization-N application (Table 2).

In a recent 2019 field study, Karki et al. (2021) evaluated N_2O emissions from furrow-irrigated rice with and without cover crops in a Sharkey silty-clay soil (Chromic Epiaquerts; USDA-NRCS, 2013) in northeast Arkansas. The furrow-irrigated treatment without cover crops was fertilized with urea in a three-way split of 82 kg N ha^{-1} prior to the first irrigation, 82 kg N ha^{-1} nine days after the first irrigation, and 50 kg N ha^{-1} 16 days after the first irrigation, for a total of 214 kg N ha^{-1} (Karki et al., 2021). Karki et al. (2021) reported peak N_2O fluxes approximately one week after the first mid-season fertilizer-N application. The peak N_2O fluxes from the three-way split, furrow-irrigated treatment were 1.5 to 2.3 times greater in the more aerated up-slope position, but 2.5 to 4.0 times lower in the down-slope position (Karki et al., 2021) compared to the peak fluxes measured across all four fertilizer-N treatment in the current greenhouse study.

Similar to Karki et al. (2021), Slayden et al. (2021) measured N_2O fluxes in the field throughout the 2018 and 2019 growing seasons from hybrid (214-Gemini in 2018 and CL7311 for 2019) rice cultivars grown with optimal N fertilization (i.e., 168 kg N ha^{-1} total) under CT and no-tillage (NT) and at up-, middle-, and down-slope field positions in a furrow-irrigated production system on a silt-loam soil (Typic Albaqualfs) in east-central Arkansas. Peak N_2O fluxes from the current greenhouse study were most similar peak fluxes measured under NT in 2019, which were the lowest peak fluxes experienced for both the 2018 and 2019 growing seasons (Slayden et al., 2021). However, peak N_2O fluxes in 2018 ranged from 1.7 to 6.6 times greater and up to 3 times greater in 2019 than the peak N_2O fluxes measured from the current greenhouse study. The lower fluxes measured in the current study as compared to Karki et al. (2021) and Slayden et al. (2021) were most likely attributable to the small-scale, controlled environment of the greenhouse that alleviated large soil moisture fluctuations from variable water additions from rainfall and/or irrigation, despite having a greater total fertilizer-N application amount on account of the limited soil in the tubs in the greenhouse study. Furthermore, the greenhouse study was purposefully managed to maintain as uniform soil water content as possible, which also likely contributed to decreased N_2O fluxes compared to measured fluxes from the field studies.

Using a similar 30-cm-dimeter, closed-chamber approach as the current study, Rector et al. (2018b) measured N_2O fluxes throughout the 2017 growing season from a pure-line rice cultivar (CL172) grown with NBPT-coated and non-coated urea (i.e., 118 kg N ha^{-1} total) under CT and NT in a full-season, flood-irrigated production system on a silt-loam soil (Typic Albaqualfs) in east-central Arkansas. Peak N_2O fluxes for rice fertilized with NBPT-coated urea occurred at the end of the growing season [i.e., 55 and 87 days after flood (DAF) for NT and CT, respectively] and peak N_2O fluxes ranged from 24 to 71 times lower than the peak fluxes from the current study (Rector et al., 2018b). However, the Rector et al. (2018b) study was conducted in a flood-irrigated water management scheme with one pre-flood, fertilizer-N application with NBPT-coated urea. As a result, the establishment of the flood directly after N fertilization likely suppressed N_2O production until the end of the season when the flood was removed, and the soil was reaerated before harvest.

Similarly, Rector et al. (2018a) measured N_2O fluxes throughout the 2016 growing season from rice grown under a full-season, flood-irrigated and intermittent-flood production system on a silt-loam soil (Typic Albaqualfs) in east-central Arkansas using the same 30-cm-diameter, closed-chamber approached as used in the current study. Peak N_2O fluxes were also reported at the end of the growing season (i.e., 74 DAF) from the intermittent-flood treatment for both a pure-line (LaKast) and hybrid (XL753) rice cultivar (Rector et al., 2018a), where the intermittent-flood water management system behaves somewhat like a furrow-irrigated system in terms of more wet-dry cycles than the full-season-flood approach. Field plots under both irrigation schemes received a pre-flood and a mid-season fertilizer-N application (i.e., 26 DAF) as NBPT-coated urea, where, approximately one week after N fertilization, the initial flood was established, consequently creating a similar scenario as the flood-irrigation in Rector et al. (2018b) where N_2O production was likely suppressed until the end of the growing season when the soil became reaerated prior to harvest. Rector et al. (2018a) reported that the near-surface soil oxidation-reduction (redox) potential was only in the range for nitrification to occur early in the growing season, thus N_2O production was limited resulting in relatively low N_2O fluxes. Nitrous oxide fluxes reported by Rector et al. (2018a) were numerically greater compared to those reported by Rector et al. (2018b), but both sets of field-measured N_2O fluxes ranged from 4 to 19 times lower than the fluxes measured in the greenhouse in the current study from furrow-irrigation.

Season-long N_2O Emissions

Nitrous oxide emissions numerically ranged from 0.42 kg N_2O ha^{-1} season^{-1} from the UC to 0.65 kg N_2O ha^{-1} season^{-1} from the OPOS treatment, but, in contrast to N_2O fluxes, did not differ (P = 0.60) among N-fertilizer treatments (Table 5). Consequently, N_2O emissions averaged 0.58 kg N_2O ha^{-1} season^{-1} across all four treatments (Table 5).

Nitrous oxide emissions from the current study were most similar to Rector et al. (2018b), who reported N_2O emissions of 0.50 and 0.42 kg N_2O ha^{-1} $season^{-1}$ from flood-irrigated rice grown under NT and CT, respectively, fertilized with NBPT-coated urea (Rector et al., 2018b). Flood-irrigation is known to suppress N_2O production because the soil becomes too anaerobic for nitrification occur, while flood-irrigation is known for stimulating CH_4 production and emissions.

The previous studies in which alternative water management schemes to flood-irrigation were used (i.e., Rector et al., 2018a; Karki et al., 2021; Slayden et al., 2021) reported greater season-long N_2O emissions than those from the current greenhouse study with furrow-irrigation. Rector et al. (2018a) reported N_2O emissions most similar to the current study, where the intermittent-flood irrigation/pure-line treatment was less than two times greater than the mean N_2O emissions among the four N-fertilizer treatments, while the intermittent-flood irrigation/hybrid treatment had N_2O emissions that ranged from two to three times greater than season-long emissions measured in the current greenhouse study with a pure-line cultivar grown under furrow-irrigation. Season-long N_2O emissions from the current greenhouse study ranged from 3.6 to 28 times lower compared to N_2O emissions from the furrow-irrigated, three-way split fertilization treatment reported in the field study Karki et al. (2021) on a clayey soil. Compared to N_2O emissions from both the NT and CT treatments reported in Slayden et al. (2021), emissions from the current greenhouse study ranged from 4.2 to 7.5 (2018) and 2 to 6 (2019) times lower.

The closely managed soil water content, to achieve as uniform soil water content as possible throughout the growing season, was likely responsible for the low magnitude of N_2O emissions in the current greenhouse study. The ability to keep the soil moisture content within a certain range, where neither nitrification nor denitrification would be triggered, is likely what kept N_2O emissions much lower than N_2O emissions measured in the field under furrow-irrigation, which were also subject to a myriad of other environmental influences. Consequently, from a management perspective, irrigating more frequently with potentially less water to maintain a more uniform soil water content over time may be a strategy to minimize N_2O losses from furrow-irrigated rice compared to less-frequent irrigations with greater water volumes that perpetuate the cycle of soil wetting and drying that is known to exacerbate N_2O production and emissions (Della Lunga et al., 2020a).

The lack of a fertilizer-N-timing effect in this study was not surprising considering that the total fertilizer-N amount applied was the same among the three N-fertilized treatments. However, it was surprising that the UC treatment, which received no fertilizer-N application, did not result in significantly lower N_2O emissions compared to the three N-fertilized treatments. The result suggests that native soil N, either present in the soil from the beginning of the growing season or mineralized from SOM during the growing season, still has potential to be nitrified then denitrified under warm, nearly saturated soil conditions. Though not included in the study, applying all fertilizer-N at once, rather than in any split application, may save a producer some time and labor costs if it can be documented that there is little to no negative effect on rice yield. Despite the rather low magnitude of season-long N_2O emissions measured in the current study, it must be remembered that N_2O is approximately 10 times more potent of a GHG in the atmosphere than CH_4 and approximately 300 times more potent than carbon dioxide (IPCC, 2014).

Plant Response and Emissions Intensity

Rice yields differed among fertilizer-N treatments ($P < 0.01$), where rice yield was numerically largest from the HOPTS treatment (11.3 Mg ha^{-1}), but did not differ among the three N-fertilized treatments, all of which had yields that were at least 9.7 times greater than from the non-N-fertilized control (0.9 Mg ha^{-1}; Table 5). Rice yields did not differ among the three N-fertilized treatments on account of uniform total fertilizer-N application among each. Similarly, rice grain yields from three recent studies conducted on a furrow-irrigated, Dewitt silt-loam soil in Arkansas did not differ among different urea fertilizer-N treatments (Henry et al., 2019; Kandpal and Henry, 2017; Pickelmann et al., 2018). Rice yields from all three N-fertilized treatments grown in tubs in the greenhouse ranged from 77 to 99.6% of the yield from a similar hybrid cultivar grown in 2019 in the field under flood-irrigated conditions on the same soil as used in this greenhouse experiment (11.3 Mg ha^{-1}) as reported from the annual rice cultivar testing program in Arkansas (Hardke, 2019).

Rice yields from the current greenhouse study were also approximately two times greater than yields for both the 2018 and 2019 growing seasons reported by Slayden et al. (2021) in the field. Unlike the current study, the field study of Slayden et al. (2021) experienced an abundance of weeds and little precipitation during the 2018 growing season, which contributed to relatively low rice yields. Furthermore, the field study was managed with a single pre-irrigation fertilizer-N application (i.e., 168 kg N ha^{-1}) compared to the split applications applied in the current study. Splitting N applications, as was done in the current study, allowed for more efficient N uptake during the vegetative growth stages of the rice crop (Chlapecka et al., 2020; Hardke and Chlapecka, 2020). Yields reported in the current greenhouse study under simulated furrow-irrigation were similar to yields reported from other field studies examining N_2O emissions, specifically Karki et al. (2021) under furrow-irrigation on a clay soil and Rector et al. (2018a,b) under flood-irrigation on a silt-loam soil.

Similar to yields, above- and belowground and total dry matter (DM), above- and belowground N uptake, grain N concentration and uptake, and total N uptake all differed ($P < 0.01$) among fertilizer-N treatments (Table 5). Above- and belowground and total DM did not differ among N-fertilized treatments, averaging 18.1, 12.2, and 40.5 Mg ha^{-1}, respectively, but were 2.5, 4.8, and 3.4 times, respectively, greater than that from the non-N-fertilized control (Table 5). The non-N-fertilized nature of the unamended control treatment used in this study was expected to result in poor rice growth compared to N-fertilized treatments. The uniform total fertilizer-N added among N-fertilized treatments clearly influenced rice DM more than the timing of fertilizer-N applications.

Della Lunga et al. (2021b) conducted a field study under furrow-irrigation with CT and NT and with the same rice cultivar as used in the current greenhouse study and reported numerically lower aboveground DM than in the current study, which was likely due to a lower plant-stand density experienced in the field compared to in the greenhouse environment. A 2019 study, conducted in a greenhouse setting, evaluated the effect of soil moisture regime (moist, slightly below saturation, and flooded) on plant properties and greenhouse gas emissions from a hybrid rice cultivar (RT7311CL) on a silt-loam soil (Della Lunga et al., 2020a). The slightly-below-saturation water regime closely resembled the water regime used in the current study. Della Lunga et al. (2020a) reported belowground DM more than two times greater than that reported in the current study. Unlike the current study, where rice was irrigated daily, rice in Della Lunga et al. (2020a) was irrigated on an alternate day schedule, which allowed for a more aerobic environment, thus promoting more root growth than what is expected in the likely oxygen-limited soil environment of the current study with nearly continuously saturated, but not flooded, soil. However, aboveground DM from the current study was similar to that reported in Della Lunga et al. (2020a).

In contrast to DM, above- and belowground N concentrations did not differ ($P > 0.05$) among fertilizer-N treatments, averaging 0.011 and 0.004 g g^{-1}, respectively, across all four treatments (Table 5). However, the variations in DM and N concentrations among individual replications resulted in differences in above- and belowground N uptake among fertilizer-N treatments (Table 5). Similar to yield and belowground DM, belowground N uptake did not differ among the three N-fertilized treatments, averaging 46.5 kg ha^{-1}, but was at least four times greater than that from the non-N-fertilized control (Table 5). In contrast to aboveground DM and belowground N uptake, aboveground N uptake in the HOPTS was 1.6 times greater than that in the OPTS treatment, while aboveground N uptake in the OPOS treatment was intermediate and similar to that in both the HOPTS and OPTS treatments (Table 5). Aboveground N uptake from the OPOS and OPTS treatments, which did not differ, was at least 2.8 times greater than that from the non-N-fertilized control (Table 5).

The efficiency of N uptake from the soil into rice plants is affected by cultural system, rice cultivar, soil texture, soil moisture, and several other factors (i.e., fertilizer-N rate and fertilizer-N type; UA-DA-CES, 2018). The numerically largest aboveground N uptake from the HOPTS treatment can be attributed to the relationship between fertilizer-N application and the stage of vegetative growth (UA-DA-CES, 2019). At the time of the second N application, the HOPTS treatment had only received half of the optimum, early season N rate, leaving the rice plants in the HOPTS treatment at a slight N deficit compared to the other two N-fertilized treatments. Therefore, N uptake following the second fertilizer-N application was likely greatest in the HOPTS treatment. Nitrogen uptake has been reported to continue to increase until the tillering stage (Ramanathan and Krishnamoorthy, 1973), which coincided with the second fertilizer-N application. During the vegetative growth phase, plant N is stored in the stem and leaf tissues, but plant N is subsequently transported throughout the plant during periods of N deficit or during specific growth stages, such as grain filling (UA-DA-CES, 2019), to potentially result in differential grain-N concentrations due to fertilizer-N treatment differences.

In contrast to above- and belowground tissue N concentrations, but similar to rice yield and above- and belowground DM, rice grain N concentration did not differ among N-fertilized treatments, averaging 0.02 g g^{-1}, but was at least 1.2 times greater than that in the non-N-fertilized control (Table 5). Grain-N concentrations from all treatments in the current greenhouse study, including the UC, were numerically greater than those reported by Della Lunga et al. (2021b) for furrow-irrigated, hybrid rice grown under CT and NT in a soil-loam soil. The self-contained tubs used in the greenhouse for the current study did not allow for any runoff or leaching losses of N, as could potentially occur in the field, therefore retaining all possible N inputs throughout the growing season.

Following the differences in grain-N concentration, grain-N uptake did not differ among N-fertilized treatments, averaging 184.2 kg ha^{-1}, but was at least 4.4 times greater than that in the non-N-fertilized control (Table 5). Grain-N uptake in the current study was three to four times greater than that measured in the field in 2018 under CT using the same hybrid rice cultivar as used in the current study, but the total fertilizer-N only about half of what was used in the current study (Della Lunga et al., 2021b). Furthermore, the adaptability of hybrid rice cultivars to biotic and abiotic stressors likely at least partially explains the lack of difference between belowground and grain N uptake among the three N-fertilized treatments (Della Lunga et al., 2021b).

As the sum of above- and belowground and grain N uptake, differences in total plant N uptake followed the differences in aboveground N uptake among treatments (Table 5). Total N uptake in the HOPTS was 1.5 times greater than that in the OPTS treatment, while total N uptake in the OPOS treatment was intermediate and similar to that in both the HOPTS and OPTS treatments (Table 5). Total N uptake from the OPOS and OPTS treatments, which did not differ, was at least 3.4 times greater than that from the non-N-fertilized control (Table 5). During grain filling, the grain increases in size and weight due to translocated carbohydrates (i.e., sugars and starch) from the culms and leaf sheaths, where approximately 60% of the carbohydrates are produced from photosynthesis, leaving approximately 40% for the grain (UA-DA-CES, 2019). Similarly, grain-N uptake measured in the current study ranged from 39.3 to 42.6% of the total N uptake (Table 5), confirming the plant-N dynamics achieved from rice grown in the greenhouse in the current study followed what is expected from rice grown in the field.

Similar to rice yields and numerous other rice property responses, N_2O emissions intensity differed (P = 0.02) among fertilizer-N treatments (Table 5). Emissions intensity was at least 2.7 times greater from the UC (0.19 kg N_2O Mg yield^{-1}) than from the N-fertilized treatments, which did not differ from one another and averaged 0.06 kg N_2O Mg yield^{-1} (Table5). Emissions intensities associated with the N-fertilized treatments from the current greenhouse study were similar to those reported by Rector et al. (2018b), which averaged 0.06 kg N_2O Mg yield^{-1} for both NT and CT treatments under flood-irrigation. However, the emissions intensity under intermittent-irrigation of a hybrid cultivar reported in Rector et al. (2018a) was approximately 1.7 times greater than that from the current study. The similar N_2O emissions and greater emissions intensity from the non-N-fertilized control compared to the N-fertilized treatments underscores that even mineralized N from native SOM throughout a rice growing season is just as susceptible to nitrification followed by denitrification to be lost to the atmosphere as N_2O, and contribute to an agroecosystem's GWP, as fertilizer-derived N under the right soil conditions.

Conclusions

The main environmental goals for the future of rice production should include increasing water-use efficiency, while maintaining yields, and decreasing CH_4 and N_2O emissions, thus decreasing the overall GWP of rice production systems. Alternative water management practices, such as furrow-irrigation, use less water (Liu et al., 2016) and emit less CH_4 than flood-irrigation (Liu et al., 2016), but the environmental impact with respect to N_2O emissions from furrow-irrigated rice is not fully known. The implications of amount and timing of fertilizer-N additions to rice, which are essential for maximum production, will be critical to understanding how best to manage furrow-irrigated rice for optimal production, as well as minimizing GHG emissions. Consequently, this study aimed to evaluate the effects of N-fertilization amount and timing on N_2O fluxes and season-long emissions and plant response from a silt-loam soil in a greenhouse trial simulating a CT, furrow-irrigated rice production system.

As hypothesized, both the OPOS and HOPTS treatments had relatively low N_2O fluxes at the beginning, numerically increasing fluxes during the middle, and had relatively low fluxes again at the end of the growing season. Nitrous oxide fluxes from the OPTS treatment fluctuated during the season, with numerically greater fluxes primarily in the first half compared to the second half of the season. Nitrous oxide emissions numerically ranged from 0.42 kg N_2O ha^{-1} $season^{-1}$ from the UC to 0.65 kg N_2O ha^{-1} $season^{-1}$ from the OPOS treatment, but, contrary to what was hypothesized, did not differ among N-fertilizer treatments. This result indicated that the timing of fertilizer-N application was less influencing on season-long N_2O emissions than the total amount of fertilizer-N added, which was uniform among the N-fertilized treatments. The similarity in season-long emissions from the non-N-fertilized control compared to the N-fertilized treatments highlights how native soil N is just as susceptible to N_2O loss as fertilized-derived N.

Though rice yield was similar among the N-fertilized treatments, aboveground and total N uptake were only numerically greater from the HOPTS than the OPOS treatment, but was significantly greater than that from the OPTS treatment, which only partially supported the original hypothesis that rice under the two-split treatments will have greater total N uptake. In contrast to that hypothesized, grain-N uptake did not differ among N-fertilized treatments.

In order to reduce GHG emissions, namely N_2O, from furrow-irrigated rice systems, it is essential to practice proper fertilizer-N and water management. Avoiding over-application of fertilizer-N can help reduce unnecessary N losses from a production system. Furthermore, managing irrigation water inputs to reduce soil water content fluctuations also appears to be a useful potential strategy to minimize N_2O emissions. The ability to maintain a stable soil water content minimized denitrification from occurring. Further studies must continue to evaluate the environmental effects of alternative rice management practices to maintain sustainable rice production systems in the US.

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Tables and Figures

Table 1. Summary of mean [± standard error (SE)] soil physical and chemical properties (n = 5) of the silt-loam soil use for the greenhouse experiment.

Soil Property	**Mean (± SE)**
Sand (g g^{-1})	0.14 (0.01)
Silt (g g^{-1})	0.73 (0.01)
Clay (g g^{-1})	0.13 (0.05)
pH	6.0 (0.03)
Electrical conductivity (dS m^{-1})	0.11 (0.01)
Extractable soil nutrients (kg ha^{-1})	
Phosphorus	14.7 (0.7)
Potassium	125.7 (3.2)
Calcium	759.7 (19)
Magnesium	122.0 (2.5)
Sulfur	8.8 (0.8)
Sodium	36.0 (1.6)
Iron	181.6 (3.0)
Manganese	262.5 (3.3)
Zinc	14.8 (0.3)
Soil organic matter (Mg ha^{-1})	18.1 (0.13)
Total carbon (Mg ha^{-1})	7.21 (0.10)
Total nitrogen (Mg ha^{-1})	0.77 (0.01)
Carbon:nitrogen ratio	9.42 (0.11)

Table 2. Summary of the rate and timing of N-(n-butyl) thiophosphoric triamide (NBPT)-coated urea for four nitrogen (N) fertilization treatments added to tubs of a silt-loam soil managed in the greenhouse to mimic a furrow-irrigated rice production system.

Treatment	4- to 5-leaf Stage	Weeks After First Application 1	2	3	Total†
	g urea tub^{-1}				
Optimum plus one split	9.9	0	0	7.6	17.5
Half optimum plus two splits	5.0	0	5.0	7.5	17.5
Optimum plus two splits	9.9	0	3.8	3.8	17.5
Unamended control	0	0	0	0	0
	kg N ha^{-1}				
Optimum plus one split	177	0	0	133	310
Half optimum plus two splits	89	0	89	132	310
Optimum plus two splits	177	0	66.5	66.5	310
Unamended control	0	0	0	0	0

† The 17.5 g urea tub^{-1} were equivalent, on an area basis, to a field fertilization rate of 258 kg N ha^{-1} plus 20% on account of the limited soil depth in the tubs (~10 cm) for a total of 310 kg N ha^{-1}

Table 3. Analysis of variance summary of the effect of fertilizer-nitrogen treatment, days after planting (DAP), and their interaction on nitrous oxide fluxes from rice grown in a silt-loam soil under furrow-irrigation in the greenhouse.

Source of Variation	*P*
Treatment	< 0.01
DAP	< 0.01
Treatment*DAP	< 0.01

Table 4. Summary of nitrous oxide flux means among fertilizer-nitrogen (N) [i.e., optimum plus one split (OPOS), half optimum plus two splits (HOPTS), optimum plus two splits (OPTS), and unamended control (UC)] and days after planting (DAP) treatment combinations from rice grown in a silt-loam soil under furrow-irrigation in the greenhouse.

	Fertilizer-N Treatments			
DAP	**OPOS**	**HOPTS**	**OPTS**	**UC**
	$mg\ m^{-2}\ hr^{-1}$			
22	0.53a-h[†]*	0.24c-h*	1.26a-d*	0.09hi
29	0.61a-h*	0.61a-h*	0.78a-f*	0.18d-i
36	1.66a-c*	0.33a-h*	2.11ab*	0.19d-i
43	0.50a-h*	0.59a-h*	0.55a-h*	0.22c-i
50	0.42a-h*	0.23c-i	1.35a-d*	0.33a-h*
57	0.18d-i	0.94a-e*	0.54a-h*	0.51a-h*
63	2.33a*	1.90ab*	0.67a-g*	0.28b-h*
69	0.73a-g*	2.15ab*	0.13e-i	0.03i
78	1.06a-d*	0.78a-f*	1.20a-d*	0.38a-h*
85	0.62a-h*	0.31a-h*	0.03i	0.39a-h*
92	0.38a-h*	0.25c-h*	0.22c-i	1.48a-c*
99	0.29b-h*	0.34a-h*	< 0.01j	0.54a-h*
106	0.10f-i	0.42a-h*	0.13e-i	< 0.01j
113	0.48a-h*	0.24c-h*	0.19d-i	0.74a-g*
120	< 0.01j	0.10g-i	< 0.01j	1.35a-d*

* An asterisk denotes a mean nitrous oxide flux that differed from zero ($P < 0.05$)

[†] Means followed by a letter with the same case do not differ ($P > 0.05$)

Table 5. Analysis of variance summary and mean season-long nitrous oxide (N_2O) emissions, rice yield, above- and belowground and total dry matter (DM), above- and belowground nitrogen (N) concentration and uptake, grain N concentration and uptake, total N uptake, and N_2O emissions intensity for four fertilizer-N treatments [i.e., optimum plus one split (OPOS), half optimum plus two splits (HOPTS), optimum plus two splits (OPTS), and unamended control (UC)] from rice grown in a silt-loam soil under furrow-irrigation in the greenhouse.

		Fertilizer-N Treatments				**Overall**
Property	***P***	**OPOS**	**HOPTS**	**OPTS**	**UC**	**Mean**
Emissions (kg ha^{-1} $season^{-1}$)	0.60	0.65 a	0.63 a	0.61 a	0.42 a	0.579
Yield (Mg ha^{-1})	< 0.01	11.1 a	11.3 a	8.7 a	0.9 b	-
Aboveground DM (Mg ha^{-1})	< 0.01	19.0 a	19.3 a	16.1 a	6.4 b	-
Belowground DM (Mg ha^{-1})	< 0.01	11.6 a	13.3 a	13.3 a	2.4 b	-
Total DM (Mg ha^{-1})	< 0.01	41.0 a	43.4 a	37.1 a	11.0 b	-
Aboveground N (g g^{-1})	0.06	0.012 a	0.014 a	0.011 a	0.009 a	0.011
Belowground N (g g^{-1})	0.49	0.004 a	0.004 a	0.003 a	0.004 a	0.004
Aboveground N (kg ha^{-1})	< 0.01	221.6 ab	267.5 a	170.3 b	61.0c	-
Belowground N (kg ha^{-1})	< 0.01	47.3 a	49.0 a	43.1 a	10.7 b	-
Grain N (g g^{-1})	< 0.01	0.020 a	0.020 a	0.019 a	0.016 b	-
Grain N (kg ha^{-1})	< 0.01	201.7 a	205.1 a	145.9 a	33.5 b	-
Total N (kg ha^{-1})	< 0.01	473.7 ab	521.9 a	358.9 b	105.0 c	-
Intensity (kg N_2O Mg $yield^{-1}$)	0.02	0.06 b	0.06 b	0.07 b	0.19 a	-

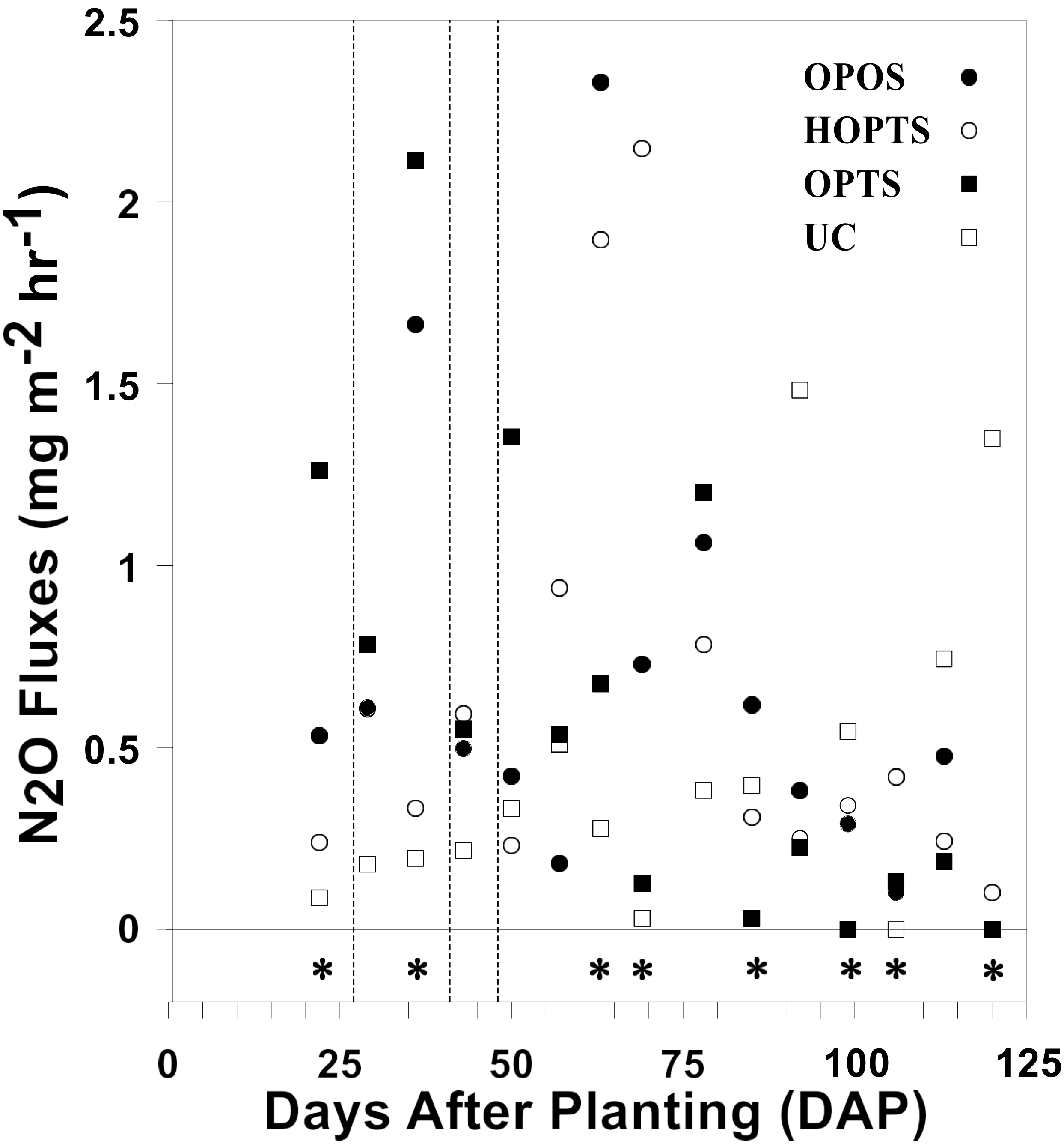

Figure 1. Nitrous oxide (N_2O) fluxes for four fertilizer-nitrogen treatments [i.e., optimum plus one split (OPOS), half optimum plus two splits (HOPTS), optimum plus two splits (OPTS), and unamended control (UC)] over time from rice grown in a silt-loam soil under furrow-irrigation in the greenhouse. Asterisks below the zero-flux line denote measurement dates when a significant ($P < 0.05$) treatment difference exists. Dashed lines indicate the day of nitrogen fertilizer application (i.e., 27, 41, and 48 days after planting).

Thesis Conclusions

Previous research has evaluated potential environmental impact of rice production systems, but mainly in flooded-soil conditions. Factors like tillage, water management regime, and fertilizer application in relation to GHG have been studied. However, the spatial variability of N_2O fluxes and emissions from furrow-irrigated rice has not been well-documented yet, specifically in relation to best management practices. Therefore, the current study focused on the quantification of N_2O fluxes and season-long emissions from rice cultivation in field and greenhouse settings in relation to tillage (i.e., CT, NT), site position (i.e. up-, mid-, and down-slope), and fertilizer application timing.

In the field study, N_2O fluxes were measured and season-long emissions were estimated from the up-, mid-, and down-slope positions under NT and CT management over the 2018 and 2019 growing seasons from a production-scale, furrow-irrigated rice field on a silt-loam soil in east-central Arkansas. In contrast to that hypothesized, N_2O fluxes differed between tillage treatments over time in both growing seasons, with CT having consistently numerically greater fluxes than NT. Though N_2O fluxes were hypothesized to be greater from the up- and mid-compared to the down-slope position, N_2O fluxes differed among site position-tillage treatment combinations over time in both growing seasons and fluxes were often numerically larger from the down-slope position in the drier 2018 growing season, but often numerically larger from the up- and mid-slope positions in the wetter 2019 growing season. Thus, in contrast to tillage treatment, there was little consistent effect of site position on N_2O fluxes over the furrow-irrigated rice growing season.

In contrast to that hypothesized, season-long N_2O emissions were consistently at least numerically greater from CT than from NT. Although it was hypothesized that the mid- and up-slope positions would be greater, season-long N_2O emissions were greater from the down-slope position in the drier 2018 growing season but were unaffected by site position in the wetter 2019 growing season.

In the greenhouse trial, as hypothesized, both the OPOS and HOPTS treatments had relatively low N_2O fluxes at the beginning, numerically increasing fluxes during the middle, and had relatively low fluxes again at the end of the growing season. Nitrous oxide fluxes from the OPTS treatment fluctuated during the season, with numerically greater fluxes primarily in the first half compared to the second half of the season. Nitrous oxide emissions numerically ranged from 0.42 kg N_2O ha^{-1} $season^{-1}$ from the UC to 0.65 kg N_2O ha^{-1} $season^{-1}$ from the OPOS treatment, but, contrary to what was hypothesized, did not differ among N-fertilizer treatments. This result indicated that the timing of fertilizer-N application was less influencing on season-long N_2O emissions than the total amount of fertilizer-N added, which was uniform among the N-fertilized treatments. The similarity in season-long emissions from the unamended control compared to the N-fertilized treatments highlights how native soil N is just as susceptible to N_2O loss as fertilized-derived N. Though rice yield was similar among the N-fertilized treatments, aboveground and total N uptake were only numerically greater from the HOPTS than the OPOS treatment, but were significantly greater than that from the OPTS treatment, which only partially supported the original hypothesis that rice under the two-split treatments will have greater total N uptake. In contrast to that hypothesized, grain-N uptake did not differ among N-fertilized treatments.

Nitrous oxide fluxes and emissions are notoriously challenging to accurately quantify in agricultural settings because of the many environmental factors that influence the nitrification and denitrification processes and their large temporal and spatial variabilities. However, the greater potency of N_2O as a GHG, relative to CO_2 and CH_4, substantiates the critical need to quantify trace gas emissions and their impacts on the GWP of various production systems that occupy large areas in many agricultural regions. Consequently, further investigation is still required to achieve the most accurate representation of the long-term implications and environmental sustainability and to better understand the agronomic, climatic, and soil- and plant-property effects on N_2O fluxes and emissions in the emerging furrow-irrigated water management system in areas of concentrated rice production, such as in the Lower Mississippi River Valley.