



## Tillage and Coated-Urea Effects on Nitrous Oxide Emissions from Direct-Seeded, Delayed-Flood Rice Production in Arkansas

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### Abstract

Rice (*Oryza sativa* L.) is a key component of the diet of billions of humans, thus rice is a main agricultural product in many regions, particularly in eastern Arkansas, USA. Rice production is known to be a source of greenhouse gases, namely methane (CH<sub>4</sub>), but, under certain conditions, nitrous oxide (N<sub>2</sub>O) as well. The objective of this study was to evaluate the effects of tillage practice [conventional tillage (CT) and no-tillage (NT)] and urea fertilizer type [N-(n-butyl) thiophosphoric triamide (NBPT)-coated and non-coated urea] on N<sub>2</sub>O fluxes, season-long N<sub>2</sub>O emissions, and the global warming potential (GWP) from rice grown in eastern Arkansas in a direct-seeded, delayed-flood production system on a silt-loam soil. Gas samples were collected from enclosed chambers at 20-min intervals for 1 hr on a weekly basis between establishment of a full-season flood and four days after end-of-season flood release. Nitrous oxide fluxes were unaffected ( $P > 0.1$ ) by tillage practice, urea fertilizer type, or time throughout the 2017 rice growing season. Nitrous oxide emissions ranged from 0.27 to 0.50 kg N<sub>2</sub>O-N ha<sup>-1</sup> season<sup>-1</sup> from the NT/NBPT-coated urea and NT/non-coated urea treatment combinations but were unaffected ( $P > 0.1$ ) by tillage practice or fertilizer type. Total global warming potential (GWP) ranged from 1324 to 2204 kg CO<sub>2</sub>-equivalent ha<sup>-1</sup> season<sup>-1</sup> from the CT/NBPT-coated urea and NT/non-coated urea treatment combinations but was also unaffected ( $P > 0.05$ ) by tillage practice or urea fertilizer type. However, though not significant ( $P > 0.05$ ), averaged across tillage treatments, GWP was 14.2% numerically lower from NBPT-coated than from non-coated urea. With limited studies in Arkansas evaluating the impacts of tillage practice or urea fertilizer type on N<sub>2</sub>O emissions, it is important to quantify and evaluate potential agronomic factors affecting N<sub>2</sub>O emissions from rice production to properly determine if changing to alternative management practices for improved soil health (i.e., no-tillage) or to limit ammonia volatilization (i.e., NBPT-coated urea) will impact N<sub>2</sub>O emissions.

### Keywords

Conventional tillage, No-tillage, Greenhouse gas emissions, Silt-loam

### Introduction

The uncommon use flood irrigation during the growing season for rice production, compared to upland grain crops [i.e., soybean (*Glycine max* L.), corn (*Zea mays* L.), and wheat (*Triticum aestivum* L.)], can be viewed as both beneficial and detrimental to the environment. Anaerobic soil conditions in flood-irrigated rice production can increase soil nutrient availability and facilitate weed management, but at the same time can lead to the unintended production of greenhouse gases (GHG), such as methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O).

Nitrous oxide, along with CH<sub>4</sub>, is a common and po-

tent GHG produced and emitted from soils used for rice production as a consequence of water management practices. Between 1700 and the present, atmospheric N<sub>2</sub>O

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**Accepted:** July 14, 2018; **Published online:** July 16, 2018

**Citation:** Rector C, Brye KR, Humphreys J, et al. (2018) Tillage and Coated-Urea Effects on Nitrous Oxide Emissions from Direct-Seeded, Delayed-Flood Rice Production in Arkansas. J Rice Res Dev 1(1):25-37

and CH<sub>4</sub> concentrations have increased globally by 20 and 150%, respectively [1]. It is expected that, from rice production alone, non-carbon-dioxide (CO<sub>2</sub>) emissions (i.e., N<sub>2</sub>O and CH<sub>4</sub>) will increase 2% by 2030 [2]. Nitrous oxide and CH<sub>4</sub> are more potent in the atmosphere than CO<sub>2</sub>, with global warming potentials (GWP) that are 298 and 34 times, respectively, greater than that of CO<sub>2</sub> [3]. The magnitudes of GHG emissions are known to differ among a variety of agronomic practices.

Tillage is a frequent soil management practice in many crops and is used extensively in rice production. However, the preparation of crop fields with CT prior to planting can lead to detrimental effects on the environment because CT removes residue from the soil surface, leaving a bare soil surface to potentially increase soil erosion [4]. Other tillage practices, such as conservation tillage and no-tillage (NT), have been utilized to reduce soil erosion. No-tillage practices minimize soil erosion and support soil health by improving soil structure and increasing water infiltration and retention [5,6]. No-tillage also generally increases soil organic matter (SOM), which not only provides nutrients to crops, but also supplies an increased amount of carbon (C) substrate to microbial communities that are known to facilitate the production of N<sub>2</sub>O in partially saturated-soil conditions [7,8].

Research studies evaluating the impacts of differing tillage practices (i.e., CT, reduced/conservation tillage, and/or NT) on N<sub>2</sub>O fluxes and/or emissions from row crops [i.e., barley (*Hordeum vulgare* L.), corn, wheat, and rice) have been inconclusive. A few studies have reported a significant difference between CT and NT [7,8], while others reported no effect of tillage practice on N<sub>2</sub>O emissions [9,10]. The potential effects that tillage practices have on N<sub>2</sub>O emissions are inconsistent, but, when a significant difference has been reported, N<sub>2</sub>O emissions tended to be greater from NT than CT. In addition to extensive CT being a common pre-plant agronomic activity associated with rice production, N management is also a careful consideration for optimal rice production.

Nitrogen is an essential plant macronutrient that most crops become deficient with due to many soils' limited N-mineralization and N-supplying capacity relative to N requirements for optimal production [11]. For rice specifically, sufficient N is most important during vegetative growth before panicle differentiation, which ultimately influence grain yield [12]. To compensate for N deficiencies in soils, synthetic N fertilizers are used. The two most regularly used N fertilizers in rice production are uncoated urea (46% N) and N-(n-butyl) thiophosphoric triamide (NBPT)-coated urea (46% N) because of their large N concentration [12,13].

Urea has two amine groups, instead of nitrate groups, which help reduce N loss through denitrification. However, when urea is applied to a dry soil surface and not flooded within a day or two to limit aerobic conditions (i.e., nitrification), significant loss of mineral N through ammonia (NH<sub>3</sub>) volatilization can occur [14,15]. Urease enzymes, which commonly exist in the soil, are the catalyst for NH<sub>3</sub> volatilization, therefore inhibitors are used to limit activity of the urease enzyme and reduce N-volatilization losses. The compound NBPT is a urease inhibitor that has been reported to reduce NH<sub>3</sub> volatilization by as much as 30% [13]. If N is not lost as NH<sub>3</sub>, the N is hydrolyzed to ammonium (NH<sub>4</sub><sup>+</sup>) and is either taken up by the plant or is adsorbed to the surrounding soil colloids. Nitrogen from non-treated urea is lost rapidly in the field through volatilization, thus rendering that lost N unusable by the plants and can result in less growth (i.e., aboveground biomass and/or yield). However, the urease-inhibitor-coated urea is reported to provide a more slow release of N [13], thereby allowing the plant to use more of the applied N to potentially result in more biomass and/or yield.

Field studies evaluating NBPT-coated-urea effects on N<sub>2</sub>O emissions from rice production are absent, however, studies of seasonal N<sub>2</sub>O emissions from NBPT-coated urea have been conducted in corn (*Zea mays* L.) and pasture land, where seasonal N<sub>2</sub>O emissions either increased from non-coated urea compared to NBPT-coated urea [16,17] or no difference was reported [18]. The general trend of increased N<sub>2</sub>O emissions from non-coated urea is likely related to the ability of urea to hydrolyze more in a wet to nearly saturated soil profile than in dry-soil conditions.

There are no known studies evaluating effects of tillage practice and NBPT coating of urea on N<sub>2</sub>O emissions in Arkansas. Therefore, the objective of this study was to evaluate the effects of tillage practice (i.e., NT and CT) and urea fertilizer type (NBPT-coated and non-coated) on N<sub>2</sub>O fluxes, season-long N<sub>2</sub>O emissions, and GWP (i.e., N<sub>2</sub>O and CH<sub>4</sub> combined) from rice grown on a silt-loam soil from a drill-seeded, delayed-full-season-flood production system in Arkansas. It was hypothesized that N<sub>2</sub>O fluxes, season-long N<sub>2</sub>O emissions, and GWP would be greater from the NT/non-coated-urea than from any other tillage/fertilizer-type treatment combination because NT will increase the C concentration near the soil surface more than CT, therefore increasing microbial activity and the non-coated urea will supply a more labile form of N.

## Materials and Methods

### Site description

Research was conducted between May and October

2017 at the University of Arkansas, Division of Agriculture's Rice Research and Extension Center (RREC) near Stuttgart, AR (34.46°N, 91.46°W). A Dewitt silt loam (fine, smectitic, thermic Typic Albaqualfs) with < 1% slope was present throughout the research site [19,20]. Replicate, large research plots under long-term NT management for at least 10 years [21] and an adjacent area that has been under CT management for over 75 years were used for this study. The NT plots used in this study were sub-areas of larger NT plots that were part of an on-going, long-term NT phosphorous (P) fertilization study [21].

The area surrounding Stuttgart, AR is classified as humid subtropical, which includes warm weather with periodic precipitation year-round [22]. The average monthly air temperature is 16.5 °C, ranging from a minimum of -1.1 °C in January to a maximum of 33.3 °C in July, and annual precipitation is 125.6 cm [23]. The 2017 growing season (i.e., May-September) had an average daily temperature of 25.0 °C, which was similar to the 30-year (i.e., 1981 to 2010) average of 25.1 °C for the same months [24]. Precipitation during the 2017 growing season was 55.0 cm, 1.3 times larger than the 30-year average of 43 cm [24].

### Treatments and experimental design

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

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

### Plot management

Conventionally tilled plots were disked with one pass then floated (i.e., smoothed to prepare for planting) with two passes on 20 November 2016 and 25 April, 2017, respectively. Pre-plant fertilization of 29.4 kg P ha<sup>-1</sup> as triple superphosphate, 83.8 kg K ha<sup>-1</sup> as muriate of potash, and 11.2 kg Zn ha<sup>-1</sup> as zinc sulfate were applied to CT plots on 22 March 2016. No-tillage plots were pre-plant fertilized only with 83.8 kg K ha<sup>-1</sup> as K<sub>2</sub>O on 22 March 2017 and seeds were pre-treated with Zn. No-tillage plots were cropped to soybean, while the CT plot area was left fallow during the 2016 growing season. The pure-line cultivar 'CL172', which is a long-grain, semi-dwarf cultivar that was bred by the University of Arkansas, was planted on 9 May in the NT plots and on 11 May 2017 in the CT plots. An Obey (FMC Corp., Philadelphia, PA), which is a mixture of clomazone (2-[(2-chlorophenyl)methyl]-4,4-dimethyl-3-isoxazolidinone) and quinclorac (3,7-dichloro-8-quinolinecarboxylic acid), and Permit Plus [halosulfuron-methyl, methyl 3-chloro-5-(4,6-dimethoxyppyrimidin-2-ylcarbamoylsulfamoyl)-1-methylpyrazole-4-carboxylate; Gowan Co., Yuma, AZ] herbicide mixture was sprayed pre-emergence on 9 May 2017 for weed control, while no additional herbicide applications were made the remainder of the season.

Two separate bays for full-season-flood water management were created with a levee that was established around the NT and CT plot areas after planting and two to three weeks prior to flooding. A recommended single, pre-flood N application at the rate of 118 kg N ha<sup>-1</sup>, determined according to the N-Soil Test for Rice (N-STaR; [13]) in the NT portion of the study area, was broadcast manually within each gas sampling chamber to dry soil in both CT and NT plots on 12 June 2017. The N-STaR fertilizer-N recommendation scheme was based on soil samples to a depth of 46 cm and refined based on cultivar selection and soil textural class [13]. The delayed, full-season flood was established at the 5-leaf rice stage on 13 June 2017, after which the flood was maintained at a 10 cm depth with periodic water additions made on an as-needed basis until two weeks prior to harvest when the flood was released.

### Soil sampling and analyses

On 30 May 2017, two weeks before flood establishment, soil samples were collected from the top 10 cm in each plot prior to N fertilization and flooding. Soil samples were collected for bulk density determinations using a 4.8 cm-diameter, stainless-steel core chamber and slide hammer. Eight additional soil cores per plot were collected from the top 10 cm prior to N fertilization and flooding using a 2 cm-diameter, stainless-steel push probe that were combined and used for particle-size

and chemical analyses. Soil samples were dried at 70 °C for at least 48 hr and weighed. Dried soil samples were sieved to pass a 2 mm mesh screen. A modified 12 hr hydrometer method was used to determine particle-size distribution [25]. A 1:2 soil mass:water volume suspension was used to determine soil pH and electrical conductivity (EC) potentiometrically. Mehlich-3 extractable nutrient concentrations (i.e., P, K, Ca, Mg, Fe, Mn, Na, S, Cu, and Zn) were determined using inductivity coupled, argon-plasma spectrophotometry after extraction in a 1:10 soil mass-to-solution-volume ratio [26]. Total carbon (TC) and nitrogen (TN) concentrations were determined by high-temperature combustion with a Vario-Max CN analyzer (Elementar Americas Inc., Mt. Laurel, NJ; [27]). Soil organic matter (SOM) concentration was determined by weight-loss-on-ignition [28]. Using the measured bulk density and 10 cm sample depth, measured elemental concentrations ( $\text{g kg}^{-1}$ ) were converted to contents ( $\text{kg or Mg ha}^{-1}$ ).

### Soil redox potential and temperature

Soil oxidation-reduction (redox, Eh) potential sensors (Model S650KD-ORP, Sorex, Garden Grove, CA) and thermocouples (Type E, chromel-constantan) were installed adjacent to two NT/NBPT-U and two NT/NC-U gas sampling chambers in the NT plots and adjacent to two chambers in the CT/NBPT-U and CT/NC-U plots at a depth of 7.5 cm the day of flooding and at a depth of 4 cm a day prior to flooding, respectively. The flood bays were oriented east-to-west with the prevailing slope, with three sets of sensors positioned (i.e., CT/NBPT-U, and CT/NC-U) on the east end and three sensors on the west end of the CT bay. Soil Eh sensors and thermocouples were placed at depth in the soil vertically and horizontally, respectively. Each sensor was connected to a CR1000 datalogger (Campbell Scientific, Inc., Logan, UT) to record data at 15 min intervals and output averaged data at 1 hr intervals throughout the flooded portion of the growing season and for several additional days after the flood was released to prepare for harvest. There was one datalogger in the NT bay and two in the CT bay to accommodate the length of the bay. Soil Eh measurements from the silver/silver-chloride reference electrodes were adjusted by adding 199 mV to each sensor to convert to the standard hydrogen electrode Eh measurement [29]. Recorded sensor data were collected weekly, at which time all sensors were checked for proper functioning. Soil Eh and soil temperature data were summarized based on the values recorded at 0900 hrs on each gas sampling date, except for 89 days after flooding (DAF) since sensors had been removed prior to that date.

### Trace gas sampling and analyses

Using procedures described in detail in Rogers, et al.

[30] and Smartt, et al. [31,32], 30 cm-tall by 30 cm-diameter, polyvinyl chloride (PVC) base collars [33] were installed in both NT and CT plots prior to pre-flood fertilization. Chamber extensions, 30 cm in diameter by either 40 or 60 cm in length made out of PVC, were used to accommodate the growing rice throughout the season. Extensions were outfitted with a rubber flap to connect to the base collar or each other. Wooden boardwalks were constructed between field plots and over adjacent levees to limit soil disturbance next to the chambers during gas sampling.

A 10 cm-tall, 30 cm-diameter PVC cap was placed on top of the upper-most extension immediately prior to sampling and sealed with a rubber flap to create an enclosed headspace chamber that traps gases for sampling [34]. Sampling occurred between 0930 and 1030 hours (i.e., a comparable time to previous studies; [30-32,35]). A 2.5  $\text{cm}^2$  fan (MagLev GM1202PFV2-8, Sunon Inc., Brea, CA), powered by a 9-V battery, was installed on the bottom side of the cap and used to circulate the entrapped gas in the headspace during sampling.

Gas sample collection was accomplished by inserting a 20 mL syringe [Beckton Dickson and Co (B-D), Franklin Lakes, NJ] into a septa (part #73828A-RB, Voigt Global, Lawrence, KS) at the top of the cap. The gas sample was transferred from the syringe into a pre-capped (20 mm headspace crimp cap; part #700-181, SUN-SRi, Rockwood, TN) and pre-evacuated, 10-mL glass vial (part #405-134, SUN-SRi, Rockwood, TN). Samples were collected in 20-min intervals for 1 hr (i.e., at 0, 20, 40, 60 min) once the caps were placed over the chambers. Sampling occurred on a weekly basis from after the establishment of the full-season flood until four days after flood release at the end of the season in preparation for harvest. Air temperature, relative humidity, and barometric pressure were recorded adjacent to the chamber at the time of sampling. Chamber height was measured from the top of the floodwater, or soil surface if no standing flood was present, to the bottom of the cap for chamber volume determinations.

Gas samples were stored at room temperature and analyzed as soon after collection in the field as possible, which was typically within 48 hours. However, several sets of weekly samples had to be stored for several weeks due to instrument malfunction. Gas samples were analyzed on a Shimadzu GC-2014 gas chromatograph (Shimadzu North America/Shimadzu Scientific Instruments Inc., Columbia, MD) using a flame-ionization detector for  $\text{CH}_4$  detection and an electron-capture detector for  $\text{N}_2\text{O}$ . Nitrous oxide and  $\text{CH}_4$  fluxes were determined based on the change in concentration in a chamber over the 1-hr sampling interval [30-32]. The concentration at each 20 min interval ( $\text{mL L}^{-1}$ ) was plotted against the time

interval (min) and fitted with a linear regression equation to determine the change in concentration over time (i.e., slope of the regression line; [30-32]) to determine the flux ( $\mu\text{L m}^{-2} \text{min}^{-1}$ ; [33]). Total season-long  $\text{N}_2\text{O}$  and  $\text{CH}_4$  emissions were calculated by linear interpolation between consecutive sample dates on a chamber-by-chamber basis (i.e., area-scaled emissions). Total seasonal emissions were also converted to  $\text{CO}_2$ -equivalent global warming potential (GWP) for each treatment combination using the climate-carbon-feedback, 100-yr GWP conversion rates of 298 and 34 for  $\text{N}_2\text{O}$  and  $\text{CH}_4$ , respectively [3]. Hereafter, all comparative studies have had GWP conversion rates for  $\text{CH}_4$  adjusted from 25 to 34.

### Plant sampling

Aboveground biomass in each base collar was collected by harvesting rice plants 2 cm above the soil surface on 10 September 2017 (i.e., four days after flood release). Biomass samples were dried at 55 °C for 3 weeks and weighed to determine aboveground dry matter. Yield was determined by clipping panicles on a chamber-by-chamber basis, then weighing and adjusting the panicle masses to 12% grain moisture. Season-long  $\text{N}_2\text{O}$  emissions were also divided by the rice panicle yield on a chamber-by-chamber basis to calculate an emissions efficiency (i.e., yield-scaled emissions).

### Statistical analyses

A two-factor analysis of variance (ANOVA) was performed using SAS 9.4 (SAS Institute, Inc., Cary, NC) to determine the effects of tillage practice, pre-assigned N-fertilization type, and their interaction on initial soil properties in the top 10 cm. A three-factor ANOVA was performed to evaluate the effects of tillage, N-fertilizer type, time, and their interactions on  $\text{N}_2\text{O}$  fluxes. A two-factor ANOVA was performed to evaluate the effects of tillage practice, N-fertilizer type, and their interaction on panicle yield, pre- and post-flood-release area-scaled  $\text{N}_2\text{O}$  emissions, area- and yield-scaled, season-long  $\text{N}_2\text{O}$  emissions, and GWP. When appropriate, means were separated by least significant difference (LSD) at the  $\alpha = 0.1$  level for  $\text{N}_2\text{O}$  fluxes and emissions due to the low expected magnitudes and large expected variability. All other data sets had means that were separated by LSD at the  $\alpha = 0.05$  level.

## Results and Discussion

### Pre-flooding soil physical and chemical properties

Pre-flooding soil properties were measured to evaluate field plot uniformity among pre-assigned urea-fertilizer and tillage treatment combinations. Soil bulk density and extractable soil K differed ( $P < 0.05$ ) among

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

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

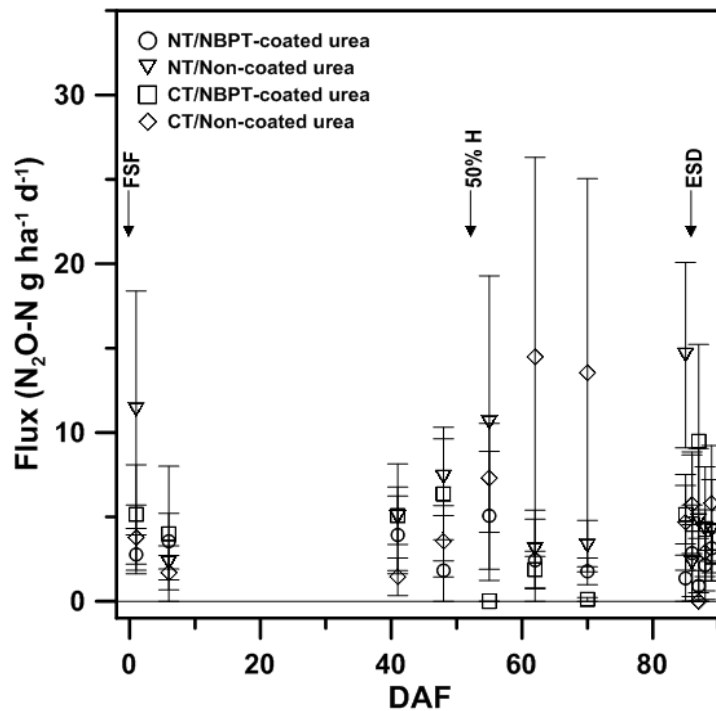
<sup>†</sup>Means in a row with different letters are different at the  $P < 0.05$  level; the a and b notations show the results of statistical analyses.

tillage-fertilizer treatment combinations, while soil pH and extractable soil P, Mg, Na, Fe, Mn, and Zn differed ( $P < 0.05$ ) between tillage treatments (Table 1). All other soil properties measured in the top 10 cm before flooding (i.e., sand, silt, and clay; EC; extractable soil Ca, S, and Cu; TN, TC, C:N ratio; and SOM) were unaffected ( $P > 0.05$ ) by tillage or fertilizer treatment (Table 1).

Pre-flood soil bulk density did not differ between fertilizer treatments under CT; however, bulk density in the CT/NBPT-U and CT/NC-U treatment combinations (1.38 and 1.37 g cm<sup>-3</sup>, respectively) were 11 and 19% greater ( $P < 0.05$ ) than bulk density in the NT/NBPT-U and NT/NC-U treatment combinations (1.23 and 1.15 g cm<sup>-3</sup>, respectively), where bulk density in the NT/NBPT-U was 7% greater than that in the NT/NC-U treatment combination. Pre-flood extractable soil K content only differed between NT/NBPT-U (156 kg ha<sup>-1</sup>) and NT/NC-U (135 kg ha<sup>-1</sup>) treatment combinations and did not differ between fertilizer treatments under CT (143 kg ha<sup>-1</sup>). However, all treatment combinations had extractable soil K concentrations in the top 10 cm of soil that fell within the “Medium” (91 to 130 mg K kg<sup>-1</sup>) soil-test category for fertilizer recommendations for rice grown in Arkansas [13].

Pre-flood soil pH was 13% greater in the CT (pH = 6.1) than in the NT treatment (pH = 5.4), but soil pH

in both tillage treatments were within the optimal pH range for rice production (~5.0 to 6.75; [11]; Table 1). Pre-flood extractable soil P, Mg, Na, Mn, and B contents were 12, 60, 45, 24, and 18%, respectively, greater under CT than under NT, while extractable soil Fe and Zn contents were 1.2 and 2.1 times, respectively, greater under NT than under CT (Table 1). Extractable soil Zn concentrations were 2.1 and 5.1 mg kg<sup>-1</sup> under CT and NT, respectively, with CT having a soil-test category of “Low” and NT “Optimum” [13]; however, a yield response would not have been expected from the application of a small amount of additional Zn. Unlike extractable soil K and Zn, the extractable soil P concentration under both tillage treatments were in the “Very Low” (i.e., ≤ 15 mg kg<sup>-1</sup>) soil-test category [13]; however, like for Zn, based on experience at this particular research location, a yield response would not have been expected from additional P. Furthermore, the NT study plots were part of a long-term P study, which superseded the adjustment of the soil-test P to a more optimum level. Mean sand, silt, and clay fractions (0.14, 0.71, and 0.15 g g<sup>-1</sup>, respectively) in the top 10 cm confirmed a silt-loam soil surface texture for both tillage treatments (Table 1). Though several soil physical and chemical properties differed prior to flooding, differences were relatively minor and generally non-agronomically significant, and it was reasonably assumed that any measured differences in N<sub>2</sub>O fluxes and/



**Figure 1:** Nitrous oxide (N<sub>2</sub>O) fluxes over time during the 2017 rice-growing season at the Rice Research and Extension Center near Stuttgart, AR among tillage practice [i.e., conventional (CT) and no-tillage (NT; n = 8)]-urea fertilizer type [i.e., N-(n-butyl) thiophosphoric triamide (NBPT)-coated and non-coated urea (n = 8)] treatment combinations. Arrows (↓) indicate establishment of the full-season-flood [FSF; 0 days-after-flood (DAF)], growth stages [50% heading (50% H; 53 DAF)], and end-of-season drain (ESD; 85 DAF). Error bars associated with treatment means are standard errors (n = 4).

or emissions were the result of imposed treatment effects rather than due to large, inherent differences among plots prior to flooding.

### Nitrous oxide fluxes

Unlike previous reports for CH<sub>4</sub> [30-32], N<sub>2</sub>O fluxes during the 2017 growing season (i.e., establishment of full-season flood to four days after end-of-season flood release) did not show any discernable trend over time. Mean N<sub>2</sub>O fluxes did not exceed 15 N<sub>2</sub>O-N g ha<sup>-1</sup> d<sup>-1</sup> at all during the 2017 growing season, with peak numeric N<sub>2</sub>O fluxes ranging in occurrence from 62 DAF from the CT/NC-U treatment combination (14.5 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>) to 85 DAF from the NT/NC-U treatment combination (14.6 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>) (Figure 1). All treatment combinations had peak numeric N<sub>2</sub>O fluxes that occurred after 50% heading. However, the NT/NC-U, CT/NC-U, and NT/NBPT-U (5.1 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>) treatment combinations had peak numeric N<sub>2</sub>O fluxes that occurred prior to the end-of-season drain, while the CT/NBPT-U (9.5 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>) treatment combination had a peak numeric flux after the end-of-season drain.

In contrast to that hypothesized, neither tillage practice nor fertilizer type affected ( $P > 0.1$ ) N<sub>2</sub>O fluxes throughout the 2017 growing season (Table 2). Similarly, averaged across field treatments, N<sub>2</sub>O fluxes did not differ over time throughout the 2017 growing season (Table 2). A multi-week gap occurred between 6 and 41 DAF, where no N<sub>2</sub>O fluxes were measured due to analytical difficulties, may have impacted the ability to ascertain field treatment and/or time effects on N<sub>2</sub>O fluxes. However, though non-significant due to large variability associated with flux measurements, N<sub>2</sub>O fluxes from non-coated-urea treatment combinations tended to be numerically greater than fluxes from NBPT-coated urea treatment combinations (Figure 1). It was somewhat expected that there was no difference in N<sub>2</sub>O fluxes over time because there was no split N-fertilizer application made. Rice grown in the delayed-flood system are known to take up available N efficiently [13]. Furthermore, both tillage treatments had a full-season flood that minimized fluctuations of soil Eh that would have promoted N<sub>2</sub>O production and release.

Limited research has been conducted evaluating individual or combined effects of tillage practice and urease-inhibiter-coated urea on N<sub>2</sub>O fluxes. Studies investigating NT and/or CT effects on N<sub>2</sub>O fluxes are few and inconclusive. Based on a 3 yr, wheat-rice rotation study in China on a silty-clay-loam soil, Zhang, et al. [26] documented no numerical trends or difference in N<sub>2</sub>O fluxes among tillage practice [i.e., NT or reduced tillage (RT) and CT] in rice production. In contrast, based on a 1 yr study in China on a silty-clay-loam soil, Ahmad, et al.

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

Measured property/Treatment effect	P
<b>N<sub>2</sub>O fluxes</b>	
Tillage practice	0.86
Fertilizer	0.13
DAF	0.97
Tillage practice × fertilizer	0.35
Tillage practice × DAF	0.82
Fertilizer × DAF	0.51
Tillage practice × fertilizer × DAF	0.22
<b>Pre-flood-release N<sub>2</sub>O emissions</b>	
Tillage practice	0.99
Fertilizer	0.26
Tillage practice × fertilizer	0.81
<b>Post-flood-release N<sub>2</sub>O emissions</b>	
Tillage practice	0.30
Fertilizer	0.93
Tillage practice × fertilizer	0.43
<b>Season-long, area-scaled N<sub>2</sub>O emissions</b>	
Tillage practice	0.96
Fertilizer	0.27
Tillage practice × fertilizer	0.79
<b>Season-long, yield-scaled N<sub>2</sub>O emissions</b>	
Tillage practice	0.87
Fertilizer	0.22
Tillage practice × fertilizer	0.70
<b>Total GWP</b>	
Tillage practice	0.19
Fertilizer	0.17
Tillage practice × fertilizer	0.87

[8] reported NT produced greater peak N<sub>2</sub>O fluxes than CT, with peaks occurring after application of N fertilizer. Zhang, et al. [26] measured a peak flux at ~24 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>, while Ahmad, et al. [8] measured a peak N<sub>2</sub>O flux at 240 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>, with both peak N<sub>2</sub>O fluxes 1.6 to 16 times greater than the peak flux measured in this study (14.6 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>). Liu, et al. [7] conducted a 1 yr corn study in Colorado on a clay-loam soil, while Chatskikh and Olesen [9] conducted a 1yr barley study in Denmark on loamy-sand soil, with both study results supporting a numerical trend of NT producing greater N<sub>2</sub>O fluxes than CT.

The limited research on NBPT-coated urea and its effect on N<sub>2</sub>O fluxes are more consistent, where generally lower numeric peak N<sub>2</sub>O fluxes have been reported from treatments using urease inhibitors (i.e., NBPT; [16-18]). Ding, et al. [17] conducted a 1 yr study in corn on a sandy-loam soil in China and reported a peak N<sub>2</sub>O flux (120 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>) that was 1.5 times greater from a NC-U

than from a NBPT-U treatment, where both treatments had peak fluxes after N-fertilizer application. Sanz-Cobena, et al. [18] conducted a 2 yr study, also in corn, on a sandy-clay-loam soil in Spain and reported peak N<sub>2</sub>O fluxes from a NC-U treatment that ranged from 80 to 160 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>, which were 60% greater than peak N<sub>2</sub>O fluxes from a NBPT-U treatment. Dawar, et al. [16] conducted a 1 yr study in New Zealand, mainly in silt-loam soils, under grazed pasture landuse that excluded cattle one year prior to initiating the study and reported a peak N<sub>2</sub>O flux (20 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>) from a NC-U

treatment that was two times greater than the peak N<sub>2</sub>O flux from a NBPT-U treatment, where all peak fluxes occurred during large rainfall or irrigation events.

### Aboveground dry matter and yield

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

Similar to aboveground biomass, rice panicle yield for CL172 was unaffected ( $P = 0.54$ ) by fertilizer treatment but differed ( $P = 0.01$ ) between tillage practices (**Table 3**). Panicle yield was 15% greater from CT (8.9 Mg grain ha<sup>-1</sup>) than from NT (7.8 Mg grain ha<sup>-1</sup>). Rice yields measured in this study were slightly lower than the multi-location mean yield for CL172 (9.2 Mg grain ha<sup>-1</sup>) based on Arkansas yield trials [36]. In this study, the same quantity of fertilizer N was applied to plots in both tillage treatments, but, unlike CT, the NT treatment was not fertilized with additional P due to the long-term nature of P-fertilization treatments the NT plots were a part of that were used in this study.

### Nitrous oxide emissions

Area-scaled N<sub>2</sub>O emissions for the pre-flood-release (i.e., establishment of flood to end-of-season drain) portion of the 2017 growing season ranged from 0.26 kg N<sub>2</sub>O-N ha<sup>-1</sup> period<sup>-1</sup> in the NT/NBPT-U to 0.49 kg N<sub>2</sub>O-N ha<sup>-1</sup> period<sup>-1</sup> in the NT/NC-U treatment (**Table 4**). However, area-scaled N<sub>2</sub>O emissions for the pre-flood-release portion of the 2017 growing season were unaffected ( $P > 0.10$ ) by tillage practice or fertilizer treatment (**Table 2**). There was also no discernable trend in pre-flood-release N<sub>2</sub>O emissions among treatment combinations (**Table 4**). Though not significant, treatments with NBPT-U (0.47 kg N<sub>2</sub>O-N ha<sup>-1</sup>) had pre-flood-release, area-scaled N<sub>2</sub>O emissions that were nearly twice that from the NC-U treatments (0.28 kg N<sub>2</sub>O-N ha<sup>-1</sup>, **Table 4**).

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

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

**Table 4:** Mean pre- (i.e., establishment of the delayed flood to end-of-season flood release) and post-flood-release (i.e., end-of-season flood release to harvest) nitrous oxide (N<sub>2</sub>O) emissions and post-flood-release fraction of season-long N<sub>2</sub>O emissions among tillage practice [i.e., conventional tillage (CT) and no-tillage (NT; n = 8)]- urea fertilizer type [i.e., N-(n-butyl) thiophosphoric triamide (NBPT)-coated and non-coated urea (n = 8)] treatment combinations measured in 2017 at the Rice Research and Extension Center near Stuttgart, AR.

Treatment combination	Pre-flood-release N <sub>2</sub> O emissions (kg N <sub>2</sub> O-N ha <sup>-1</sup> period <sup>-1</sup> )	Post-flood-release N <sub>2</sub> O emissions (kg N <sub>2</sub> O-N ha <sup>-1</sup> period <sup>-1</sup> )	Percent (%) post-flood-release N <sub>2</sub> O emissions (kg N <sub>2</sub> O-N ha <sup>-1</sup> season <sup>-1</sup> )
NT/Non-coated urea	0.49	0.016	3.1
NT/NBPT-coated urea	0.26	0.009	3.4
CT/Non-coated urea	0.45	0.014	3.1
CT/NBPT-coated urea	0.30	0.020	6.2



**Table 5:** Mean season-long, area- and yield-scaled nitrous oxide (N<sub>2</sub>O) emissions and total global warming potential (GWP) among tillage practice [i.e., conventional tillage (CT) and no-tillage (NT; n = 8)]-urea fertilizer type [i.e., N-(n-butyl) thiophosphoric triamide (NBPT)-coated and non-coated urea (n = 8)] treatment combinations measured in 2017 at the Rice Research and Extension Center near Stuttgart, AR.

Treatment combination	Area-scaled N <sub>2</sub> O emissions (kg N <sub>2</sub> O-N ha <sup>-1</sup> season <sup>-1</sup> )	Yield-scaled N <sub>2</sub> O emissions (kg N <sub>2</sub> O-N (Mg grain) <sup>-1</sup> )	Total GWP (kg CO <sub>2</sub> equivalent ha <sup>-1</sup> season <sup>-1</sup> )
NT/Non-coated urea	0.50	0.06	2204
NT/NBPT-coated urea	0.27	0.04	1972
CT/Non-coated urea	0.47	0.06	1612
CT/NBPT-coated urea	0.32	0.04	1324

Area-scaled N<sub>2</sub>O emissions for the post-flood-release (i.e., end-of-season drain to harvest) portion of the 2017 growing season ranged from < 0.01 kg N<sub>2</sub>O-N ha<sup>-1</sup> period<sup>-1</sup> in the NT/NBPT-U to 0.02 kg N<sub>2</sub>O-N ha<sup>-1</sup> period<sup>-1</sup> in the CT/NBPT-U treatment (Table 4). However, area-scaled N<sub>2</sub>O emissions for the post-flood-release portion of the 2017 growing season were also unaffected (*P* > 0.10) by tillage practice or fertilizer treatment (Table 2). Similar to pre-flood-release emissions, there was no discernable trend in post-flood-release N<sub>2</sub>O emissions among treatment combinations (Table 4). Post-flood-release N<sub>2</sub>O emissions accounted for less than 7% of total season-long emissions across all treatment combinations (Table 4). No known studies have reported differences between pre- and post-flood-release N<sub>2</sub>O emissions among tillage treatments or among differing urea-fertilizer treatments. However, Zhao, et al. [37], who evaluated the effects of water management practice on N<sub>2</sub>O emissions, and Adviento-Borbe, et al. [38], who evaluated the effects of N-fertilizer rate on N<sub>2</sub>O emissions, determined that emissions during the post-flood-release period could contribute between 0 and 82% of total season-long N<sub>2</sub>O emissions.

Season-long, area-scaled N<sub>2</sub>O emissions ranged from 0.27 kg N<sub>2</sub>O-N ha<sup>-1</sup> season<sup>-1</sup> in the NT/NBPT-U to 0.50 kg N<sub>2</sub>O-N ha<sup>-1</sup> season<sup>-1</sup> in the NT/NC-U treatment (Table 5). However, similar to pre- and post-flood-release N<sub>2</sub>O emissions, season-long, area-scaled N<sub>2</sub>O emissions were unaffected (*P* > 0.10) by tillage practice or fertilizer treatment (Table 2). Nitrous oxide emissions averaged 0.39 kg N<sub>2</sub>O-N ha<sup>-1</sup> season<sup>-1</sup> across all tillage-fertilizer treatment combinations, which was 11% greater than the expected 0.35 kg N<sub>2</sub>O-N ha<sup>-1</sup> season<sup>-1</sup> based on the Intergovernmental Panel on Climate Change's N<sub>2</sub>O emissions factor of 3 g N<sub>2</sub>O-N (kg N-input)<sup>-1</sup> for a N input of 118 kg ha<sup>-1</sup> season<sup>-1</sup> [39].

Few studies have evaluated the effect of tillage practice and/or urease-inhibitor-coated urea, such as NPBT, on season-long N<sub>2</sub>O emissions. However, studies investigating NT and/or CT practices in various crops either reported significantly greater N<sub>2</sub>O emissions from NT than from CT [8,40] or reported only a numerical difference [7,10]. Ahmad, et al. [8] reported a 32% increase in

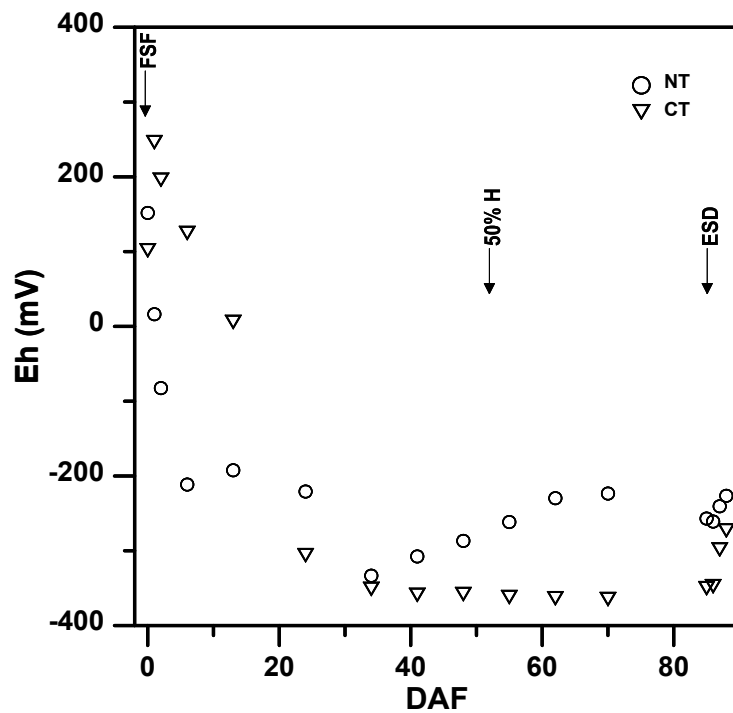
season-long N<sub>2</sub>O emissions from NT (7.4 kg N<sub>2</sub>O-N ha<sup>-1</sup>) compared to CT (5.6 kg N<sub>2</sub>O-N ha<sup>-1</sup>) from rice. Venterea, et al. [40] conducted a 2 yr corn study in Minnesota on a silt-loam soil and reported greater N<sub>2</sub>O emissions from NT than from CT. Liu, et al. [7] reported N<sub>2</sub>O emissions that were more than two times numerically greater from NT (0.90 kg N<sub>2</sub>O-N ha<sup>-1</sup>) than from CT (0.44 kg N<sub>2</sub>O-N ha<sup>-1</sup>). During a 3 yr wheat-rice rotation study, Zhang, et al. [10] reported numerically greater season-long N<sub>2</sub>O emissions from CT (0.15 kg N<sub>2</sub>O-N ha<sup>-1</sup>) than from NT (0.12 kg N<sub>2</sub>O-N ha<sup>-1</sup>) during rice production.

In contrast to tillage effects, the few studies evaluating NBPT-coated urea and its effect on N<sub>2</sub>O emissions were more consistent, with NBPT-coated urea resulting in significantly lower N<sub>2</sub>O emissions than non-coated urea from corn production [16,18] and from pastureland [17]. During a 2-yr study, Sanz-Cobena, et al. [18] reported N<sub>2</sub>O emissions that were two times greater from NC-U than from NBPT-U; however, there was no difference in N<sub>2</sub>O emissions between NC-U and NBPT-U treatments in one of two years. Ding, et al. [17] also reported greater N<sub>2</sub>O emissions from NC-U than from NBPT-U, while Dawar, et al. [16] measured an 8% increase in N<sub>2</sub>O emissions from NC-U than from NBPT-U.

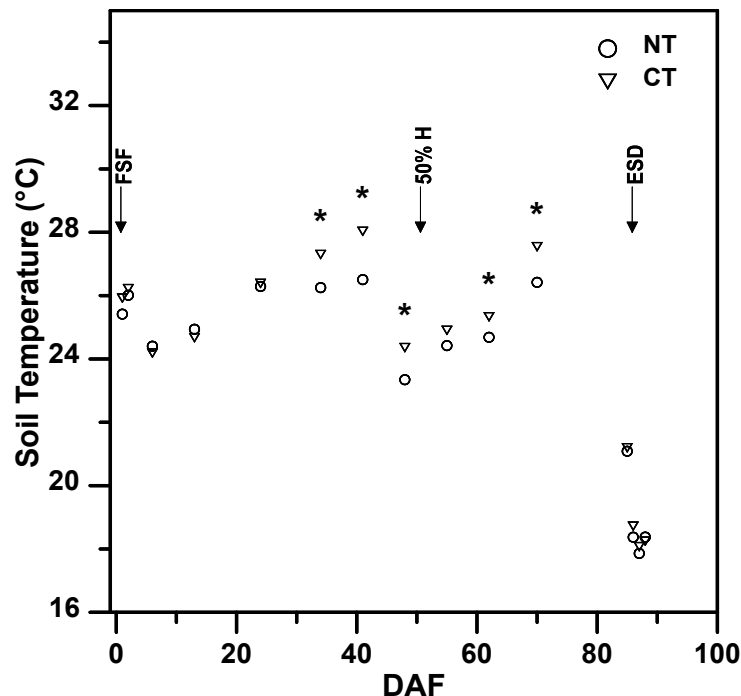
Similar to season-long, area-scaled N<sub>2</sub>O emissions, yield-scaled N<sub>2</sub>O emissions were also unaffected (*P* > 0.10) by tillage practice or fertilizer treatment (Table 2). Yield-scaled N<sub>2</sub>O emissions averaged 0.05 kg N<sub>2</sub>O-N (Mg grain)<sup>-1</sup> across all tillage-fertilizer treatment combinations (Table 5). Sanz-Cobena, et al. [18] also report yield-scaled N<sub>2</sub>O emissions did not differ between NBPT-U and NC-U treatments.

### Soil Eh and temperature

The reduction of NO<sub>3</sub><sup>-</sup> occurs efficiently when soil reduction-oxidation (redox) potential (Eh) ranges from 220 to 280 mV, therefore increasing the likelihood of N<sub>2</sub>O production [41]. Soil Eh at the 7.5 cm depth differed between tillage practices over the growing season (*P* < 0.01) and differed between tillage-fertilizer treatment combinations (*P* < 0.01; Table 3). However, means separation could not specifically identify which sample dates soil Eh differed between tillage treatments, but differences in soil



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



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

Eh between tillage treatments tended to be greater early than late in the growing season (Figure 2). Optimal (246 mV) or near optimal (195 mV) soil Eh for  $\text{NO}_3^-$  re-

duction was only measured 1 and 2 DAF in NT, while there were no sample dates under CT that were within or near the optimal soil Eh range for  $\text{NO}_3^-$  reduction. Soil

Eh fell below 0 mV between 13 and 24 DAF and did not increase above 0 mV throughout the remainder of the rice growing season (Figure 2). Averaged over time, soil Eh among tillage-fertilizer treatment combinations [NT/NC-U (-55.6 mV), NT/NBPT-U (-340 mV), CT/NC-U (-199 mV), and CT/NBPT-U (-183 mV)] were variable, but specific differences were also unable to be identified with means separation.

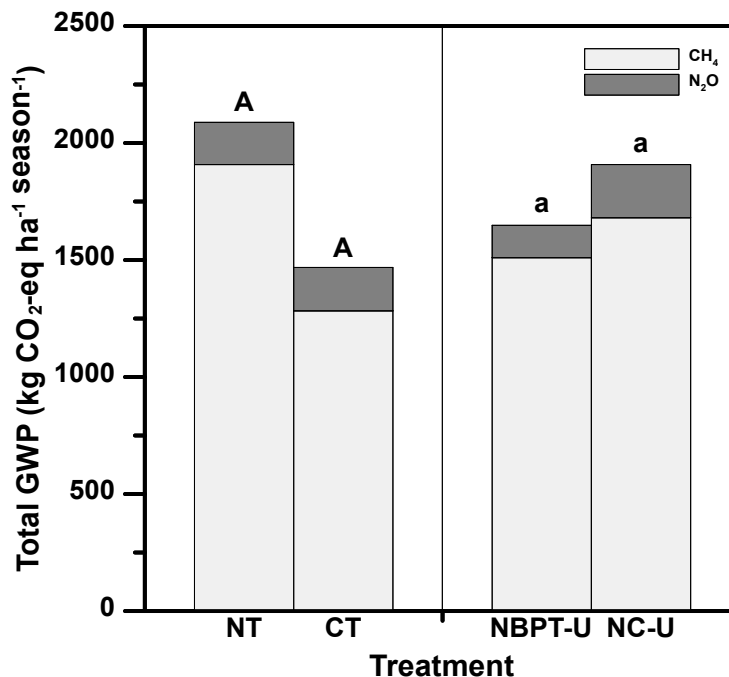
Soil temperatures at the 7.5 cm depth fluctuated throughout the growing season, where soil temperature started around 26 °C, increased to around 28 °C mid-season (41 DAF), and decreased to below 20 °C after the end-of-season drain (86-88 DAF; Figure 3). Similar to soil Eh, soil temperature at the 7.5 cm depth differed between tillage practices throughout the season ( $P < 0.01$ ) and differed between tillage-fertilizer treatment combinations ( $P = 0.03$ ; Table 3). The soil temperature was significantly greater under CT than under NT on numerous dates during the middle of the flooded portion of the growing season (i.e., 34, 41, 48, 55, 62, and 70 DAF), but did not differ by more than 2 °C on any given date (Figure 3). Averaged across measurement dates, the mean soil temperature was significantly warmer in the CT/NBPT-U (24.5 °C) and CT/NC-U (23.8 °C), which did not differ, than in the NT/NBPT-U (23.5 °C) and NT/NC-U (23.6 °C) treatment combinations, which did not differ. Brye, et al. [42] documented an impact of day and

nighttime air temperatures on CH<sub>4</sub> emissions from silt-loam soils in Arkansas, but there is currently no known study that has evaluated the potential impact of day and/or nighttime air temperatures on N<sub>2</sub>O emissions.

### Total global warming potential

Total GWP (i.e., the combination of CO<sub>2</sub>-equivalent CH<sub>4</sub> and N<sub>2</sub>O emissions) during the 2017 growing season (i.e., flood establishment to harvest) ranged from 1324 to 2204 kg CO<sub>2</sub> equivalent ha<sup>-1</sup> season<sup>-1</sup> from the CT/NBPT-U and NT/NC-U treatment combinations, respectively (Table 5). However, total GWP was unaffected ( $P > 0.05$ ) by tillage practice or fertilizer treatment (Table 2). Nitrous oxide accounted for ≤ 12% of the total GWP across all treatments (Figure 4).

Few studies have reported total GWP of non-CO<sub>2</sub> emissions (i.e., N<sub>2</sub>O + CH<sub>4</sub>) among tillage practices. Methane emissions from rice under a full-season flood can contribute over 90% of the total GWP [35,43]. Ahmad, et al. [8] reported a significant difference in CH<sub>4</sub> emissions in rice between CT (180 kg CH<sub>4</sub>-C ha<sup>-1</sup>) and NT (140 kg CH<sub>4</sub>-C ha<sup>-1</sup>) tillage practices, consequently, explaining the significantly greater total GWP in CT (24097 kg CO<sub>2</sub> equivalent ha<sup>-1</sup>) than NT (19781 kg CO<sub>2</sub> equivalent ha<sup>-1</sup>) despite N<sub>2</sub>O emissions being numerically greater from NT (4.9 kg N<sub>2</sub>O-N ha<sup>-1</sup>) than from CT (3.6 kg N<sub>2</sub>O-N ha<sup>-1</sup>). However, Zhang, et al. [10] report-



**Figure 4:** Total global warming potential (GWP), reported as carbon dioxide equivalents (CO<sub>2</sub>-eq), for nitrous oxide (N<sub>2</sub>O) and methane (CH<sub>4</sub>) for tillage practices [i.e., conventional (CT) and no-tillage (NT; n = 8)] and urea fertilizer type [i.e., N-(n-butyl) thiophosphoric triamide (NBPT)-coated (NBPT-U) and non-coated urea (NC-U; n = 8)] from the 2017 rice growing season at the Rice Research and Extension Center near Stuttgart, AR. Different capital letters atop bars denote significant differences between water management practices (n = 8;  $P < 0.05$ ) averaged across fertilizer treatments. Different lower-case letters atop bars denote significant differences between fertilizer treatments (n = 8;  $P < 0.05$ ) averaged across water management practices.

ed greater CH<sub>4</sub> emissions from NT than from CT, which could be inferred that an increase in CH<sub>4</sub> emissions could result in an increase in total GWP, since it is commonly understood that CH<sub>4</sub> emissions are the dominant driver of GWP for non-CO<sub>2</sub> emissions.

Considering only a few studies have evaluated the effects of NBPT-coated urea on N<sub>2</sub>O emissions, there are no known studies that have evaluated NBPT-coated urea effects on non-CO<sub>2</sub> total GWP. Malla, et al. [44] evaluated the impact of the urease inhibitor hydroquinone (HQ) and reported no change in GWP from rice production when HQ was used with urea compared to urea not used with a urease inhibitor. Unlike Malla, et al. [44], Xu, et al. [45] reported a significant decrease in CH<sub>4</sub> emissions from urea mixed with HQ compared to non-treated urea for rice production. Considering the potential for NBPT-coated urea to reduce N<sub>2</sub>O emissions [16-18] and the lack of consensus among studies on the potential to reduce GWP, further studies examining the context dependency of NBPT-coated urea effects on GWP are still needed.

### Environmental implications

Averaged across all treatment combinations, N<sub>2</sub>O accounted for only 10% of the total GWP, with the remainder of the total GWP due to CH<sub>4</sub>. Methane as the key driver of GWP for rice production is supported by other studies evaluating GHG emissions from rice grown on silt-loam soils in the Lower Mississippi River Delta region of eastern Arkansas [43,46].

Nitrous oxide emissions, in combination with CH<sub>4</sub>, from agricultural sources are expected to rise through the next decade and beyond [2]. Even more concerning is that N<sub>2</sub>O and CH<sub>4</sub> are more potent as GHGs than CO<sub>2</sub> in the atmosphere. Therefore, in order to make responsible decisions regarding crop production, N<sub>2</sub>O emissions need to be quantified and the effects of traditional and alternative production practices on N<sub>2</sub>O emissions need to be evaluated. Expanding research on N<sub>2</sub>O emissions is of increasing importance because the human population continues to grow, which will require a similar increase in crop production, especially commonly consumed grains such as rice. A proper understanding of N<sub>2</sub>O emissions can help mitigate or offset detrimental environmental impacts resulting from increased crop production.

### Conclusions

Contrary to that hypothesized, neither N<sub>2</sub>O fluxes nor season-long emissions (i.e., area- or yield-scaled) ( $P > 0.1$ ) or total GWP were affected ( $P > 0.05$ ) by tillage practice (CT or NT) or type of urea fertilizer (i.e., NBPT-coated and non-coated) from rice grown under a direct-seeded, delayed-flood production system during the 2017 growing season on a silt-loam soil in eastern

Arkansas. However, though not significant, averaged across tillage treatments, GWP was 14.2% numerically lower from NBPT-coated than from non-coated urea, which supports the theoretical expected effect of using a urease-inhibitor-coated urea as the N source for rice production. Despite the lack of statistically significant differences, this study has contributed valuable information to the limited knowledge of N<sub>2</sub>O emissions from rice production. The global importance of rice production makes it imperative to quantify GHG emissions and evaluate potential traditional and alternative agronomic and environmental factors that may affect N<sub>2</sub>O production and emissions.

### Acknowledgments

This study was supported by the University of Arkansas System Division of Agriculture. Planning and field assistance provided by Donna Frizzell and Eddie Castaneda-Gonzalez were greatly appreciated.

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