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Greenhouse Gas Emissions from Rice Production in Arkansas

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Importance of Greenhouse Gases

Climate change and climate change mitigation are important environmental and agronomic issues. One factor responsible for climate change is increasing greenhouse gas (GHG) concentrations in the atmosphere.

The major greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and water vapor (H_2O). In an agricultural setting, CO_2, CH_4, and N_2O are the main GHGs of concern. Microbial and plant root respiration are the primary sources of carbon dioxide emissions associated with agricultural crop production.

Carbon dioxide is the by-product of the aerobic breakdown of organic matter by microorganisms in the soil and is released from plant roots into the rhizosphere. Methane is produced via methanogenesis from the microbial decomposition of organic matter in the soil, but under anaerobic (i.e., lacking oxygen) soil conditions. Nitrous oxide is produced from the incomplete conversion of soil nitrate (NO_3-) to dinitrogen gas (N_2) in the process of denitrification, which can occur during wet and dry cycles, commonly under oxygen-limited soil conditions.

Because concentrations of CO_2, CH_4, and N_2O are not large in the atmosphere, they are referred to as trace gases (Smartt et al., 2016a). They can, however, trap outgoing long-wave radiation (i.e., heat energy) emitted from the Earth's surface. Preventing the escape of long-wave radiation increases the temperature of the Earth's atmosphere, just as a greenhouse traps heat inside a structure for plant growth.

Even small increases in the atmospheric air temperature can disrupt many global processes. The melting of glaciers and ice caps has resulted in sea-level rise, for example, and shifting weather patterns have caused increased the frequency drought, flooding and other extreme conditions.

Collectively, the sum of CO_2, CH_4, and N_2O concentrations in the atmosphere are used to calculate the global warming potential (GWP), as reported in CO_2 equivalents. Individually, CH_4 and N_2O are both more potent GHGs than CO_2, with GWPs ~ 25 to 30 and ~ 265 to 300 times greater, respectively, than that of CO_2 alone (Smartt et al., 2016a).

Other typical quantifications of GHGs include GHG flux (mass per unit area per unit time) and GHG emissions (mass per unit area summed over a specific period). Understanding how various production systems and associated management practices influence GHG emissions is critical for sustainable agriculture. Studies on GHG fluxes and emissions in agricultural settings can also provide information to help guide management decisions to maintain and improve soil health, as C and N are closely connected to soil health goals, but C and N emissions represent potentially major loss pathways from ecosystems.

Greenhouse Gas Emissions in Rice Production

Rice production in Arkansas occupies a substantial agricultural land area (typically between 1 million and 1.5 million acres each year) that is critical for the social and economic systems in Arkansas, collectively supplying jobs, income, and food for tens of thousands of residents. However, the U.S. Environmental Protection Agency has identified rice production as a significant contributor of GHG emissions, namely CH_4, from the traditional direct-seeded, delayed, continuous flood-irrigation water management scheme (USEPA, 2011) that has been the dominant water management scheme for rice production in Arkansas for decades.

Flood-irrigation for rice production produces anaerobic soil conditions within just a few weeks of flood application (Brye et al., 2013), making traditional flood-irrigated rice production uniquely susceptible to CH_4 production via methanogenesis and the release of CH_4 to the atmosphere. Under flood-irrigated rice, the main conduit from CH_4 emissions to the atmosphere is through specialized cells in the rice plants themselves. Secondary pathways for CH_4 from the soil to the atmosphere under flood-irrigated rice include diffusion and ebullition (bubbles) through the floodwater.

Though the development of saturated, anaerobic soil conditions under flood-irrigated rice increases CH_4 production and release, application of a flood for rice production greatly reduces CO_2 and N_2O production and emissions. However, due to the relatively shallow flood-water layer commonly used in rice production systems in the United States (Henry et al., 2021a; Liu and Wu, 2004; Vories et al., 2002), CO_2 and N_2O emissions are never completely eliminated.

Several alternative water management schemes use significantly less water than traditional, continuous flood-irrigated rice production. Alternative practices, such as alternate wetting and drying (AWD), intermittent flooding and the more recent wide-scale implementation of furrow-irrigated rice (row rice), have been shown to reduce overall water use (He, 2010; Henry et al., 2021a). These alternatives also provide some economic savings from reduced labor and energy costs compared to traditional flood-irrigated rice production, which requires the establishment and maintenance of levees to contain flood water (Henry et al., 2021a,b).

These alternate schemes have their own environmental consequences, however. The greater frequency of wet-and-dry soil cycles will reduce CH_4 production, but will generally stimulate greater CO_2 and N_2O production and emissions. Several important soil/plant characteristics and agricultural management practices in Arkansas are known to affect GHG emissions, particularly CH_4.

Soil texture (i.e., silt-loam versus clay soil) affects CH_4 emissions, where the fine-textured clay soils generally have lower CH_4 emissions than coarser-textured silt-loam soils, which reduce more quickly and have a greater proportion of larger pores, allowing gas to escape the soil more quickly (Brye et al., 2013).

Cultivar selection (i.e., pure-line versus hybrid) affects CH_4 emissions, as hybrid cultivars typically have more vigorous growth and greater biomass production than pure-line cultivars, which allowed for a more oxygenated rhizosphere to covert CH_4 back to CO_2 in the soil before escaping to the atmosphere (Rogers et al., 2014).

Fertilizer-nutrient source (i.e., inorganic versus organic), particularly nitrogen source, affects CH_4. Organic fertilizers, such as poultry litter, provide a readily available source of carbon in the soil that can be converted to CH_4 upon the decomposition of the organic material — this doesn't happen with inorganic fertilizer-nutrient sources (Rogers et al., 2017).

Poultry litter as a fertilizer-nutrient source or general organic soil amendment will also increase CO_2 emissions (Brye et al., 2006). Since rice is generally considered a high-residue-producing crop, the amount of carbon-containing plant material that is recycled back to the soil each year can be quite high. Therefore, the previous crop and/or crop rotation (e.g., rice-soybean versus rice-rice rotation) can affect CH_4 emissions, where emissions are generally larger when rice is grown in consecutive years, compared to fields in which soybean was the previous crop. Soybean is generally a low-residue-producing crop that returns much less readily decomposable C to the soil than does a rice crop (Rogers et al., 2014).

Additionally, when rice follows rice, the soil tends to stay more reduced and is quicker to become further reduced in the following rice crop, thus allowing CH_4 emissions to occur sooner.

Conventional tillage has been shown to affect N_2O emissions from furrow-irrigated rice (Slayden et al., 2022a), where N_2O emissions were greater from conventional tillage than from no-tillage, while tillage has been shown to have little effect on CH_4

emissions from both flood-irrigated (Rector et al., 2018a) or furrow-irrigated (Della Lunga et al., 2023) rice production. However, Della Lunga et al. (2023) demonstrated that GWP tended to be lower from no-tillage compared to conventional tillage in furrow-irrigated rice.

Figure 1. Greenhouse gas emissions field research set-up for flood-irrigated rice, out-fitted with boardwalks between plots to minimize soil disturbance, 30-cm diameter chambers, sensors, and a data logger to continuously measure and record soil temperatures and soil oxidation-reduction (redox) potentials (left panel). Chamber cap used to collect gas samples from the chamber headspace, which was mixed with a small, 9-V-battery-operated fan, using a syringe poked through a septum (right panel).

Summary of Research

Since 2013, numerous field and greenhouse studies have evaluated various soil, plant and agricultural effects on GHG emissions from rice production in Arkansas. Some studies have measured CO_2, CH_4, or N_2O only, while others have measured multiple trace gases. Except for the CO_2-only studies, GHG research has been conducted using the vented, non-flow-through, non–steady-state closed-chamber approach (Parkin and Venterea, 2010), with chamber diameters of 15 or 30 cm (Figures 1 and 2).

CO_2 Only Studies

Brye et al. (2006) evaluated soil CO_2 fluxes from pelletized and fresh poultry litter before flooding rice on silt-loam soil. Results showed that soil CO_2 fluxes were generally unaffected by poultry litter form, but generally increased as the litter application rate increased (Brye et al., 2006). Motschenbacher et al. (2015) evaluated tillage and crop rotation effects on soil CO_2 fluxes during the non-flooded period of flood-irrigated rice on silt-loam soil. After more than 10 years of consistent management, few differences in early and late-season soil CO_2 fluxes occurred between tillage treatments and among various crop rotations including rice (Motschenbacher et al., 2015).

CH_4 Only Studies

Rogers et al. (2013) evaluated CH_4 fluxes over time with and without plants in the measurement chamber (Figure 1), with chambers both in and between rows and with optimal and no-N fertilization in drill-seeded, delayed-flood rice on silt-loam soil. Results showed that CH_4 emissions were greater with than without plants, but unaffected by N fertilization (Rogers et al., 2013). Brye et al. (2013) summarized the effects of soil texture on CH_4 fluxes from optimally N-fertilized rice grown in drill-seeded, delayed-flood rice on a silt-loam and clay soil, where season-long CH_4 emissions from silt-loam soil were greater than from clay soil.

Rogers et al. (2014) evaluated the effects of rotation (soybean-rice and rice-rice) and cultivar (pure-line and hybrid) on season-long methane emissions in drill-seeded, delayed-flood rice on silt-loam soil. Results showed that season-long CH_4 emissions were greater from a rice-rice than a rice-soybean rotation and greater from a pure-line than from a hybrid cultivar (Rogers et al., 2014). Smartt et al. (2016b) evaluated the effects of N-fertilized, non-N-fertilized and bare-soil treatments on CH_4 emissions from drill-seeded, delayed-flood rice on clay soil. Results showed that season-long CH_4 emissions were greater when rice was fertilized with N. Brye et al. (2016) summarized the effects of soil texture, rice cultivar and crop rotation on CH_4 emissions, where results showed that season-long CH_4 emissions were greater from silt-loam than clay soils, greater from a pure-line than a hybrid cultivar and greater from a rice-rice than a rice-soybean rotation.

Rogers et al. (2017) evaluated the effects of fertilizer-N source (ammonium sulfate, urea only and pelletized poultry litter plus urea), previous crop (soybean and rice) and soil texture (silt loam and clay) on CH_4 emissions from drill-seeded, delayed-flood rice. Results showed that season-long CH_4 emissions were greater from pelletized poultry litter than from ammonium sulfate or urea, greater from a silt-loam than clay soil and greater when rice was the previous crop compared to soybean on the clay soil, but were unaffected by previous crop on the silt-loam soil (Rogers et al., 2017).

Brye et al. (2017a) evaluated the diurnal variation in CH_4 fluxes and emissions during vegetative and reproduction growth stages in a silt-loam and clay soil, where results showed that CH_4 fluxes differed over time throughout the day and were greater from a pure-line than a hybrid cultivar on silt-loam soil, but not on clay soil. Brye et al. (2017b) evaluated the effects of rice cultivar selection (one hybrid and two pure-line cultivars) and crop rotation (rice-rice and soybean-rice) on CH_4 fluxes and emissions across multiple years from drill-seeded, delayed-flood rice production. Results showed that season-long CH_4 emissions were greater from the two pure-line cultivars than from the hybrid and greater following rice than soybean (Brye et al., 2017b).

Smartt et al. (2018) evaluated the effects of three hybrid (CLXL729, CLXL745, and XL753) and a pure-line (Roy J) rice cultivar on CH_4 fluxes and seasonal emissions from silt-loam soil. Results showed that season-long CH_4 emissions were greater from the pure-line than from any of the three hybrid cultivars (Smartt et al., 2018). Humphreys et al. (2018a) evaluated the effects of water management scheme (full-season flood and mid-season drain) on season-long CH_4 emissions in the direct-seeded, delayed-flood rice production system on silt-loam soil. Results showed that season-long CH_4 emissions were greater from the full-season-flood than from the mid-season-drain water management scheme.

Humphreys et al. (2018b) evaluated the effects of tillage (conventional tillage and no-tillage) and coated and uncoated urea on CH_4 fluxes in the direct-seeded, delayed-flood rice production system on silt-loam soil, where results showed that season-long CH_4 emissions were unaffected by tillage or urea type. Humphreys et al. (2018c) evaluated the effects of soil organic matter (SOM) concentration on CH_4 emissions from direct-seeded, delayed-flood rice in silt-loam soils, where results showed that season-long CH_4 emissions increased as initial SOM concentration increased.

N_2O Only Studies

Rector et al. (2018a) evaluated the effects of tillage practice (conventional tillage and no-tillage) and urea-fertilizer type (coated and uncoated) on N_2O fluxes and season-long emissions from direct-seeded, delayed-flood rice on silt-loam soil, where results showed that neither tillage nor urea-fertilizer type affected season-long N_2O emissions. Rector et al. (2018b) evaluated the effects of water management scheme (full-season flood and intermittent flood) and rice cultivar (pure-line and hybrid) on N_2O fluxes and season-long emissions from direct-seeded, delayed-flood rice on silt-loam soil, where results showed that neither water management scheme nor rice cultivar affected season-long N_2O emissions.

Slayden et al. (2022a) evaluated the effects of site position (up-, middle- and down-slope) and tillage (conventional tillage and no-tillage) on N_2O emissions in furrow-irrigated rice on silt-loam soil (Figure 2). Results showed that season-long N_2O emissions were greater from the down-slope than the up-slope or mid-slope positions and greater from conventional tillage than no-tillage (Slayden et al., 2022a).

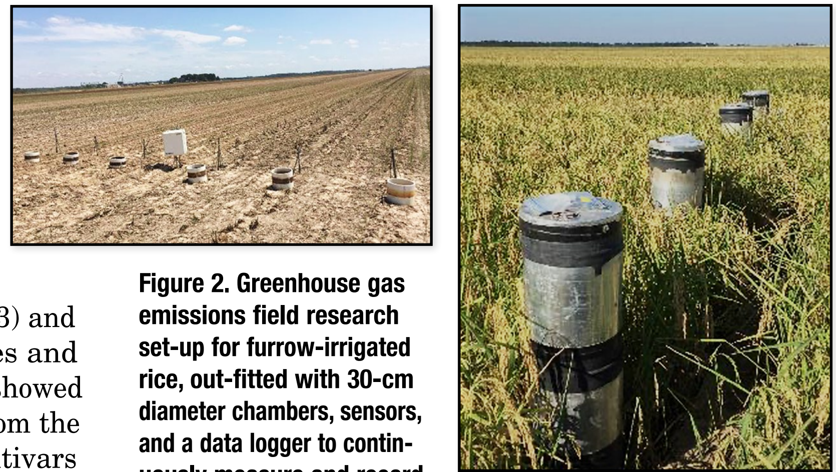

Figure 2. Greenhouse gas emissions field research set-up for furrow-irrigated rice, out-fitted with 30-cm diameter chambers, sensors, and a data logger to continuously measure and record soil temperatures and soil oxidation-reduction (redox) potentials at one site position in a production-scale field (left panel). Greenhouse gas chambers with caps and extenders to accommodate growing rice later in the growing season (right panel).

Slayden et al. (2022b) evaluated the effects of fertilizer-N rates and application timings on N_2O fluxes and season-long emissions in simulated furrow-irrigated rice grown on silt-loam soil in a greenhouse. Results showed that season-long N_2O emissions were unaffected by fertilizer-N rate or application timing, but that numeric reductions in season-long N_2O emissions could be achieved with split N applications. In general, season-long N_2O emissions are typically several orders of magnitude lower than season-long CH_4 emissions across rice production practices and soil characteristics.

CO_2, CH_4, and/or N_2O Combined Studies

Della Lunga et al. (2020) evaluated the effects of soil moisture status (flooded; saturated, but not flooded; and moist soil, slightly below saturation) on season-long CO_2, CH_4, and N_2O emissions from rice grown on silt-loam soil in the greenhouse. Results showed that season-long CO_2 and CH_4 emissions were greater from the flooded-soil condition than the other water management regimes, while season-long N_2O emissions were unaffected by water management regime (Della Lunga et al., 2020).

Della Lunga et al. (2021a) evaluated the relationships among soil moisture, oxidation-reduction (redox) potential and soil temperature and CO_2, CH_4, and N_2O fluxes and emissions across the elevation gradient in a furrow-irrigated rice field on silt-loam soil. Results showed that CO_2 fluxes were directly correlated with soil moisture and temperature, but inversely correlated with soil redox potential; CH_4

fluxes were directly correlated with soil moisture and inversely correlated with soil redox potential; and N_2O fluxes were directly correlated with soil redox potential (Della Lunga et al., 2021a).

Della Lunga et al. (2021b) evaluated the effects of site position (up-, middle- and down-slope) and tillage practice (conventional tillage and no-tillage) on diurnal variations of CO_2, CH_4, and N_2O fluxes during vegetative rice growth in a furrow-irrigated rice field on silt-loam soil. Results showed that daily CO_2, CH_4, and N_2O flux maxima occurred in the late afternoon, while flux minima occurred in the early morning (Della Lunga et al., 2021b).

Della Lunga et al. (2023) evaluated the effects of site position (up-, middle- and down-slope) and tillage (conventional tillage and no-tillage) on CO_2 and CH_4 emissions and GWP in furrow-irrigated rice on silt-loam soil. Results showed that season-long GWP was generally greater from conventional tillage than from no-tillage and was greater at the down-slope than at the up-slope or mid-slope positions (Della Lunga et al., 2023).

Recommendations to Minimize Greenhouse Gas Emissions from Rice Production

Agricultural decisions involving soil/plant characteristics and management practices can often be adjusted to reduce a single GHG (Table 1). However, it is more challenging to prescribe a course of action that will simultaneously reduce multiple GHGs.

Table 1. Summary of major known soil and agronomic factors affecting greenhouse gas (GHG) emissions from rice production, the specific soil/plant characteristic or management practice to choose to minimize methane (CH_4) or nitrous oxide (N_2O) emissions, and the relevant reference(s) to support the recommendation.

Major Factor	Specific Soil/Plant Characteristic or Practice	Characteristic/Practice to Minimize Specific GHG Emissions		Relevant References
		CH_4	N_2O	
Soil texture	Silt loam		-†	Brye et al. (2013), Brye et al. (2016) Rogers et al. (2017)
	Clay	X	-	
Cultivar selection	Pure-line		-	Rogers et al. (2014), Brye et al. (2016), Brye et al. (2017), Smartt et al. (2018), Rector et al (2018b)
	Hybrid	X	-	
Nutrient source	Inorganic	X	-	Rogers et al. (2017)
	Organic		-	
Nutrient application timing	Optimum N + one split	-		Slayden et al. (2022b)
	Half optimum N + two splits	-	X	
	Optimum N + two splits	-	X	
Water management scheme	Flood irrigation		X	Humphreys et al. (2018a), Rector et al. (2018b)
	Non-flood irrigation	X		
Previous crop	Soybean	X	-	Rogers et al. (2014), Brye et al. (2016), Brye et al. (2017)
	Rice		-	
Tillage	Conventional tillage	-		Rector et al. (2018a), Humphreys et al. (2018b), Slayden et al. (2022a) Della Lunga et al. (2021b), Della Lunga et al. (2023)
	No-tillage	-	X	
Soil moisture condition	Flooded		-	Della Lunga et al. (2020)
	Saturated, but not flooded	X	-	
	Moist, near saturation, but not saturated	X	-	
Soil moisture and temperature variations	Small variation	-	X	Della Lunga et al. (2020)
	Large variation	-		

† Dashes indicate either little measured effect from the specific characteristic or practice, or the research has not been conducted yet to confirm any effect.

Based on the results of field and greenhouse research studies conducted in Arkansas, here are some recommendations for reducing individual GHGs and multiple GHGs simultaneously:

CO_2

- Decreased tillage intensity and/or frequency will contribute to reduced CO_2 emissions.
- Cover crop and/or crop residue presence will reduce soil temperature and moisture fluctuations, reducing the rate of soil respiration and lowering CO_2 emissions.
- Maintaining uniform soil moisture conditions or avoiding large and frequent soil moisture fluctuations in furrow-irrigated rice production will contribute to reduced CO_2 emissions.

CH_4

- Flood-irrigated rice production on clay soils will result in reduced CH_4 emissions compared to silt-loam or coarser-textured soils.
- Flood-irrigated rice production with a hybrid rice cultivar will contribute to reduced CH_4 emissions.
- Using inorganic fertilizer-nutrient sources in flood-irrigated rice production will contribute to reduced CH_4 emissions.
- Flood-irrigated rice production in rotation with soybean will contribute to reduced CH_4 emissions.
- Non-flood-irrigated rice production techniques such as AWD, intermittent flooding and furrow-irrigation, will contribute to reduced CH_4 emissions.

N_2O

- Flood-irrigated rice production will contribute to reduced N_2O emissions.
- Furrow-irrigated rice production with no-tillage will contribute to reduced N_2O emissions.
- Maintaining uniform soil moisture conditions or avoiding large and frequent soil moisture fluctuations in furrow-irrigated rice production will contribute to reduced N_2O emissions.
- Split applications of inorganic N fertilizer will contribute to reduced N_2O emissions.

CO_2, CH_4 and/or N_2O Combined

- Maintaining uniform soil moisture conditions or avoiding large and frequent soil moisture fluctuations in furrow-irrigated rice production will contribute to reduced CO_2 and N_2O emissions.
- Flood-irrigated rice production on clay soils contributes to reduced CH_4 and N_2O emissions.
- Furrow-irrigated rice production with no-tillage will contribute to reduced CH_4 and N_2O emissions.
- Furrow irrigation can reduce GWP compared to flood-irrigated conditions.

Conclusions

Greenhouse gas emissions from Arkansas' rice-producing soils, most importantly silt-loam soils, are a concern for conservation planning and for maintaining sustainable use of the state's soil, water and air resources. As one of the major land uses in Arkansas and a significant contributor to Arkansas' agricultural economy, traditional flood-irrigated rice has been specifically identified as a major source of GHG emissions, namely CH_4.

Field research in Arkansas has confirmed soil texture and water management scheme are the most important factors affecting GHG emissions, namely CH_4 and N_2O, from rice production. Flood-irrigated rice production on silt-loam soils is much more of a concern than on clay soils. While being most widespread, flood-irrigated rice production, especially on silt-loam soils, produces greater CH_4 emissions than non-flood-irrigated rice production or clay soils.

Despite greater CH_4 emissions from flood-irrigated rice on silt-loam soil than from non-flood-irrigated rice production or from clay soils, season-long GHG emissions, namely CH_4, from direct field measurements from rice production in Arkansas are generally lower than what EPA has suggested for season-long emissions from rice production in general.

Furthermore, direct field measurements of season-long CH_4 emissions from rice production in Arkansas are generally lower than those reported for many other rice production systems around the world, particularly deep-flooded paddy rice. Reducing GHG emissions would be a significant conservation measure that would benefit Arkansas' agricultural producers and landowners in general, not just rice producers.

Although GHGs are being emitted, it appears that Arkansas rice production generates less GHG than once thought as compared to other rice-producing states and countries. Nevertheless, continued research regarding rice production and GHG emissions is necessary to conserve Arkansas' valuable soil, water and air resources.

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