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Chapter 8

Methane Emissions from Rice Production in the United States — A Review of Controlling Factors and Summary of Research

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Additional information is available at the end of the chapter

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Abstract

Flooded rice (*Oryza sativa* L.) cultivation has been identified as one of the leading global agricultural sources of anthropogenic methane (CH_4) emissions. Furthermore, it has been estimated that global rice production is responsible for 11% of total anthropogenic CH_4 emissions. Considering that CH_4 has a global warming potential that is approximately 25 times more potent, on a mass basis, than carbon dioxide (CO_2) and rice production is globally extensive and concentrated in several mid-southern and southern states and California, the purpose of this review is two-fold: (i) discuss the factors known to control CH_4 production in the soil and transport to the atmosphere from rice cultivation and (ii) summarize the historic and recent research conducted on CH_4 emissions from rice production in the temperate United States. Though some knowledge has been gained, there is much more that still needs to be learned and understood regarding CH_4 emissions from rice production in the United States, its contribution to climate change, and potential mitigation strategies. Extending the current knowledge base surrounding CH_4 emissions from rice cultivation will help regulatory bodies, such as the Environmental Protection Agency, refine greenhouse gas emissions factors to combat the potential negative effects of climate change.

Keywords: Methane, emissions, rice production, agriculture, soil texture

1. Introduction

Methane (CH_4) is a known and potent greenhouse gas that is produced by anaerobic *Archaea* under anoxic conditions. Agricultural activities have been recognized as contributing an estimated 50% to global anthropogenic CH_4 emissions [1], while an estimated 31% of anthropogenic CH_4 emissions have been attributed to agricultural activities in the United States (US)

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[2]. Due to the anaerobic conditions that form in saturated soils, which is a prerequisite for CH_4 production, flooded rice (*Oryza sativa* L.) cultivation has been specifically identified as one of the leading global agricultural sources of anthropogenic CH_4 emissions, accounting for approximately 22% of the total global agriculturally related CH_4 emissions [3]. Furthermore, it has been estimated that global rice production is responsible for 11% of total anthropogenic CH_4 emissions [1,3].

While numerous factors have been determined to impact CH_4 emissions from rice cultivation, due to a general lack of field data, the United States Environmental Protection Agency (USEPA) currently uses a single emissions factor for all non-California-grown, primary rice crops [4]. Therefore, the purpose of this review is two-fold: (i) discuss the factors known to control CH_4 production in the soil and transport to the atmosphere from rice cultivation and (ii) summarize the historic and recent research conducted on CH_4 emissions from rice production in the temperate United States.

2. The greenhouse effect

The greenhouse effect is a mechanism by which certain gases such as carbon dioxide (CO_2), CH_4, nitrous oxide (N_2O), and water (H_2O) vapor absorb and release infrared radiation, interfering with the ability of solar radiation to leave Earth's atmosphere. The absorption of thermal radiation by H_2O and CO_2 was discovered through laboratory experiments in 1859 [5]. However, other gases including CH_4 and N_2O were not recognized as greenhouse gases until the 1970s [6].

Global warming potential (GWP) is a metric that allows the warming impact of various greenhouse gases to be quantitatively compared on the same scale. The assignment of GWP values to gases requires knowledge of the contribution to global warming of gas emissions over time based on the amount of radiation per mass that the gas can absorb and emit as well as the atmospheric lifetime of the gas. Global warming potentials are assigned relative to that of CO_2, thus the 100-yr GWP of CO_2, CH_4, and N_2O are 1, 25, and 298, respectively [7]. For example, 1 kg of CH_4 released to the atmosphere is equivalent to 25 kg of CO_2 being released. Global warming potentials allow greenhouse gas emissions to be reported as CO_2 equivalents in order to compare warming effects of various gases on a single scale.

The current climate change problem is not a result of the greenhouse effect itself, but rather from an increasing greenhouse effect resulting from anthropogenic activities that have increased atmospheric concentrations of greenhouse gases. Prior to 1750, the atmospheric CO_2 mixing ratio was about 280 parts per million (ppm) [8]. Since the beginning of the industrial era, atmospheric CO_2 has risen drastically to 379 ppm in 2005 [7] and 395 ppm as of April 2013 [9]. Between 1750 and 2005, atmospheric CH_4 increased from about 700 parts per billion (ppb) to 1,774 ppb [7]. Nitrous oxide was more variable ranging from 180 to 260 ppb prior to 1750, but has similarly increased to a mixing ratio of 319 ppb in 2005 [7]. While atmospheric N_2O and CO_2 concentrations have increased steadily over the past several decades, the growth rate (i.e., concentration increase) of atmospheric CH_4 seems to be declin-

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ing. The growth rate of atmospheric CH_4 has decreased from highs of about 1% per year in the 1970s and 1980s to nearly zero between 1999 and 2005. However, the decreasing growth rate is poorly understood [7].

3. Greenhouse gas emissions

Globally, CO_2 accounted for about 76% of greenhouse gas emissions in 2004, with around 75% of CO_2 emissions resulting from fossil fuel use and much of the remainder from deforestation and biomass decomposition [10]. Methane and N_2O accounted for 14 and 8%, respectively, of the estimated global greenhouse gas emissions in 2004. Major CH_4 sources include agricultural activities, waste management, and energy use, while N_2O emissions are primarily a result of agricultural activities, such as fertilizer use and soil management [10]. In the US in 2013, an estimated 82% of the total greenhouse gas emissions were CO_2, 10% were CH_4, and 5% were N_2O [2]. Major sources of greenhouse gas emissions are generally the same in the US as the global sources mentioned above. The major global sectors responsible for greenhouse gas emissions are energy supply (26%), industry (19%), forestry (17%), agriculture (14%), and transportation (13%) [10]. In comparison, the major US sectors responsible for greenhouse gas emissions are energy supply (31%), transportation (27%), industry (21%), commercial and residential (12%), and agriculture (9%) [2].

Although agricultural activities do not dominate total greenhouse gas emissions, agriculture contributes an estimated 50 and 60% of global anthropogenic emissions of CH_4 and N_2O, respectively [1]. Agriculture in the US is responsible for an estimated 36% of anthropogenic CH_4 emissions and 79% of anthropogenic N_2O emissions [2]. Enteric fermentation, rice cultivation, and manure management contribute an estimated 64, 22, and 8%, respectively, to global anthropogenic agricultural CH_4 emissions, while agricultural N_2O emissions are dominated by agricultural soil management (80%) [3]. In comparison, enteric fermentation, rice cultivation, and manure management contribute to 70, 4, and 26% of US anthropogenic agricultural CH_4 emissions [2]. Although rice cultivation makes up a small portion of CH_4 emissions in the US, globally rice cultivation accounts for approximately 11% of total anthropogenic CH_4 emissions.

Methane emissions from US rice cultivation were estimated to be 8.3 Tg CO_2 equivalents in 2013, a reduction from 9.3 Tg CO_2 equivalents in 2012 due to a decline in rice production area [2]. Arkansas was responsible for 36% of the estimated CH_4 emissions from rice cultivation, although Arkansas accounted for 43% of the total US rice production in 2013. Louisiana was the next leading contributor to CH_4 emissions accounting for 27% of 2013 emissions, while harvesting 16% of 2013 production [2,11]. Louisiana and Texas CH_4 emissions are large relative to their production areas due to extensive ratoon cropping in 2013, which occurred on an estimated 38 and 68%, respectively, of the production area in those states [2]. A ratoon crop is a second crop that is managed and produced after the first or primary crop is harvested. California, Mississippi, and Missouri, none of which reported any ratoon cropping, contributed 14, 3.6, and 4.5%, respectively, to the estimated 2013 CH_4 emissions from US rice cultivation [2].

The USEPA periodically publishes CH_4 emissions factors based on research data. Separate emission factors of 178 kg CH_4-C ha^{-1} $season^{-1}$ and 585 kg CH_4-C ha^{-1} $season^{-1}$ were used in the inventory estimates for non-California-grown, primary rice cropping and ratooned cropping areas, respectively, as is consistent with the Intergovernmental Panel on Climate Change [3], which recommends calculating separate emissions factors for as many different factors and cultural practices as is possible. Emissions factors for California rice production are 200 and 100 kg CH_4-C ha^{-1} $season^{-1}$ for winter-flooded and non-winter-flooded rice, respectively [2]. While it is known that factors such as water management, soil properties, rice cultivar, fertilizer management, and residue management have strong impacts on CH_4 emissions from rice cultivation, data available from US studies limit the further disaggregation of these factors [2]. The non-California-grown, primary crop emissions factor is based on US studies with emissions ranging from 46 to 375 kg CH_4-C ha^{-1} $season^{-1}$ [13–20] and the ratoon crop factor is based on studies conducted in Louisiana with emissions ranging from 361 to 1118 kg CH_4-C ha^{-1} $season^{-1}$ [21,22]. The California-specific emissions factors include studies with emissions ranging from 47 to 166 kg CH_4-C ha^{-1} $season^{-1}$ for the non-winter-flooded and from 98 to 277 kg CH_4-C ha^{-1} $season^{-1}$ for the winter-flooded rice [23,24].

4. Rice production

Rice is a semi-aquatic, cereal grain that makes up about 21% of total global grain production [25]. The importance of rice is further exemplified by the fact that rice is a staple food crop for about half of the global population, with direct human consumption accounting for 85% of rice production compared to 72% of wheat (*Triticum aestivum* L.) and 19% of maize (*Zea mays* L.) production [26,27]. In Southeast Asia, 60% of human food intake is provided by rice as well as 35% of food intake in both East Asia and South Asia [26]. Rice has the ability to support more people per unit of land area than wheat or maize because rice produces, on an average yield basis, more food energy and protein per hectare than wheat or maize [28]. Therefore, any potential negative environmental consequences associated with rice production have to be taken seriously.

4.1. Rice production extent

Common rice (*Oryza sativa*) is commercially produced in 112 countries worldwide, spanning latitudes from 53°N along the Amur River at the China–Russia border to 35°S in central Argentina [26]. In 2012, more than 158 million ha globally were planted to rice, with average yields of 4.4 Mg ha^{-1} for a total global production of 470 Tg of rice. Comparatively, nearly 216 million ha were planted in wheat in 2012, with average yields of 3.0 Mg ha^{-1} for a total of 656 Tg of global wheat production. More than 174 million ha were planted in maize in 2012, with an average yield of 4.9 Mg ha^{-1} and a total global production of 857 Tg of maize [25]. Global rice production peaked in 1994 at 534 Tg of rice, with Asia being responsible for 90% of that production [29]. The majority of global rice production occurs in east, south, and southeast Asia, which together accounted for 90% of global production in 2012. Substantial production

also occurs in South America (Brazil and Peru), Sub-Saharan Africa (Nigeria and Madagascar), Europe (Italy and Spain), Egypt, and the US [25].

China and India currently dominate global rice production accounting for 30 and 22%, respectively, of the total global production in 2012. The third-, fourth-, and fifth-ranked global producers in 2012 were Indonesia (8%), Bangladesh (7%), and Vietnam (6%). The remaining top 10 producers, in order, were Thailand, the Philippines, Burma, Brazil, and Japan, followed by the eleventh-ranked US, which accounted for 1.3% of global production [25]. The US, however, plays a larger role in global exports contributing 9% of 2012 global exports and ranking fifth after Thailand (21%), India (20%), Vietnam (20%), and Pakistan (10%). Global exports in 2012 were estimated to be 8% of total production, while the US exported 55% of 2012 production [30]. Global rice yields in 2012 were estimated to be 4.4 Mg ha^{-1} compared to 8.3 Mg ha^{-1} in the US, which was second only to Egypt (8.8 Mg ha^{-1}) among the major rice-growing countries. The two top rice-producing countries, China and India, had estimated yields of 6.7 and 3.6 Mg ha^{-1}, respectively [25].

Nearly 1.1 million ha of rice were planted in the US in 2012, yielding an average of 8.3 Mg ha^{-1} for a total production of 9.0 Tg of rice prior to milling, compared to 23 million ha planted with an average yield of 3.1 Mg ha^{-1} for a total of 62 Tg of wheat production, and over 39 million ha of planted maize with average yields of 7.7 Mg ha^{-1} for a total production of 274 Tg [11]. The four major regions that produce rice in the US are the Arkansas Grand Prairie, the Mississippi Delta, which is made up of portions of Arkansas, Missouri, Mississippi, and Louisiana, the Gulf Coast (Texas and southwest Louisiana), and California's Sacramento Valley. Most US states produce primarily long-grain cultivars, while much of the medium-grain rice and nearly all of the short-grain rice is produced in California [11]. Although Oklahoma and Florida are often included as rice-producing states, the six previously mentioned states have made up essentially all of US production in recent years [11]. Arkansas is the leading state in both area of cultivation and total production, contributing 48% of total US rice production in 2012, followed by 23% of production by California and 13% of production by Louisiana [11]. Arkansas rice production takes place in the eastern portion of the state with the top five rice-producing counties in 2012 being Poinsett, Lawrence, Arkansas, Greene, and Cross, which made up 35% of the state's production area [31].

4.2. Global rice production practices

Rice production practices vary globally based on economic, cultural, and climatic factors, each of which show temporal and spatial variability throughout the rice-growing countries. A simple classification or characterization of rice production systems is nearly impossible on a global scale due to the variability of factors that influence production. Classifications of rice production techniques are commonly based upon flood presence (e.g., upland or lowland), water source (e.g., irrigated or rainfed), and stand establishment technique (e.g., transplanting, direct-seeding, or water-seeding) with many combinations and variations of these techniques occurring throughout the globe [32]. In one of the most recent classification attempts, Chang [33] classified global rice production into five major agroecosystems: (i) irrigated wetland, which made up 53% of global rice production area and had the greatest yield potential at 3 to

5 Mg ha^{-1}, (ii) rainfed wetland, making up 26% of global area and yielding 2 to 4 Mg ha^{-1}, (iii) flood-prone or tidal swamps, which made up an insignificant area, (iv) deep water (1–5 m), making up 8% of global area, and (v) dryland, which made up an estimated 13% of global production area with average yield potentials of 1 to 1.5 Mg ha^{-1}.

While a small portion of rice is produced under upland conditions, the majority of rice production requires substantial quantities of water in order to maintain a flood on the semi-aquatic crop. In much of the tropical rice-growing area, particularly south and southeast Asia, rainfed rice is the main production system, where most of the production comes from wet-season harvests and the cropping season is determined by rainfall patterns [32]. In temperate production areas, rice production must coincide with suitable temperatures for the crop which, coupled with inadequate rainfall, requires that temperate rice be almost entirely irrigated in order to maintain a flood for the duration of the growing season [32]. The utilization of irrigation in temperate areas allows greater control of environmental factors, which ultimately tends to increase yields, while rainfed systems may suffer from droughts and floods that may substantially damage crops and reduce yields [32].

Direct-seeding and transplanting are common establishment techniques in both irrigated- and rainfed-wetland systems, while direct-seeding is the major practice in dryland and deep-water agroecosystems [33]. While transplanting does occur in irrigated- and direct seeding occurs in rainfed-wetland systems, it is more common for irrigated systems to utilize direct-seeding and for rainfed systems to use transplanting techniques [32]. Transplanting systems involve raising seedlings in a nursery seedbed area at the beginning of the season and transplanting into puddled paddy soils early in the vegetative growth stage. Transplanting is the major establishment system for rainfed rice in tropical Asia, with the majority of production in northeast India, Bangladesh, and Thailand relying upon transplanting techniques [32]. Direct-seeding by grain-drilling or broadcasting pre-germinated seeds onto puddled soil is practiced in parts of India, Sri Lanka, Bangladesh, and the Philippines, while drill-seeding into dry soil is the most common practice in the US and other mechanized regions such as Australia [32]. Rice seed may be broadcast onto dry or moist soil by airplane followed by harrowing to cover seeds, but this establishment method requires more seed and stand establishment is often poorer than with drill-seeding [32]. Water-seeding is an establishment technique that originated and is practiced in parts of Asia, where pre-germinated seeds are broadcasted from an airplane into already flooded paddies or fields [32]. The rice-production system, and associated specific production practices, can significantly affect CH_4 production and emissions.

4.3. Rice production practices in the US

Rice production under mechanized US systems requires high temperatures, nearly level land, plentiful water, and soils that inhibit percolation of floodwater, so production is limited to Arkansas, Louisiana, Mississippi, Missouri, Texas, California, and Florida [34]. All US rice is produced using high-input, mechanized production practices, but practices vary somewhat from region to region based on differences in climate, soils, weed proliferation, and other factors that influence production. Essentially, all US rice is irrigated and sources of irrigation water include shallow or deep groundwater, runoff reservoirs, rivers, bayous, and lakes [34].

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It is estimated that between 1000 and 2500 m^3 ha^{-1} of water are required to produce a rice crop in the southern US and generally less than one third of that requirement is met by rainfall [35]. Levees, which separate fields into bays, or paddies, and control flood depth (i.e., by use of gates or spills), are commonly constructed on contours that were surveyed on 3 to 6 cm vertical intervals. This creates winding, contour-shaped levees in fields that are not precision-leveled, whereas precision leveling to a uniform grade of 0.2% or less allows the construction of uniformly spaced, straight levees and may reduce the number of levees required [34].

The two stand establishment techniques utilized in the US are dry-seeding and water-seeding. Dry-seeding techniques, particularly drill-seeding, are predominant in most of the US, while water-seeding techniques are used extensively in California and to a small degree in southwest Louisiana and other regions as a weed control method [34]. A continuously flooded, water-seeding technique is used in California, where pre-germinated seeds are broadcast by airplane into flooded fields and the seedlings grow through a standing flood, while a pinpoint-flood, water-seeding technique is used in Louisiana, where seeds are broadcast into a flooded field that is drained within a few days and then permanently flooded after drying for 3 to 5 days [34,36]. In dry-seeded systems, seed is most often drilled into a well-pulverized, firm, and weed-free seedbed in 15- to 25-cm rows to a depth of 2.5 cm or less. When rice is following a high-residue crop, such as rice, maize, or wheat, it is necessary to till the land in the fall or early spring so that decomposition of the residue does not immobilize nutrients after the subsequent rice crop is planted, whereas rice following soybean (*Glycine max* L.), a crop that produces relatively little residue, may not require as much preparation because crop residues are not as abundant or as persistent compared to that of rice or maize [34,37].

Water management at and shortly after planting varies across US systems, but a permanent flood is established in all systems usually by the four- to five-leaf vegetative growth stage/beginning tillering (V4-5) [38]. Flush irrigation is used as necessary to promote germination and seedling growth in dry-seeded rice systems prior to establishment of a permanent flood, which typically occurs three to four weeks after emergence (i.e., the V4 to V5 growth stage). Drainage during the season is typically avoided except if a nutrient deficiency, such as zinc, is detected, to aerate the soil in order to treat or prevent disorders, such as straighthead and hydrogen sulfide toxicity, or to apply pesticides. Fields are drained prior to harvest in order to dry the soil enough for operation of harvest equipment [34]. Fields are flooded again within five to seven days after primary-crop harvest in ratoon cropping systems, which are common in southwest Louisiana, Texas, and Florida, and the flood is again maintained until harvest of the ratoon crop [34].

Crop rotations are important in rice, especially where weedy/red rice is problematic and difficult to control during rice cropping seasons. In order to suppress weedy rice, nearly all rice in Louisiana is grown either in a 1:1 rotation with soybean or a 1:1:1 rotation where crawfish (*Procambarus clarkia*) are double-cropped following rice, with soybean produced the following season [34]. In 2012, greater than 70% of Arkansas rice was produced in rotation with soybean, with most of the remaining production in a rice–rice rotation [39]. In California, approximately 70% of rice is produced in a rice–fallow or rice–rice rotation [40].

4.4. Arkansas rice production practices

Arkansas is the leading rice-producing state, accounting for 40 to 50% of total annual production in the US [11]. Rice production in Arkansas began in 1902 when 0.4 ha were planted in Lonoke County. Production increased over time until 1955 when government quotas limited production to 202,350 ha. The limitation was lifted in 1974 and production increased again, peaking in 1981 at 623,240 ha, again in 1999 with 667,755 harvested hectares, and finally in 2010 with 724,413 ha [31]. In 2012, 518,016 ha rice were harvested in Arkansas [11]. Rice production in Arkansas is highly mechanized with a heavy dependence upon synthetic fertilizers, chemical pest control, and machinery. Planting of rice in Arkansas generally begins the last week of March and extends into early June with floods typically being established by the end of May or early June. Harvesting operations usually begin in mid-August and peak in early- to mid-September [31].

Arkansas rice is produced on a wide variety of soils ranging from sandy to clay soils with the differing textural classes generally requiring different management, especially with regards to tillage practices and nutrient management [39, 41]. Production on sands and sandy loams is minor and has been decreasing from 3.1 and 5.2% of Arkansas area, respectively, in 2007 to 0.7 and 3.7%, respectively, in 2012. Arkansas production on clay and clay-loam soils, however, has increased from under 40 to 48% between 2007 and 2009 but declined to 43% in 2012. Production on silt-loam soils has remained fairly steady at 52% in 2007 and 53% in 2012 [39,42].

Dry-seeding techniques have always dominated in Arkansas. Water-seeding has varied between 2 and 8% of the production area between 2007 and 2012, with an estimated 5% of the 2012 Arkansas rice area being water-seeded [39,42]. Approximately 80% of 2012 Arkansas rice area was drill-seeded, compared to approximately 20% being broadcast-seeded [39]. Conventional tillage accounted for over half of Arkansas planted-rice area, while stale-seedbed (i.e., tillage and floating, or leveling the field, in the fall or winter) and no-tillage accounted for 35 and 10% of the planted-rice area, respectively, in 2012 [39]. Stale-seedbed and no-tillage are oftentimes utilized on clay soils where conventional tillage produces a cloddy seedbed with poor seed-to-soil contact [41].

While pinpoint, water-seeding techniques do occur in Arkansas, over 90% of the Arkansas rice production area utilizes a delayed-flood system, where the permanent flood is not established until the four- to five-leaf growth stage, which generally occurs approximately three to four weeks after emergence [39]. Fields are drained two to three weeks prior to harvest and most fields remain unflooded until the subsequent rice crop is produced, while nearly 20% of Arkansas rice area is winter-flooded [34,39]. Over 75% of Arkansas rice is irrigated by groundwater with 10 and 13% of the rice area utilizing water stored in reservoirs and from streams/rivers, respectively [39].

The two methods of nitrogen (N) fertilization in Arkansas are (i) the standard two-way split system, where 65 to 75% of the total N is applied pre-flood with the remainder applied at mid-season in one or two applications between beginning internode elongation and half-inch internode elongation [i.e., reproductive stage 0 (R0) to 1 (R1)], and (ii) the single optimum pre-flood system, where a single N application is made immediately prior to flooding. Nitrogen

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fertilizer rate recommendations have previously been based only on cultivar, soil texture, and previous crop. Implementation of the new N-Soil Test for Rice (N-STaR) enables recommendations to be adapted to the soil's ability to supply N to the rice crop on a field-by-field basis, reducing the likelihood of over- and under-fertilization of N [43]. Ammonium-N sources, such as urea and ammonium sulfate, are used in order to prevent N loss through denitrification that occurs with nitrate-containing fertilizers. Phosphorus and potassium are incorporated prior to planting as recommended by routine soil tests [43]. Organic amendments are uncommon, although poultry litter is utilized to a small degree, especially in precision-leveled fields.

5. Flooded soils

The saturated soils that occur during wetland, or lowland, rice cultivation give rise to a set of physical, chemical, and biological properties that are quite different from upland soils. Rice is the only major row crop produced under flooded-soil conditions and the absence of air-filled pores along with reduced soil–atmosphere interactions result in an almost entirely different set of processes than those occurring in upland cropping systems.

5.1. Physical characteristics of flooded soils

The major physical difference between saturated and unsaturated soils involves the availability and rates of movement for gases and solutes. Under aerated conditions, the soil atmosphere contains essentially the same gases as the atmosphere although the proportions of oxygen (O_2) and CO_2 differ from the atmosphere due to soil respiration [44]. Carbon dioxide diffuses into the atmosphere from the soil due to production during respiration and O_2 diffuses into the soil as it is consumed during respiration. The saturation and ponding of flooded soils greatly reduce gas transport between the soil and atmosphere compared to aerated soils and plant-mediated transport of gases by diffusion is often the main exchange mechanism between the soil and atmosphere in saturated or flooded systems [45]. As a flooded soil dries, gases trapped in the soil may escape due to increases in diffusion and convective flow rates that occur as water escapes soil pores.

While solute movement by diffusion may be greater in saturated soils due to an increase in water-filled pore space, diffusion of gases through water is roughly three to four orders of magnitude slower than diffusion of gases through air [46,47]. Both diffusive and convective flow of gases and solutes are related to pore connectivity and tortuosity, so it is expected that movement of gases and solutes are slower in fine-textured soils, such as clays and clay loams, than in coarser-textured soils, such as silt loams and sands, which generally have larger, more connected pores [47]. Convective flow of gases in saturated soils can occur as dissolved gases move with moving soil water, which is dependent largely upon soil texture and structure, and as ebullition, which is where gases escape as bubbles through ponded water [47]. Generally, diffusion dominates gas transport in fine-textured soils, such as clay loams and clays, and diffusion rates typically decrease as particle size decreases, which is due to differences in size, orientation, and shape of soil pore spaces [45,48]. Soil texture also affects the amount of time

it takes for a soil to become saturated with infiltration rates in clayey soils estimated to be 1 to 5 mm hr^{-1} compared to 10 to 20 mm hr^{-1} in soils such as silt loams [47]. The amount of time a soil takes to become saturated has an effect on chemical and biological processes that develop as the system becomes anaerobic.

5.2. Soil redox potential

Isolation of flooded soils from the atmosphere and depletion of soil O_2 induces biological and chemical reactions that create anaerobic and reducing conditions rather than the aerobic and oxidized conditions that generally occur in upland soils. Organic matter decomposition slows under anaerobic conditions, but as organic matter is oxidized, transformations such as denitrification and manganese (Mn) and iron (Fe) reduction occur as well as production of gases such as hydrogen sulfide (H_2S) and CH_4. Soil reduction/oxidation (redox) reactions are coupled half-reactions where the oxidation of organic matter, which provides electrons, is coupled with the reduction of elements or compounds that act as electron acceptors [49]. Oxygen is the major electron acceptor under aerobic conditions, but as O_2 is depleted, the sequence of electron acceptors shifts to NO_3^-, MnO_2, $Fe(OH)_3$, SO_4^{2-}, and CO_2, which are theoretically reduced in that order based on thermodynamic favorability [44,50]. The reduced forms of the previously mentioned terminal electron acceptors are H_2O, N_2, Mn^{2+}, Fe^{2+}, H_2S, and CH_4, respectively. Soil redox reactions in a controlled laboratory environment may follow the theoretical sequence, but environmental conditions in the field result in spatial variability of oxidizable organic compounds, electron acceptors, and microorganisms that cause substantial overlap of the terminal electron acceptor sequence [44,49].

Soil redox potential (Eh) is a measure of the electrical potential status of a system that results from the tendency of substances in the system to donate or acquire electrons [51]. Soil redox potential is measured in millivolts (mV) using a platinum electrode along with a mercury chloride (HgCl) or silver chloride (AgCl) reference electrode, both connected to a voltmeter [49]. Combination platinum electrodes are also available that can continuously monitor soil Eh when connected to a logger box. When using AgCl electrodes, a correction factor of approximately +200 mV is added to field-measured voltages in order to adjust measurements to the standard hydrogen electrode [52]. In well-aerated soils, soil Eh may be as great as +700 mV, but Eh values near –300 mV may be observed in saturated organic-matter-rich soils [51]. As a system shifts from aerobic to anaerobic and soil redox potential declines, atmospheric O_2 is reduced first at +380 to +320 mV, followed by NO_3^- (+280 to +220 mV), MnO_2 (+220 to +180 mV), $Fe(OH)_3$ (+110 to +80 mV), SO_4^{2-} (–140 to –170 mV), and CO_2 (–200 to –280 mV), based on measurements by Patrick and Jugsujinda [53].

6. Methane emissions from rice

Methane emissions from any ecosystem, particularly a rice agroecosystem (Figure 1), are governed by the magnitude and balance of microbial CH_4 production (methanogenesis) and oxidation (methanotrophy), which occur by separate microbial communities. The two groups

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of microorganisms are adapted to different environmental conditions, and, as a result, are affected differently based on the structure and conditions of an ecosystem, which results in variability of CH_4 production and oxidation potentials across time and space [54]. With low CH_4 production rates or long diffusion pathways, it seems that the majority of the CH_4 produced is oxidized. Conversely, in cases where CH_4 production rates are high or diffusion paths are short, less CH_4 is oxidized and a greater portion reaches the atmosphere [54] (Figure 1).

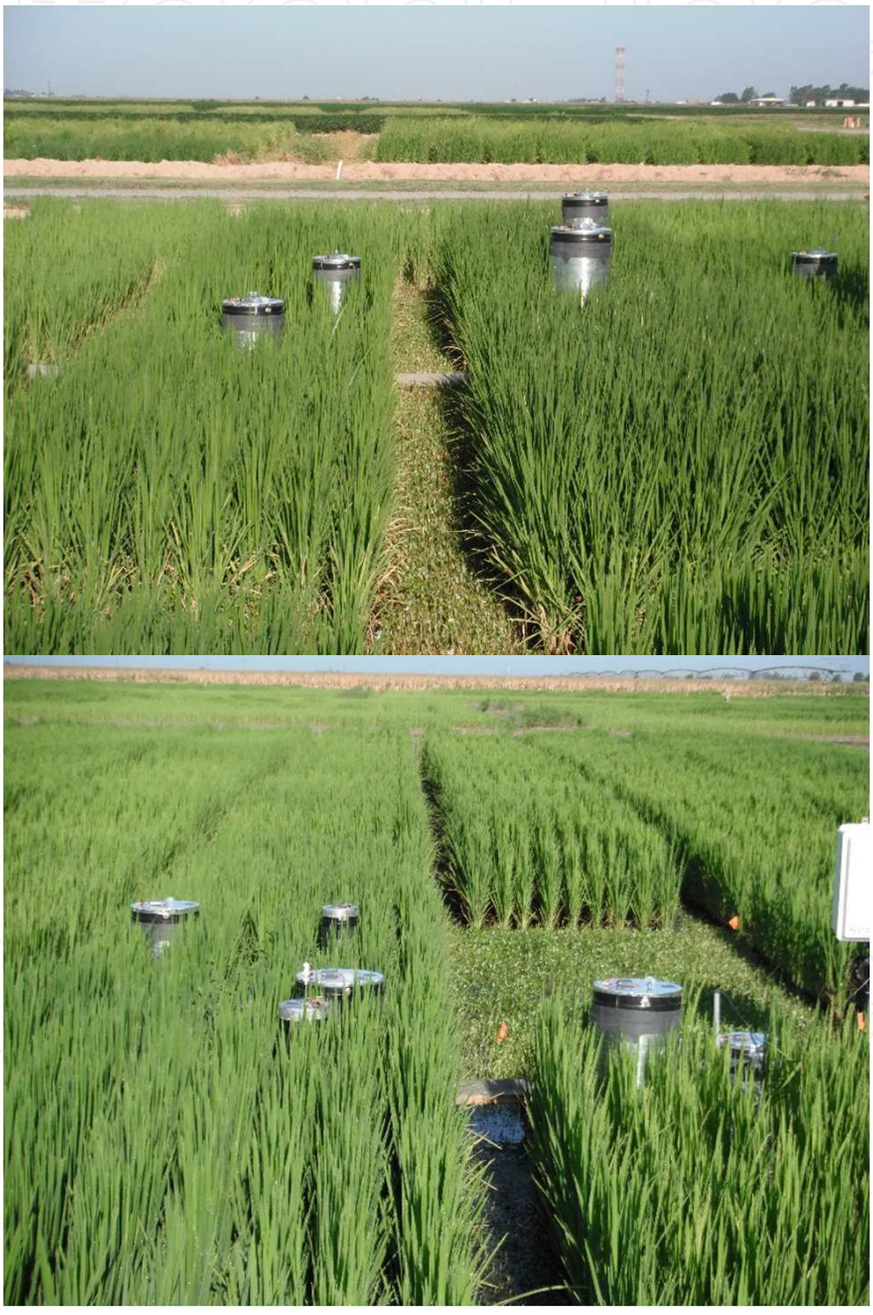


Figure 1. Chamber-based measurements of methane emissions from small plots at the Rice Research and Extension Center near Stuttgart, AR (top), and at the Northeast Research and Extension Center at Keiser, AR (bottom). Photographs taken by K. Brye.

6.1. Methane production and oxidation

Methane production occurs toward the end of a complex anaerobic decomposition process in which soil organic matter (SOM) is degraded to acetate, hydrogen gas (H_2), and CO_2 by a community of various fermenting microorganisms, which are mostly bacteria. Methanogenic *Archaea* are then able to split acetate into CH_4 and CO_2 (i.e., acetoclastic methanogenesis) or utilize H_2 and CO_2 to produce CH_4 (i.e., hydrogenotrophic methanogenesis) [55,56]. Methanogens encompass a large group of strictly anaerobic, obligate *Archaea*, which is currently composed of three classes, six orders, 12 families, and 35 genera [56]. Rice Cluster I is a specific group of methanogens identified by Grosskopf et al. [57] that contains enzymes in order to detoxify highly reactive O_2 species, allowing the methanogens to survive in aerated soils or oxygenated rhizospheres, and occurs preferentially in environments that undergo transient aerobic conditions, such as in rice fields [55,58]. Rice Cluster I has been detected in almost all rice field soils tested [59,60] and occurs in great abundance in rice soils and on rice roots, representing up to 50% of total methanogens in rice fields [61]. Rice Cluster I has been identified as occupying a niche on rice roots by producing CH_4 from photosynthates released as root exudates [55,62]. Recent research has confirmed that methanogens are ubiquitous in aerobic soils and have the ability to produce CH_4 as soon as anoxic conditions form and substrate is available [56]. Conrad [63] reported that methanogens isolated from the soil of rice fields were not killed but only inhibited by high redox potentials or O_2 exposure, allowing them to survive drainage and maintain their population size throughout the year in a state of low activity.

Most methanogens are mesophiles and neutrophiles, with optimal growth occurring between 30 and 40°C and between a pH of 6 and 8 [54]. Methanogens are highly sensitive to variations in temperature and pH and CH_4 production is greatly reduced when soil temperatures are low or in acidic or alkaline soils [56]. Within the optimal temperature range, which is generally the case during the rice growing season, temperature has a positive effect on methanogenesis, causing an increase in CH_4 production as temperature increases [54,56].

Methane oxidation is achieved by a group of aerobic *Proteobacteria* known as methanotrophs, which only utilize CH_4 or methanol as a source of C and energy and are currently classified into two phyla, three orders, four families, 21 genera, and 56 species [56]. One group, known as low-affinity methanotrophs, is capable of oxidizing high CH_4 concentrations (>100 ppm) and exists at oxic–anoxic interfaces, where the methanotrophs consume CH_4 produced in anoxic environments [56]. Another group, known as high-affinity methanotrophs, exists in upland soils and possesses the ability to oxidize CH_4 at low atmospheric levels (<2 ppm) [64]. Unlike methanogenesis, methanotrophy is not impacted greatly by temperature, although CH_4 oxidation is decreased below 10°C and above 40°C, or pH, as similar CH_4 oxidation has been observed in soils with pH values ranging from 3.5 to 8 [56]. Due to the differing effect of temperature on methanogenesis and methanotrophy, CH_4 production increases as soil temperatures increase, while CH_4 oxidation changes little, resulting in a general increase in CH_4 emissions as soil temperature increases throughout the rice growing season. This effect has been confirmed in a laboratory incubation of anaerobic soils at various temperatures between 5 and 25°C [65].

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6.2. Substrate for methane production

Available SOM stimulates CH_4 production due to enhanced fermentative production of acetate and H_2/CO_2 and, in principle, CH_4 production could be expected to be proportional to organic C inputs, but the reduction of nitrate (NO_3^-), iron (Fe), manganese (Mn), and sulfate (SO_4^{2-}) all precede methanogenesis and reduce the amount of available C for CH_4 production [54]. Methane production may be stimulated by root exudates [66–68] or the application of animal manures [69], green manures [70–73], or rice straw [67,70,73–75], while the application of composted organic C sources does not greatly increase CH_4 production [73,75,76]. This indicates that the amount of available organic C (OC) is more important in determining CH_4 production than total OC (TOC), as composted residue contains lower amounts of degradable C, on a mass basis, compared to fresh residues [77]. Yagi and Minami [73] and Wang et al. [78] confirmed a positive correlation between CH_4 production and readily mineralizable C, while studies have indicated no clear relationship between soil TOC and CH_4 production [68,79–81]. Research conducted by Denier van der Gon and Neue [76] determined that increasing fresh OM inputs would result in increases in CH_4 production up to a point where another factor becomes limiting; however, fresh green manure inputs up to 20 Mg ha^{-1} still indicated OC limitations. In most rice production situations, organic residue inputs are below 20 Mg ha^{-1} and will generally exhibit an increase in CH_4 emissions as organic inputs increase.

Using ^{13}C-labeled rice straw incorporated at 6 Mg ha^{-1}, Watanabe et al. [82] determined that 42% of season-long CH_4 emissions originated from rice straw C, 37 to 40% from the rice plant, and 18 to 21% from SOM. The contribution of SOM to CH_4 production was fairly consistent over the growing season, while the contribution from rice straw decreased from nearly 90% at 14 days after transplanting to only 11 to 16% during heading and grain fill. In contrast, the contribution of living rice plants to CH_4 production increased over time and amounted to 65 to 70% during heading and grain fill [82]. Chidthaisong and Watanabe [83] also observed that the contribution of rice straw to CH_4 production was greatest at 20 to 40 days after flooding, while plant-derived C became increasingly more influential as the season progressed. The link between root exudates and CH_4 production has been observed directly by Aulakh et al. [84], who showed a positive correlation between TOC in root exudates and CH_4 production. Several others have observed an inverse relationship between grain yield and CH_4 production [19,85], indicating that lower grain yields are accompanied by greater CH_4 production as a result of greater root exudation, which was confirmed by Aulakh et al. [66]. Using ^{13}C-labeled CO_2, it was observed that photosynthates were a major source of CH_4 and accounted for 4 to 52% of CH_4 under field conditions [86,87].

6.3. Duration and timing of methane production

Methane production occurs for some period of time following a period of prolonged saturated conditions and continues until the C substrate becomes limiting or environmental conditions limit methanogenesis (i.e., the soil becomes too cold, hot, or aerated). In flooded soils, the rate of reduction processes is determined by the composition and texture of a soil as well as the content of inorganic electron acceptors [i.e., NO_3^-, MnO_2, $Fe(OH)_3$, SO_4^{2-}] and available C, so the amount of time between flooding a soil and the onset of methanogenesis can vary from

several days to several weeks [88]. From the onset of methanogenesis, CH_4 emissions from rice systems generally increase over time as the soil becomes more reduced and usually shows one or more of three general peak flux trends. Early season peak fluxes are generally attributed to decomposition of freshly incorporated residues and generally occur within 20 to 40 days after flooding [83,89] and late-season peaks are thought to result from decomposition following senescence of rice roots [90,91]. The other time period of peak fluxes generally occurs near the time of 50% heading (i.e., approximately the time of anthesis) and has been linked to the sink-source relationship of photosynthates in the plant when CH_4 fluxes have been observed to increase during vegetative growth as root exudates increase and decrease following heading as fixed-C is translocated to developing grain. This plant-related peak has been observed in several studies [15–17,80,92–94,95] and similar seasonal trends have been observed in root growth [96–98], root exudation rates [66], and anaerobic root respiration rates [99].

6.4. Transport mechanisms

The three mechanisms by which CH_4 is transported from a ponded soil to the atmosphere are diffusion through the floodwater, ebullition, and plant-mediated diffusion. Diffusion of CH_4 through overlying floodwater is minor as diffusion of gases is approximately 10,000 times slower through water than through air [46]. Ebullition, bubbles forming and forcing their way to the surface, may be a significant transport mechanism early in the season, especially with high OM inputs, soil disturbances, and in coarse-textured soils, but generally plays only a small role in CH_4 transport, which diminishes as plants mature and plant-mediated transport (PMT) increases [76,100]. The majority of CH_4 emissions from a rice system occur through the rice plants via aerenchyma cells, where studies have indicated that about 90% of season-long emissions are released through the rice plants, compared to 8 to 9% released by ebullition and 1 to 2% by diffusion through the floodwater [100–104].

Based on experiments using artificial atmospheres of various gas compositions, Denier van der Gon and van Breemen [105] determined that PMT is driven by molecular diffusion and not affected by transpiration or stomatal opening. Others have observed a decreasing CH_4 concentration gradient from the soil to the rice root aerenchyma, shoot aerenchyma, and atmosphere, indicative of a diffusive transport pathway from the soil to the atmosphere through the plant [104,106]. Other studies have also confirmed that CH_4 transport is not related to transpiration and is unaffected by cutting plants just above the water surface [103,104,107]. However, Hosono and Nouchi [108] determined that PMT was reduced linearly as roots were cut and increased with root growth up to heading, indicating that the surface area of roots in contact with soil solution is important in determining PMT. Several studies have determined that the most restrictive zone of CH_4 transport through the rice plant is the root–shoot transition zone where dense intercalary meristem cells restrict movement from the root aerenchyma to the shoot aerenchyma [101,105,106,109,110].

It has been postulated that CH_4 in the gaseous form or dissolved in water enters into root aerenchyma, which forms by degeneration of cortical cells between the exodermis and the vascular bundle, where the dissolved CH_4 is gasified and moves by diffusion from the root aerenchyma through the restrictive transition zone into the aerenchyma of the culm and then

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to the atmosphere [104,107,109]. It has been determined that CH_4 is released from the rice plant mainly through the lower leaf sheaths. Examining the cultivar 'Koshihikari' with a scanning electron microscope, Nouchi et al. [104] and Nouchi and Mariko [107] observed CH_4 release from 4-μm diameter, hook-shaped micropores arranged regularly approximately 80 μm apart on the abaxial epidermis of leaf sheaths as well as from the connections of leaf sheaths to the culm at nodes. Butterbach-Bahl et al. [106] also determined that CH_4 is primarily released through the lower leaf sheaths, however, micropores were not observed in the cultivars 'Roma' or 'Lido'. More research is required to determine differences in CH_4 release from various cultivars. It has been determined that rice cultivars have differences in CH_4 transport capacity, likely in relation to differences in aerenchyma morphology and the root–shoot transition zone [101] and that CH_4 transport capacity increases as soil temperature increases [108]. Research indicates that PMT is the dominant mechanism of CH_4 release from rice soils and that the rate of transport can be influenced by cultivar or environmental conditions.

7. Factors affecting methane emissions from rice

Through numerous research efforts since the 1980s, several factors have been determined to affect CH_4 emissions from rice cultivation. Due to the complex balance of methanogenesis and methanotrophy that determines how much CH_4 escapes the rice system to the atmosphere along with the large variety of cultural and environmental conditions around the globe, there is large variability in the impact of different factors across time and space. There are a few soil, environmental, and plant factors, however, that seem to have somewhat consistent impacts on CH_4 emissions from rice.

7.1. Soil factors affecting methane emissions from rice

Various studies have observed inconsistent results of N fertilizer application on CH_4 emissions including an increase in emissions with added N [85,90,111,112], a decrease in emissions with added N [113,114], or no impact of added N on CH_4 emissions [15,75,115]. Banger et al. [116] conducted a meta-analysis and determined that CH_4 emissions were significantly greater from N-fertilized rice in 98 out of 155 data pairs, indicating that the increase in plant growth and C fixation resulting from N-fertilization generally increases CH_4 emissions. Wang et al. [78] postulated that the effect of urea on CH_4 emissions may be impacted by pH, where it was observed that urea may cause a decrease in emissions in alkaline soils as urea hydrolysis increases soil pH, limiting the neutrophilic methanogens. In acidic soils, however, the increase in pH from urea hydrolysis shifts the soil pH toward neutral and enhances methanogenesis. Research has consistently indicated that ammonium sulfate reduces CH_4 emissions relative to urea application [70,113,116], likely due to the impact of soil acidification and sulfate reduction decreasing the available C substrate for methanogenesis. Similarly, other studies have determined that oxidized Fe [80,117–120] or NO_3^- [120] amendments have the ability to reduce CH_4 emissions. In addition, Lu et al. [121] observed a 19 to 33% reduction in CH_4 emissions with the application of P due to enhanced root growth and root exudation that was measured in the P-deficient treatment.

Multiple studies have indicated no significant correlations between CH_4 emissions and any static soil properties [68,81] or between CH_4 emissions and total soil C [79,80], while readily mineralizable C has been shown to be positively correlated with CH_4 emissions [75,78]. Particle-size distribution is one soil property that has been regularly related to CH_4 emissions as emissions have been positively correlated with soil sand content [78,80,118,119,122] and inversely correlated with soil clay content [71,78,118,119,122,123]. Studies have observed an increase in CH_4 entrapment resulting from increasing clay contents [71,78], and Sass and Fisher [91] attributed the reduction in CH_4 emissions from clay soils to the entrapment and slow movement of CH_4 that allows more CH_4 to be oxidized in aerated zones surrounding roots and at the soil surface. In a laboratory incubation study, Wang et al. [78] observed varying degrees of CH_4 entrapment, even among soils with similar sand and clay contents, where the greatest entrapment (98%) was measured from a Sharkey clay (very-fine, smectitic, thermic Chromic Epiaquerts) soil compared to 81 and 68% entrapment from a Beaumont clay (fine, smectitic, hyperthermic Chromic Dystraquerts) and a Sacramento clay (very-fine, smectitic, thermic Cumulic Vertic Endoaquolls), respectively. This research indicates that clayey soils have the capability of restricting movement of CH_4 to the atmosphere and that other factors, such as clay minerology and soil chemical properties, may impact emissions more than simply the total amount of clay.

7.2. Environmental factors affecting methane emissions from rice

Two major environmental factors that impact CH_4 emissions from rice are temperature and soil saturation status. Numerous studies have observed increases in CH_4 fluxes in relation to increasing soil temperatures [100,108,124]. A study conducted in Japan observed a 1.6-fold increase in emissions from one year to another under the same management and location resulting from an increase in average air temperature from 24.6 to 26.9°C [119]. Methanotrophic activity changes only slightly between 10 and 40°C, while temperature has a strong influence on methanogenesis [56], which leads to a decrease in the proportion of CH_4 oxidized and an increase in emissions as soil temperature increases. Van Winden et al. [65], for example, reported 98% CH_4 oxidation at 5°C compared to 50% oxidation at 25°C.

Soil saturation status has a profound influence on CH_4 emissions through the impact of saturation on soil redox processes, such as methanogenesis. Methane emissions have been observed from soils at an Eh as great as –100 mV [125], while emissions increase as Eh decreases. The amount of time required after saturation to reach low redox potentials conducive to methanogenesis varies based on soil textural and chemical properties [119], but generally occurs within several days or weeks after flooding. Studies have indicated that a single mid-season drainage can reduce CH_4 emissions by as much as 65% [68,70,75,95,113,126], however, the potential for greenhouse gas mitigation is reduced or negated due to an increase in N_2O emissions resulting from the drainage [70,113,126,127]. Further research is needed in order to more adequately understand the balance between CH_4 and N_2O emissions under various water management regimes as well as the impact that N management has on emissions when fields are drained.

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7.3. Plant factors affecting methane emissions from rice

Due to the strong impact of rice plants on CH_4 transport and CH_4 production from root exudates and residue, there are several plant factors that significantly impact emissions from rice cultivation. A strong relationship between plant growth and CH_4 emissions has been observed in many studies [16,17,80,92–95], particularly in temperate regions, where much of the previous crop's residue decomposes during the winter. Studies have indicated that CH_4 emissions are up to 20 times greater from soil planted with rice than from unvegetated soil [67,107,123], indicating the large influence of rice plants on emissions.

One of the major plant factors impacting CH_4 emissions from rice is whether or not a ratoon crop is grown. This impact is reflected in the USEPA's emissions factors, which are 178 kg CH_4-C ha^{-1} for non-California primary rice crops and an additional 585 kg CH_4-C ha^{-1} when a ratoon crop is produced [2], based on ratoon crops studied in Louisiana [21,22]. The large increase in emissions from ratoon crops is likely a result of large quantities of residue inputs from the harvest of the primary crop in addition to well-developed root systems that further increase the available C for methanogenesis. Lindau et al. [22] observed a significant positive correlation between rice straw additions from a primary crop and resulting emissions from the following ratoon crop.

Another plant factor that has a substantial impact on CH_4 emissions is biomass accumulation. Huang et al. [128] determined that CH_4 fluxes measured during the growing season were positively correlated to aboveground and belowground dry matter on the dates of flux measurements. Additional studies have observed positive correlations between season-long CH_4 emissions and aboveground [16,72,102,128] and belowground dry matter [129]. These studies have indicated a strong relationship between plant growth and CH_4 emissions, which may result from an increase in available substrate as root exudates have been correlated to biomass [66].

Cultivar selection has also been shown to be an important plant factor influencing CH_4 emissions from rice. While the mechanisms for cultivar differences in CH_4 emissions have not been extensively studied, it appears that differences likely arise from variability in CH_4 transport capacity, biomass or dry matter production, root exudation, and microbial community dynamics among cultivars. Butterbach-Bahl et al. [101], for example, attributed a 24 to 31% difference in emissions between two pure-line cultivars to differences in CH_4 transport capacities, as no differences were observed between CH_4 production or oxidation. Aulakh et al. [84] observed a positive correlation between TOC from root exudates and CH_4 production potential, indicating the potential for cultivar differences in emissions based on variable root exudation rates. Previous studies have reported reduced emissions from semi-dwarf relative to standard-stature cultivars [22,91,130]. The difference in CH_4 emissions between semi-dwarf and standard-stature cultivars observed in these studies may be a result of the positive correlation between dry matter and C exudation rates from roots [84] or between aboveground dry matter and CH_4 emissions [16,72,102,128]. While a reduction in emissions from semi-dwarf cultivars is oftentimes linked to reduced dry matter accumulation, Rogers et al. [93] observed a reduction in aboveground dry matter that was not accompanied by a reduction in emissions. Furthermore, Sigren et al. [130] measured greater emissions accompanied by greater soil

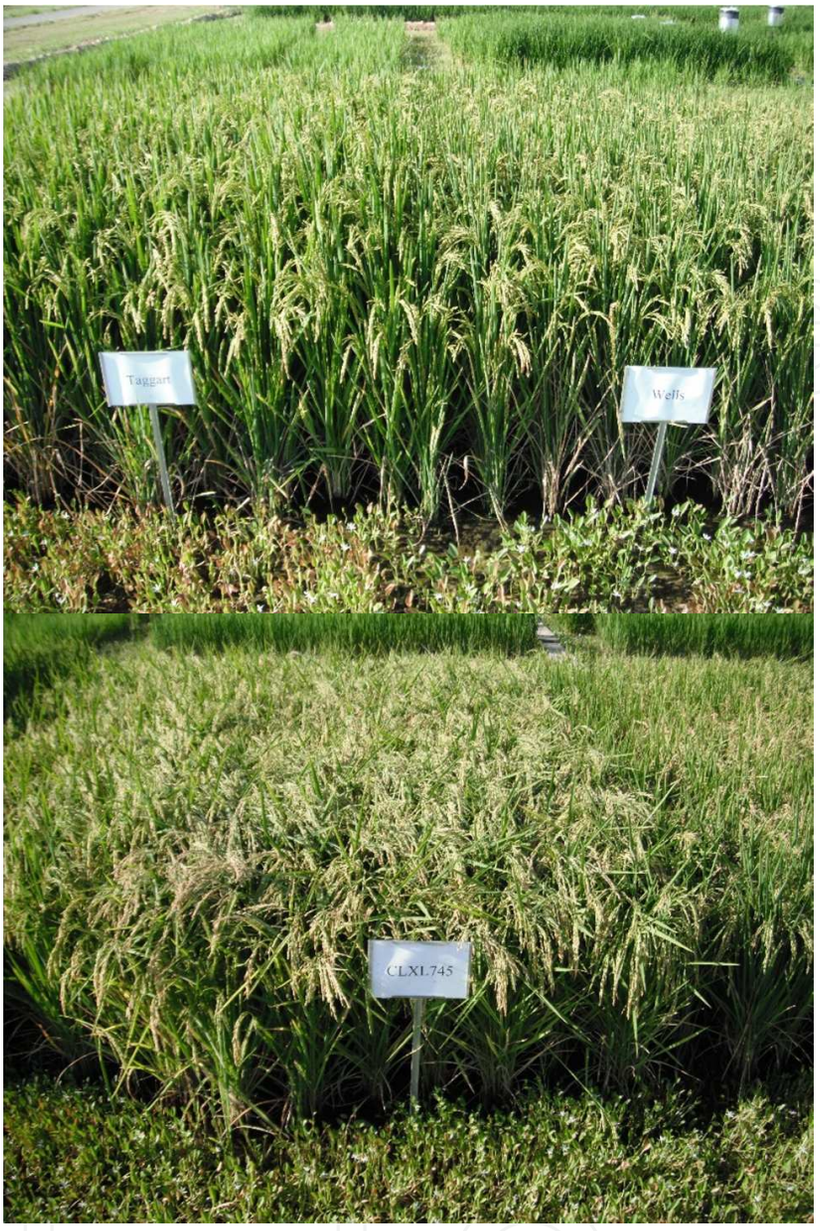


Figure 2. Methane emissions from standard-stature, conventional rice varieties, such as "Taggart" (top left) and "Wells" (top right), and hybrids varieties, such as "CLXL745" (bottom) have recently been studied in the field at the Rice Research and Extension Center near Stuttgart, AR. Photographs taken by K. Brye.

acetate concentrations from a standard stature ('Mars') relative to a semi-dwarf cultivar ('Lemont'), while aboveground dry matter was similar between the two cultivars. Huang et al. [128] indicated that, while biomass may explain differences in emissions within one cultivar, the intervarietal differences in biomass are small in comparison to differences in emissions, indicating that another factor besides aboveground dry matter impacts intervarietal differences in CH_4 emissions.

Cultivar differences, however, extend beyond the impact of biomass production on emissions. Ma et al. [131] observed a 67% increase in CH_4 oxidation from a hybrid cultivar accompanied

by a reduction in emissions and soil CH_4 concentration relative to pure-line cultivars. Additional studies have also identified 25 to 37% reductions in fluxes from hybrid relative to pure-line cultivars [93,132,133] (Figure 2). This indicates that greater methanotrophic activity in the rhizosphere of hybrid cultivars may reduce CH_4 fluxes by oxidizing a greater proportion of the produced CH_4. It is clear that cultivar selection has the potential for mitigation of CH_4 from rice cultivation. However, due to the lack of understanding the mechanisms for differences in emissions, it appears that direct CH_4 flux measurements from various cultivars are necessary in determining emissions differences until further research clarifies the understanding for cultivar differences in CH_4 emissions (Figure 2).

8. Conclusions

Though some knowledge has been gained, there is much more that still needs to be learned and understood regarding CH_4 emissions from rice production in the US, its contribution to climate change, and potential mitigation strategies. Additional field research needs to be conducted to better assess the magnitudes and relative contributions the various known factors have on CH_4 production and emission from soils used for rice production.

It is possible that a single CH_4 emissions factor for application to all non-California-grown, primary-crop rice in the US is too general. Consequently, the single CH_4 emissions factor may be a severe overestimation for some rice-producing areas, while being an underestimation for other areas. Only after additional data have been generated can regulatory agencies, such as the USEPA, further refine greenhouse gas emissions factors to reflect the large variety of soils and agronomic cultural practices throughout the temperate US and combat the potential negative effects of climate change.

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