Spatial Differences in Methane Emissions from Rice Production in the Mid-South

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Abstract

This study estimates average county/parish and state-level CH_4 emissions per hectare (kg CH_4 ha^{-1}) as well as CH_4 efficiency levels (kg rice/kg CH_4 ha^{-1}) in rice production for Arkansas, Louisiana and Mississippi in order to meassure spatial differences in CH_4 emissions. This study focuses on existing rice production practices, specifically, variety selection, crop rotation, and soil texture, which directly affect CH_4 emissions. Historical data on varietal selection, crop rotations, and soil texture maps are used to estimate CH_4 emissions from 2003-2014. Our findings suggest that on average Mississippi was the most efficient at converting CH_4 into rice (267.46 kg rice/kg CH_4 ha^{-1}), followed by Arkansas (189.92) and Louisiana (178.80). Specifically, Louisiana was negatively impacted by its large ratoon crop in terms of CH_4 use efficiency, with 38% of its primary rice crop being ratooned. Overall, these results provide rice buyers, producers and consumers with important information about the spatial aspects of sustainability in rice production. Furthermore, it gives insight to producers and policy makers about which production practices and locations could benefit from increased demand for sustainable products and more restrictive environmental policies.

Introduction

Today, greenhouse gas (GHG) emissions from agriculture and associated land use change generate around one-quarter of annual global GHG emissions (Searchinger et al. 2013). By 2050, world food demand is expected to increase by 70 percent (FAO 2009). If the world generates this increased demand, agricultural emissions are likely to grow to a level that equals 70 percent of the total allowable budget of emissions from all human sources estimated to global warming at acceptable levels (Adhya et. al., 2014). If emissions in agriculture grew at this rate, it would seem unlikely to limit total GHG emissions within the acceptable global limit because there would be little room for growth in other sectors with high GHG emissions such as transportation and energy. Agricultural emissions would have to decline by two-thirds from present levels if agriculture were to reduce its emissions by the same proportion as other sources to meet the generally recognized target of limiting global warming to just 2^{o} Celsius. This limiting would have to be accomplished while increasing food production by 70 percent (Adhya et. al., 2014). As such, consumers, producers and governments are increasingly attempting to regulate GHG emissions from agricultural production.

Compounding this food-GHG issue is the fact that rice (*Oryza sativa L.*) is a staple food globally, providing the primary source of calories for more than 50% of the world's population (International Rice Research Institute [IRRI] 2012). Given the large projected increase in the world's population, rice will continue to play an important nutritional role because rice is a staple food in many countries experiencing rapid population growth. Continuously flooded rice, which is the predominant production practice in the United States, accounts for a significant percentage of total agricultural GHG emissions, mainly through methane (CH_4) emissions. CH_4 production occurs when organic matter is decomposed and anaerobic conditions exist for extended periods of time in microorganism-mediated soils. However, most of the CH_4 produced is oxidized by aerobic methanotrophic bacteria in the soil. As a result, only about 30% of the CH_4 produced is actually emitted into the atmosphere, and this is generated mainly through the rice plant itself, air bubbles from the soil, and molecular diffusion (Wang et al. 2013). In the United States, rice is ranked as the largest crop emitter of GHGs. Flooded-rice production accounts for 11% of the total agricultural CH_4 emissions in the US, ranking third behind enteric fermentation and manure management (Wang et al. 2013).

While a small global player in terms of production and consumption, producing only 2% of the world's rice, the US is the third largest rice exporter (Bennett 2010). Thus, while consumer demand for more sustainable agricultural production practices grows stronger in high-income countries like the United States, any shock to the US supply of rice via reductions or changes in production practices could result in ripple effects globally. Since rice provides 21% of global human per capita energy and 15% of per capita protein (IRRI, 2013), price/supply shocks can have large impacts on low-income rice consumers. For example, in 2008, when rice prices tripled due largely to trade restrictions in India and Egypt, the World Bank estimated that an additional 100 million people were pushed into poverty (IRRI, 2012). This price turmoil occurred with only an 8% reduction in trade from 2007 to 2008 (Childs 2009). Furthermore, 10.2% of global rice exports were provided by the US in 2009 (Childs and Baldwin 2010). Given that the global rice market is so thinly traded, one large concern about environmental regulations on production in high-income rice-producing countries is the threat of decreased supply and its effects on low-income countries who depend on rice as their staple.

In high-income countries, increased consumer demand for food products with lower GHG emissions have prompted row crop producers to reduce GHG emissions associated with their production. More importantly, agricultural producers face increasing demand and in some cases requirements from the private industry to reduce GHG emissions associated with crop production. Wal-Mart, for instance, recently announced a potential plan to label each of its products with a sustainability rating and subsequently requested that every Wal-Mart supplier provide its product's GHG footprint, a direct measure of climate impact (Wal-Mart Stores Inc. 2016). In response to these commercial pressures, agricultural producers and processors have sought to increase production efficiency with respect to GHG emissions. Specifically, rice production (from seed to farm gate) has been identified as a significant source of atmospheric CH_4 emissions from U.S. agricultural production (United States Environmental Protection Agency [USEPA] 2011). As a result, producers and large-scale purchasers of U.S. rice have attempted to search for ways to increase the efficiency of GHG emissions in rice production.

Alternate wetting and drying (AWD) is one potential way to reduce CH_4 emissions and is practiced in rice growing regions where water is a constraining factor. AWD irrigation in rice production is a practice in which rice producers allow the soils in their rice fields to drain intermittently (either intentionally or naturally through evapotranspiration and percolation) during the rice life-cycle rather than continuously flooding the rice paddy up to a specific depth. The rate and timing of water applications is a function of rainfall, soil moisture, soil type, and rice growth stage. Periodic aeration of flooded soils inhibits CH_4 producing bacteria; as such AWD can substantially reduce CH_4 emissions (Yan et. al., 2005). The Intergovernmental Panel on Climate Change (IPCC 2006) recognizes the effects of aeration on CH_4 emissions with an average of 40% reduction in CH_4 emissions for single aeration events and 48% for multiple aeration events. However, in a review of 31 published articles, Bouman and Tuong (2001) reported that 92% of the AWD studies resulted in as much as a 70% yield reduction relative to flooded rice. Previous studies in the Mid-South concluded that rice produced under non-flooded conditions using furrow and sprinkler irrigation were not economically viable due to large yield penalties (Hoek et al. 2001). While AWD has large potential to reduce CH_4 emissions given its unconventional (non-flooded) production practice, only a handful of producers in the United States have adopted it (Nalley et. al., 2015).

AWD requires producers to change their production practices to obtain large reductions in CH_4. However, previous studies have shown that less radical changes in production could be made to lessen CH_4 emissions. Methane emissions from flooded-rice cultivation are affected by numerous soil and plant properties, particularly soil texture and soil management practices (Brye et. al., 2013; Sass and Fisher, 1997; Sass et. al., 1994), previous crop (Rogers et al. 2013; Rogers et al. 2014), and cultivars selected i.e., conventional versus hybrid (Huang et. al.,1997; Lindau et. al., 1995; Ma et. al., 2010; Rogers et al., 2014; Sigren et. al., 1997), among other factors, across a variety of production systems (USEPA, 2014). That is, a producer could change: 1) the variety (hybrid vs conventional) of rice grown, 2) the location on the farm which rice is grown (if soil texture varies across the farm), and 3) crop rotations to lower CH_4 emissions. Brye et al. (2016) found that silt loam soils emitted 211% more CH_4 than clay textured soils; inbred cultivars accounted for 55-70% more CH_4 emissions than hybrid cultivars; and a soybean-rice rotation produced 58% less CH_4 emissions than a rice-rice rotation. Unlike AWD, these changes in production practices are standard but are typically driven by market prices for outputs and are not motivated by minimizing GHG emissions. As such, producers could more seamlessly transition to changing the variety of rice grown than changing to a radically new production practice like AWD to reduce GHG.

With the notion that rice producers can change cultivars, crop rotations and the production location for rice (soil texture) fairly easy, this study set out to estimate county, crop reporting district (CRD) and state total CH_4 emissions based on historical, county-level rice varietal planting, crop rotations and soil textures from 2005-2014. Furthermore, historical county/parish-level yields from Arkansas, Louisiana and Mississippi were used to estimate CH_4 efficiency levels (kg rice/ kg CH_4 ha^{-1}). Data were aggregated up to CRD levels due to the fact that rice mills typically do not process rice from only one county but rather a number of counties located near its proximity. Thus, the results of this study can give rice buyers, processors, consumers and policy maker's context of the spatial variability of the CH_4 emissions in rice production in the Mid-South. Specifically, it allows rice buyers the ability to source from more sustainable areas, and it provides rice producers the information needed to make production decisions if they so choose to market their rice as "sustainable". Lastly, it provides policy makers information on spatial variation in CH_4 emissions for potential taxation or capping of GHG emissions at a regional scale.

Methodology

Methane emissions from rice production are estimated for each of the historical (2005-2014) 96 rice-growing counties/parishes in Arkansas, Louisiana, and Mississippi using a two-step approach, consistent with the Intergovernmental Panel on Climate Change (IPCC 2006). In the first step, methane estimation data from field research (Rogers et al. 2013; Brye et al. 2013) were used in a regression model to estimate representative CH_4 emission factors based on rice cultivar type (hybrid vs. conventional/pure line), soil texture (loamy vs. clayey), and crop rotation (rice-rice vs. soybean-rice). The field research was conducted in 2012 and 2013 at the University of

Arkansas System Division of Agriculture Rice Research and Extension Center (RREC) near Stuttgart, AR on a DeWitt silt loam and at the Northeast Research and Extension Center (NEREC) at Keiser, AR on a Sharkey clay. At both locations, the study areas had previously been managed under a rice-soybean rotation for at least 15 years. Subsequently, in 2012 and 2013 at RREC, four replications of the conventional cultivars 'Taggart' and 'Cheniere' and the hybrid cultivar 'CLXL745' were sown following the previous crops of rice or soybean. In 2012, at NEREC, four replications of 'Taggart' were sown following soybean as the previous crop; while in 2013, four replications of 'Taggart', 'Cheniere', and 'CLXL745' were sown following the previous crops of rice or soybean. Each year at each location, plots were outfitted with a 30-cm diameter, enclosed-headspace gas sampling chamber assemblage to measure CH_4 emissions.

Unlike previous studies, this experimental design allowed for a direct comparison of the effects of soil texture, cultivar type, and crop rotation on CH_4 emissions. Research efforts have identified a diel CH_4 emission pattern with soil texture, air and water temperature, soil organic carbon, and cultivar as contributing factors to overall CH_4 emissions. Furthermore, previous studies have quantified the proportion of CH_4 emissions by independently altering each factor mentioned above while holding the other two constant, leading to potentially biased estimates. The goal of the first step is to holistically identify those factors contributing to CH_4 emissions as a result of three sources of variation—soil type, cultivar, and preceding crop. Using the data collected by Brye et al. (2016), we model CH4 emissions as a function of holistic production practices found in Mid-South rice production. This model was estimated based on Equation (1):

$$Y_{ipst} = \alpha_0 + \alpha_{ips} X_{ipst} + u_{ipst}, \tag{1}$$

where Y_{ipst} is the CH_4 emissions (kg CH_4-C ha^{-1}) for cultivar i, under crop rotation p, grown on soil with texture s, in year t. The variable X_{ipst} is a categorical variable formed by the combination of soil texture (clayey and loamy), cultivar type (conventional and hybrid: due to lack of degrees of freedom, both conventional cultivars were analyzed as 'conventional' and 'not specific cultivar lines'), and crop rotation (rice-rice and soybean-rice). The eight categories formed are: (1) conventional cultivar grown on clay soil following a rice-rice rotation, (2) conventional cultivar grown on clay soil following a soybean-rice rotation, (3) conventional cultivar grown on loamy soil following a rice-rice rotation, (4) conventional cultivar grown on loamy soil following a soybean-rice rotation, (5) hybrid cultivar grown on clay soil following a rice-rice rotation, (6) hybrid cultivar grown on clay soil following a soybean-rice rotation, (7) hybrid cultivar grown on loamy soil following a rice-rice rotation, and (8) hybrid cultivar grown on loamy soil following a soybean-rice rotation. The error term is assumed to be independent of the soil, the cultivar, and the rotation effects. By omitting one of the categories in X_{ipst} in Equation (1), the parameter α_0 serves as the emission factor for the omitted category. Further, the seven α_{ips} parameters are the marginal differences between the omitted and the category for which α_{ips} is estimated. The omitted category in this case is category (1) - conventional cultivar grown on clay soil following a rice-rice rotation. Thus, the emission factor for a category not omitted is given by the summation of α_0 and the appropriate component of α_{ips}.

In the second step, the parameter estimates from Equation (1) are extrapolated to the 96 rice-growing counties/parishes in Arkansas, Louisiana, and Mississippi to simulate their respective total CH_4 emissions for 2014 and an annual average of CH_4 emissions for the period 2005-2014. The extrapolations are done by first synthesizing for each county, eight compositions formed by their respective combination of soil type (loamy vs. clayey soils), cultivar (hybrid vs. conventional rice), and preceding crop (rice-rice vs. rice-soybean ration).

The eight compositions are synthesized assuming equal proportion. To illustrate, using actual data from Clay county Arkansas which has a distribution represented as: soil type (loamy-84.26% and clayey-15.74 %), cultivar (hybrid-34.79% and conventional-65.21 %) and crop ratio (rice-rice-22.95% and rice-soybean-77.05 %). Then the eight compositions, based on the equal proportion assumption, will be: conventional cultivar grown on clay soil following a rice-rice rotation 2.36% (65.21% × 15.74% × 22.95%), hybrid cultivar grown on loamy soil following a soybean-rice rotation 22.59% (34.79% × 84.26% × 77.05%), and so on for the six other combinations of soil texture, crop rotation and variety combinations. This assumption, while naïve, is necessary because while acreage of hybrid and conventional varieties are known from planting histories and percentages clay and loamy soils are known from soil maps, the percentages of given cultivars planted on given soil type is not known. A similar line of reasoning follows for crop rotation. Accordingly, we assume equal proportions.

Ideally, a CH_4 measurement from each of the eight compositions would be obtained from field plots in each county/parish. However, given the high cost of observing CH_4 emissions, we are forced to extrapolate. Data on the historical areas seeded to hybrid and to conventional rice cultivars at the county level were collected from various annual publications of the Proceedings of the Rice Technical Working Group (Rice Technical Working Group [RTWG], various years). Soil texture data were collected from the Web Soil Survey (WSS) provided by the USDA Natural Resources Conservation Service (USDA 2015b), and data on crop rotations were sourced from over twenty extension agents throughout the Arkansas, Louisiana, and Mississippi since a comprehensive dataset on county/parish crop rotations is nonexistent.

Uncertainties

The calculations of the total CH_4 are confounded uncertainties such as knowing the actual values of the α parameters in (1) and the impact of all omitted factors as represented by the error term. Additionally, we do not know how applicable the models estimated are for all of the counties in the Mid-South nor are we able to know the contemporaneous correlation of the error terms across counties. We do not incorporate the latter two sources of uncertainty in our computations. We use Monte Carlo simulations (1000 iterations) instead of calculating a point estimate for each county. The simulations for both the 2014 CH_4 emissions and the annual average for the period 2005-2014 recognize that, since the regression parameters from Equation (1) are based on sample data, they represent a source of uncertainty since these parameters are not known with certainty. Thus, in each of the 1000 iterations, a vector of emission factors (the α parameters) was drawn, assuming normality – with mean and standard deviation equal to the estimated emission factors and their standard errors, respectively – and using the covariance matrix of the estimated emission factors.

A drawback to examining only one year—2014—is that yields, acreages and allocations between cultivars, soil types and rotations are fixed to observations for that year. To get a more robust estimate of average, annual emissions and emissions per kg of rice, ten years of data (2005-2014) on seeded rice area, hybrid adoption proportion, and yield were utilized to get means and variances of these three factors at the county level for each of the 96 counties.[1] For a given county

[1] Rotation and soil proportions were held fixed at 2014 levels since the rotation levels for earlier years are unknown and soil type proportions do not vary over time.

uncorrelated draws on yield, acres and cultivar proportion were taken for each county in each year for the period 2005-2014. The randomness in seeded rice area and hybrid adoption reflects the variation in factors such as market condition and agricultural research and extension services that could influence farmers' decisions on seeded rice area and hybrid adoption. Furthermore, the randomness in rice yields reflects weather variation as well as advances in research and extension services that could affect rice yields. Thus, in each of the 1000 iterations, a vector containing the seeded rice area, hybrid adoption, and yield was drawn for each county in each year assuming normality, with mean and standard deviation equal to that of their observed values from 2005-2014. As with the 2014 computations, the eight compositions are computed for a given draw and weighted as discussed earlier.

The 2014 total simulated CH_4 emissions ($\tilde{e}_{j14}$) for the primary rice crop (non-ratooned) in the j^{h} county/parish is represented as:

$$\tilde{e}_{j14} = \sum_i \sum_p \sum_s \left[h_{jips}\left(\tilde{\alpha}_{ips} + \tilde{\alpha}_0\right)\right] \tag{2}$$

where the accent ~ indicates simulated values; h_{jips} is the total area of rice seeded to cultivar i, under crop rotation p, and grown on a soil with texture s; and $\tilde{\alpha}_{ips}$ and $\tilde{\alpha}_0$ are the simulated emission factors estimated from Equation (1). Note that the values for total area of rice represented are calculated by multiplying the total observed seeded rice area by their synthesized compositions. For the annual average CH_4 emissions for the period 2005-2014, the total simulated CH_4 emissions ($\tilde{e}_{jT}$) for the primary rice crop in the j^{h} county/parish is:

$$\tilde{e}_{jT} = \sum_i \sum_p \sum_s \left[\tilde{h}_{jips}\left(\tilde{\alpha}_{ips} + \tilde{\alpha}_0\right)\right] \tag{3}$$

where $\tilde{h}_{jips}$ is the annual average simulated rice seeded to cultivar i, under crop rotation p, and grown on soil s for a given year.

Previous literature suggests that ratoon rice crops generate CH_4 at a considerably higher rate than primary crops. Ratoon crops are second crops produced from regrowth of the stubble remaining after the harvest of the first rice crop. This happens because the amount of organic carbon available for anaerobic decomposition (from the crop residue of the primary crop) is considerably higher during the ratoon crop production relative to the primary crop due to the lack of a delay between cropping seasons (which allows the rice stubble to decay aerobically) (Wang et al. 2013).

The climatic conditions of Texas, Louisiana, Arkansas, and Florida allow for ratoon crop production, with the majority of ratooning located in Texas and Southwest Louisiana (USEPA, 2015). Previous studies estimate the seasonal emission factor for primary and ratoon crops to be 237 kg CH_4-C ha^{-1} and 780 kg CH_4-C ha^{-1}, respectively (USEPA, 2015). Thus, CH_4 emissions from ratoon crops are approximately 3.29 (780 kg /237 kg) times that of the primary crop for the same area. Thus, if a county/parish ratooned rice the total emissions from ratoon crop in the j^{h} county/parish for t=2014 CH_4 emissions ($\tilde{e}^{r}_{j14}$) and the for the average annual CH_4 emissions for the period 2005-2014 (e^{r}_{jT}) are calculated as:

$$\tilde{e}^{r}_{j14} = 3.29\left(\tilde{e}_{j14}/h_{j14}\right)h^{r}_{j14} \quad (4)$$

$$\tilde{e}^{r}_{jT} = 3.29\left(\tilde{e}_{jT}/\tilde{h}_{jT}\right)\tilde{h}^{r}_{jT} \quad (5)$$

where h_{j14} and h^{r}_{j14} are the total area seeded to primary and ratoon rice in the j^{h} county/parish, and

$\tilde{h}_{jT}$ and $\tilde{h}_{jT}^{r}$ are their respective simulated values for the case of the 2005-2014 annual average emissions. Thus, the total emissions of the j^{h} county/parish are:

$$\tilde{e}_{j14}^{*} = \tilde{e}_{j14} + \tilde{e}_{j14}^{r} \quad (6)$$

$$\tilde{e}_{jT}^{*} = \tilde{e}_{jT} + \tilde{e}_{jT}^{r} \quad (7)$$

Finally, using NASS-reported (USDA 2015a) total rice production (kg) including ratooned rice for each of the 96 counties/parishes, the CH_4 emissions efficiency from rice production - measured as the kg of rice produced per unit of CH_4 emitted (kg of rice/kg CH_4-C ha^{-1}) - are calculated as:

$$\widetilde{qe}_{j14}^{*} = q_{j14}/\tilde{e}_{j14}^{*} \quad (8)$$

$$\widetilde{qe}_{jT}^{*} = \tilde{q}_{jT}/\tilde{e}_{jT}^{*} \quad (9)$$

where q_{j14} and $\widetilde{qe}_{j14}^{*}$ are rice yields and CH_4 emissions efficiency in the j^{h} county/parish for 2014, and $\tilde{q}_{jT}$ and $\widetilde{qe}_{jT}^{*}$ are their respective simulated values for the case of the 2005-2014 annual average. From these calculations we identify: 1) those locations with the largest net CH_4 emissions, 2) those locations with the highest efficiency in terms of kg rice/kg CH_4, and 3) state averages of CH_4 emissions efficiency to provide state aggregates. Given the fact that rice mills often source from various locations from one state, state averages eliminate the need for a potential buyer of rice to determine what location it originated in, rather which state. Furthermore, counties were aggregated up to crop reporting district in an effort to highlight regional differences in a state which implicitly assumes a mill sources only from counties in its CRD.

Results and Discussion

The regression estimates from Equation (1) are displayed in Table 1. The R^2 value indicates that 91% of the variation in CH_4 emissions is explained by the change across the eight categories formed by the combination of soil texture, cultivar type, and crop rotation, as replicated from Brye et al. (2016). The results from the regression indicate that the driving factor for CH_4 emissions appears to be soil texture with loamy soils, emitting 815% more than clayey soils. The next largest factor in CH_4 emissions is cultivar type with the conventional emitting 49% more CH_4 than hybrids, and crop rotation with rice-rice rotations emitting 38% more CH_4 than rice-soybean. Thus, hybrids grown on clayey soils after soybeans had the lowest season-long CH_4 emissions (5.82 kg CH_4-ha^{-1}), while conventional rice grown on loamy soil after rice had the largest CH_4 emissions (181.95 kg CH_4-ha^{-1}).

In the interest of brevity, the values of $\widetilde{\mathrm{qe}}^*_{j14}$ and $\widetilde{\mathrm{qe}}^*_{jT}$ discussed in this study are those aggregated at the crop reporting district and state averages. The ten year (2005-2014) average provides a more holistic representation of CH_4 efficiency use as rice yields are a function of climatic variables which this study does not measure. However, the most recent year of 2014 provides the most up-to-date results based on current hybrid adoption (which affects average yields), as well as average CRD yields. As such, both the 2014 and10-year average results are presented on Tables 2 and 3, respectively.

In aggregate, those areas counties/parishes/CRDs/states with higher percentages of clayey soils had higher levels of CH_4 use efficiency. These areas, defined by CRD, included the Delta (upper and lower) Mississippi and East (Northeast and East Central) Louisiana (Table 2). Yields also played a large part in relative CH_4 use efficiency and those areas with higher yields could potentially offset high total CH_4 emissions with higher yields. CRDs with high yields included the Delta (upper and lower) of Mississippi, Southwest Louisiana and East (Northeast, Southeast and East central) Arkansas (Tables 2 and 3). The largest contributor to CH_4 emissions in the study, soil texture, as well as crop rotations, remained constant across time. Hybrid adoption and yield varied with time, and as such the 10 year average of CH_4 use efficiency for each CRD is reported on Table 3. There are trade-offs between a one year snapshot of results (in this case 2014) and the ten year average.

From an arithmetic average efficiency standpoint, Mississippi was the most efficient (485.58 kg rice / kg CH_4 ha^{-1}) in 2014, followed by Arkansas (228.03) and Louisiana (101.42) (Table 2). Accordingly, Louisiana was negatively affected in terms of the efficiency of CH_4 use by its large ratoon crop, which accounted for 38% of the primary growth area for rice (USEPA, 2015). To ensure unbiased comparisons, we also estimated weighted average emission efficiencies based on each crop reporting district's relative importance in total rice area and total rice production. That is, several low-yielding counties/parishes could be outliers and thus skew the state means. Weighting by both total production and total area, Table 2 indicates the same relative ranking where Mississippi had the highest CH_4 efficiency followed by Arkansas and Louisiana, respectively. Table 2 indicates that the arithmetic average CH_4 emission efficiency for the entire U.S. Mid-South in 2014 is 186.03 kg rice / kg CH_4 ha^{-1}, and its weighted average equivalence in terms of seeded area and production quantity are 947.11 kg rice / kg CH_4 ha^{-1} and 967.17 kg rice / kg CH_4 ha^{-1}, respectively.

While state averages are useful for basic comparisons, they offer little from a practicality standpoint for sourcing rice. Most rice mills will source rice from a group of surrounding counties, and as such, CRDs within states were analyzed. At the crop reporting district level, Table 2 indicates that there are statistically differences in CH_4 emission efficiency across nearly all districts. Table 2 shows that the Upper and Lower Delta districts in Mississippi had the highest CH_4 use efficiency at 572.32 and 520.56, respectively. This is primarily driven by the fact that these districts have high levels of clay soils, high levels of soy-rice rotations, and relatively high rice yields. However, three caveats should be noted when analyzing these results. First, both districts produce a small amount of rice relative to other CRDs in the Mid-South. To highlight this, the third highest CRD in terms of methane use efficiency was Arkansas-Southeast which had more rice sown than the entire state of Mississippi combined. Second, data (crop rotation and hybrid adoption) for Mississippi were not as robust as Arkansas and Louisiana and as such these results benefit, in terms of lower CH_4 emissions, from the assumption that all acreage was under a soy-rice rotation, which is a naive assumption. Third, in 2014 NASS reports that 50% of counties in Mississippi have the same rice yield. This observation is a result of the low number of rice producers in a county, and the fact that NASS must keep the data of individual producers anonymous. Furthermore, Mississippi did not report hybrid adoption at the county level, but only reported it at the state level for 2014.

Finally, we recognize the uncertainty surrounding the distribution of total areas planted to rice across each of the eight compositions synthesized by assuming equal proportions. Thus, we perform two additional simulations for the case of 2014 to ascertain the worst and best case scenarios. In the worst case scenario, the eight compositions are synthesized such that shares are apportioned to the composition that results in the maximum CH_4 emissions for each county. That is, we assume that all the conventional rice varieties are sown on silt loam soil with a rice-rice rotation. Conversely, the opposite is estimated for the case of the best case scenario where all hybrid acres are produced on clayey soils with a rice-soybean rotation. However, we require that all allocations are consistent with the observed proportions of soil type, rotation and cultivar use. When the first binding constraint is reached (for instance hybrid acreage is limited to 1000 ha but clayey acreage is 4000 ha), then the remaining clayey acreage is allocated to the second lowest feasible emitting scenario. Continuing this example, conventional varieties are planted on clayey soils under a rice-soybean rotation the next constraint is met (say all soybean rice acres are exhausted). This process continues until all acreage has been allocated in a county/parish and the allocations are consistent with the observed proportions of cultivar, rotation and soil type.

The range between best and worst case scenarios for each CRD is presented in Figure 1 (each individual county/parish is presented in Figure A1). Figure 1 shows that, again, the CRDs with the highest and lowest CH_4 emission efficiencies are the Mississippi Delta (both upper and lower) and Southwest Louisiana, respectively. Figure 1 indicates a large estimated range for both Mississippi Delta CRDs which is a function of the CRD's low CH_4 emissions – due to high levels of clay soils, high levels of soy-rice rotations – coupled with its high yield. However, we emphasis that the results from Mississippi are not as robust as Arkansas and Louisiana due to data limitations. The range between the maximums and minimums for a given CRD in Figure 1 is attributable to variation in proportions of observed soil rotation and cultivar among counties in a CRD.

Conclusions

This study utilizes measurements of the effects of rice production methods on CH_4 emissions from university test plots and scales them up to the larger Mid-South rice growing region. Unlike more radical production practices, such as AWD, this study focuses on current production decisions (variety selection, crop rotation, and soil texture), which rice producers can seamlessly change to reduce CH_4 emissions. Under increasing demand for reduced GHG emissions, knowledge of spatial differences in CH_4 use efficiencies in rice production aid producers and policy makers in developing mitigation strategies based on varietal selection, crop rotation, and locations (soil type) to produce rice. The county-level findings in this study represent a major contribution to the spatial mitigation efforts aimed at both lowering CH_4 emissions and increasing CH_4 use efficiency. Knowledge of the relationships between production practices and CH_4 emissions, combined with the results from this study, provide buyers the opportunity to source more sustainable rice and producers the knowledge needed to change their production practices to increase CH_4 use efficiency. The need for this information is growing given future population increases, climate change, and slowing growth in rice yield potential.

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Table 1. R

Methane emission (kg CH_4-ha^{-1}) sources of variation regression results and associated emission factors

Rice Type/Soil Texture/Crop Rotation (number of observations)	Estimated coefficient	Emission factor
Conventional/Clay/Rice [Constant] (n=8)	22.14*** (2.29)	22.14*** ^{B} (2.29)
Conventional/Clay/ Soybean (n=12)	-5.24 (4.30)	16.89*** ^{AB} (4.30)
Conventional/Loamy/ Rice (n=16)	159.81*** (7.28)	181.95*** (7.28)
Conventional/Loamy/ Soybean (n=16)	131.60*** (8.68)	153.74*** ^{C} (8.68)
Hybrid/Clay/Rice (n=4)	-7.55** (2.93)	14.59*** ^{A} (2.93)
Hybrid/Loamy/Rice (n=8)	-16.32*** (1.07)	5.82*** (1.07)
Hybrid/Loamy/Soybean (n=8)	134.98*** (7.28)	157.12*** ^{C} (7.28)
Hybrid/Clay/ Soybean (n=4)	50.58*** (8.51)	72.72*** (8.51)

Significance levels: * p<0.10, ** p<0.05, ***p<0.01.
Standard errors of the estimates are in parentheses
Emission factor in the same column indicated by the same superscript letters are not statistically different from one another at the 5%

Table 2. Crop Reporting District Level Methane Emission Efficiency in the U.S. Mid-South for 2014

Crop reporting district (CRD)	Soil type (%)		Rice-soybean rotation (%)[a]	Rice (ha)	Ratoon crop (ha)[b]	Hybrid adoption (%)[c]	Rice yield (kg/ha)[d]	Emission efficiency (kg rice/ kg CH_4-C ha^{-1})[d e]	
	Clay	Loamy						Mean***	SD
Arkansas									
West Central	1.23	98.77	77.05	892	0	54.10	10,117.92	82.94 HI	1.70
Southwest	24.36	75.64	77.05	1,794	0	40.00	10,418.59	100.19 A	2.21
Central	7.50	92.50	77.05	2,731	0	70.09	10,766.78	106.10 B	2.72
Northeast	19.97	80.03	77.05	272,046	0	25.31	23,438.80	201.93 C	5.64
East Central	28.99	71.01	77.05	245,249	0	43.83	23,586.01	244.82 D	5.08
Southeast	34.30	65.70	77.05	71,459	0	66.61	23,141.11	327.01 E	7.04
Louisiana									
Northwest	22.19	77.81	71.86	165	0	0.00	8,200.83	65.70 F	2.48
North Central	23.49	76.51	71.86	4,175	0	0.00	8,987.67	68.08 G	2.56
Southwest	16.70	83.30	62.46	107,682	35,756	22.94	22,040.20	82.91 H	2.11
West Central	26.49	73.51	71.86	1,543	0	21.56	9,908.63	87.84 I	2.51
South Central	61.60	38.40	71.86	2,153	775	45.18	22,228.16	130.47 J	3.36
Central	39.52	60.48	64.39	43,892	4,784	28.18	20,433.74	139.96 K	3.36
Northeast	52.76	47.24	75.87	24,458	0	28.28	20,663.88	240.07 D	6.32
East Central	69.82	30.18	71.86	233	0	100.00	11,336.66	324.80 E	10.44
Mississippi									
North Central	9.56	90.44	100.00	3,209	0	38.00	12,884.46	113.68 B	3.42
Central	13.37	86.63	100.00	49	0	38.00	12,884.46	119.06 O	3.58
Lower Delta	65.11	34.89	100.00	12,967	0	38.00	21,958.09	520.56 P	25.38
Upper Delta	67.36	32.64	100.00	33,255	0	38.00	23,426.81	572.32 Q	28.82

State and U.S. Mid-South aggregate

	State average		State weighted average[f] by seeded area		State weighted average[f] by production	
	Mean***	SD	Mean***	SD	Mean***	SD
Arkansas	228.03 A	5.27	248.00 A	5.38	249.12 A	5.40
Louisiana	101.42 B	2.56	138.96 B	3.93	140.95 B	3.95
Mississippi	485.58 C	21.36	560.15 C	30.53	577.10 C	31.54
Pooled	186.03 D	4.41	947.11 D	37.83	967.17 D	38.84

[a] 77.05% of rice in Arkansas is assumed to be grown under a rice-soybean rotation in 2014. All rice in Mississippi is assumed to be under a soybean-rice rotation.
[b] A five-year average (2010-2014) was used for the area under ratoon
[c] The RTWG (2014) Mississippi seeding report denoted only state aggregate level of hybrid adoption of 38% and not county level. Thus, this study assumes each county had 38% adoption.
[d] Means and standard deviations (SD) based on 1000 simulations
[e] Ordered from lowest efficiency level to highest by state
*** Emission efficiencies in the same column indicated by the same superscript letters are not statistically different from one another at the 5% significance level. Comparisons are done with Bonferroni adjustments.
[f] Average resulting from the product of each crop reporting districts' emission efficiency and its importance in seeded area (production) – calculated as its share in total seeded area (production) in Arkansas, Louisiana, and Mississippi – and then taking the sum of the resulting product across all crop reporting districts.
See Table A1 to A3 for county/perish specific results

Table 3. Crop Reporting District Level Annual Average Methane Emission Efficiency (kg rice/ kg CH_4-C ha^{-1}) in the U.S. Mid-South from 2005-2014

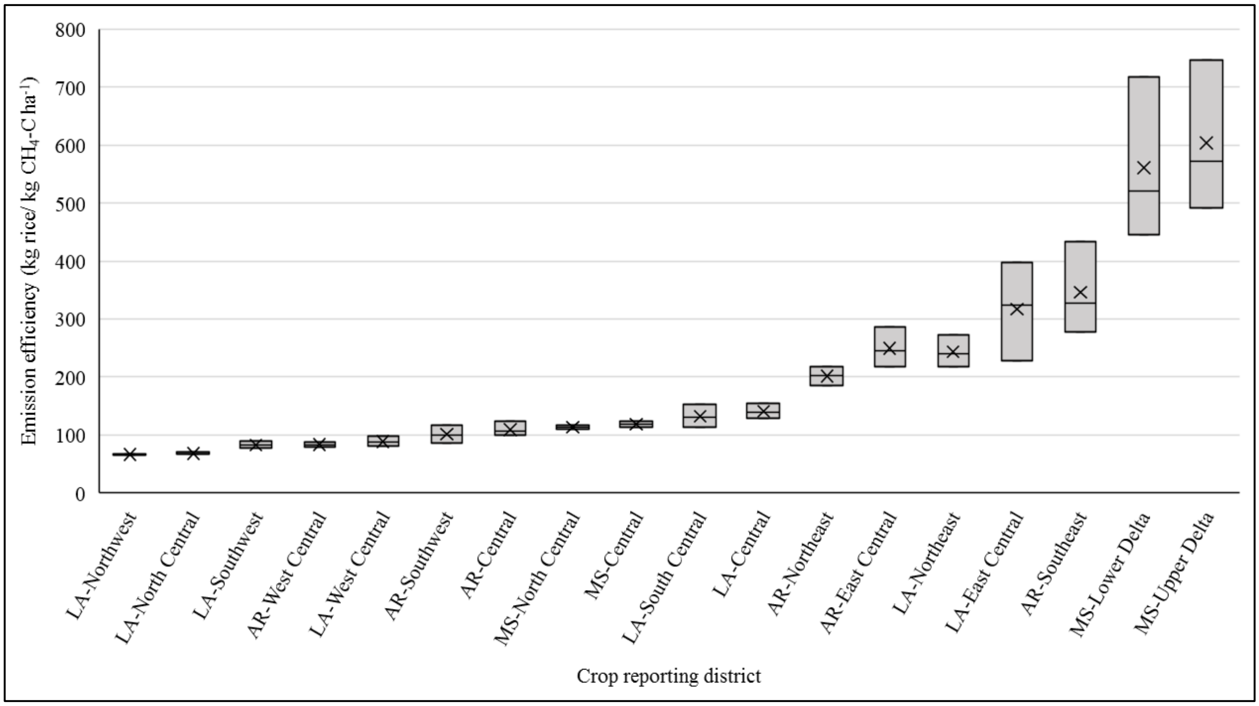
Crop Reporting District (CRD)	Soil type (%)		Rice-soybean rotation (%)[a]	Rice seeded area (ha)	Ratoon crop (ha)[b]	Hybrid adoption (%)	Rice yield (kg/ha)	2005-2014 annual average emission efficiency (kg rice/ kg CH_4-C ha^{-1})[c d]	
	Clay	Loamy						Mean***	SD
Crop reporting district level aggregate									
Arkansas									
Southwest	24.36	75.64	77.05	2,789	0	50.08	11,966.27	121.44 A	25.79
Central	7.50	92.50	77.05	3,333	0	50.09	14,373.63	125.26 A	22.10
Northeast	19.97	80.03	77.05	254,422	0	50.01	20,829.23	201.81 BC	14.40
East Central	28.99	71.01	77.05	229,052	0	50.00	21,529.61	226.00 B	15.36
Southeast	34.30	65.70	77.05	73,139	0	50.01	20,984.47	267.24 B	25.25
Louisiana									
Southwest	16.70	83.30	62.37	98,349	32,133	50.01	18,619.24	79.24 A	8.82
South Central	61.60	38.40	71.86	3,575	438	49.02	14,245.45	102.97 A	25.41
Central	39.52	60.48	64.95	43,646	3,858	49.89	18,582.85	152.56 AC	18.73
North Central	23.49	76.51	71.86	3,328	0	42.89	8,276.57	76.37 A	10.76
Northwest	22.19	77.81	71.86	235	0	35.94	9,408.69	87.00 A	10.93
West Central	26.49	73.51	71.86	1,250	0	50.04	14,247.88	144.81 AB	42.79
Northeast	52.76	47.24	75.19	26,756	8	44.47	17,767.92	236.21 AB	39.52
East Central	69.82	30.18	71.86	131	0	50.04	11,336.66	234.94 AB	40.42
Mississippi									
Central	13.37	86.63	100.00	69	0	51.20	12,028.17	121.80 A	29.36
North Central	9.56	90.44	100.00	3,077	0	50.05	14,044.05	135.29 A	30.34
Lower Delta	65.11	34.89	100.00	30,370	0	50.02	20,790.24	517.31 D	74.57
Upper Delta	67.36	32.64	100.00	48,816	0	50.01	21,222.83	549.51 D	76.17

State and U.S. Mid-South aggregate

	State average		State weighted average[e] by seeded area		State weighted average[e] by production	
	Mean***	SD	Mean***	SD	Mean***	SD
Arkansas	217.45 A	10.16	229.31 A	11.23	230.21 A	11.39
Louisiana	102.31 B	8.80	144.82 B	11.57	143.54 B	13.23
Mississippi	498.66 C	47.98	561.87 C	69.28	576.08 C	72.94
Pooled	187.73 D	8.10	244.39 D	11.87	248.87 A	12.52

[a] 77.05% of rice in Arkansas is assumed to be grown under a rice-soybean rotation in 2014. All rice in Mississippi is assumed to be under a soybean-rice rotation.
[b] A five-year average (2010-2014) was used for the area under ratoon
[c] Means and standard deviations (SD) based on 1000 simulations
[d] Ordered from lowest efficiency level to highest by state
[e] Average resulting from the product of each crop reporting districts' emission efficiency and its importance in seeded area (production) – calculated as its share in total seeded area (production) in Arkansas, Louisiana, and Mississippi – and then taking the sum of the resulting product across all crop reporting districts.
*** Emission efficiencies in the same column indicated by the same superscript letters are not statistically different from one another at the 5% significance level. Comparisons are done with Bonferroni adjustments.

Figure 1. Crop Reporting District Level Methane Emission Efficiency Range in the U.S. Mid-South for 2014



See Figure A1 for county/perish specific results.

Appendix

Table A1. 2014 County Level Methane Emission Efficiency in Arkansas [a]

County	Soil texture (%)		Rice (ha)	Hybrid adoption (%)	Rice yield (kg/ha)	Emission efficiency (kg rice/ kg CH_4-C ha^{-1}) [b c]	
	Clayey	Loamy				Mean	SD
Pope	1.23	98.77	5,158	26.74	23,487	172.15	4.68
Faulkner	4.40	95.60	14,430	36.49	22,831	178.21	4.11
Lafayette	24.36	75.64	42,166	24.77	23,104	182.85	5.15
Pulaski	15.54	84.46	4,578	41.67	22,889	192.28	4.09
Lawrence	12.70	87.30	5,339	70.03	21,483	211.83	5.56
Craighead	9.82	90.18	32,984	34.79	24,866	211.96	5.04
Independence	4.39	95.61	24,076	25.97	22,601	213.25	6.01
Randolph	5.99	94.01	4,525	67.79	22,048	217.52	5.35
Jackson	13.29	86.71	36,889	56.68	24,816	217.68	4.42
Drew	10.83	89.17	15,558	18.29	22,387	225.97	7.35
White	10.91	89.09	25,754	49.39	23,970	226.27	4.42
Clay	15.74	84.26	31,729	42.62	23,401	226.35	4.76
Monroe	28.75	71.25	49,197	13.31	24,681	229.78	7.92
Ashley	12.32	87.68	12,108	37.62	23,512	232.25	5.33
Arkansas	6.94	93.06	25,060	36.29	22,507	238.80	5.70
St. Francis	37.02	62.98	35,627	26.41	24,587	241.86	6.82
Prairie	18.17	81.83	13,210	39.51	21,785	254.64	5.88
Greene	23.66	76.34	36,313	69.81	24,439	259.52	6.57
Poinsett	32.54	67.46	8,707	72.49	23,509	306.83	7.68
Lee	27.71	72.29	29,325	80.21	23,265	319.20	10.01
Woodruff	34.05	65.95	10,225	35.41	23,235	361.58	10.63
Cross	31.98	68.02	21,667	26.30	25,302	390.83	13.57
Phillips	40.04	59.96	20,654	53.91	22,240	545.92	16.67
Lonoke	18.17	81.83	14,099	65.04	23,020	548.57	12.47
Lincoln	34.15	65.85	5,158	26.74	23,487	172.15	4.68
Jefferson	34.15	65.85	14,430	36.49	22,831	178.21	4.11
Desha	59.06	40.94	42,166	24.77	23,104	182.85	5.15
Mississippi	61.12	38.88	4,578	41.67	22,889	192.28	4.09
Crittenden	74.60	25.40	5,339	70.03	21,483	211.83	5.56
Chicot	70.77	29.23	32,984	34.79	24,866	211.96	5.04

[a] 77.05% of rice in Arkansas is assumed to be grown under a rice-soybean rotation and no ratoon crop in 2014

[b] Ordered from lowest efficiency level to highest

[c] Means and standard deviations (SD) based on 1000 simulations

Table A2. 2014 Parish Level Methane Emission Efficiency in Louisiana [a]

Parish	Soil texture (%)		Rice–soybean rotation (%)	Rice (ha)	Ratoon (ha)	Hybrid adoption (%)	Rice yield (kg/ha)	Emission efficiency (kg rice/ kg CH_4-C ha^{-1}) [b c]	
	Clayey	Loamy						Mean	SD
Lafayette	9.53	90.47	71.86	216	338.21	10.69	9,489	10.88	0.36
Caldwell	27.64	72.36	71.86	462	0.00	0.00	7,723	63.27	2.43
La Salle	12.52	87.48	71.86	224	0.00	0.00	9,208	64.06	2.44
Rapides	20.33	79.67	71.86	4,452	0.00	0.00	8,612	64.97	2.48
Beauregard	3.89	96.11	71.86	505	330.63	58.77	24,403	65.02	1.28
Red River	25.72	74.28	71.86	165	0.00	0.00	8,201	65.70	2.52
Ouachita	19.84	80.16	71.86	3,713	0.00	0.00	9,145	68.63	2.62
Acadia	9.10	90.90	60.61	34,578	12367.64	18.37	23,181	75.20	2.08
Jefferson Davis	14.71	85.29	60.61	33,785	12692.59	32.84	21,388	75.64	1.69
Allen	0.00	100.00	71.86	6,247	1434.12	35.99	20,351	83.87	1.87
Natchitoches	26.49	73.51	71.86	1,543	0.00	21.56	9,909	87.84	2.54
Vermilion	31.25	68.75	60.61	21,621	6465.74	9.79	21,749	95.31	3.02
Calcasieu	8.27	91.73	71.86	6,156	1034.44	33.62	22,110	109.99	2.55
Evangeline	6.97	93.03	60.61	18,577	2993.10	40.41	22,274	110.04	2.18
St Mary	67.43	32.57	71.86	89	0.00	0.00	7,723	118.73	5.65
Point Coupee	60.31	39.69	71.86	752	0.00	0.00	10,231	135.97	5.97
Franklin	22.67	77.33	100.00	1,216	0.00	82.66	10,272	149.19	9.00
St. Landry	45.76	54.24	60.61	10,547	1621.55	10.63	21,542	151.81	4.97
Catahoula	61.06	38.94	71.86	526	0.00	43.85	9,854	163.31	4.13
Cameron	71.36	28.64	71.86	4,789	1431.19	11.05	21,581	192.37	8.88
Morehouse	32.61	67.39	71.86	15,223	0.00	22.33	22,572	216.20	6.26
West Carroll	24.46	75.54	71.86	872	0.00	74.74	20,496	233.00	5.95
St. Martin	65.79	34.21	71.86	1,391	436.58	62.35	24,657	245.75	4.99
Richland	32.96	67.04	100.00	2,272	0.00	48.64	23,140	287.68	7.79
East Carroll	86.39	13.61	71.86	643	0.00	36.71	9,432	300.19	17.23
West Baton Rouge	69.82	30.18	71.86	233	0.00	100.00	11,337	324.80	10.96
Iberia	57.94	42.06	71.86	456	0.00	18.00	23,688	326.01	11.61
Avoyelles	64.24	35.76	71.86	4,851	45.61	24.19	22,364	347.57	12.40
Tensas	88.34	11.66	71.86	1,271	0.00	40.86	10,136	357.79	21.68
Madison	85.37	14.63	71.86	2,962	0.00	0.00	20,225	514.13	36.91
Concordia	84.72	15.28	71.86	3,962	124.22	58.94	23,751	733.34	30.14

[a] A five-year average (2010-2014) was used for the area under ratoon
[b] Ordered from lowest efficiency level to highest
[c] Means and standard deviations (SD) based on 1000 simulations

Table A3. 2014 County Level Methane Emission Efficiency in Mississippi [a]

County	Soil texture (%)		Rice (ha)	Rice yield (kg/ha)	Emission efficiency (kg rice/ kg CH_4-C ha^{-1}) [b c]	
	Clayey	Loamy			Mean	SD
Grenada	1.89	98.11	114	12,884	106.59	3.16
Tate	3.56	96.44	378	12,884	108.25	3.20
Panola	6.07	93.93	2,235	12,884	110.82	3.27
Holmes	13.37	86.63	49	12,884	119.06	3.50
Desoto	26.66	73.34	482	12,884	137.73	4.06
Tallahatchie	35.53	64.47	2,818	23,027	274.87	8.24
Humphreys	76.22	23.78	597	12,884	331.10	17.47
Sunflower	65.33	34.67	5,518	22,525	442.38	17.69
Leflore	67.21	32.79	1,580	21,869	447.79	18.62
Sharkey	87.55	12.45	175	12,884	487.77	40.67
Coahoma	70.93	29.07	3,282	23,635	528.24	23.97
Quitman	74.05	25.95	3,547	22,324	540.55	26.70
Issaquena	92.19	7.81	451	12,884	604.85	65.71
Bolivar	78.90	21.10	13,652	23,399	650.78	37.56
Tunica	80.45	19.55	9,956	23,903	697.96	42.63
Washington	81.96	18.04	4,646	23,704	727.48	47.12

[a] The RTWG (2014) Mississippi seeding report denoted only state aggregate level of hybrid adoption of 38% and not county level. Thus, this study assumes each county had 38% adoption. All rice in Mississippi is assumed to be under a soybean-rice rotation.
[b] Ordered from lowest efficiency level to highest
[c] Means and standard deviations (SD) based on 1000 simulations
NASS uses yield estimates of 12,884 kg/ha for several counties given the low number of rice producers in each county, to prevent a specific rice producer being identified. The average for the crop reporting district is used in these cases.

Figure A1. County Level Methane Emission Efficiency Range in the U.S. Mid-South for 2014