DRAFT FOR PUBLIC COMMENT
11.28.2017

Greenhouse Gas Emissions Metric: Estimating Methane Emissions from US Rice Production Systems

Field to Market Greenhouse Gas Emissions Metric: Estimating Methane Emissions from US Rice Production Systems

Contributors: Mathias Marcos and Bruce Linquist (UC Davis), Merle Anders (U of Arkansas), Dustin Harrell (LSU), Ben Runkle (U of Arkansas), Michele Reba (USDA ARS), Arlene Adviento-Borbe (USDA ARS), Allison Thomson (Field to Market)

Initial peer-review and member review: August 17, 2017
Revised: November 6, 2017
Approved by Metrics Committee: November 14, 2017

1. Introduction

The Field to Market Rice Methane Subgroup met several times in early 2017 to consider appropriate methodologies to adopt for revision of the Greenhouse Gas Emissions Metric. Rice methane (CH_4) emissions are currently estimated based on relationships between yield, production, and published inventory report estimates. The subgroup discussed potential alternatives that would better meet the Field to Market criteria of scientifically robust methods that are transparent, relatively easy to implement, and provide feedback to a user on actions they can take to improve their sustainability performance. The subgroup determined that the current metric does not achieve this objective, and that alternative approaches existed that should be considered for a revision.

After considering available measurement methodologies for rice methane emissions, including process-based simulation models (e.g. DayCent/DNDC) as used in the 2016 US GHG Inventory report (USEPA, 2016), the California Rice Methane offset protocol (CARB, 2015), and the published guidelines on GHG Estimation methodology from the USDA (Ogle et al., 2014), the group recommended adopting the USDA methodology as described in the USDA Guidelines[1] (Ogle et al., 2014, section 3.5.6). The group determined that this approach would meet the needs of transparency and robustness, as well as ease-of-use by non-experts and providing feedback on methane emissions-reducing practices.

The method relies on establishing standard emissions factors for methane from rice production, as well as region-specific scaling factors. In order to establish these factors for US rice production systems, a meta-analysis of published research was necessary. This report outlines the overall approach, recommended standard emissions factors, and recommended scaling factors for relevant management practices for two distinct US rice producing regions (Southern and California). A literature review and meta-analysis of rice field research was conducted to determine the appropriate factors. A separate

---

[1] Available from: https://www.usda.gov/oce/climate_change/Quantifying_GHG/USDATB1939_07072014.pdf

journal manuscript has been prepared and submitted to further document the methods reported here (Linquist et al., submitted).

Field to Market's Metrics Committee reviews each metric once every three years at a minimum; members can request an earlier review in the event of new scientific findings or resources. Throughout the document we identify several practices and regions where there is currently very limited literature with methane emissions measurements but where we are aware of ongoing research projects. Thus, we anticipate that we will be able to incorporate new research into this metric over time.

The resulting method will be implemented in the Fieldprint Platform and used by rice growers and their advisors to better understand the magnitude of their methane emissions, and to provide guidance on relevant practice changes that can be used to mitigate those emissions. The Fieldprint Platform is typically used by groups of growers in a supply region, in partnership with their supply chain; thus, the results from groups of growers may also be used to highlight opportunities for improvement in the greenhouse gas footprint of rice supply by downstream businesses and brands. Field to Market's Supply Chain Sustainability Program provides a framework for use of the Fieldprint Platform and metric results, including processes for verification of sustainability claims by organizations.

2. Regional Emissions Factors

2.1 Defining standard practices

To develop baseline methane emissions for US rice production systems, CH_4 flux observations were extracted from peer-reviewed publications. An exhaustive literature survey of peer-reviewed publications was carried out using Google Scholar (Google Inc., Mountain View, CA, USA) for articles published before July 2017. Studies needed to meet several criteria to be included in our analysis. First, CH_4 fluxes must have been measured under field conditions for (at least) the entire flooded cropping season. Second, seasonal fluxes and the number of field replications had to be reported, or easily extracted from figures or tables. Third, the experiments must have occurred in the USA. A list of these studies is provided in the Appendix.

There are two main rice cropping regions in the USA with both distinct agronomic practices and sufficient published data to discern impacts of management practices on methane emissions: the Southern US (including AR, LA, MS, MO, TX), and California. Therefore, separate baseline methane emission factors were developed for each region.

To develop the baseline methane emission factor, we only considered observations from peer-reviewed publications that employed "standard" practices for the region. These standard practices are intended to represent the most common set of practices in each region; alternative practices will then be used as scaling factors, as described later in this document. Thus, we recognize and attempt to account for the full range of practices with the method described here. Standard practices as used to calculate the overall regional emissions factor for each region are shown in Table 1.

Table 1. Definition of "standard" practice in each region. Observations must have met the following criteria to be included in the development of the baseline emission factor estimate.

Practice	Southern US	California

Crop rotation	Rotated with soybean	Continuous rice
Previous crop rice straw management	*Not applicable* - previous crop not rice	Incorporated after harvest
Previous winter water management	As rainfall dictates	Flooded
Seeding method	Drill seeded to a dry seed bed (continuously flooded from 3-6 leaf stage to final drain for harvest)	Water seeded (continuously flooded from seeding to final drain before harvest)
Variety	Semi-dwarf, non-specialty, non-hybrid, long grain cultivars	Semi-dwarf, non-specialty, non-hybrid, medium grain cultivars
Nitrogen fertilizer	N-Fertilized (if N-rate study, most appropriate rate was used)	N-Fertilized (if N-rate study, most appropriate rate was used)
Green manure/farmyard manure	None	None
Sulfate additions	None	None

2.2. Data analysis for standard practices

Emissions were tabulated from the standard practice in each study and then R statistical software (R Core Team, 2016) was used to analyze the data and generate figures.

To limit the bias from observations from the same soil and in the same year, we weighted the observations based on the number of replicates and the number of observations in each data set from the same year with the same soil (Eq. (1)):

$$Weight = \frac{n_{rep}}{n_{obs}}$$

where $\boldsymbol{n}_{rep}$ was the number of experimental replicates, and $\boldsymbol{n}_{obs}$ was the number of methane emissions from the same soil in the same year. This weighing method gives those observations with more replication more weight, while also reducing the influence of multiple observations done in the same year in the same soil. To prevent extraordinarily high weights from studies with many experimental replicates, the number of replicates that could contribute to the weighting was capped at four (4). Two studies had observations with more than four replicates: McMillan et al. 2006 had six replicates and Sass et al. 2002 had 24 replicates. The weighted mean was then calculated and used as the CH_4 baseline emissions factor.

Outliers were considered as ±5 standard deviations from the weighted mean; however, no outliers were present. Finally, bootstrapped 95% confidence intervals (CI) for the mean were generated using the “boot” package in R with 4999 iterations. The CH_4 baseline emissions factors are presented as seasonal emissions with units of kg CH_4 ha^{-1} $season^{-1}$.

Considerable variation was present in the baseline emissions factor of each region. To explore the cause of variation, we examined effects of time and soil properties. We performed backward elimination stepwise regression analysis (Hocking 1976) to determine if we could attribute the variability in CH_4 emissions observations to soil pH, soil carbon, soil clay content, or study year. Specifically, a full model with soil pH, soil carbon, soil clay content, study year was developed for each region (Eq. (2)):

$$CH_4 = a + B_1 * pH + B_2 * Carbon + B_3 * Clay + B_4 * Year + e$$

whereby, CH_4, *pH*, *Carbon*, *Clay*, and *Year*, refer to the CH_4 emissions, soil pH, soil carbon, soil clay content, and study year, respectively, for each observation. The coefficient *a* corresponds to the intercept for the model, while *e* corresponds to the error associated with the model. The terms B_1, B_2, B_3, and B_4 correspond to the coefficients for each term.

Then, the least significant term (i.e. the term with the largest p-value), was sequentially removed and the model reassessed until only significant terms remained ($p < 0.05$).

2.3 Regional emissions factors for standard practices

The location of all study sites used for the emissions factor and scaling factor analyses is shown in Figure 1. For the Southern US region, most studies occurred on research stations, while for California, most studies occurred on commercial rice fields. There were 17 studies with 27 observations that contributed to the baseline emissions factor for the Southern US, while there were 7 studies with 13 observations that contributed to the baseline emissions factor for California. The baseline emissions factors were 194 kg CH_4 ha^{-1} $season^{-1}$ and 218 kg CH_4 ha^{-1} $season^{-1}$, for the Southern US and California, respectively (Table 2, Figure 2). These baseline emissions factors are lower than those reported by the US EPA (2015), which were 237 kg CH_4 ha^{-1} $season^{-1}$ and 266 kg CH_4 ha^{-1} $season^{-1}$ for the Southern US and California, respectively.

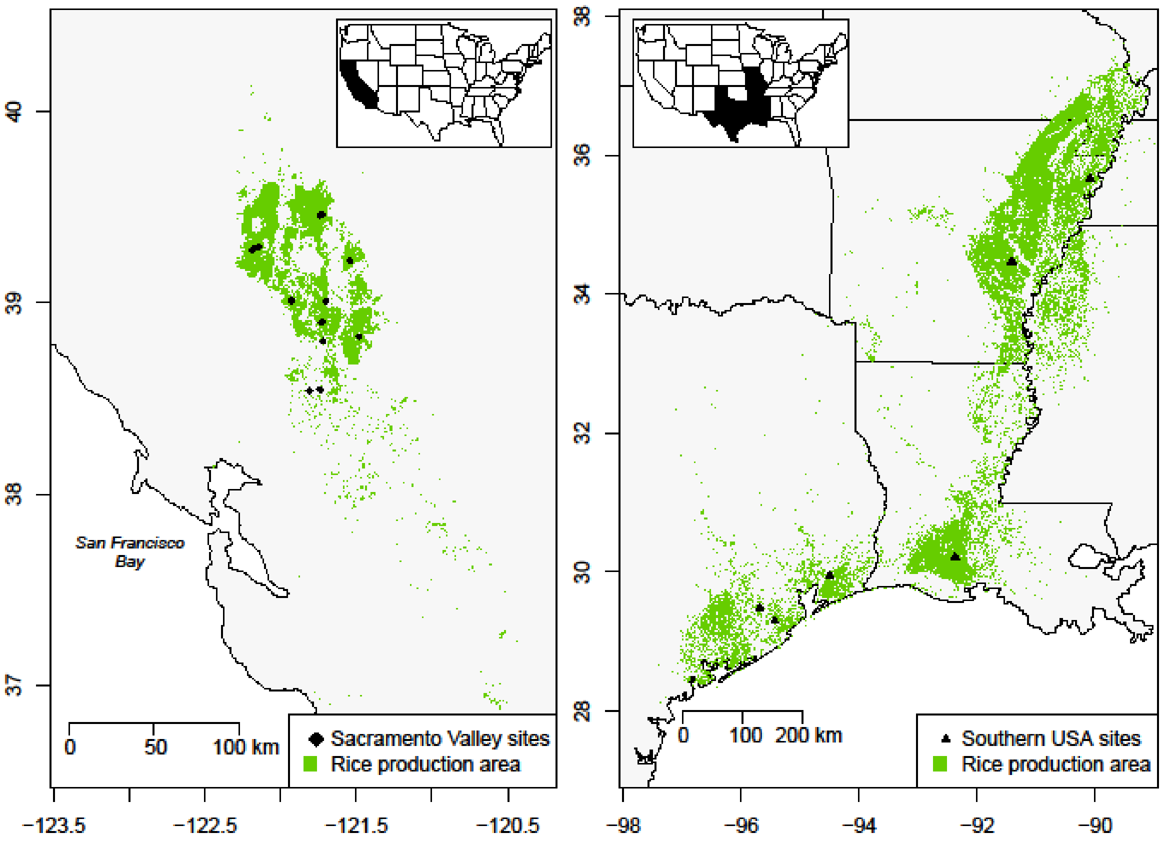

Figure 1. Study site locations for methane emissions factor and scaling factor analyses.

Table 2: Tabulated seasonal standard methane emissions (kg CH_4 ha^{-1} season^{-1}) by region for the main crop and the ratoon crop. Lower and upper limits represent bootstrapped 95% confidence levels for the mean. Minimum and maximum values, number of studies and observations are also reported.

Region	Weighted Mean CH_4	Lower Limit	Upper Limit	Studies	Observations	Min CH_4	Max CH_4	Avg % clay
South (Main Crop)	194	129	260	17	27	9	510	26
California (Main Crop)	218	153	284	7	13	67	446	45
South (Ratoon Crop)[2]	1013	526	1673	2	4	465	1490	*N/A*

---

[2] Ratooning is only practiced in the southern Texas and Louisiana. The ratoon crop emissions factor estimate is added to the main crop emissions.

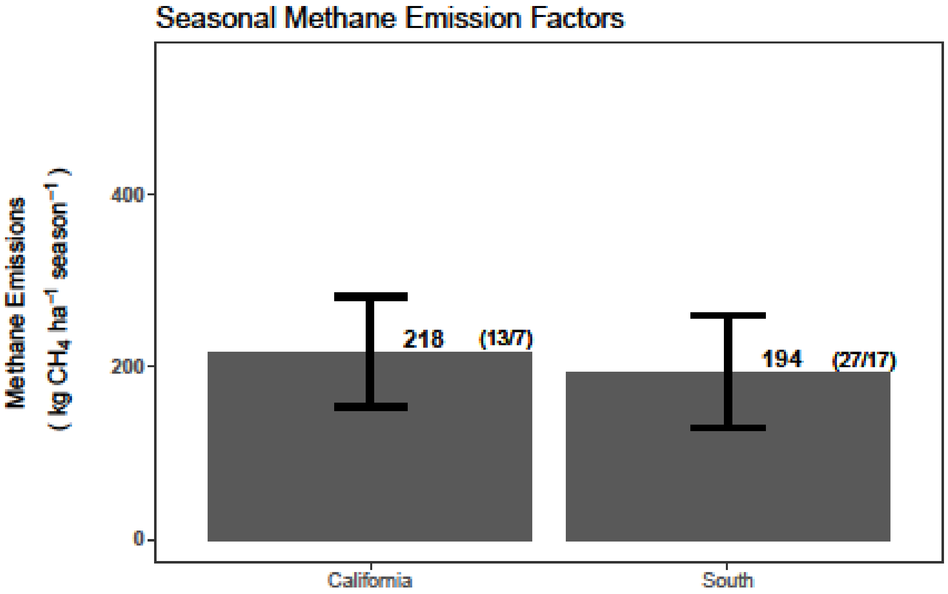

Figure 2. Seasonal baseline methane emissions (kg CH_4 ha^{-1} $season^{-1}$) by region. Error bars represent bootstrapped 95% CI for the mean. Parentheses refer to (# of Observations/ # of Studies) used to develop the baseline emissions factor.

2.4 Emissions Factor Adjustment – Clay Content

The range of main crop CH_4 standard emissions observations was 9 to 510 kg CH_4 ha^{-1} $season^{-1}$ and 67 to 446 kg CH_4 ha^{-1} $season^{-1}$ for the Southern US and California, respectively (Table 2). The large range in standard CH_4 emissions observations is not uncommon for gas flux measurements in agricultural systems. However, we considered the effect that edaphic factors (soil pH, soil carbon, and soil clay content) or study year could have on the variability of methane emissions. The backward elimination stepwise regression analysis concluded that only clay content significantly influenced CH_4 emissions (Figure 3) and explained 25 to 41% of the variation. As there is evidence that suggests clay content can influence CH_4 emissions, our goal was to establish a representative baseline emissions factor for these regions with a conservative accounting for variation based on clay content.

Thus, we elected to use the linear relationship between clay content and the standard practice methane emissions to establish a clay-determined baseline emissions factor for each region. That is, each user will be assigned a starting emissions factor based on their region (south or CA) and their clay content. Percent clay will be determined automatically based on soil property databases used in the Fieldprint Platform (currently USDA SSURGO database).

The standard emissions factors defined above are assigned to the average clay content from each region, determined based on the clay content of the studies assessed here. This results in an average clay content of 26% for the southern region, corresponding to the regional EF of 194 kg CH_4 ha^{-1} $season^{-1}$ and an average clay content of 45% for California, corresponding to the regional EF of 218 kg CH_4 ha^{-1} $season^{-1}$. The linear relationship then will be used to account for variations from these average clay contents. The equations described in Figure 3 corresponds to a reduction of 6.1 kg CH_4 ha^{-1} $season^{-1}$ for each 1% increase in clay content in the South and a reduction of 8.1 kg CH_4 ha^{-1} $season^{-1}$ for each 1% increase in clay content in California.

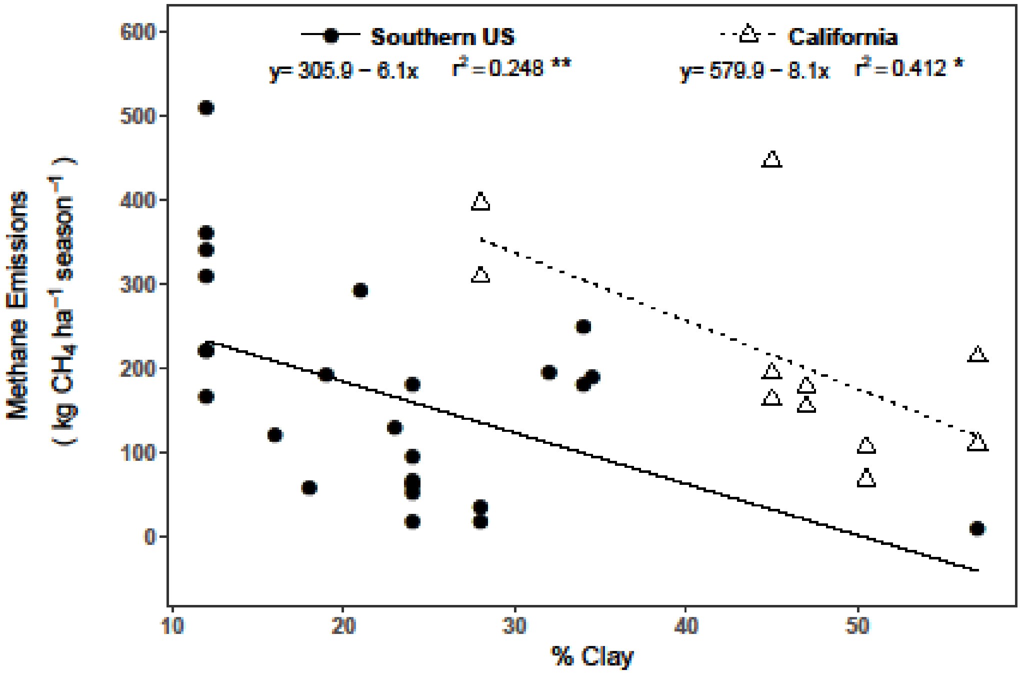

Figure 3. In California and in the Southern US, there is a significant negative correlation between % Clay and CH_4 emissions.

2.5. Ratoon emissions modifier for the Southern US region

In addition to the baseline emissions factors, we developed an emissions modifier for ratoon cropping. Ratoon cropping is the practice of harvesting the main crop then allowing an additional crop to grow from the remaining stubble. Ratoon cropping is limited, but occurs in the southern-most areas of the Southern region (primarily along the Gulf Coast of Louisiana and Texas) where there is a longer growing season than further north. A ratoon crop is an additional crop and, therefore, we feel the ratoon crop emissions factor should be added onto the main crop emissions factor after all scaling factors have been incorporated.

The methodology used to develop the modifier was similar to that used to develop the baseline emissions factors. Observations used for the ratoon crop emissions factor were those which followed a main crop that met our criteria of a “standard” practice. Ratoon crop observations were weighted the same as observations used to develop the baseline emissions factors (Eq.1). Confidence intervals for the weighted mean were generated using the “boot” package in R with 4999 iterations. For a ratoon crop, the emissions factor is 1013 kg CH_4 ha^{-1} $season^{-1}$ (Table 2, Figure 4).

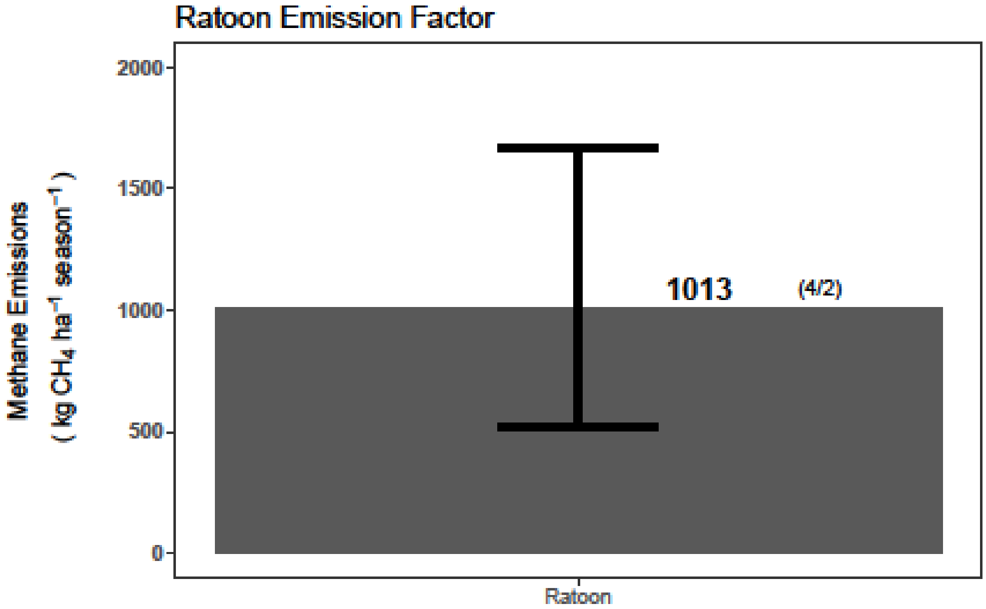

Figure 4. CH_4 emissions with a ratoon crop. If a ratoon crop is added, CH_4 emissions increase by 1013 kg CH_4 ha^{-1} season^{-1}.

There are two studies from Louisiana which report large increases in CH_4 emissions when ratoon cropping. While more studies would greatly improve the estimated effect of ratooning, we are confident that ratooning greatly increases CH_4 emissions. If there is a ratoon crop, CH_4 emissions are increased by 1013 kg CH_4 ha^{-1} season^{-1}. This ratoon crop emissions factor is added to the emissions factor for the main crop, after all relevant scaling factors have been considered. This emissions factor is only for the Southern US region, as ratoon cropping is not practiced in California.

The mechanism for large CH_4 emissions from ratoon cropping is clear. When ratoon cropping, rice straw from the main crop is left in the field. The field is then re-flooded and sometimes re-fertilized with N to stimulate growth, and due to the large amount of straw in an anaerobic environment with relatively large temperatures, there is a greatly increased rate of methanogenesis, and consequently CH_4 emissions, from the re-growing rice plants.

3. Emissions scaling factors for selected production practices

3.1. Data analysis for scaling factors

Rice crop management strategies thought to have an effect on methane emissions were considered as potential scaling factors to modify the standard practice emissions factor described above. We employed a meta-analytic approach to analyze the effect of various management practices on methane emissions from rice fields. Only peer-reviewed publications, with side-by-side comparisons of management practices were used. The side-by-side comparisons had all other management factors the same, except for the scaling factor being considered. Due to wide variations in reported methane emissions, our analysis focused on the percent change in methane emissions resulting from a given management practice. Similar to other quantitative reviews and meta-analyses (Linquist et al. 2012, Carrijo et al. 2016), the natural logarithm of the response ratio was used as the effect size (Eq. (3)):

$$Effect\ Size = \ln\left(\frac{CH_{4\,Emissions\ with\ the\ Scaling\ Factor}}{CH_{4\,Emissions\ without\ the\ Scaling\ Factor}}\right)$$

Secondly, the effect sizes were weighted in the same manner as baseline emissions factor observations (Eq. 1). Two observations were removed as outliers, one observation from the Alternate Wetting and Drying (AWD) Multiple Drain dataset and another from the Sulfur dataset. Finally, the mean effect size of each scaling factor was calculated as the mean of the weighted effect sizes of the observations and bootstrapped 95% confidence intervals (CI) were generated using the “boot” package in R with 4999 iterations.

The mean effect size of each scaling factor was considered significantly different from the control if its CI did not overlap zero. For ease of interpretation, all the graphs herein show the back-transformed effect sizes as the percentage change caused by each scaling factor in relation to the control.

We examined a variety of rice crop management strategies as potential scaling factors for both regions including AWD, Previous Crop, Burning Rice Straw, and Sulfur Additions. Additionally, for California, we examined Seeding Method and Winter Flooding, while for the Southern US we also examined Cultivar. All potential scaling factors had a significant effect on CH_4 emissions, except for Winter Flooding; therefore, Winter Flooding was not considered as a scaling factor. Additionally, due to the similar mechanisms for affecting CH_4 emissions and similar magnitude of the effect, we grouped Previous Crop and Burning Rice Straw into one scaling factor termed “Crop Residue Management”.

3.2 Scaling factors selection and results

In total, five unique scaling factors had a significant effect on CH_4 emissions and were important to consider. Three of these scaling factors can be applied nationally: Alternate Wetting and Drying (AWD), Sulfur Additions, and Crop Residue Management. Another scaling factor, Cultivar, is only applicable to the Southern US, while the final scaling factor, Seeding Method, is only applicable to California.

Table 3. Scaling factors and their effect on CH_4 emissions grouped by region. The number of studies and observations used to develop each scaling factor is shown. The Scaling Error refers to the bootstrapped 95% confidence interval for the scaling.

Region	Scaling Factor	# Studies	# Obs.	Effect on CH_4 (as % relative to standard)	Scaling	Scaling Error
Southern US	AWD					
	- Single Drain	4	9	-39	0.61	0.53 – 0.70
	- Multiple Drains	3	10	-83	0.17	0.09 – 0.35

	Sulfur	5	14	variable[3]	-	-
	High Crop Residue[4]	9	23	116	2.16	1.72 – 2.74
	Cultivar					
	- CLXL745	3	8	-26	0.74	0.63 – 0.88
	- Tall Varieties	7	32	31	1.31	1.13 – 1.50
California	AWD					
	- Single Drain	4	9	-39	0.61	0.53 – 0.70
	- Multiple Drains	3	10	-83	0.17	0.09 – 0.35
	Sulfur	5	14	variable[3]	-	-
	Little or No Crop Residue	9	23	-54	0.46	0.37 – 0.58
	Seeding Method (Drill Seeded)[5]	2	3	-60	0.40	0.32 – 0.52

[3] A linear relationship exists between amount of sulfur added and % reduction in CH_4 emissions. For every 30 kg S ha^{-1} (up to a maximum of 338 kg S ha^{-1}), CH_4 emissions are reduced by 4%.

[4] Crop Residue refers to non-harvested plant biomass from a high-residue crop (like rice or corn) being left in the field from the previous season.

[5] The Drill Seeded scaling factor cannot be combined with the Crop Residue scaling factor, as the reduction in CH_4 due to drill seeding would likely not occur without crop residue in the field.

For the Southern US, High Crop Residue had the largest effect, increasing CH_4 emissions by 116% (Table 3). For California, AWD with Multiple Drains had the largest effect, decreasing CH_4 emissions by 83%. The Crop Residue scaling factor had the opposite effect in the Southern US compared to California because the standard practices in the two regions differ. In California, it is standard practice to have a high amount of crop residues in the field (i.e. in a continuous rice rotation), while in the Southern US, it is standard practice to plant rice with little to no previous crop residue in the field (i.e. in rotation with a very low residue crop).

Further explanation of these scaling factors, the rationale for including these scaling factors, as well as the current mechanistic understanding of how these management practices reduce CH_4 emissions are discussed below.

3.2.1 Alternate Wetting and Drying (AWD)

Explanation of scaling factor and rationale for inclusion: AWD is a water management practice that is known to decrease CH_4 emissions from rice fields and is included in the IPCC guidelines. A single drain during the season significantly reduced CH_4 emissions, on average, by 39%, while multiple drains reduced CH_4 emissions by 83%. The IPCC guidelines have a single aeration scaled at 0.60, and multiple aerations scaled at 0.52 (IPCC 2006), while our results indicate a scaling of 0.61 and 0.17 for single and multiple drains, respectively.

Aeration periods in US experiments averaged 8.4 days, with the 25th and 75th quantiles corresponding to aeration periods of 6 and 10 days, respectively. Aeration periods from US study observations are much longer than the 3-day minimum aeration period required in the IPCC guidelines.

Thus, to be able to apply these scaling factors, it is recommended that fields must be drained for a minimum of 6 days; this corresponds to the 25th quantile of all observations.

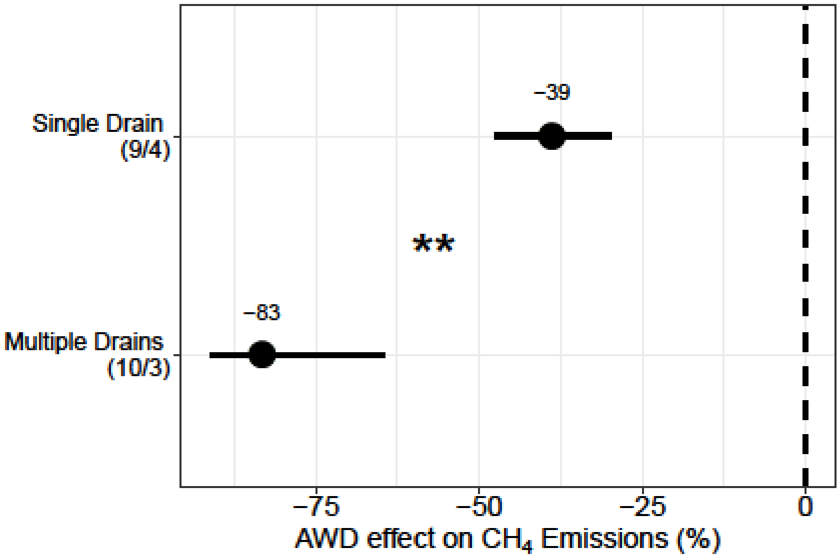

Figure 5. Effect of AWD on CH_4 emissions. A 39% and 83% reduction in CH_4 emissions, corresponding to scaling coefficients of 0.61 and 0.17, for a Single Drain and Multiple Drains, respectively. ** indicates that the effect of single vs multiple drains on CH4 emissions are significantly different ($P<0.01$).

Mechanistic understanding of how this practice reduces CH_4 emissions: AWD introduces aerobic periods into the rice cropping system, and decreases the production of methane, which occurs under anaerobic soil conditions. The decomposing carbon in the soil is released as CO_2 and not as CH_4 under aerobic soil conditions, and therefore seasonal CH_4 emissions are reduced. However, to achieve this, the soil must be sufficiently aerobic for some period of time. This is why we stress that the fields must be drained and unsaturated for a minimum of 6 days to receive the CH_4-reducing benefits of AWD.

Potential N_2O increase with AWD: Importantly, AWD schemes have the potential to increase nitrous oxide (N_2O) emissions. In the two US studies that measured N_2O emissions under AWD water management (one study in California and another in Arkansas), the dry-down events all occurred when soil N was expected to be low. In California, a water-seeded system where most fertilizer N is applied before planting, the first dry-down occurred roughly 6 to 7 weeks after planting and measured soil extractable mineral N levels were low (LaHue et al., 2016). Similarly, in the Southern US study, the dry-down occurred about 3 weeks after permanent flood, when it was expected that soil mineral N levels would also be low (Norman et al., 2013). As a result, N_2O emissions during the dry-down periods were negligible in the California study (LaHue et al., 2016), and low in the Southern US study (Linquist et al., 2015). In the California study, AWD fields had lower seasonal N_2O emissions than continuously flooded fields (on average lower by 0.015 kg N_2O ha^{-1} season^{-1}); however, in the Southern US study, AWD fields had greater seasonal N_2O emissions than continuously flooded fields (on average greater by 0.452 kg N_2O ha^{-1} season^{-1} (Table 4)).

Therefore, in addition to the recommendation that fields must be drained for at least 6 days, we also recommend that fields should not be allowed to dry-down unless it is sure that soil mineral N levels are low, determined by time since last fertilizer application. Guidelines for users will be developed prior to metric implementation.

Table 4. Comparisons of N_2O emissions (kg N_2O ha^{-1} season^{-1}) between fields under AWD water management and fields under continuously flooded conditions, separated by region.

Author	State	Year	Control N_2O	AWD N_2O	Difference
Linquist et al., 2015	Arkansas	2012	0.049	0.163	0.115
Linquist et al., 2015	Arkansas	2012	0.049	0.360	0.311
Linquist et al., 2015	Arkansas	2012	0.049	0.215	0.167
Linquist et al., 2015	Arkansas	2013	0.110	0.613	0.503
Linquist et al., 2015	Arkansas	2013	0.110	0.629	0.519
Linquist et al., 2015	Arkansas	2013	0.110	1.65	1.54
Linquist et al., 2015	Arkansas	2013	-0.013	0.044	0.057
Linquist et al., 2015	Arkansas	2013	-0.013	0.311	0.324
Linquist et al., 2015	Arkansas	2013	-0.013	0.517	0.530
		Southern US Mean	**0.049**	**0.500**	**0.452**
LaHue et al., 2016	California	2013	-0.035	-0.060	-0.025
LaHue et al., 2016	California	2014	-0.039	-0.044	-0.005
		California Mean	**-0.037**	**-0.052**	**-0.015**

3.2.2 Sulfur Additions

Explanation of scaling factor and rationale for inclusion: Sulfur is often added to rice fields as an ammonium sulfate (AS) application in a starter fertilizer blend upon planting, or as a top-dress nitrogen (N) application. The amount of S that would typically be applied in such cases is around 30 kg S ha^{-1}. In addition, sulfur may be added as potassium sulfate and can be a contaminant in some phosphorus fertilizers. Studies that have tested the effect of S additions on CH_4 emissions have applied S at rates much greater (ranging from 69 to 1860 kg S ha^{-1}) than would normally be applied in commercial rice fields. Therefore, to include Sulfur Additions as a scaling factor for more typical applied S rates, we could not follow the same procedures as for other scaling factors.

To use Sulfur Additions as a scaling factor, we generated a piecewise regression model, forcing the regression equation through the origin, and based the scaling factor on S rates inputted into the regression equation. There was a significant linear relationship between S rate and percent reduction in CH_4 up to S application rates of 338 kg S ha^{-1}, with every 30 kg S ha^{-1} reducing CH_4 emissions by 4% (Figure 6). Above an application rate of 338 kg S ha^{-1}, there was no relationship between applied S and CH_4 emissions reductions.

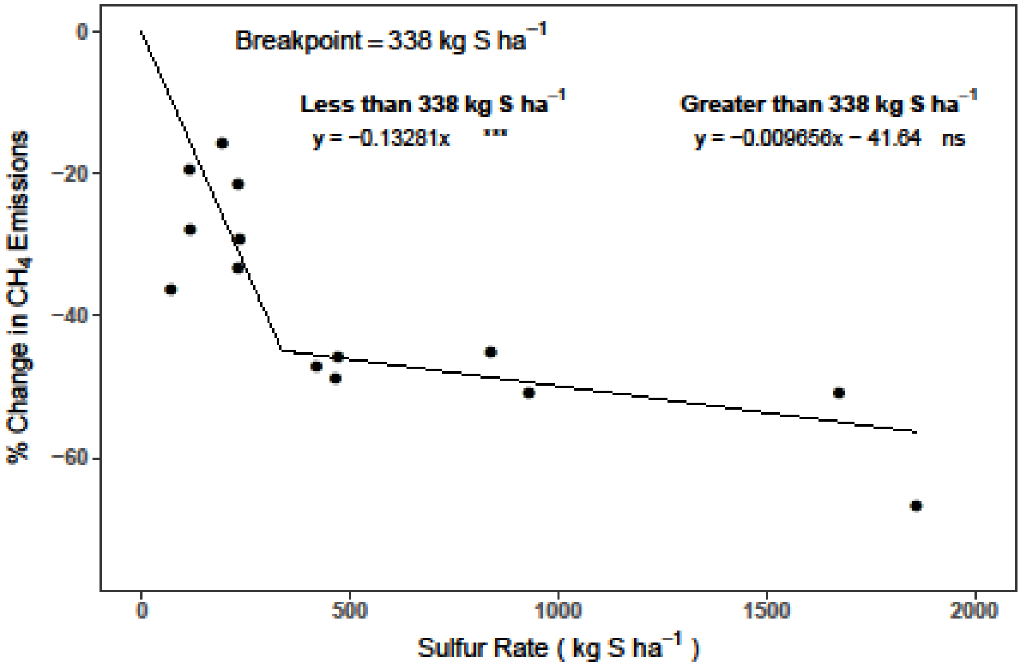

Figure 6. Relationship between the applied sulfur rate and CH_4 emissions reductions.

Mechanistic understanding of how this practice reduces CH_4 emissions: Sulfur additions enhance substrate competition between sulfate-reducing bacteria and methanogens, thereby potentially reducing CH_4 production and emissions in anaerobic systems (Denier van der Gon et al., 2001).

3.2.3 Crop Residue Management

Explanation of scaling factor and rationale for inclusion: Crop residues left on the soil can have a large impact on CH_4 emissions from rice fields. The standard practice in the Southern US is to plant rice in a field with little to no residue on the soil surface (i.e. the previous season was either fallow or a crop with little post-harvest surface residue, like soybean). In California, the standard practice is to continuously plant rice year after year, and to leave a high amount of residue in the field after harvest.

For this scaling factor, we grouped observations where the previous crop was soybean, the field was previously fallow, or the rice straw was burned after harvest[3]; this was termed "Little or No Crop Residue". The justification for this combined grouping is shown in Figure 8. In Figure 8, the three

---

[3] Emissions from crop residue burning are accounted for in a separate component of the Field to Market Greenhouse Gas Emissions metric, and therefore is not explicitly accounted for here.

practices are shown individually in the top three data points, while the bottom data point is the combination of the three residue practices. In Figure 8, the practices that result in little or no crop residue from the previous season were compared to the standard of continuous rice cultivation, whereby there was a large amount of crop residue left on the soil surface from the previous season.

For this analysis, studies that added exogenous inputs of crop residues prior to planting were not considered.

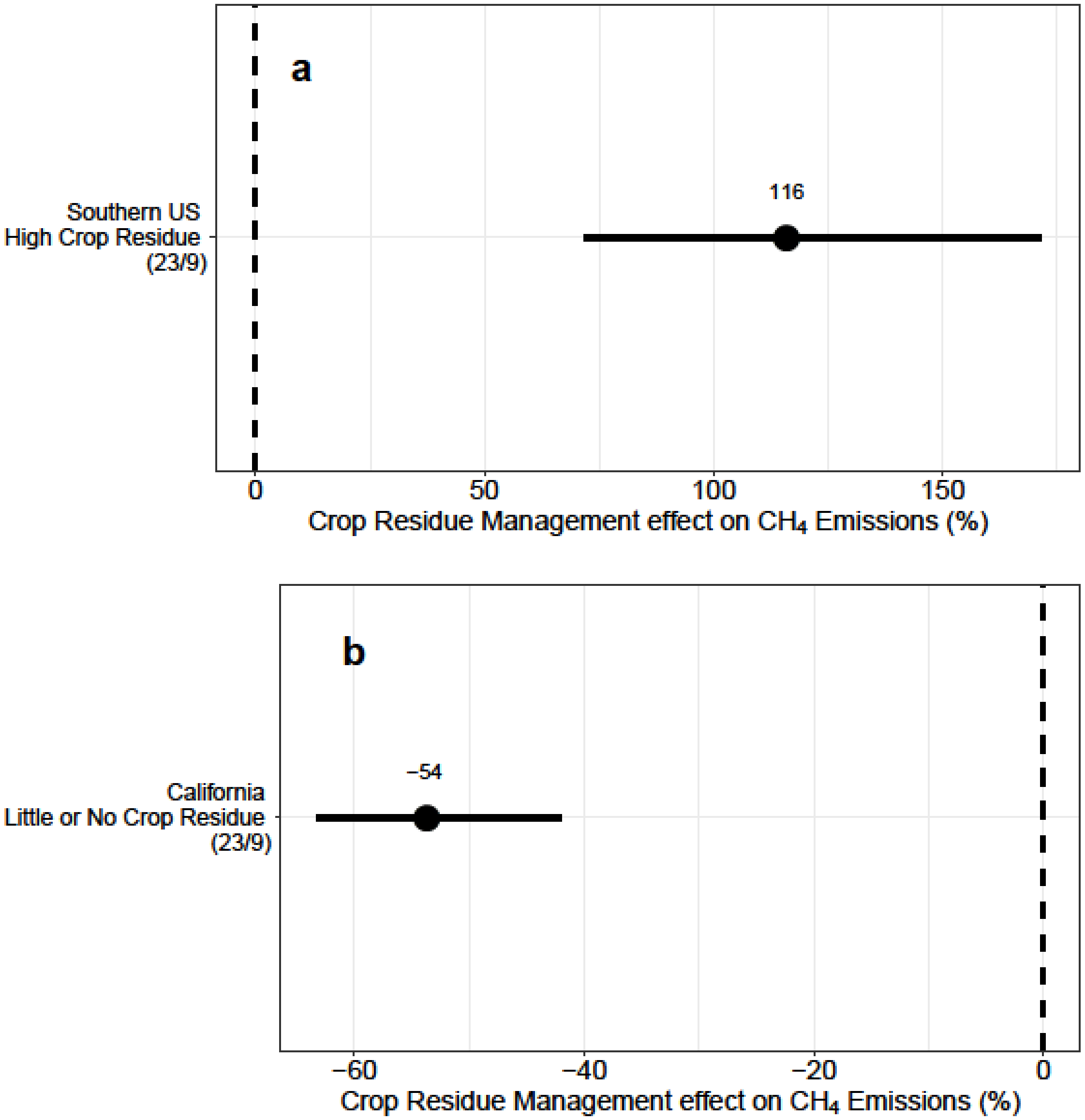

Figure 7(a,b). Crop residue effect on effect CH_4 emissions compared to standard practices for the region. In the Southern US (Figure 7a), it is standard practice to have little to no residue from the previous season in the field before planting; therefore, having a large amount of crop residues will increase CH_4 emissions by 116%, which corresponded to a scaling factor of 2.16. In California (Figure 7b), it is standard practice to have a large amount of crop residues from the previous season in the field before planting; therefore, having little to no crop residues will reduce CH_4 emissions by 54%, which corresponds to a scaling factor of 0.46.

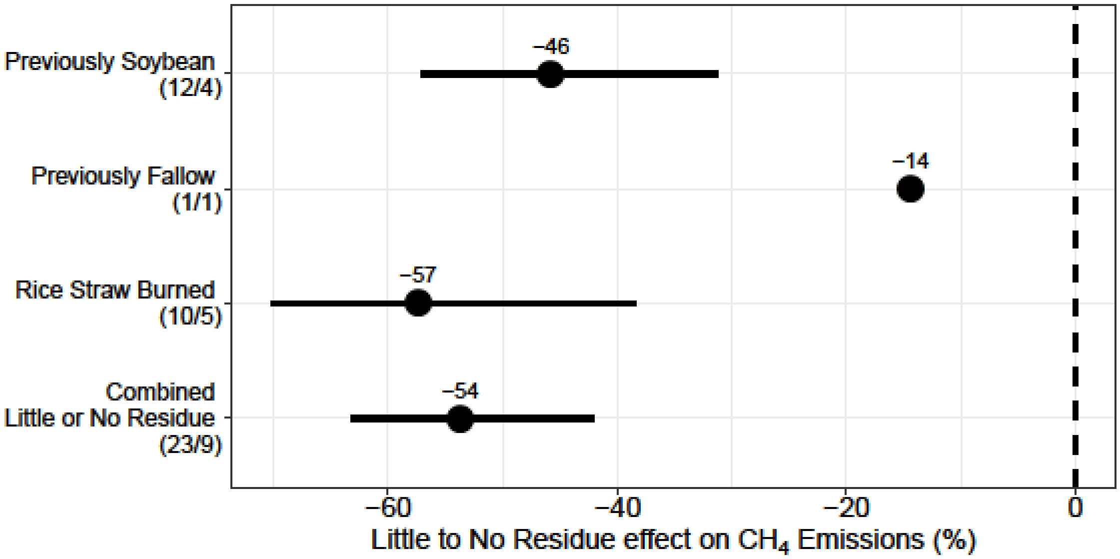

Figure 8. Effect of having little to no crop residue left in the field on CH_4 emissions. The top three data points show management practices that result in little or no crop residues in the field. Since the direction and magnitude for the three management practices were similar, we grouped these observations together (shown in the bottom data point), and developed one scaling factor for practices that result in little or no crop residue.

The data used for Figure 7 were the same for both the Southern US and California; however, due to the regions having different standard practices, the effect on standard CH_4 emissions is opposite in the two regions. Since the standard in the Southern US is to have little to no crop residue on the soil at planting, having a large amount of crop residue in the field from the previous crop will increase CH_4 emissions. While in California, since the standard is to have a large amount of crop residue on the soil surface at planting, having little or no crop residues will reduce CH_4 emissions.

Mechanistic understanding of how this practice effects CH_4 emissions: Having a large amount of crop residue on the soil provides carbon substrate for methanogenesis during the flooded rice cropping season. Little or no residue left from the previous season will tend to result in less CH_4 emissions, while large amounts of residue left from the previous season will tend to result in more CH_4 emissions.

3.2.4 Seeding Method (California)

Explanation of scaling factor and rationale for inclusion: There are only two studies with side-by-side comparisons of Drill Seeded and Water Seeded rice; however, in both studies, there were significant and large decreases in CH_4 emissions from the Drill Seeded compared to the Water Seeded system. Drill seeding is considered standard practice for the Southern US and is not considered as a separate scaling factor.

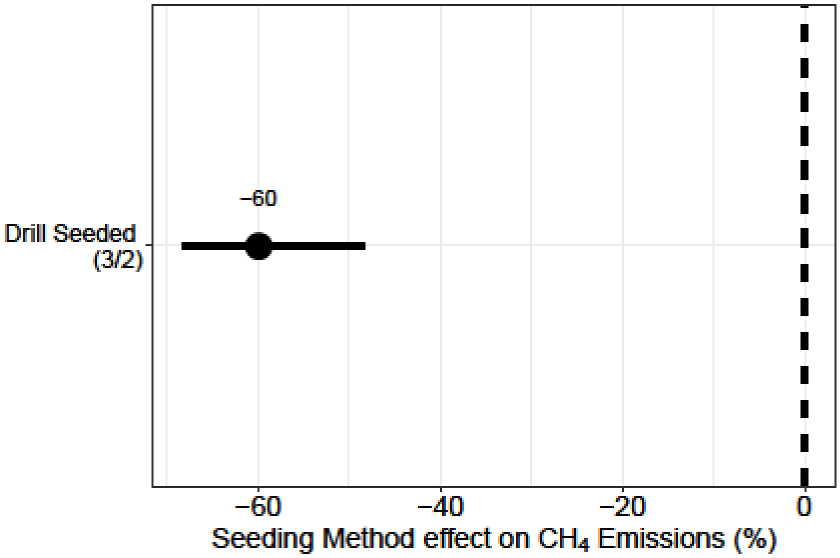

Figure 9. Effect of Drill Seeding on CH_4 emissions. In California, where the standard practice is Water Seeding, Drill Seeding can reduce CH_4 emissions by 60%, corresponding to a scaling factor of 0.40.

Mechanistic understanding of how this practice increases CH_4 emissions: Drill Seeding postpones the flooded cropping season until the 3-6 leaf stage, roughly one month after seeding. However, the soil may be moist before the field is flooded from rainfall, allowing rice straw that is present in the soil to partially decompose, releasing CO_2, and reducing the amount of substrate available for methanogenesis later when the field becomes flooded. Additionally, Drill Seeding reduces the number of days that a field is flooded, thereby reducing the potential for methanogenesis during the rice growing season.

Given the limited number of studies, both from California, we recommend this scaling factor only be applied in conditions consistent with those studies, namely this scaling factor should not be used if there is no crop residue in the field (i.e. the previous year's rice straw has been removed or burned, or the previous crop has left little residue).

3.2.5 Cultivar (Southern US)

Explanation of scaling factor and rationale for inclusion: Multiple studies have investigated rice varietal effects on CH_4 emissions and have reported differences. A few studies have reported the hybrid CLXL745 as having reduced CH_4 emissions compared to pure-line varieties, while many studies have also reported tall varieties to increase CH_4 emissions compared to short-stature varieties. Currently, we cannot conclude that all hybrids reduce CH_4 emissions, as CLXL745 is the only hybrid for which CH_4 emissions have been sufficiently studied. Since CLXL745 is a widely grown, long grain rice variety in the Southern US, the single variety may be appropriate to include as its own scaling factor; however, the life span of most varieties is relatively short and it is not clear how much longer the hybrid CLXL745 will be a dominate variety.

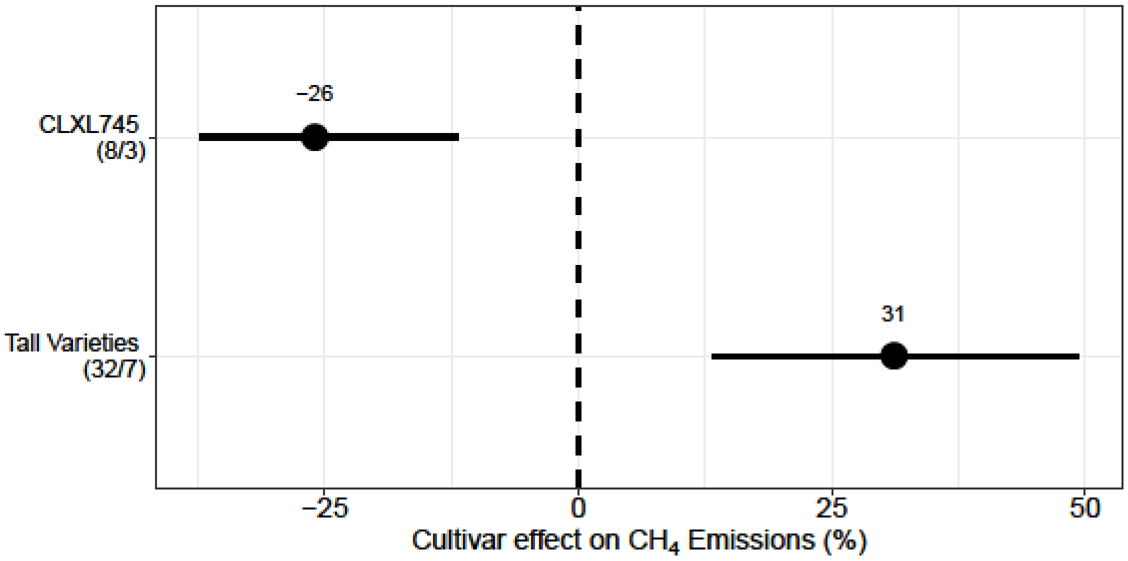

Figure 10 shows varietal effects on CH_4 emissions. Compared to short-stature, non-hybrid (i.e. pure-line) semi-dwarf varieties, the hybrid CLXL745 reduces CH_4 emissions by 26%, which corresponds to a scaling factor of 0.74, while tall varieties increase CH_4 emissions by 31%, which corresponds to a scaling factor of 1.31.

Mechanistic understanding of how this practice increases CH_4 emissions: It is currently not clear why certain varieties emit more or less CH_4. Many hypothesis have been proposed, including: varietal differences in oxygen leakage in the roots resulting in rhizospheric oxidation (Bilek et al., 1999), the ability of the plant to transport methane (Ding et al., 1999), and yield potential (Jiang et al., 2017).

4. Implementation of emissions factors

4.1 Using multiple scaling factors

The IPCC methodology adapted here allows for scaling factors to be “stacked” in a multiplicative manner (i.e. if using multiple scaling factors, the scaling factors from each of those factors are multiplied together). To help assess the impact that combining multiple scaling factors can have on the reliability of our estimates, modeling was performed on observations within the dataset for which one or more scaling factors were appropriate.

For this analysis, we only used studies in which the study control met our criteria of a “standard” practice. To generate predicted emissions (i.e. estimates of CH_4 emissions using our scaling factors), we applied the appropriate scaling factors to the control of the study. We then compared this to the actual observed CH_4 emissions from that study. In our dataset, we had 41 observations with one scaling factor and 6 observations with two scaling factors.

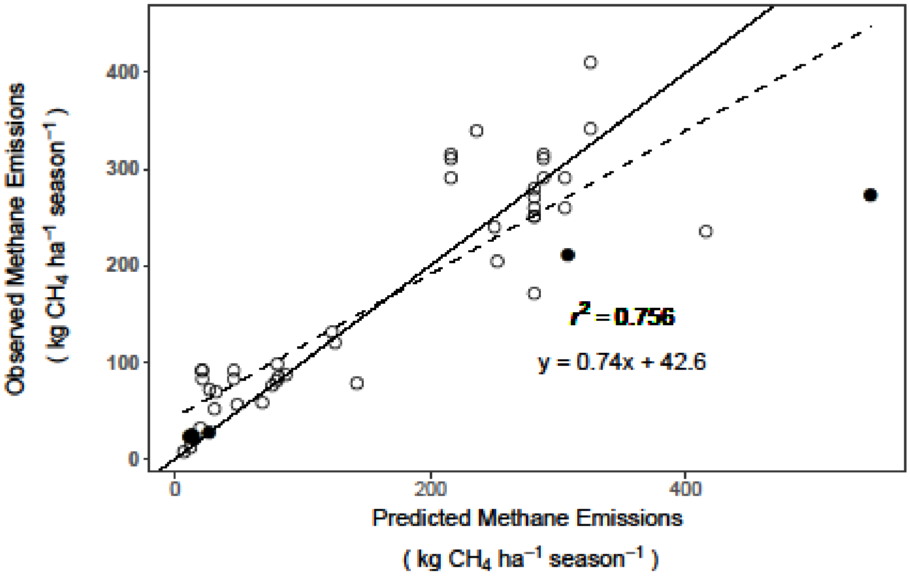

Figure 11. Predicted vs observed methane emissions. Open circles are observations with one scaling factor. Solid circles are observations with two stacked scaling factors. The solid line is the 1:1 line, while the dashed line is the best-fit line. The r^2 value and equation correspond to best-fit line.

Figure 11 illustrates that most observations align with the 1:1 line, indicating that the predictions for CH_4 emissions using our scaling factors reasonably matched the observed CH_4 emissions. Five of the 6 observations with two stacked scaling factors (Fig. 11 filled circles) were in line with observations with only one scaling factor.

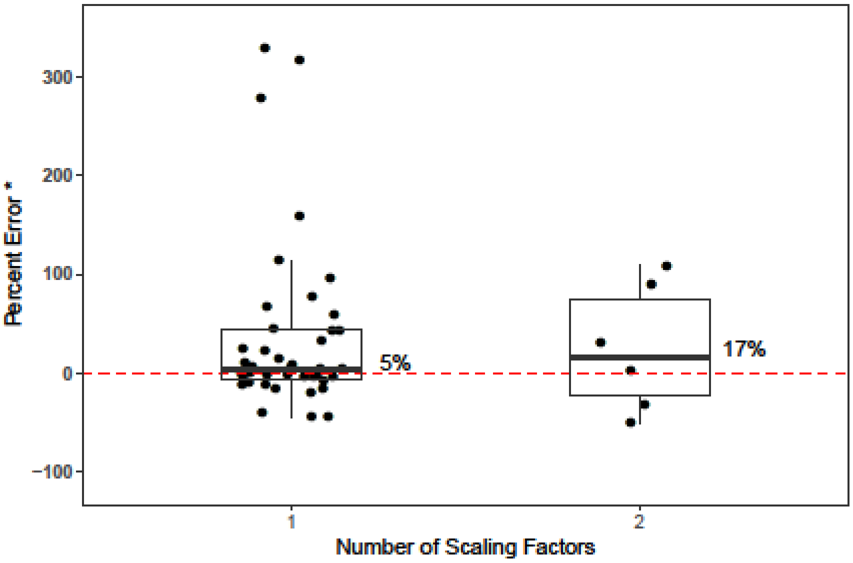

Figure 12. Percent error without the absolute value ((Observed CH_4 – Predicted CH_4)/ Predicted CH_4), for one and two scaling factors. This allows for an indication of the magnitude and direction of the error.

Points above the red dashed line indicate that the observed CH_4 emissions were greater than the predicted CH_4 emissions, while observations below the red line indicate that the predicted CH_4 emissions were greater than the observed emissions. Data points are staggered for visual interpretation. A boxplot is overlaying the data points, with median values displayed to the right of the boxplot.

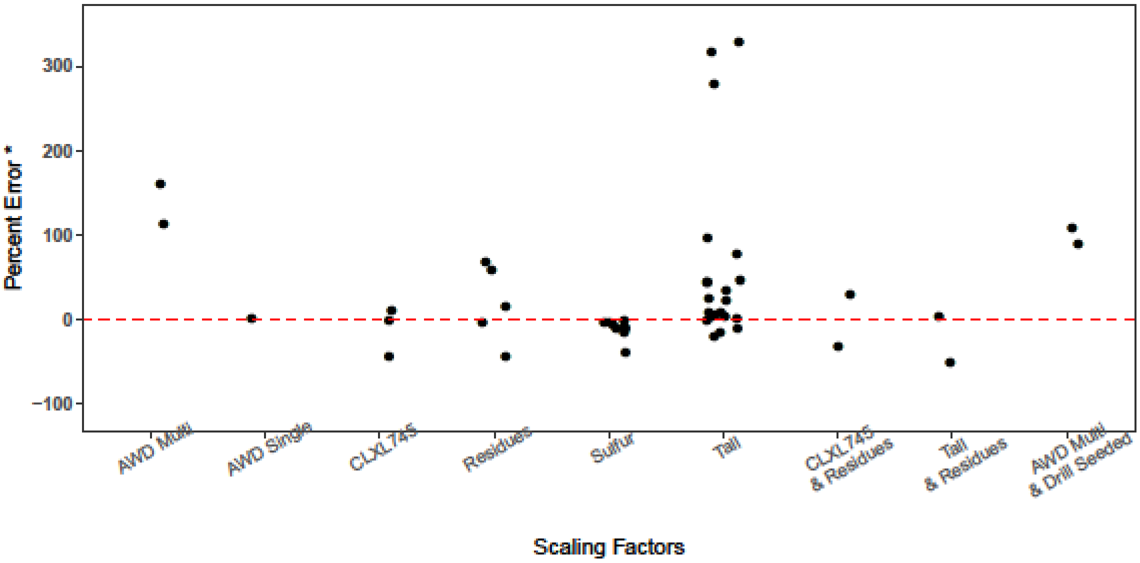

Figure 13. Percent error without the absolute value ((Observed CH_4 – Predicted CH_4)/ Predicted CH_4) for specific scaling factors. This allows for an indication of the magnitude and direction of the error based on the specific scaling factor. Points above the red dashed line indicate that the observed CH_4 emissions were greater than the predicted CH_4 emissions, while observations below the red line indicate that the predicted CH_4 emissions were greater than observed emissions. Data points are staggered for visual interpretation.

Figures 12 and 13 indicate that using two scaling factors stacked together does not increase the error relative to using only one scaling factor. While the number of observations with multiple scaling factors is very small, these data support the IPCC methodology for stacking scaling factors in a multiplicative manner for two scaling factors.

We do not have data where more than two scaling factors would be appropriate; therefore, we cannot provide guidance for stacking more than two scaling factors.

5. Sensitivity analysis for Methane Calculator Tool

To evaluate the proposed method, we conducted two tests. First, we designed a set of management practices to “stress test” the combinations of scaling factors with the most extreme values, to determine the full range of possible results. These practices were not based on actual practices and therefore we don’t necessarily anticipate such extreme results. Second, we gathered actual practice data from 24 rice fields in the Field to Market program to assess how the proposed metric would influence their greenhouse gas emissions metric score.

Presented below are the ranges of CH_4 emissions using the calculator tool, results from actual grower fields, and ranges of the observed CH_4 emissions from the literature used in this analysis.

5.1 Stress Test

Table 5. Range of CH_4 emissions (kg CH_4 ha^{-1} $season^{-1}$) possible using the proposed method.

Region	Minimum CH_4 Emissions	Maximum CH_4 Emissions (without ratoon crop)	Maximum CH_4 Emissions (with ratoon crop)
Southern US	13.2	3758	4771
California	8.0	1488	NA

The maximum predicted CH_4 emissions in the Southern US using the proposed method was 4771 kg CH_4 ha^{-1} $season^{-1}$ (Table 5). This maximum includes a field with a large amount of residue from the previous season, the use of a tall rice variety, an application of 50 tonnes ha^{-1} of green manure, as well as a ratoon crop (without a ratoon crop the maximum CH_4 emissions was 3758 kg CH_4 ha^{-1} $season^{-1}$).

The proposed method does not have a maximum possible value for CH_4 emissions, as the addition of Organic Amendments has no limits, and will lead to an increase in CH_4 emissions. However, to calculate a maximum using the proposed method, we limited the maximum rate of Organic Amendments to a fresh mass of 50 Tonnes ha^{-1}.

The minimum predicted CH_4 emissions in the Southern US using the proposed method was 13.2 kg CH_4 ha^{-1} $season^{-1}$ (Table 5). This minimum included a field under AWD water management with multiple aerations, the use of the hybrid CLXL745, and the maximum rate of applied S. The maximum S application rate was any amount greater than 338 kg S ha^{-1}, as there was no reducing benefit from S applications above this rate.

The maximum predicted CH_4 emissions in California using the proposed method was 1488 kg CH_4 ha^{-1} $season^{-1}$ (Table 6). This maximum included a field with an application of 50 tonnes ha^{-1} of green manure.

The minimum predicted CH_4 emissions in California using the proposed method was 8.0 kg CH_4 ha^{-1} $season^{-1}$ (Table 6). This minimum included a Drill-Seeded field under AWD water management with multiple aerations, as well as the maximum rate of applied S. The maximum rate of applied S was any amount greater than 338 kg S ha^{-1}, as there was no reducing benefit from S applications above this rate.

5.2 Literature Observations and Grower Results

Table 6: Results from the proposed method for rice grower fields, compared to values from the literature used in this study.

	Minimum CH_4	Maximum CH_4 (without Ratoon)	Maximum CH_4 (with Ratoon)
Southern US-Growers	24	303	1206

Southern US-Literature	2.3	728.7[1]	1830
California-Growers	132	203	
California-Literature	8.4	1360	

[1] The observed maximum CH_4 emissions (without ratoon) was 7450 kg CH_4 ha^{-1} $season^{-1}$. This was from an unusual observation reported in Kongchum et al. (2006), which applied 24 tonnes ha^{-1} of rice straw immediately before planting. As this was a very unusual practice, it was not included in this table.

In the Southern US, the minimum observed CH_4 emissions was 2.3 kg CH_4 ha^{-1} $season^{-1}$ (Table 5), which came from a field under AWD water management with multiple aerations growing the hybrid CLXL745. The maximum observed CH_4 emissions (without a ratoon crop) was 728.7 kg CH_4 ha^{-1} $season^{-1}$, which came from a field using a specialty variety. The maximum observed CH_4 emissions (with a ratoon crop) was 1830 kg CH_4 ha^{-1} $season^{-1}$, which was a standard main crop and ratoon observation (i.e. no scaling factors applied). Using practice data from 21 rice fields in the southern region, representing a range of actual practices, the range of methane emissions from the calculator tool is between 24 and 303 kgCH4 per hectare without ratoon, and reaches 1206 kg CH4/ha with ratoon.

In California, the minimum observed CH_4 was 8.4 kg CH_4 ha^{-1} $season^{-1}$ (Table 6), which came from a field that had little to no residue from the previous crop. The maximum observed CH_4 was 1360 kg CH_4 ha^{-1} $season^{-1}$, which came from a field that applied a green manure. Only two grower fields supplied data for testing the California version of the Calculator tool, and both were well within the potential range of observed values

Table 7: Range of practices for grower field practices and the methane emissions under the old Field to Market methodology compared to the new method.

ID	State	Yield (lbs/ ac)	Water Regime	Residue	Seeding Method	Cultivar	Sulfur	Organic Amd.	Ratoon	Old CH4 kg/ha	New CH4 kg/ha
1	AR	9540	AWD-multiple	Little/no residue	N/A	CLXL745	none	none	no	340	24
2	AR	8640	AWD-Single	Little/no residue	N/A	CLXL745	none	none	no	308	88
3	AR	7695	AWD-multiple	Little/no residue	N/A	CLXL745	none	none	no	274	24
4	AR	8865	AWD-multiple	Little/no residue	N/A	CLXL745	none	none	no	316	24
5	MO	6750	Continuous	Little/no residue	N/A	semi-dwarf	none	none	no	240	194
6	MO	8955	Continuous	Little/no residue	N/A	Tall	none	none	no	319	254
7	MO	8955	AWD-	High	N/A	Tall	none	none	no	319	92

			multiple	Residue							
8	MO	7020	AWD-multiple	Little/no residue	N/A	semi-dwarf	none	none	no	250	32
9	AR	8505	Continuous	Little/no residue	N/A	CLXL745	22 kg ha	2.5 ton manure	no	303	166
10	AR	8640	AWD-Single	High Residue	N/A	CLXL745	11 kg ha	none	no	308	187
11	AR	7830	Continuous	Little/no residue	N/A	Tall	none	2.5 ton manure	no	279	304
12	AR	8190	AWD-Single	Little/no residue	N/A	CLXL745	22 kg ha	2.5 ton manure	no	292	102
13	AR	9090	Continuous	Little/no residue	N/A	semi-dwarf	none	none	no	324	194
14	AR	10125	Continuous	Little/no residue	N/A	semi-dwarf	none	none	no	360	194
15	AR	7650	Continuous	Little/no residue	N/A	semi-dwarf	none	none	no	272	194
16	AR	7650	Continuous	Little/no residue	N/A	semi-dwarf	none	none	no	272	194
17	CA	8219	AWD-Single	High residue	Water	N/A	none	none	N/A	293	133
18	CA	8219	Continuous	High residue	Water	N/A	48 kg ha	none	N/A	293	204
19	AR	7425	Continuous	Little/no residue	N/A	semi-dwarf	20 kg/ha	none	no	264	189
20	AR	6750	Continuous	Little/no residue	N/A	Tall	none	none	no	240	254
21	AR	8325	Continuous	Little/no residue	N/A	CLXL745	20 kg/ha	none	no	296	140
22r	LA	12537	AWD-multiple	High Residue	N/A	Tall	none	none	yes	446	1104
23r	LA	9828	AWD-multiple	Little/no residue	N/A	semi-dwarf	none	none	yes	350	1045
24r	LA	9450	Continuous	Little/no residue	N/A	semi-dwarf	none	none	yes	336	1206

The values in Table 7 represent a range of actual rice fields from growers involved in Field to Market. While not representing a full spectrum of all possible practices, these help to illustrate for users the difference between the old metric scores and the new metric scores, and also provide context in relation to the values from the literature used in development of the new metric.

6. Conclusion and Next Steps

The emissions and scaling factors developed here will be implemented into the Fieldprint Platform for use by any interested grower. The Platform is freely available to the general public from an online portal (www.fieldtomarket.org) and is widely used by growers engaged in supply chain partnership programs and in agricultural extension outreach efforts.   The new method will provide greater accuracy and a stronger connection to scientifically accepted methods and observed methane emissions measurements. It will also provide clear guidance to users on what practices would increase or reduce their methane emissions and thus achieves our goal of a decision support tool that can be used to factor in sustainability considerations to annual planning by growers.

After implementation, the Field to Market Metrics Committee will continue to follow developments in the literature and will consider revisions and updates to the region definitions, emissions factors and scaling factors developed here. We encourage researchers engaged in this subject to provide feedback and bring to our attention any new studies relevant to the topic.

Works Cited

Bilek, R.S., Tyler, S.C., Sass, R.L., Fisher, F.M., 1999. Differences in CH4 oxidation and pathways of production between rice cultivars deduced from measurements of CH4 flux and 13C of CH4 and CO2. Global Biogeochem. Cycles 13, 1029–1044.

CARB (California Air Resources Board), 2015. Compliance Offset Protocol Rice Cultivation Projects. Californial Air Resources Board. Adopted June 25, 2015. https://www.arb.ca.gov/regact/2014/capandtradeprf14/capandtradeprf14.htm

Carrijo, D.R., Lundy, M.E., Linquist, B.A., 2017. Rice yields and water use under alternative wetting and drying irrigation: A meta-analysis. Fields Crops Research 203, 173–180.

Denier Van Der Gon, H.A.D., Van Bodegom, P.M., Wassmann, R., Lantin, R.S., Metra-Corton, T.M., 2001. Sulfate-containing amendments to reduce methane emissions from rice fields: mechanisms, effectiveness and costs. Mitig. Adapt. Strat. Glob. Change 6, 71–89.

Ding, A., Willis, C.R., Sass, R.L., Fisher, F.M., 1999. Methane emissions from rice fields: Effect of plant height among several rice cultivars. Global Biogeochem. Cycles 13, 1045–1052.

Hocking, R.R., 1976. The Analysis and Selection of Variables in Linear Regression. Biometrics 32, 1–49.

IPCC (Intergovernmental Panel on Climate Change), 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

Jiang, Y., Van Groenigen, K.J., Huang, S., Hungate, B.A., Van Kessel, C., Hu, S., Zhang, J., Wu, L., Yan, X., Wang, L., Chen, J., Hang, X., Zhang, Y., Horwath, W.R., Ye, R., Linquist, B.A., Song, Z., Zheng, C., Deng, A., Zhang, W., 2017. Higher yields and lower methane emissions with new rice cultivars. Glob. Change Biol. 2017, 1–11.

Kongchum, M., Bollich, P.K., Hudnall, W.H., DeLaune, R.D., Lindau, C.W., 2006. Decreasing methane emission of rice by better crop management. Agron. Sustain. Dev. 26, 45–54.

Lahue, G.T., Chaney, R.L., Adviento-Borbe, M.A., Linquist, B.A., 2016. Alternate wetting and drying in high yielding direct-seeded rice systems accomplishes multiple environmental and agronomic objectives. Agric. Ecosyst. Environ. 229, 30–39.

Linquist, B.A., Adviento-Borbe, M.A., Pittelkow, C.M., Van Kessel, C., Van Groenigen, K.J., 2012. Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. Field Crops Research 135, 10–21.

Linquist, B.A., Anders, M.M., Adviento-Borbe, M.A.A., Chaney, R.L., Nalley, L.L., Da Rosa, E.F.F., Van Kessel, C., 2015. Reducing greenhouse gas emissions , water use , and grain arsenic levels in rice systems. Glob. Change Biol. 21, 407–417.

Linquist, B.A., Marcos, M., Anders, M., Harell, D., Linscombe, S., Meba, M.L., Runkle, B., Tarpley, L. Thomson, A.M. 2018. Greenhouse gas emissions and management practices that impact them in US rice systems. Journal of Environmental Quality (*submitted*)

McMillan, A.M.S., Goulden, M.L., Tyler, S.C., 2007. Stoichiometry of CH4 and CO2 flux in a California rice paddy. J. of Geo. Res.112, 1–13.

Norman R.J., Slaton, N.A., Roberts, T.L., 2013. Soil Fertility. In: Rice Production Handbook. Hardke J. (ed.). Misc. Publ. 192. Arkansas Coop. Ext. Serv., Little Rock, AR.

Ogle, S.M., P.R. Adler, F.J. Breidt, S. Del Grosso, J. Derner, A. Franzluebbers, et al. 2014. Chapter 3: Quantifying Greenhouse Gas Sources and Sinks in Cropland and Grazing Land Systems. In Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory. Technical Bulletin Number 1939. Office of the Chief Economist, U.S. Department of Agriculture.

Washington, DC. 606 pages. July 2014. Eve, M., D. Pape, M. Flugge, R. Steele, D. Man, M. Riley-

Gilbert, and S. Biggar, Eds.

Sass, R.L., Fisher, F.M., Andrews, J.A., 2002. Spatial variability in methane emissions from a Texas rice field with some general implications. Global Biogeochem. Cycles 16, 1–7.

US Environmental Protection Agency (USEPA). 2015. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2013

US Environmental Protection Agency (USEPA). 2016. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2014

Appendix: Literature included in the meta-analysis

All studies used to develop the baseline emission and the scaling factors discussed in the main document.

Author/year	State	Study year(s)	Gases Examined	Soil Series	Included in Baseline Emission Factor	Included in Ratoon Emission Factor	Scaling Factors Examined
Adviento-Borbe et al., 2016	California	2012	CH_4, N_2O	various	x		
Bilek et al., 1999	Texas	1995	CH_4	Bernard-Morey	x		Variety
Bossio et al., 1999	California	1997	CH_4	Willows clay			Crop Residue Management
Byrd et al., 2000	Texas	1995, 1996	CH_4	Bernard-Morey	x		Variety
Ding et al., 1999	Texas	1993	CH_4	Lake Charles clay	x		Variety
Fitzgerald et al., 2000	California	1995, 1996	CH_4	Willows silty clay	x		Crop Residue Management
Kongchum et al., 2006	Louisiana	2003	CH_4	Crowley silt loam			AWD(s)
LaHue et al., 2016	California	2013, 2014	CH_4, N_2O	Esquon-Neerdobe complex	x		AWD(m), Seeding Method
Lauren et al., 1994	California	1992	CH_4	Nueva Loam			Crop Residue Management
Lindau and Bollich, 1993	Louisiana	1991	CH_4	Crowley silt loam	x	x	
Lindau et al., 1991	Louisiana	1990	CH_4	Crowley silt loam	x		
Lindau et al., 1993	Louisiana	1991	CH_4	Crowley silt loam	x		Sulfur
Lindau et al., 1994	Louisiana	1992	CH_4	Crowley silt loam			Sulfur
Lindau et al., 1995	Louisiana	1993	CH_4	Crowley silt loam	x	x	Variety
Lindau et al., 1998	Louisiana		CH_4	Crowley silt loam	x		Sulfur

Lindau, 1994	Louisiana	1992	CH_4	Crowley silt loam	x	Sulfur
Linquist et al., 2015	Arkansas	2012, 2013	CH_4, N_2O	Dewitt silt loam		AWD(s), AWD(m), Crop Residue Management
McMillan et al., 2007	California	2002	CH_4	Willows clay	x	
Pittelkow et al., 2013	California	2010, 2011	CH_4, N_2O	Clear lake clay	x	
Pittelkow et al., 2014	California	2008	CH_4	Esquon-Neerdobe complex	x	Seeding Method
Redeker et al., 2000	California	1998, 1999	CH_4	Willows clay	x	Crop Residue Management
Rogers et al., 2014	Arkansas	2011	CH_4	Dewitt silt loam	x	
Rogers et al., 2014	Arkansas	2012	CH_4	Dewitt silt loam	x	Crop Residue Management, Variety
Rogers et al., 2017	Arkansas	2013	CH_4	Dewitt silt loam, Sharkey clay		Sulfur, Crop Residue Management
Sass et al., 1992	Texas	1991	CH_4	Bernard-Morey		AWD(s), AWD(m)
Sass et al., 1994	Texas	1991, 1992	CH_4	Lake Charles clay, Bernard-Morey		Crop Residue Management
Sass et al., 2002	Texas	2000	CH_4	Edna fine sandy loam	x	
Sigren et al., 1997	Texas	1994, 1995	CH_4	Bernard-Morey	x	Variety
Sigren et al., 1997	Texas	1994, 1995	CH_4	Bernard-Morey, mixed Bernard-Edna	x	AWD(s), AWD(m)
Simmonds et al., 2015	California, Arkansas	2011, 2012	CH_4, N_2O	various	x	Variety
Smartt et al., 2016	Arkansas	2013	CH_4	Sharkey clay	x	Crop Residue Management, Variety

Smith et al., 1982	Louisiana	1980	N_2O	Crowley silt loam	x
Yao et al., 2001	Texas	1997	CH_4	Bernard-Morey	x