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To cite this article: Colby W Reavis *et al* 2023 *Environ. Res. Lett.* **18** 124020

ENVIRONMENTAL RESEARCH
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RECEIVED
16 June 2023

REVISED
30 October 2023

ACCEPTED FOR PUBLICATION
2 November 2023

PUBLISHED
13 November 2023

LETTER

Assessing the methane mitigation potential of innovative management in US rice production

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Keywords: methane, rice, alternate wetting and drying, mitigation potential

Abstract

Rice is an important global crop while also contributing significant anthropogenic methane (CH_4) emissions. To support the future of rice production, more information is needed on the impacts of sustainability-driven management used to grow rice with lower associated methane emissions. Recent support for the impacts of different growing practices in the US has prompted the application of a regional methodology (Tier 2) to estimate methane emissions in different rice growing regions. The methodology estimates rice methane emissions from the US Mid-South (MdS) and California (Cal) using region-specific scaling factors applied to a region-specific baseline flux. In our study, we leverage land cover data and soil clay content to estimate methane emissions using this approach, while also examining how changes in common production practices can affect overall emissions in the US. Our results indicated US rice cultivation produced between 0.32 and 0.45 Tg CH_4 annually, which were approximately 7% and 42% lower on average compared to Food and Agriculture Organization of the UN (FAO) and US Environmental Protection Agency (EPA) inventories, respectively. Our estimates were 63% greater on average compared to similar methods that lack regional context. Introducing aeration events into irrigation resulted in the greatest methane reductions across both regions. When accounting for differences between baseline and reduction scenarios, the US MdS typically had higher mitigation potential compared to Cal. The differences in cumulative mitigation potential across the 2008–2020 period were likely driven by lower production area clay content for the US MdS compared to Cal. The added spatial representation in the Tier 2 approach is useful in surveying how impactful methane-reducing practices might be within and across regions.

1. Introduction

Rice production accounts for 8% of global anthropogenic methane (CH_4) emissions and contributes as much as 20% of the global caloric consumption (Juliano and FAO 1993, Khush 2003, Saunois *et al* 2020). Two key challenges for future rice production are the limitation of water supply and increasing methane emissions associated with global climate change (Zhang *et al* 2011, Prasad *et al* 2017, Li *et al* 2020). In many areas, including the US, irrigation water supplies are consumed at unsustainable rates, leading to economic burden and decreasing yields for producers (Bouman *et al* 2007, Reba *et al* 2017, Boazar *et al* 2020). Additionally, global rice methane estimates range between 36.9 and 67.6 Tg CH_4 yr^{-1}, an uncertainty that complicates the determination of mitigation potentials in the rice production system (Solazzo *et al* 2021, Worden *et al* 2022). Furthermore, the Intergovernmental Panel on Climate Change has indicated that global methane emissions need to be reduced between 37% and 44% to reach scenario targets set in the Paris Agreement (Shukla *et al* 2022). To address increasing rice methane emissions, innovative management practices are needed (van Groenigen *et al* 2013, Zhang *et al* 2016, Moreno-García *et al* 2021, Runkle *et al* 2021).

In the US, rice production is concentrated in the Mid-South (MdS) and California (Cal), each influenced by distinct agronomic and environmental conditions (Singh *et al* 2017, McBride *et al* 2018). The MdS, encompassing Eastern Arkansas, coastal Texas, Louisiana, western Mississippi, and southeastern Missouri, accounts for about 80% of annual US rice production (USDA-NASS, 2021). The MdS also contributes more to national methane emissions due to its larger production area, with Arkansas alone representing 50%–54% of MdS methane emissions from 2005 to 2015 (US Environmental Protection Agency 2021). Rice management practices, such as pre-season flooding, floodwater management, crop rotations, and seeding methods, differ between the MdS and Cal (Hill *et al* 2006, Brodt *et al* 2014). Through adjusted management, producers can modify traditional practices, including floodwater and residue management, to mitigate seasonal methane emissions (Zou *et al* 2005, Anders *et al* 2012, Romasanta *et al* 2017, Reba *et al* 2019).

Because methane emissions are a product of the inundated field environment, alternative irrigation practices can reduce methane by interrupting or removing the sustained flood during the growing season (Xu *et al* 2015). For example, the alternate wetting and drying (AWD) irrigation practice introduces drying events during the growing season (Lampayan *et al* 2015). The introduction of aerobic events can disrupt anaerobic methane production, reducing growing season methane emissions by at least 60% (LaHue *et al* 2016, Runkle *et al* 2019). Additionally, residue management impacts methane production as specific crops can carry larger amounts of field residue, serving as feedstock for methane production during the following growing season (Chidthaisong and Watanabe 1997, Linquist *et al* 2006, Brye *et al* 2016, Belenguer-Manzanedo *et al* 2022). Baseline methane fluxes resulting from various production practices have been synthesized for the MdS and Cal through chamber experiments (Linquist *et al* 2018). Outside of management, the estimated baseline regional flux in Linquist *et al* (2018) also accounts for the variety of clay contents across production areas, where higher clay content may result in lower methane emissions due poor microbial access to organic matter or improved retention of methane within the soil–water matrix (Wang *et al* 1993, Malyan *et al* 2016). The IPCC's tiered system incorporates national or regional data depending on availability, with scaling factors representing management's impact on baseline flux values from national scales (Tier 1), where little information on rice emissions and management is present, to regional (Tier 2) scales, where regional emissions are constrained and unique regional management practices are well-defined (Ogle *et al* 2019). However, further assessment is needed to understand the broader effects of practice adoption. While the current Tier 1 framework considers adjustments for floodwater and residue management, it overlooks regional management variations. Currently, no recognized Tier 2 method exists for estimating methane emissions in US rice, although Tier 2 methods are employed in the Field to Market Alliance's Fieldprint Platform and are being reviewed in the rice section of the revised USDA's Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory (Eve *et al* 2014, Marcos *et al* 2018).

In this work, we examine the potential for the reduction of rice methane emissions in the US through region-specific alternative management, both temporally and spatially. First, we estimate methane emissions from these areas using the IPCC Tier 2 method with regional scaling factors based on synthesized chamber experiments from Linquist *et al* (2018). We compare Tier 2 methane emissions to Tier 1 emissions across the US. Additionally, we compare our estimated emissions to other annual US methane budgets from the US Environmental Protection Agency (EPA) and Food and Agriculture Organization of the UN (FAO). Second, we apply different residue and floodwater management scenarios at the regional and state levels in order to assess the potential to mitigate emissions in the MdS and Cal.

2. Methods

2.1. Data inventory description

The scope of our analysis was limited to the major US rice producing regions in the MdS and Cal. The USDA NASS Cropland Data Layer (CDL) was used to determine which counties or parishes (hereafter referred to as counties) grew rice within each region (USDA-NASS (U.S. Department of Agriculture, National Agricultural Statistics Service) 2022). The two primary data sources for estimating regional methane emissions were soil clay content and cropland classification. Web Soil Survey (WSS) clay content and USDA-NASS CDL information were meshed to generate datasets with a 30 m pixel resolution for MdS and Cal counties from 2008 to 2020 (Boryan *et al* 2011, Soil Survey Staff, USDA-NRCS 2018).

2.2. IPCC Tier 1 methane emissions calculations

The IPCC Tier 1 method required information on floodwater management during and prior to the growing season (Ogle *et al* 2019). We assumed no organic amendments were applied to the soil prior to planting, as the practice is uncommon in both the MdS and Cal. Tier 1 methane emissions were then calculated as:

$$EF_{\mathrm{Tier1}} = EF_{C,1} \times SF_w \times SF_P \qquad (1)$$

where EF_{Tier1} is the estimated flux for a given area in kg CH_4 ha^{-1} d^{-1}, $EF_{C,1}$ is a constant baseline flux of 0.65 kg CH_4 ha^{-1} d^{-1} for the US, SF_w is a scaling factor for irrigation management, and SF_p is a scaling factor for pre-season floodwater management (Ogle *et al* 2019). In line with Ogle *et al* (2019), we assigned a value of 2.41 to SF_P as fields in the MdS and Cal are typically flooded for more than 30 d in the pre-season. We assigned values of 1.00, 0.71 and 0.55 to SF_w to create three different irrigation scenarios representing continuous flooding, single aeration, and multiple aeration, respectively (Ogle *et al* 2019; table 5.12). The assumed season length for Tier 1 emissions in US rice is 139 d (Ogle *et al* 2019).

2.3. IPCC Tier 2 methane emissions calculations

The IPCC Tier 2 method required soil clay content and management information to estimate methane emissions and is based on Linquist *et al* (2018). In both the MdS and Cal, the baseline scenario assumed no organic or sulfur amendments and no deviation from conventional regional seeding practices. In the MdS, the baseline flux represented a continuously flooded, drill-seeded rice field with low residue prior to planting and intentional pre-season flooding. In Cal, the baseline flux represented a continuously flooded, water-seeded field with high residue prior to planting and intentional pre-season flooding. Based on Linquist *et al* (2018), the baseline flux, EF_C was calculated across the MdS and Cal using WSS clay content, C (equation (2)):

$$EF_{C,2} = \left(EF_{SA} - \left[(C - BPC) * C_f\right]\right) / C_P \qquad (2)$$

where $EF_{C,2}$ is the calculated baseline methane emissions rate in kg CH_4 ha^{-1} d^{-1}, EF_{SA} is the seasonal average methane flux in kg CH_4 ha^{-1} d^{-1}, C is the clay content for the given area in percent clay, BPC is a baseline percent clay, C_f is a regionally defined clay factor in kg CH_4 ha^{-1}, and C_P is the length of the cultivation period in days (Linquist *et al* 2018). In the MdS and Cal, EF_{SA} was assigned a value of 194 and 218 kg CH_4 ha^{-1} $season^{-1}$, respectively (Linquist *et al* 2018). For the MdS, BPC, C_f, and C_P were defined as 23%, 6.1 kg CH_4 ha^{-1} $season^{-1}$, and 133 d, respectively (Linquist *et al* 2018). For Cal, BPC, C_f, and C_P were defined as 46%, 8.1 kg CH_4 ha^{-1} $season^{-1}$, and 140 d, respectively (Linquist *et al* 2018). The maximum clay content in each region was limited such that $EF_{C,2}$ could not be negative, and so was set to 54% and 72% for the MdS and Cal, respectively. The minimum clay content used in this study was set to 12% in both regions to match the minimum clay content of studies collected in Linquist *et al* (2018). Clay content values exceeding the maximum or minimum in either region were set to those respective limits.

The Tier 2 EF was calculated for both regions using a similar approach as Tier 1 with an additional scaling factor for residue from Linquist *et al* (2018), (equation (3)):

$$EF_{Tier2} = EF_{C,2} \times SF_w \times SF_P \times SF_R \qquad (3)$$

where EF_{Tier2} is the estimated daily methane emission rate in kg CH_4 ha^{-1} d^{-1} using the Tier 2 approach, SF_w is a scaling factor for irrigation management, SF_P is a scaling factor based on pre-season water management, and SF_R is a scaling factor for residue management at planting. We assigned values of 1.00, 0.61 and 0.17 to SF_w to create three different irrigation scenarios representing continuous flooding, single aeration, and multiple aeration (Linquist *et al* 2018; table 5). Additional scaling factors are described in Linquist *et al* (2018), and include sulfur amendments to soils, cultivar, and seeding method. These factors were not included in the research here due to limited availability of such data at the pixel scale.

For residue management, we applied recommended scaling factors based on the common rotations and practices in the MdS and Cal. The common rotations in the MdS were soybean–rice and rice–rice, and the common rotation in Cal was rice–rice. In the MdS, we assumed low residue at planting, meaning both soybean–rice and rice–rice rotations would have an SF_R equal to 1. In rice–rice rotations, we assumed the remaining residue was reduced through burning or other residue removal practices. In Cal, SF_R had values of 1 for rice–rice rotations as the baseline scenario and burning between seasons is not common. We only estimated emissions for rice grown under baseline conditions or common rotational management, excluding rotations that were outside of these parameters. With the imposed limitation, the area of rice in our defined rotations relative to the total area of rice identified ranged between 93% and 97% annually.

2.4. Management scenarios analysis

We examined two aspects of management to evaluate the methane mitigation potential across different regions: floodwater and residue management. Cumulative reductions were estimated by comparing baseline and adjusted scenarios across all pixels in the MdS and Cal from 2008 to 2020. Aeration impacts were assessed using SF_w scaling factors (no, single, or multiple events) to simulate adjusted scenarios in both regions. To determine residue management impacts, we limited our analysis to the MdS. Because most of the Cal rice production area was developed from converted wetlands, current practices do not typically allow for rotations outside of continuous rice due to poor drainage and dedicated rice production infrastructure (i.e. zero-grade slopes, permanent levees, etc.). Given the limited potential for rotations in Cal's rice production setting, residue at planting remains consistently high. Thus, we limited analysis to the MdS. High-residue treatment was evaluated by applying a scaling factor ($SF_R = 2.16$) to pixels where rice was grown after rice from the previous year, assuming no residue reduction between seasons. Mitigation potential was calculated as the difference between the high-residue (i.e. no residue reduction) scenario and the default residue management scenario.

2.5. US emissions inventories for rice cultivation

The US EPA methane emissions estimates for rice cultivation as well as production area estimates were taken from tables 5.11 and 5.12 in the US EPA inventory report encompassing the 1990–2020 growing seasons (US Environmental Protection Agency 2021). The US EPA methane emissions were calculated using a combination of Tier 1 and Tier 3 methods based on the availability of relevant data for given regions in the US (Annex 3; US Environmental Protection Agency 2021). In the Tier 3 approach for the 2015–2020 growing seasons, the DAYCENT model estimates continuous daily methane fluxes across large agro-ecoregions, which are then scaled to national level emissions using the national resources inventory (NRI) (Nusser and Goebel 1997, Parton *et al* 1998). The EPA inventory assumed continuously flooded irrigation with winter flooding in both the Tier 1 and Tier 3 estimates. Production area estimates were not available following 2015. Because US EPA methane emissions were reported in converted units of MMT CO_2 equivalents using global warming potential (GWP), an established means of standardizing different GHGs into one CO_2-equivalent, we converted to units of CH_4 using a GWP of 25, which is consistent with the US EPA inventory approach (table ES-1; US Environmental Protection Agency Chapter 1, 2021). We also collected emissions and production area data from the FAOSTAT database for US rice cultivation for the 2008–2020 growing seasons (FAOSTAT 2009). The FAOSTAT emissions were estimated using a Tier 1 approach (Tubiello *et al* 2013). We compared cumulative seasonal emissions across methods and inventories using all available data. We compared seasonal flux estimates as well, but the US EPA amount was limited to using data between 2008–2015 due to the lack of production area. We used ordinary least-squares linear regression to examine the relationship between differences in estimated emissions between inventories to differences in their respective land areas as well as WSS clay content.

3. Results

3.1. Cumulative Tier 1, Tier 2, US EPA, and FAO methane emissions

Cumulative growing season methane emissions for the MdS and Cal were estimated between 2008 and 2020 (table 1). On average, the regional Tier 2 emissions were 63% greater than the national Tier 1 emissions across the 2008–2020 growing seasons. Comparing Tier 1 to Tier 2, MdS had the greatest difference in terms of cumulative and seasonal emissions. Additionally, the Tier 1 and Tier 2 cumulative emissions were on average approximately 64% and 42% lower, respectively, than the US EPA cumulative emissions across the 2015–2020 growing seasons. Similarly, the Tier 1 and Tier 2 cumulative emissions were 43% and 7% less than FAO estimates across the 2008–2020 growing seasons. Because the Tier 1 methodology utilizes a single baseline flux estimate across both regions, the area-normalized emissions did not vary year-to-year for FAOSTAT or Tier 1.

Given that the Tier 2 method was consistently lower than the US EPA estimates across all seasons, we examined potential sources of error. Between 2008 and 2015, the area derived from Tier 2 was between 26% and 46% lower compared to US EPA production area estimates annually. However, there was no significant ($p > 0.05$) relationship between the differences in production area and cumulative flux between Tier 2 and US EPA between 2008 and 2015. We also examined the impact of limiting crop rotations using the ratio of Tier 2 rice area to total rice area identified by the CDL year-to-year. Even so, there was not a significant ($p > 0.05$) relationship between the differences in Tier 2 and US EPA emissions to the ratio of Tier 2 rice area to total CDL rice area. Thus, the differences in US EPA and Tier 2 estimates could not be explained by annual differences in production area nor the selection criteria for Tier 2 production area.

Between 2008 and 2015, MdS had higher cumulative production area and emissions compared to Cal in both Tier 2 and US EPA estimates (figure 1). The differences in Tier 2 and EPA emissions and production area were more pronounced in the MdS region compared to Cal. On average, the US EPA production area was 59% larger in the MdS and 27% larger in Cal compared to Tier 2 estimates. When considering both regions, the average Tier 2 production area was 34% lower than the EPA estimate and 9% lower than the FAOSTAT estimate.

3.2. Implications of aeration and residue management on methane mitigation potential in the US MdS and Cal

Applying multiple aeration events to the entire production area in both the MdS and Cal using the Tier 2 approach resulted in reductions ranging from 0.26 to 0.38 Tg CH_4 yr^{-1}. Across the cumulative 2008–2020 growing seasons, the MdS region had greater mitigation potential (table 2). In Tier 1, both regions had the same mitigation potential per unit production area, while Tier 2 indicated that the MdS had a higher mitigation potential per unit production area. These differences were expected as Tier 1 relied on a fixed baseline flux for both regions, whereas Tier 2 had unique baseline flux values and accounted for clay content scaling. Tier 2 application of single and multiple aeration resulted in an average reduction of 0.14 CH_4 yr^{-1} and 0.31 Tg CH_4 yr^{-1}, respectively. Tier 1 application of single and multiple aeration resulted in an average reduction of 0.07 CH_4 yr^{-1} and 0.10 Tg CH_4 yr^{-1}, respectively.

Mitigation potential across regions was significantly linked to production area and clay content,

Table 1. Cumulative methane emissions for the 2008–2020 growing seasons for the Mid-South (MdS) and California (Cal) using the Tier 1 and Tier 2 methodology, as well as the US EPA (2021) and FAOSTAT (2009). Error denoted by ± is the standard error of the annual dataset with the lower and upper bounds at the 95% confidence interval shown in parentheses.

Method	Location	Period	Scenario	Mean cumulative emissions, Tg CH_4 season^{-1}	Mean seasonal flux, kg CH_4 ha^{-1} season^{-1}
Tier 1	MdS	2008–2020	Baseline	0.18 ± 0.026 (0.17–0.20)	217.74 ± 0.000
	Cal	2008–2020		0.04 ± 0.004 (0.04–0.05)	217.74 ± 0.000
	MdS + Cal	2008–2020		0.23 ± 0.027 (0.21–0.24)	217.74 ± 0.000
Tier 2	MdS	2008–2020	Baseline	0.32 ± 0.038 (0.29–0.34)	317.73 ± 7.115
	Cal	2008–2020		0.05 ± 0.005 (0.046–0.052)	199.86 ± 8.255
	MdS + Cal	2008–2020		0.37 ± 0.039 (0.34–0.39)	294.28 ± 4.480
US EPA	MdS + Cal	2008–2020	Reported	0.63 ± 0.05 (0.60–0.66)	N/A
		2008–2015	Reported	0.63 ± 0.06 (0.57–0.69)	404.45 ± 26.430
FAOSTAT	MdS + Cal	2008–2020	Reported	0.40 ± 0.05 (0.36–0.43)	350.00 ± 0.000

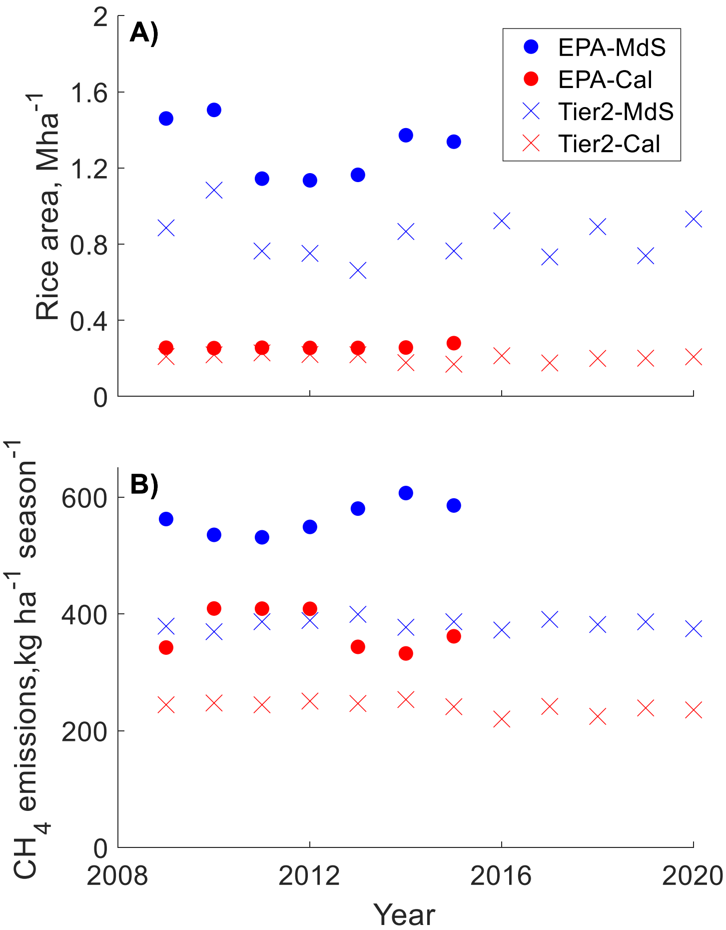

Figure 1. Comparison between (A) MdS and Cal rice area and (B) seasonal methane emissions from this study's Tier 2 approach and the available US EPA estimates.
Note: The US EPA dataset does not have production area estimates available for growing seasons following 2015.

where lower median clay content and greater production area corresponded to greater amounts of reduction in both the MdS and Cal (figure 2). For reference, approximately 75% and 98% of the production areas in MdS and Cal were within the imposed clay content limits, respectively, when no limits on clay content were imposed from the Tier 2 methodology. Annually, median clay content in the MdS was also between 11% and 37% lower than the Cal region. At the county level across all years, median clay content across the combined regions was able to significantly ($p < 0.05$) explain 40% of the variance in mitigation potential while production area was able to explain 76% of the variance in mitigation potential.

To explore the influence of clay content limitations in the Tier 2 methodology, we examined the

Table 2. Mean and standard deviation of annual production area and CH_4 mitigation potential from multiple aeration events when compared to the baseline production scenario during the 2008–2020 growing seasons. Parentheses indicate the lower and upper bounds at the 95% confidence interval for the annual reduction estimates.

Method	Region	Mean annual rice area, Mha	Mitigation potential, Tg CH_4 yr^{-1}	Area-normalized mitigation potential, kg CH_4 ha^{-1} yr^{-1}
Tier 1	MdS	0.83 ± 0.118	0.08 ± 0.01 (0.069–0.084)	98.00 ± 0.00
	Cal	0.20 ± 0.02	0.02 ± 0.00 (0.019–0.021)	98.00 ± 0.00
Tier 2	MdS	0.83 ± 0.118	0.26 ± 0.03 (0.244–0.284)	317.73 ± 7.12
	Cal	0.20 ± 0.02	0.04 ± 0.00 (0.038–0.043)	199.86 ± 8.26

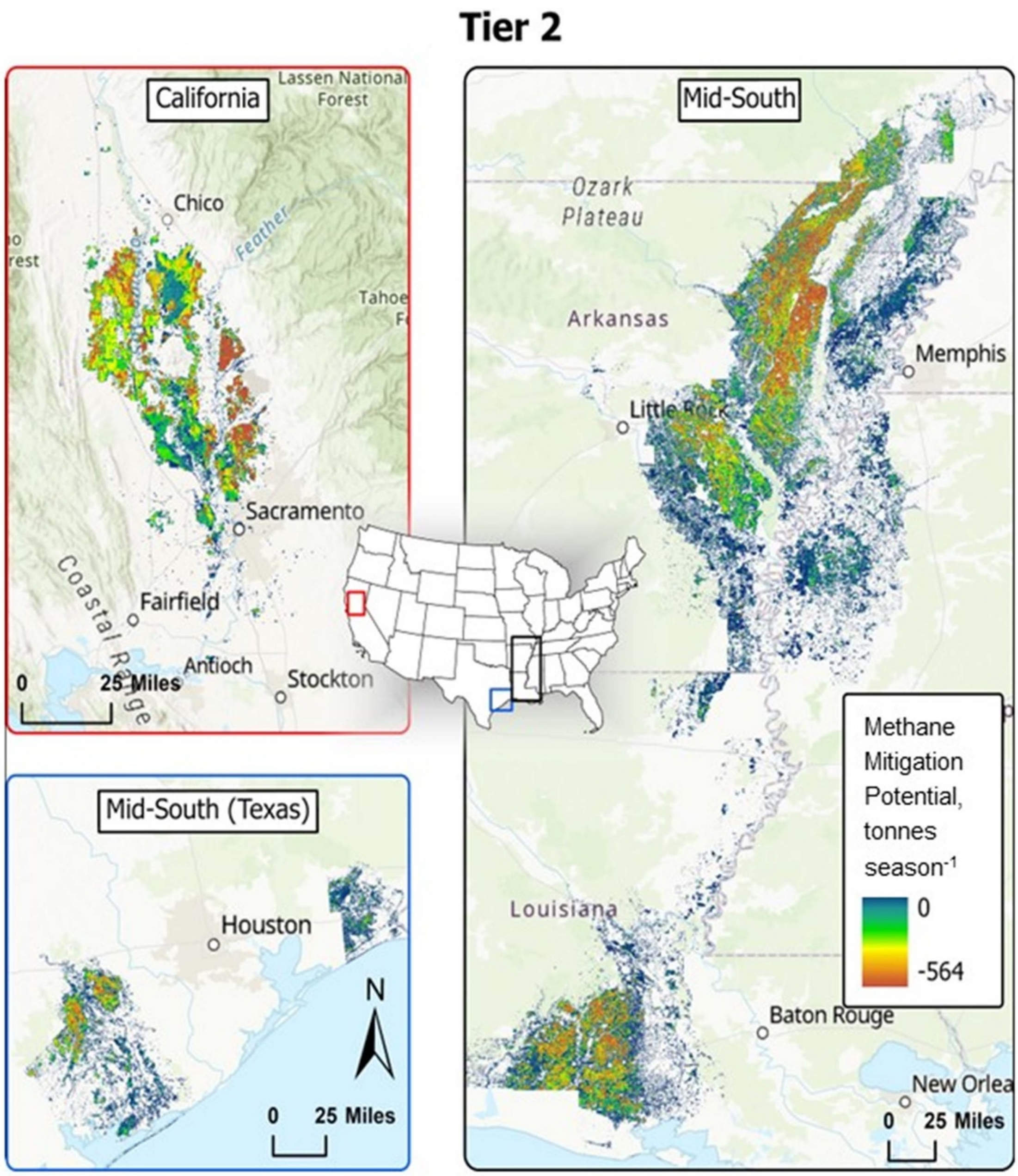

Figure 2. Distributed methane mitigation potential using multiple aeration in MdS and Cal during the 2008–2020 growing seasons. Mitigation potential is shown in tonnes CH_4. Values are reported in tonnes CH_4 yr^{-1}.

relationship between mitigation potential, production area, and the fraction of clay content falling outside the specified limits. From 2008 to 2020, approximately 23% of the MdS production area exceeded the Tier 2 maximum clay content, while 7% fell below the Tier 2 minimum. In the Cal region, 2% of production area fell below the regional minimum clay content while no production area exceeded the regional

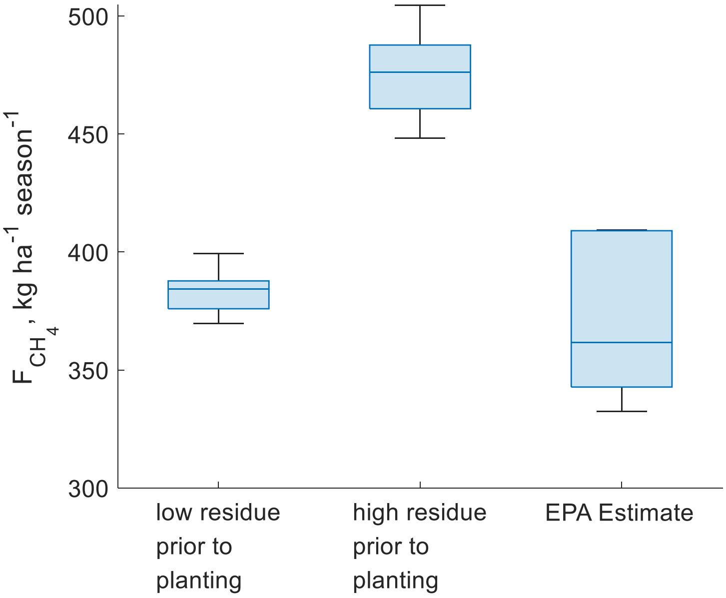

Figure 3. Comparison of 2008–2020 seasonal MdS methane flux rates for Tier 2 scenarios with low and high residue at planting applied to rice–rice rotations and added to soybean–rice rotations. The EPA estimates are added for context, where residue removal is not captured. For each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the maxima and minima of each box.

maximum clay content. Analyzing the annual ratios of clay contents within, over, and under the Tier 2 limits, we found no significant relationships ($p > 0.05$) with differences in Tier 2 methane and EPA emissions across both individual and combined regions. Therefore, although the clay content limits likely influenced Tier 2 estimates, we were still unable to explain the discrepancies between Tier 2 and the EPA inventory using the clay content constraints imposed by the Tier 2 methodology.

Under the adjusted residue management scenario in the MdS, rice–rice rotations without residue removal led to a 24% average increase (0.08 Tg CH_4 yr^{-1}) in emissions compared to baseline residue management (figure 3). This increase was concentrated in counties with the highest level of rice–rice rotations year-to-year.

4. Discussion

4.1. Tier 1 and Tier 2 US rice emissions comparisons to other inventories

Our regional Tier 2 methane emissions were greater than national Tier 1 emissions over the same production area. In our comparisons to the US EPA and FAOSTAT inventories, both the Tier 1 and Tier 2 methane emissions were consistently lower across all growing seasons. When relating the differences in modeled and observed fluxes between our Tier 2 estimates and the US EPA inventory, we found no significant link between the differences in emissions and the amount of production area within the clay content and rotational criteria imposed in this study. By limiting Tier 1 and Tier 2 estimates to common growing practices in the regions, we acknowledged some degree of underestimation since the percentage of rice pixels in common rotation ranged from 93% to 97% across the combined MdS and Cal regions.

While there is yet no Tier 2 based inventory, another study indicated that Tier 3 DAYCENT emissions were typically greater compared to Tier 1 (Wang *et al* 2018). In that study, management assumptions (e.g. all rice being continuously flooded, no residue at planting) were emphasized to create potential discrepancies between the regional and national scale. Despite the disagreement in estimates between models and inventories, reducing uncertainty by incorporating estimates from multiple methodologies is still beneficial (Liu *et al* 2023). The advantage of the Tier 2 approach applied in the US is the ability to leverage differences in management and methane production potential to target mitigation efforts. Because the Tier 1 approach assumes every rice field to have the same methane production potential, targeted approaches for methane reduction become more difficult. When studies have identified how impactful low-cost management practices can significantly reduce methane production in rice, the question of where to best apply those practices is crucial (Wang *et al* 2023a).

Few studies have attempted to quantify the regional contributions of the MdS and Cal regions to cumulative US rice methane emissions. Some papers have leveraged inventories like those provided by the US EPA to generate distributions of methane flux across the US, but there are few studies focused only on rice or applying process-based steps to account for differences in growing practices (Miller *et al* 2013, Maasakkers *et al* 2016). Our estimates using the Tier 2 methodology were similar to other large-scale efforts to estimate global rice methane emissions while accounting for differences in regional practices and environments (Yan *et al* 2009).

4.2. Driving factors for regional methane emissions and mitigation potential

In the IPCC Tier 2 method, clay content played the largest role in determining the magnitude of methane emissions and mitigation potential in both the MdS and Cal. Through comparisons of the median clay content to reductions normalized by production area, counties with rice planted in lower clay contents had greater potential reductions compared to rice planted in counties with greater clay content across the 2008–2020 growing seasons. Because MdS area typically had lower clay contents, mitigation potential was greater in those production areas. This information can easily be leveraged alongside other tools to identify areas where mitigation practices are likely to have the largest impact across a longer (>10 years) time period.

Through our analysis, we observed the potential benefits of aeration in traditionally continuously flooded rice systems. The introduction of aeration events can be applied to most systems, allowing rotational management and aeration to be used together to reduce emissions (Brye *et al* 2016, Tsiboe *et al* 2018). However, our analysis of residue management did not consider the impacts of residue removal activity on the cumulative GHG emissions balance. For instance, burning post-harvest residue has been shown to decrease methane emissions, but it should be weighed against the CO_2 released to the atmosphere and decreased air quality (Bossio *et al* 1999, Fitzgerald *et al* 2000, Qu *et al* 2012, Rogers *et al* 2014). Still, residue could be removed and assimilated into other biologically driven economies used to drive energy generation and useable byproducts, which are beneficial (Liu and Rajagopal 2019). To advance the Tier 2 approach, prioritizing the inclusion of residue and floodwater management data is crucial. Tillage and burning data could help identify low and high residue areas for the following growing season (McCarty *et al* 2007, Hively *et al* 2018, Wang *et al* 2023b). Additionally, efforts to identify production areas and optimize irrigation management during the growing season would enhance the application of the Tier 2 approach at the field scale (Huang *et al* 2021, Liang *et al* 2021).

4.3. Uncertainty among modeled and inventory methane estimates

Comparing Tier 2 to EPA and FAOSTAT estimates, Tier 2 emissions were generally lower. Challenges in the study arose from variations in estimated production areas between Tier 2, EPA, and FAOSTAT. While our approach directly derived area from the CDL, other Tier 2 implementations relied on predetermined national production area estimates. Scaling factors were then applied to the estimated portion of the production area adopting specific practices (e.g. 40% practicing single aeration). Previous studies have emphasized the difficulty in determining production area and practice distribution in different rice-producing regions globally (Peng *et al* 2016, Zhang *et al* 2016).

Despite the differences in production area between Tier 2 and the US EPA, we found no significant relationship between production area and emissions variations. We limited the production area to pixels representing common rotations in each region, utilizing regionally developed scaling factors. However, the ratio of rice grown in rotation to total rice area from the CDL did not significantly correlate with the differences in fluxes between Tier 2 and US EPA emissions. Studies comparing NRI and CDL have reported estimated area differences ranging from 3% to 7% based on landcover type for identified crops (Hendricks and Er 2018, Wang *et al* 2022). Others have also identified underestimation within CDL-derived cropland areas, where improving methodology has resulted in reduced bias over time when comparing the CDL to NRI (Johnson 2013, Lark *et al* 2017). Although discrepancies exist, the CDL and other remote sensing platforms provide valuable data continuity and finer spatial resolution compared to survey-based sources like NRI, enabling representation of spatial patterns. Using the Tier 2 approach, we were able to visually represent mitigation potential in different regions of the US, which has many potential implications on the implementation of sustainable growing practices. For example, such mapping could be used to identify which regions could benefit most from practices like introducing aeration while also weighing against other factors of adoption (Nelson *et al* 2015, Sander *et al* 2017).

Another challenge of the Tier 2 approach was the limitation of clay content for scaling baseline flux values. In our survey, 75% and 98% of the pixels in the MdS and Cal, respectively, fell within the clay limits. Estimations of emissions could be affected by underestimation or overestimation of clay content based on the applied limits introduced in Linquist *et al* (2018). Emissions would likely be underestimated when clay content fell below the 12% limit, as it was forced to a higher value. Similarly, overestimated emissions would result from clay content exceeding regional maxima. In the MdS, where 24% of the production area exceeded clay content limits, the Tier 2 approach likely overestimated emissions if the relationship between clay content and methane emissions holds true across the clay spectrum. Thus, establishing a relationship between a more representative range of clay content and Tier 2 baseline flux could enhance performance. The current Tier 2 scaling method assumes that clay content can only explain 25% and 40% of baseline fluxes in the MdS and Cal, respectively (Linquist *et al* 2018; figure 2). However, global studies have shown a less clear relationship between clay content and soil organic carbon, suggesting that the linear relationship in equation (2) may oversimplify the methane production process under different clay contents (Liao *et al* 2009, Li *et al* 2016, Liu *et al* 2021). Additionally, scaling factors for aeration were assumed to be equal across regions, based on a reduction of 83% determined from a limited number of observations (Linquist *et al* 2018). More recent studies have indicated varying seasonal methane reductions for US rice using AWD ranging from 44% to 71% across different measurement methods (Balaine *et al* 2019, Fertitta-Roberts *et al* 2019, Runkle *et al* 2019). Therefore, improving the Tier 2 method's applicability in the MdS and Cal could involve expanding the number of studies and locations where aeration practices like AWD are being applied.

5. Conclusions

In this study, we estimated annual methane emissions from rice cultivation in two distinct US production regions from 2008 to 2020. The Tier 2 methodology resulted in higher emissions estimates compared to Tier 1 for the same production area. When compared to national inventories, Tier 2 underestimated methane emissions by up to 48%. Differences in production area, crop rotation, and clay content did not significantly account for the disparities between Tier 2 emissions and other national inventories. Although the Tier 2 method requires further development, it offers a simple approach to constrain methane budgets on large spatial scales and incorporate regional practice differences. Enhancing the utility of the Tier 2 methodology necessitates better representation of field-scale methane estimates and the impacts of alternative management in both regions. Additionally, this study demonstrated how the method can identify areas of relative importance for methane mitigation potential. Therefore, while improvements are needed to enhance methodology performance and adoption, the Tier 2 method remains valuable for assessing mitigation potential across diverse regions.

Data availability statement

The data cannot be made publicly available upon publication because the cost of preparing, depositing and hosting the data would be prohibitive within the terms of this research project. The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This project was supported in part by an appointment supported by the Delta Water Management Research Unit and the Sustainable Water Management Research Unit within the USDA Agricultural Research Service (ARS), administered by ORAU through the U.S. Department of Energy Oak Ridge Institute for Science and Education (ORISE). Benjamin Runkle was supported by NSF CBET CAREER Award 1752083 and NASA CMS grant 80NSSC21K1002.

Conflict of interest

The authors declare no conflicts of interest in the conduction of this study and submission of this work.

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