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RESEARCH ARTICLE

Quantifying methane emissions in major rice growing areas of Tamil Nadu using remote sensing and land surface temperature model

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Abstract

Rice (*Oryza sativa* L.) is cultivated in diverse environments, contributing significantly to global methane (CH_4) emissions, accounting for approximately 12% of total methane emissions worldwide. With the demand for increasing rice production, methane emissions from rice fields continue to rise. This underscores the need for reliable strategies for estimation and mitigation strategies. This study aims to estimate methane emissions from rice fields of the Cauvery Delta region of Tamil Nadu using remote sensing data. Sentinel 1A Synthetic Aperture Radar (SAR) data was used to delineate rice areas and assess agronomic flooding, while Land Surface Temperature (LST) derived from MODIS satellite data was used to estimate methane emissions. The semi-empirical methane emission model was employed to estimate methane flux based on temperature-related factors and rice area. The spatial methane estimates derived from the LST-based method were compared with field observations. The results showed that during the Kharif and Rabi seasons of 2023, a total of 169679 and 356270 ha of rice area were delineated, respectively. The total methane emissions of 7.16 and 17.09 Gg were estimated for both seasons, respectively. The agreement between estimated and observed methane for both seasons was 84.74% and 87.52%, respectively. This study provides an efficient empirical method for estimating methane emissions across large areas and highlights the need for continued monitoring and the development of mitigation strategies to reduce methane emissions from rice cultivation.

Keywords

LST; methane emission; rice area; radar; static closed chamber; synthetic aperture

Introduction

Rice (*Oryza sativa L.*) is a unique crop that is grown in diverse environments from the wettest to the driest areas. Under submerged conditions, rice plants develop lysigenous aerenchyma in their roots, facilitating the exchange of oxygen (O_2) and greenhouse gases (GHGs) between the aerial parts of plant and the rhizosphere (1). Methane, from rice cultivation is a notable contributor to global GHG emissions, accounting for approximately 12% of total methane emissions and around 1.5% of total GHG emissions worldwide (2). The Inter-governmental Panel on Climate Change (IPCC) estimates that over the next 100 years, the warming effect of methane will be 25 to 30 times stronger than CO_2 per unit of weight (3). The latest IPCC report states that there is more than a 50% chance that global temperature rise will reach or surpass 1.5 °C between 2021 and 2040 under high greenhouse gas emissions (2). As the population grows, the demand for food production rises, leading to increased rice cultivation and consequently higher methane emissions. Therefore, estimating and monitoring the global methane emissions from rice fields is essential for developing effective mitigation strategies. Estimating methane emissions from rice fields involves direct measurement techniques, modeling approaches and remote sensing technologies. The choice of method often depends on the required accuracy, available resources and specific research objectives (2).

Field level methane from rice fields was estimated directly through the most common technique called the closed chamber method, allowing for real-time monitoring of methane emissions (4). This conventional method of methane estimation is tedious, time-consuming, laborious and impractical for estimating emissions over large areas. In this context, remote sensing technology offers a practical solution for assessing and monitoring methane emissions over large areas. Accurate spatial methane estimation from rice fields is crucial for methane inventory development and the formulation of mitigation strategies. Accurate estimation of methane emission rates from rice fields requires precise data on rice cultivation areas and the timing of agronomic flooding.

Sentinel 1A Synthetic Aperture Radar (SAR) data was used to delineate the rice area. Microwave sensors, which are sensitive to biophysical parameters, operate in the microwave portion of the spectrum and can acquire data day and night, regardless of weather conditions (5). MAPscape-RICE is a fully automated software (6), which identifies and classifies the rice crops using backscatter coefficients (7). The software uses VH polarized time-series data to retrieve temporal backscatter values (5). The Synthetic Aperture Radar (SAR) data was used to derive rice area and agronomic flooding days in this study (8). Land Surface Temperature (LST) derived from MODIS satellite data was used to calculate methane emission rates from rice fields.

Materials and Methods

Study area

The most extensive rice-grown regions of Tamil Nadu are the Cauvery Delta regions including Thanjavur, Thiruvarur, Nagapattinam and Mayiladuthurai districts, which were selected as the experimental areas during *Kharif* (May-August 2023) and *Rabi* (September-February 2023) seasons (Fig. 1). The total geographical area of these districts is 14.47 lakh ha, dominated by alluvial soil, with continuous irrigation facilities available throughout the crop growth, which supports the submerged conditions necessary for rice cultivation and methane emission studies.

Satellite data used

Sentinel 1A SAR satellite data is collected by a microwave satellite launched by the European Space Agency (ESA). It collects data throughout day and night periods under all weather conditions in dual polarization (VH and VV) with a temporal resolution of 12-day intervals. The VH polarization has an advantage in characterizing rice crops and growth compared to VV polarization (8). The data were downloaded for *Kharif* and *Rabi* seasons from May 2023 to February 2024 every 12 days.

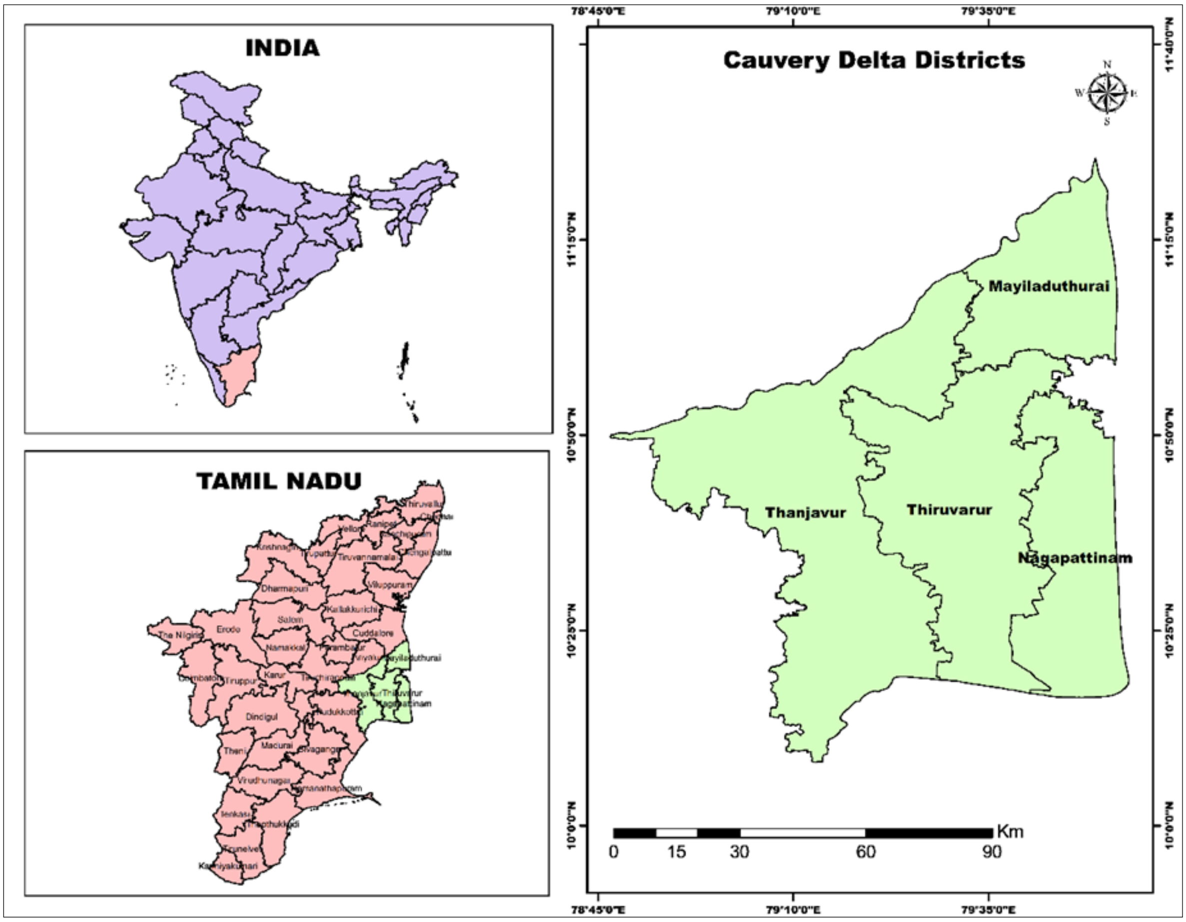

Fig. 1. Location map of study area.

The MODIS instrument provides high radiometric sensitivity (12 bit) across 36 spectral bands, with wavelength ranging from 0.4 µm to 14.4 µm and covers the earth's surface every 1 to 2 days. For this study, MODIS data with a 500 m resolution and 8-day composite was acquired between May 2023 and February 2024 to monitor LST for methane emission estimation. LST was calculated using the bands 31 (10.28-11.72 µm) and 32 (11.78-12.28 µm). The specific thermal infrared (TIR) bands were chosen for calculating LST because they are sensitive to the thermal emissions of the earth's surface and are particularly suited for capturing variations in temperature.

Rice area estimation

The MAPscape-RICE software is a fully automated processing chain module that is used to get radar backscatter coefficient (σ°) values from multi-temporal SAR GRD data (6). Basic processing includes Strip mosaicking, Co-registration, Time-series speckle filtering, Terrain geocoding, radiometric calibration and normalization, Anisotropic Non-Linear Diffusion Filtering (9) and Removal of atmospheric attenuation. The multi -temporal stack of images was analyzed through a rule-based rice detection algorithm in MAPscape-RICE. A prior knowledge of study area and field level agronomic practices such as rice maturity, duration and crop practices is required for the temporal evolution of σ°. The temporal signature which depends on both frequency and polarization, reflects crop practices and duration, making it useful for monitoring rice fields. The parameters for the rules need to be adapted to agro-ecological zones, agronomic practices and rice calendar (10). Six parameters were computed based on the temporal signature of σ° values in the monitoring fields, including minima and maxima of mean σ° values; the maximum of the minimum σ° values; the minimum and maximum of the range of σ° values across fields; and the range of σ° values in the monitoring fields. The value of the six temporal features from the monitoring locations was used to guide the choice of the six parameter values (8). These six statistics concisely characterize the key information in the rice signatures of the observed fields, and each one relates directly to one parameter.

Spatial methane estimation

The MODIS data was geo-referenced and converted the projection to Geo Lat/Long (WGS 1984). The scale factor and temperature conversion were carried out to derive LST.

LST is one of the critical parameters for studying methane emissions. An empirical model was developed to estimate methane emissions (3). T factor is a temperature-related factor that models the change in methanogenic activity as a function of temperature (11). The field experiments showed that the optimal temperature for methanogenic activity ranged from 30 ˚C to 40 ˚C (12). The basic processing of MODIS data involves scaling and conversion of the data to compute the T factor (13). Methane emission from rice growing wetland ecosystem was calculated as shown in Eqn. 1.:

$$ECH_4 = E_{obs} \times F_t \times A \qquad (1)$$

where, E_{obs} is the observed methane flux from the paddy, F_t is temperature, A is the paddy field area.

T factor is defined as follows (12):

$$Ft = \frac{F(Ts)}{\overline{F(Ts)}} \qquad (2)$$

where,

$$F(Ts) = \frac{e^{0.334(Ts-23)}}{1+e^{0.334(Ts-23)}} \qquad (3)$$

In Eqn. 3, Ts is the temperature in ˚C, calculated for each pixel using the constant emissivity method. $\overline{F(Ts)}$ is the mean of F(Ts) over land. The methodology for estimating spatial methane emission is given in Fig. 2. The global warming potential (GWP) of methane over a 100-year period (CH_4 - 28 times) was calculated using the following formula.

$$GWP = CH_4 \times 28 \qquad (4)$$

Field level methane estimation

To estimate field level methane emissions, 30 fields were selected across the study area for monitoring and validation. The closed chamber method is the most common technique used to measure the methane concentration from agricultural fields, allowing for real-time monitoring of methane emissions (4). Many studies have measured CH_4 emissions from the field through the closed chamber method (14, 15). The gas collection chambers were made from Plexiglass/ acrylic sheets, with a thickness of 3-5 mm and dimensions of 60 cm long × 40 cm wide × 100 cm high to accommodate the rice plants. Two fans powered by a 12 V battery were used in the chamber to ensure well-mixed air during sampling, along with a gas sampling port to collect gas samples (14). The chamber was placed in the field covering 3-4 rice hills for gas sampling. Gas samples were collected at 0 and 30 min after chamber closure using a 50 mL syringe attached to a stopcock, and then transferred to 20 mL glass vials (15). The CH_4 emissions concentrations were analyzed in the laboratory by Gas Chromatography (GC). It is a powerful analytical technique used to separate and analyze components within a gaseous mixture. GC (Shimadzu GC-2014, Japan) with a Flame Ionization Detector (FID) was used for methane detection (16). The CH_4 flux was calculated using Eqn. 5 and seasonal methane emission from the field was calculated based on agronomic flooding.

$$f = \frac{V}{A} \times \frac{\Delta C}{\Delta T} \qquad (5)$$

where,

f - rate of greenhouse gas emission (mg m^{-2} h^{-1}),

V - volume of the chamber above soil (m^3),

A - Cross section of the chamber (m^2),

ΔC - concentration difference between zero T times (mg cm^{-3}),

ΔT - time duration between two sampling periods (h).

Statistical analysis

The Error matrix and Kappa statistics evaluated the rice area classification accuracy. It is a comparison of the classified rice area against ground truth data. Around 200 ground truth points were collected for the validation purposes. Of those 200 points, 150 rice points were collected from the rice fields and the remaining 50 non-rice points were collected from land cover classes other than rice. The accuracy measures including overall accuracy, producer's accuracy, user's accuracy and kappa value are calculated from the error matrix (17).

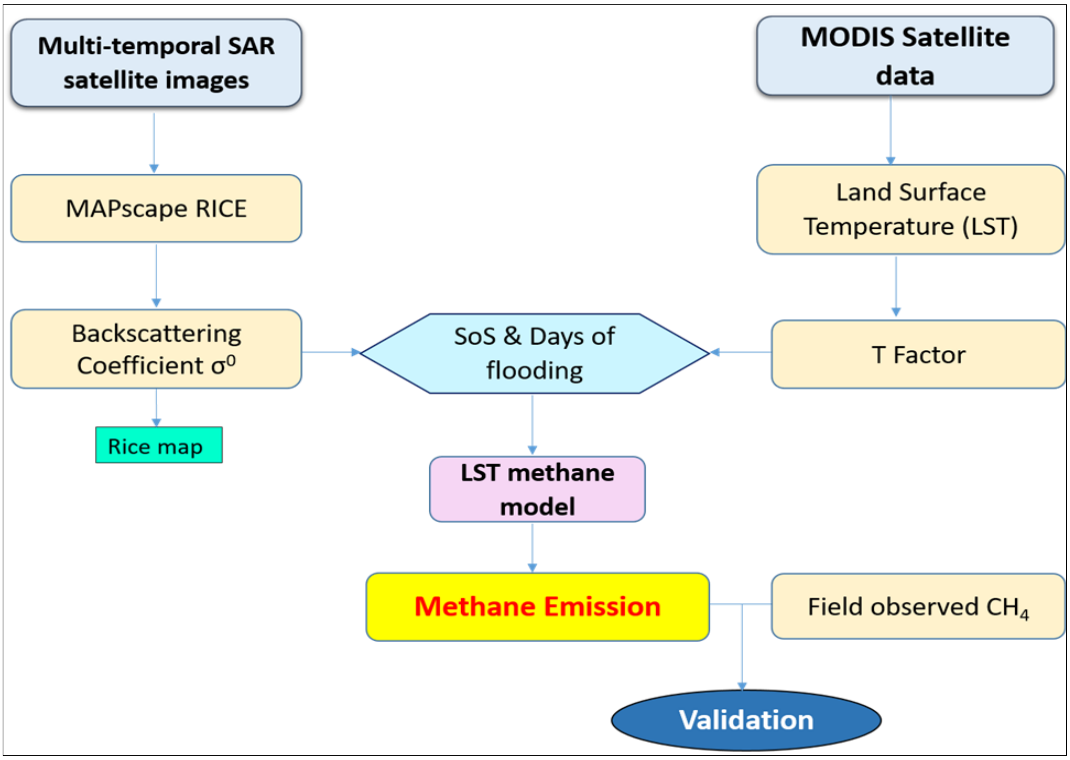

Fig. 2. Flow chart depicting the methodology to estimate rice area and spatial methane emission.

The spatial methane emission estimated from the LST based empirical model has been validated with actual methane emission observed from the rice field using a closed chamber. An analysis of the degree of coincidence between estimated and observed values was carried out using R^2, Root Mean Square Error (RMSE), Normalized Root Mean Square Error (NRMSE) and agreement %.

Results and Discussion

Radar backscattering coefficient values differ from crop to crop and for the same crop in different ecosystems (18). The backscattering coefficient helps in determining the water retention and soil structure of the field. Identifying the start of the growing season is essential for distinguishing crop types, after which the crop's radar backscatter signature is tracked to monitor its growth. The temporal signature for rice crops was derived from processed BSQ (band sequential) stack. The rice crop was identified by its backscattering signature from the multi-temporal dB stack. During the initial crop growth stage, the backscattering dB value was very low and once the crop started growing, it increased and reached a maximum at flowering. Subsequently, it decreased, which denoted the crop maturity (5). This growth pattern was used to identify and delineate rice areas. The signature curve showed an increase in backscattering during the seedling to vegetative stage of the crop and a progressive increase in the vegetative to panicle development phase followed by a decline at the maturity stage. The multi-temporal stack of terrain-geocoded σ° images of Sentinel 1A, acquired from 5th May 2023 to 25th February 2024 at 12-day intervals, were given as input to a rule-based rice detection algorithm. The backscatter signature of rice showed a minimum dB value at agronomic flooding that increases gradually, peaks at the maximum tillering to the flowering stage and starts to decline at maturity (Fig. 3). In *Kharif* and *Rabi* seasons, the dB values (-20.99 and -20.12 dB) were minimum at the start of the season due to agronomic flooding and the maximum dB values (-16.47 and -16.15 dB) were attained at maturity stage.

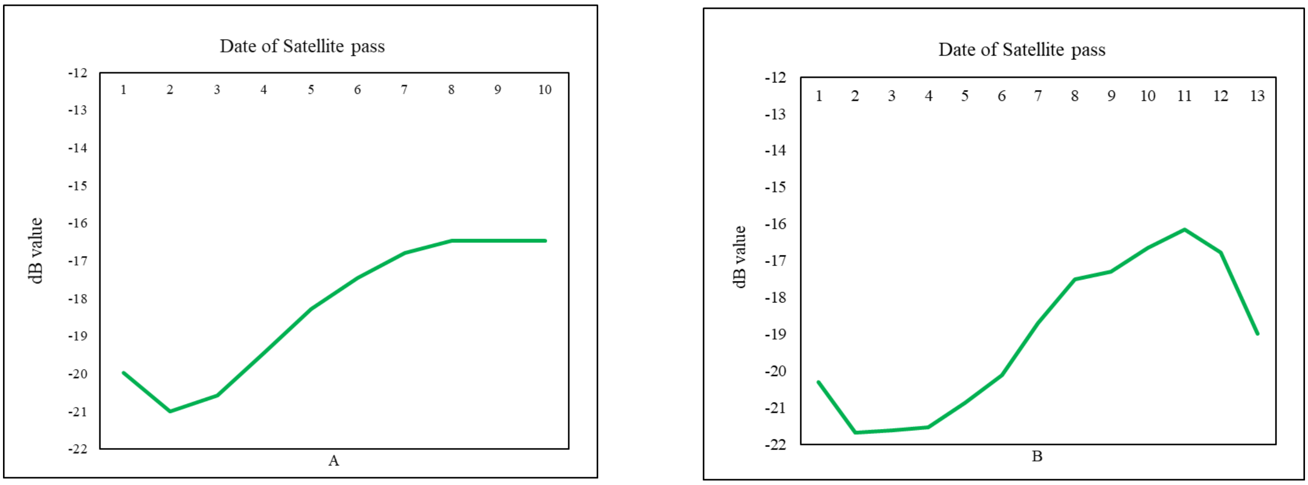

Fig. 3. Mean temporal dB curve for rice crop A *Kharif* B *Rabi*.

Rice area maps and statistics for the study area were derived using multi-temporal imagery of Sentinel 1A (Fig. 4 and Table 1). In the study area, a total of 169679 ha of rice area were delineated during *Kharif* season 2023 from the multi-temporal Sentinel 1A SAR data. This was done through a parameterized classification integrating multi-temporal features. Thanjavur recorded the highest area of about 77795 ha, followed by Thiruvarur, Mayiladuthurai and Nagapattinam with an area of 50756 ha, 24747 ha and 16381 ha, respectively. Similarly for *Rabi* 2023, a total of 356270 ha of rice area was delineated in the Cauvery Delta region. Among the districts, Thiruvarur recorded the highest area of 141456 ha followed by Thanjavur, Mayiladuthurai and Nagapattinam with 120923 ha, 50640 ha and 43251 ha, respectively.

In total, 200 ground truth points were randomly collected during the crop growing season in the study area for both seasons to validate the results. The accuracy of the rice area map was assessed through the confusion matrix using the ground truth points to classify rice and non-rice pixels (19). In *Kharif* and *Rabi*, rice points were classified with an accuracy of 94.7% and 96.0%, while non-rice points were classified with 86.0% and 90.0% accuracy (Table 2). The overall accuracy of the rice area map was 92.5% and 94.5% with an average reliability of 89.8% and 92.4%, respectively. The Kappa Coefficient was found to be 0.85 and 0.89, indicating good accuracy levels of the products.

Table 1. District-wise rice area for Cauvery Delta region

Districts	***Kharif*** **Rice Area (ha)**	***Rabi*** **Rice Area (ha)**
Thanjavur	77796	120923
Thiruvarur	50756	141456
Mayiladuthurai	24746	50640
Nagapattinam	16381	43251
Total	**169679**	**356270**

The T factor generated from MODIS data for *Kharif* and *Rabi* seasons in the Cauvery Delta Region is shown in Fig. 5. The calculated T factor ranged from 0.91 to 1.02 for *Kharif* and from 0.85 to 1.08 for *Rabi* season, respectively (20). The T factor defines how the methane emission rate varies with changes in temperature. The MODIS-derived LST values showed a strong positive correlation with *in-situ* temperature measurements (21). The rate of methane emission calculated using the LST T factor of the study area is given in Table 3. During the growing season, the average observed methane emissions from the rice fields for *Kharif* ranged from 38.25 kg ha^{-1} to 46.35 kg ha^{-1} and for *Rabi* season ranged from 42.00 kg ha^{-1} to 52.50 kg ha^{-1}. Methane emission maps for both seasons are given in Fig. 6. The total methane emissions from the Cauvery Delta Region were 7.16 Gg for the *Kharif* and 17.09 Gg for the *Rabi* season. Total methane emission was higher in *Rabi* season 2023, as the area of the season was higher compared to *Kharif* season.

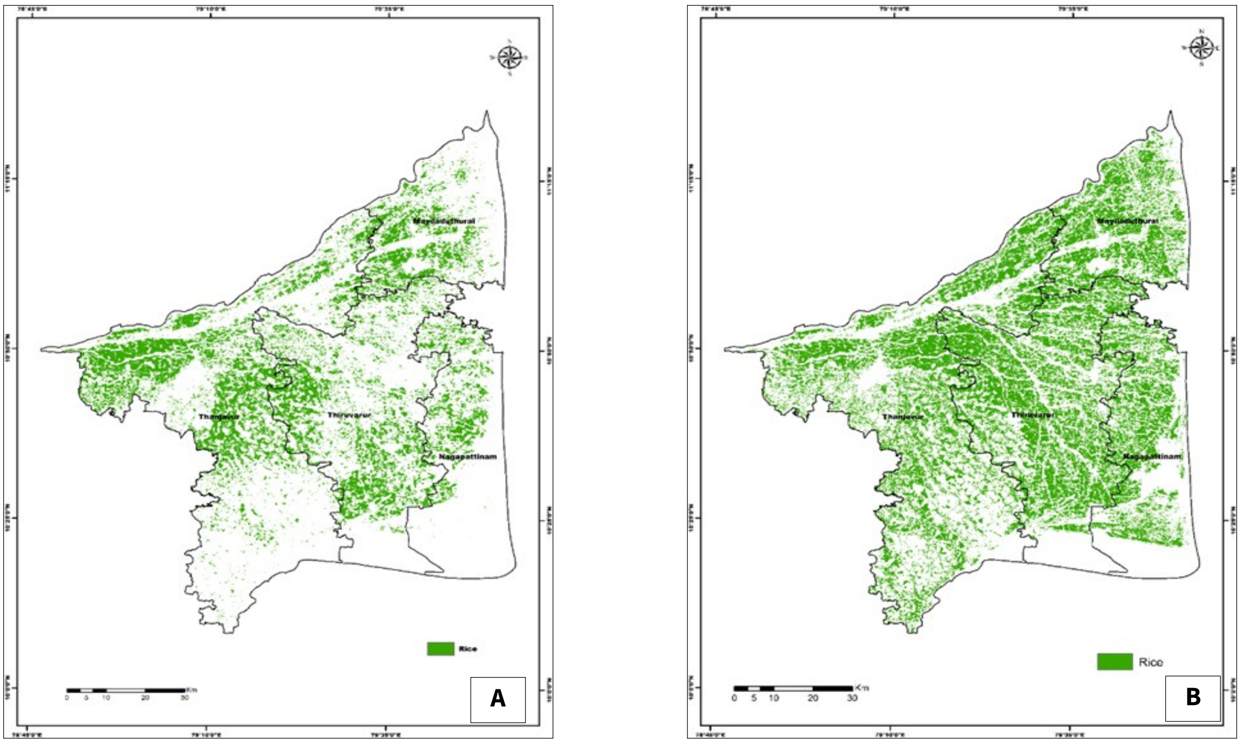

Fig. 4. Rice area map for A *Kharif* 2023 B *Rabi* 2023.

Table 2. Confusion matrix for accuracy assessment of SAR based rice area estimation

Actual class from the survey	**Predicted class from the map**						
	Season	***Kharif*** **2023**			***Rabi*** **2023**		
	Class	**Rice**	**Non-Rice**	**Accuracy (%)**	**Rice**	**Non-Rice**	**Accuracy (%)**
	Rice	142	8	94.7	144	6	96.0
	Non-Rice	7	43	86.0	5	45	90.0
	Reliability	95.3 %	84.3 %	**92.5**	96.6 %	88.2 %	**94.5**
Mean accuracy		90.3 %	**Good Accuracy**		93.0 %	**Good Accuracy**	
Average reliability		89.8 %			92.4 %		
Overall accuracy		**92.5 %**			**94.5 %**		
Kappa index		**0.85**			**0.89**		

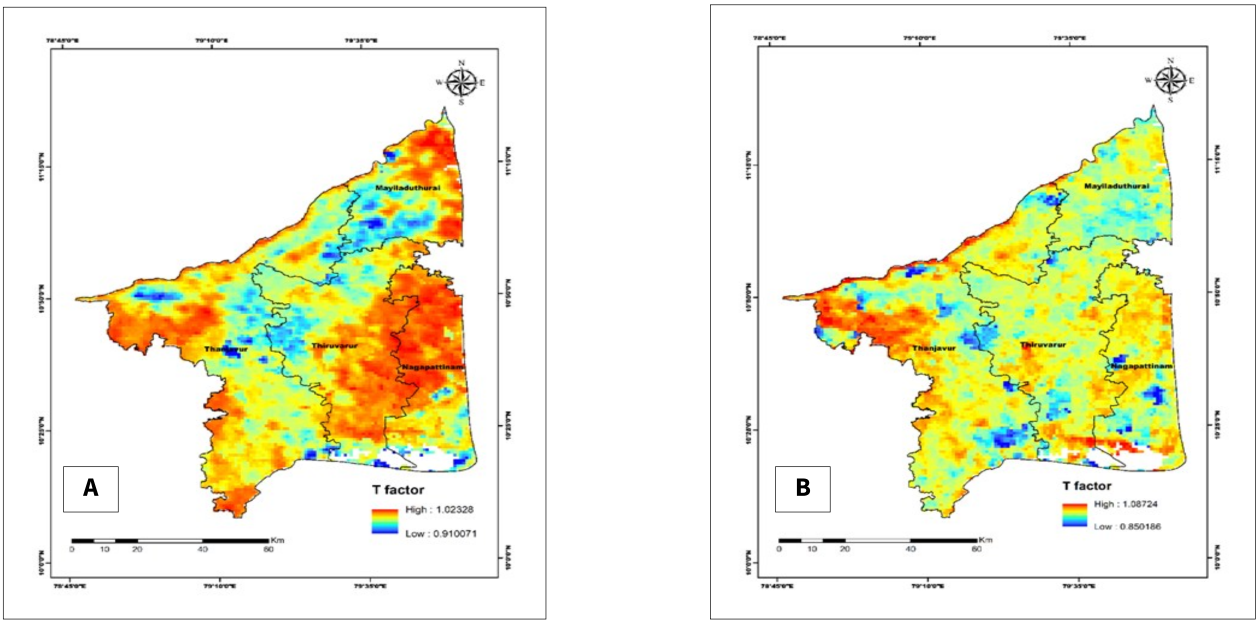

Fig. 5. T factor for rice fields of Cauvery Delta Region estimated from LST during A *Kharif* B *Rabi*

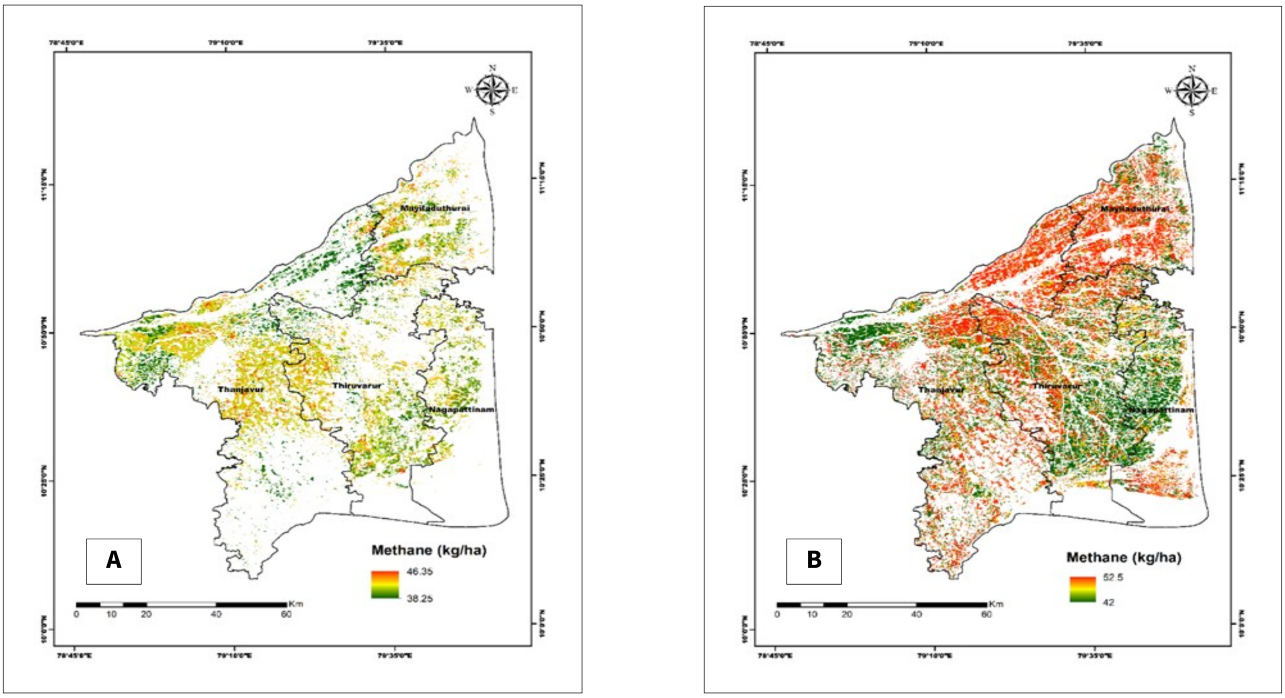

Fig. 6. LST T factor based Methane Emission (kg ha^{-1}) from rice fields during A *Kharif* B *Rabi.*

During the *Kharif* season, the average methane emission for Thanjavur district was 44.29 kg ha^{-1} followed by Thiruvarur, Mayiladuthurai and Nagapattinam districts with methane emissions of 43.46 kg ha^{-1}, 41.70 kg ha^{-1} and 39.26 kg ha^{-1}, respectively. In *Rabi* season 2023, the average methane emission for Thanjavur district was 48.57 kg ha^{-1} followed by Thiruvarur, Mayiladuthurai and Nagapattinam districts with methane emission of 47.84 kg ha^{-1}, 47.01 kg ha^{-1} and 45.96 kg ha^{-1}, respectively. Similarly, the estimation of methane emission using the LST model was performed in this region earlier (22). The methane emission was influenced by agronomic management practices (16). The average methane emissions in Mayiladuthurai and Nagapattinam districts were considerably lower, likely due to the large areas of rice cultivation using direct seeding and semi-dry practices (23). The transplanting method with continuous flooding practice was predominantly adopted in the Cauvery Delta Region, as this region is supplied with continuous water supply throughout the year (8). The continuous flooding intensifies soil reaction and the decomposition of organic matter favours methanogenesis. This results in increased methane emission while allowing intermittent aerobic conditions to reduce the overall methane emission from the rice fields (24). The global warming potential of methane for the Cauvery Delta districts was calculated and given in Table 3. In *Kharif*, the average GWP of these districts was 1160 kg CO_2 eq ha^{-1} and for *Rabi,* the average emission was 1327 kg CO_2 eq ha^{-1}.

The spatial methane estimates derived from the LST-based method were validated with field observation, as shown in Table 4. The average agreement for *Kharif* and *Rabi* was 84.74 and 87.52%, respectively. In *Kharif*, the average RMSE and NRMSE were 7.48 kg ha^{-1} and 15.25%, respectively, while in *Rabi* the average RMSE and NRMSE were 6.57 kg ha^{-1} and 12.48%, respectively. The higher agreement percentage indicates the accuracy level of the product and the suitability of this model in spatial methane estimation from rice fields.

Table 3. Methane emission and global warming potential

Districts	*Kharif* 2023				*Rabi* 2023			
	Rice Area (ha)	Methane emission (kg ha^{-1})	GWP (kg CO_2 eq ha^{-1})	Total methane emission (Gg)	Rice Area (ha)	Methane emission (kg ha^{-1})	GWP (kg CO_2 eq ha^{-1})	Total Methane emission (Gg)
Thanjavur	77796	44.29	1240	3.45	120923	51.84	1452	6.27
Thiruvarur	50756	43.46	1217	2.21	141456	48.01	1344	6.79
Mayiladuthurai	24746	41.70	1168	1.03	50640	47.12	1319	2.39
Nagapattinam	16381	39.26	1099	0.64	43251	44.96	1259	1.94
Total/Average	**169679**	**42.18**	**1181**	**7.16**	**356270**	**47.98**	**1344**	**17.09**

Table 4. Validation of LST based methane emission with observed methane emission

S. No.	Latitude	Longitude	*Kuruvai*					*Samba*				
			LST (kg ha^{-1})	Observed (kg ha^{-1})	RMSE (kg ha^{-1})	NRMSE (%)	Agreement (%)	LST (kg ha^{-1})	Observed (kg ha^{-1})	RMSE (kg ha^{-1})	NRMSE (%)	Agreement (%)
1	11.0538	79.6089	38.42	33.40	5.02	15.03	84.97	43.42	41.78	1.64	3.93	96.07
2	11.1814	79.6985	41.25	49.64	8.39	16.90	83.10	45.14	51.13	5.99	11.72	88.28
3	11.0684	79.7421	44.25	35.20	9.05	25.71	74.29	42.15	44.23	2.08	4.70	95.30
4	11.1631	79.5782	43.16	51.52	8.36	16.23	83.77	45.18	53.41	8.23	15.41	84.59
5	10.8048	79.8158	36.49	43.12	6.63	15.38	84.62	51.26	54.31	3.05	5.62	94.38
6	10.7774	79.7258	46.01	50.00	3.99	7.98	92.02	46.89	49.26	2.37	4.81	95.19
7	10.6362	79.7537	48.58	52.76	4.18	7.92	92.08	51.23	55.41	4.18	7.54	92.46
8	10.8460	79.6854	43.17	37.40	5.77	15.43	84.57	49.25	46.36	2.89	6.23	93.77
9	10.9246	79.4467	38.71	46.00	7.29	15.85	84.15	48.24	55.23	6.99	12.66	87.34
10	10.5859	79.3445	43.82	48.20	4.38	9.09	90.91	44.23	49.12	4.89	9.96	90.04
11	10.7938	78.9622	41.64	51.20	9.56	18.67	81.33	42.71	52.13	9.42	18.07	81.93
12	10.8355	79.1530	44.60	49.23	4.63	9.40	90.60	43.29	54.26	10.97	20.22	79.78
13	10.6533	79.1808	45.24	49.92	4.68	9.38	90.63	44.89	41.21	3.68	8.93	91.07
14	10.9752	79.3518	42.64	51.86	9.22	17.78	82.22	47.15	60.21	13.06	21.69	78.31
15	10.7923	79.2755	43.89	57.10	13.21	23.13	76.87	48.36	55.23	6.87	12.44	87.56
16	10.8995	79.1195	42.85	50.52	7.67	15.18	84.82	44.92	54.13	9.21	17.01	82.99
17	10.4552	79.3259	37.43	54.80	17.37	31.70	68.30	42.23	62.23	20.00	32.14	67.86
18	10.5070	79.1921	42.08	50.42	8.34	16.54	83.46	46.83	55.56	8.73	15.71	84.29
19	10.7299	79.6205	45.12	52.20	7.08	13.56	86.44	47.5	54.26	6.76	12.46	87.54
20	10.5606	79.6610	44.74	50.80	6.06	11.93	88.07	47.35	62.32	14.97	24.02	75.98
21	10.6653	79.4753	41.67	49.00	7.33	14.96	85.04	49.26	43.21	6.05	14.00	86.00
22	10.6883	79.3532	42.20	53.60	11.4	21.27	78.73	44.32	52.00	7.68	14.77	85.23
23	10.7582	79.4469	43.67	52.88	9.21	17.42	82.58	42.12	48.72	6.60	13.55	86.45
24	10.8663	79.3981	40.33	51.40	11.07	21.54	78.46	43.78	48.30	4.52	9.36	90.64
25	10.8559	79.5414	44.49	47.60	3.11	6.53	93.47	43.52	46.30	2.78	6.00	94.00
26	10.6323	79.5375	39.15	45.66	6.51	14.26	85.74	46.73	52.21	5.48	10.50	89.50
27	10.4767	79.5738	45.21	47.10	1.89	4.01	95.99	47.25	38.20	9.05	23.69	76.31
28	10.5563	79.4250	44.65	51.70	7.05	13.64	86.36	49.68	53.30	3.62	6.79	93.21
29	10.5116	79.4997	42.52	49.44	6.92	14.00	86.00	50.23	48.26	1.97	4.08	95.92
30	11.0005	79.6755	43.30	52.26	8.96	17.15	82.85	49.74	53.13	3.39	6.38	93.62
	Average		**42.71**	**48.86**	**7.48**	**15.25**	**84.74**	**51.18**	**50.36**	**6.57**	**12.48**	**87.52**

Conclusion

This study demonstrates that the remote sensing technologies, such as Sentinel 1A SAR data and MODIS-derived LST, provide an efficient and scalable method for estimating methane emissions from rice fields. The application of the semi-empirical methane emission model provides reliable methane flux estimates, which align well with field-based observations. The results highlight that methane emissions are significantly higher during the *Rabi* season due to the increased rice cultivation area in the Cauvery Delta region. Reducing methane emissions from rice fields is crucial for addressing climate change. The findings from this study underscore the importance of adopting remote sensing data in methane estimation to support effective policy decisions and sustainable agricultural practices. Continued efforts in refining these estimation models and implementing mitigation strategies will significantly contribute to reducing the overall greenhouse gas emissions from agriculture.

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Authors' contributions

RT carried out the experiment, observation and drafted the manuscript. DM guided the research by formulating the research concept and approved the final manuscript. SP guided the research by formulating the research concept and helped in securing research funds. RT, SS and NSS carried out data processing and interpretation. KPR participated in the data analysis and performed the statistical analysis. RK conceived the idea of the study and participated in its design and coordination. APS participated in the data analysis and revised manuscript. All authors reviewed the results and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare no conflict of interest.

Ethical issues: None

References

1. Iqbal MF, Liu S, Zhu J, Zhao L, Qi T, Liang J, et al. Limited aerenchyma reduces oxygen diffusion and methane emission in paddy. J Environ Manag. 2021;279:111583. https://doi.org/10.1016/j.jenvman.2020.111583
2. Lee H, Calvin K, Dasgupta D, Krinner G, Mukherji A, Thorne P, et al. IPCC, 2023: Climate change 2023: Synthesis report, summary for policymakers. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.
3. Sun M, Zhang Y, Ma J, Yuan W, Li X, Cheng X. Satellite data-based estimation of methane emissions from rice paddies in the Sanjiang plain in northeast China. PloS One. 2017;12(6):e0176765. https://doi.org/10.1371/journal.pone.0176765
4. Rolston DE, Hoffman DL, Toy DW. Field measurement of denitrification: I. Flux of N_2 and N_2O. Soil Sci Soc Am J. 1978;42(6):863-69. https://doi.org/10.2136/sssaj1978.03615995004200060004x
5. Setiyono TD, Holecz F, Khan NI, Barbieri M, Quicho E, Collivignarelli F, et al. Synthetic Aperture Radar (SAR)-based paddy rice monitoring system: Development and application in key rice producing areas in Tropical Asia. In: IOP Conf Ser Earth and Environ Sci. 2017;54 (1):012015. https://doi.org/10.1088/1755-1315/54/1/012015
6. Holecz F, Barbieri M, Collivignarelli F, Gatti L, Nelson A, Setiyono TD, et al. An operational remote sensing-based service for rice production estimation at national scale. In: Proceedings of the Living Planet Symposium; 2013 Sep.
7. Tamilmounika R, Pazhanivelan S, Ragunath KP, Sivamurugan AP, Sudarmanian NS, Kumaraperumal R, Thirumeninathan S. Paddy area estimation in cauvery delta region using synthetic aperture radar. Int J Environ Ecol Conserv. 2022;S517-22. https://doi.org/10.53550/EEC.2022.v28i01s.069
8. Pazhanivelan S, Geethalakshmi V, Tamilmounika R, Sudarmanian NS, Kaliaperumal R, Ramalingam K, et al. Spatial rice yield estimation using multiple linear regression analysis, semi-physical approach and assimilating SAR satellite derived products with DSSAT crop simulation model. Agronomy. 2022;12(9):2008. https://doi.org/10.3390/agronomy12092008
9. Aspert F, Bach-Cuadra M, Cantone A, Holecz F, Thiran JP. Time-varying segmentation for mapping of land cover changes. In: ENVISAT Symposium 2007, Switzerland.
10. Satheesh S, Pazhanivelan S, Kumaraperumal R, Radhamani S, Ragunath KP, Sudarmanian NS. Area Assessment for rice crop in Thiruvarur district assimilating Sentinel 1A satellite data. Int J Environ Clim Chang. 2022;12(10):1270-78. https://doi.org/10.9734/ijecc/2022/v12i1030924
11. Agarwal R, Garg JK. A semi-automated emperical model for estimation of CH_4 emission using coarse resolution thermal data. In: Proceedings of International Symposium on Geospatial Databases for Sustainable Development. ISPRS Commission IV and Indian Society of Remote Sensing; 2006.
12. Liu Y. Modeling the emissions of nitrous oxide (N_2O) and methane (CH_4) from the terrestrial biosphere to the atmosphere. Doctoral dissertation, 1996; MIT Joint Program on the Science and Policy of Global Change).
13. Agarwal R, Garg JK. Methane emission modelling from wetlands and waterlogged areas using MODIS data. Curr Sci. 2009;10:36-40.
14. Tirol-Padre A, Tran DH, Hoang TN, Hau DV, Ngan TT, An LV, et al. Measuring GHG emissions from rice production in Quang Nam Province (Central Vietnam): Emission factors for different landscapes and water management practices. Land Use and Climate Change Interactions in Central Vietnam: LUCCi. 2017;103-21. https://doi.org/10.1007/978-981-10-2624-9_7
15. Asch F, Johnson K, Vo TB, Sander BO, Duong VN, Wassmann R. Varietal effects on methane intensity of paddy fields under different irrigation management. J Agron Crop Sci. 2023;209(6):876-86. https://doi.org/10.1111/jac.12662
16. Islam SM, Gaihre YK, Islam MR, Ahmed MN, Akter M, Singh U, Sander BO. Mitigating greenhouse gas emissions from irrigated rice cultivation through improved fertilizer and water management. J Environ Manag. 2022;307:114520. https://doi.org/10.1016/j.jenvman.2022.114520
17. Congalton RG. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sens Environ. 1991;37(1):35-46. https://doi.org/10.1016/0034-4257(91)90048-B
18. Kannan S, Kaliaperumal R, Pazhanivelan S, Kumaraperumal R, Sivakumar K. Paddy area estimation in Nagapattinam district using sentinel-1A SAR data. Pharma Innov. 2021;10(2):112-16. https://doi.org/10.22271/tpi.2021.v10.i2b.5629
19. Stroppiana D, Boschetti M, Azar R, Barbieri M, Collivignarelli F, Gatti L, et al. In-season early mapping of rice area and flooding dynamics from optical and SAR satellite data. Euro J Remote Sens. 2019;52 (1):206-20. https://doi.org/10.1080/22797254.2019.1581583
20. Bansal S, Chakraborty M, Katyal D, Garg JK. Assessment of methane variability from natural wetlands of Uttar Pradesh, India-implications for tropical countries. Res J Environ Sci. 2015;(3):101. https://doi.org/10.3923/rjes.2015.101.118
21. Bansal S, Garg JK, Sharma CS, Katyal D. Spatial methane emission modelling from wetlands using geospatial tools. Int J Remote Sens. 2018;39(18):5907-33. https://doi.org/10.1080/01431161.2018.1513182
22. Pazhanivelan S, Sudarmanian NS, Geethalakshmi V, Deiveegan M, Ragunath K, Sivamurugan AP, Shanmugapriya P. Assessing methane emissions from rice fields in large irrigation projects using satellite-derived land surface temperature and agronomic flooding: A spatial analysis. Agriculture. 2024;14(3):496. https://doi.org/10.3390/agriculture14030496
23. Kumar A, Nayak AK, Mohanty S, Das BS. Greenhouse gas emission from direct seeded paddy fields under different soil water potentials in Eastern India. Agric Ecosyst Environ. 2016;228:111-23. https://doi.org/10.1016/j.agee.2016.05.007
24. Ariani M, Hanudin E, Haryono E. Greenhouse gas emissions from rice fields in Indonesia: Challenges for future research and development. Indones J Geogr. 2021;53(1). https://doi.org/10.22146/ijg.55681