Agriculture sector: Rice Cultivation Emissions Estimates using Sentinel-1A and -2A/B

CLIMATE TRACE

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Sector Overview

The Climate TRACE coalition provides rice cultivation emission estimates using three different methods. A summary of these approaches is described in the Climate TRACE GitHub methodology repository.

- First, our highest resolution modeling is conducted using Sentinel-1A synthetic aperture radar (SAR) and -2A/B 10m spatial resolution time-series data. The data from these satellites were applied to estimate rice cultivation emissions in the largest rice producing countries for 2022 to 2023 and, in some cases, 2021. This highest resolution approach is documented in detail in the publications:
    1) "Automated near-real-time mapping and monitoring of rice extent, cropping patterns, and growth stages in Southeast Asia using Sentinel-1 time series on a Google Earth Engine platform" (Rudiyanto et al. 2019);
    2) "High-Resolution Mapping of Paddy Rice Extent and Growth Stages across Peninsular Malaysia Using a Fusion of Sentinel-1 and 2 Time Series Data in Google Earth Engine" (Fatchurrachman et al. 2022);
    3) "SEA-Rice-Ci10: High-resolution Mapping of Rice Cropping Intensity and Harvested Area Across Southeast Asia using the Integration of Sentinel-1 and Sentinel-2 Data" (Ginting et al., manuscript in preparation for resubmission).
- Second, a model was developed that used 500m data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua satellites (https://modis.gsfc.nasa.gov/about/). Rice cultivation emissions were estimated for years 2015 to 2022. A detailed explanation of these methods can be found in the "Agriculture sector- Rice Cultivation Emission Estimates using MODIS" methodology.
- Third, for countries not modeled using the first two approaches, appropriate emission factors derived from literature review were applied to country-level data provided by The Food and Agriculture Organization (FAO) FAOSTAT.

Here, this document describes an overview of the first approach using Sentinel-1A synthetic SAR and -2A/B.

1. Overview

The Climate TRACE coalition estimates annual rice cultivation emissions for a region or country i (E_i) each year using the IPCC (1997) approach, calculated as follows (Eq.1):

$$E_i = (A1 \times EF1)_i + (A2 \times EF2)_i + (A3 \times EF3)_i \qquad \text{(Eq. 1)}$$

Where:

- A1, A2, A3 are the harvested rice areas for the first, second, and third seasons, respectively (in hectares).
- EF1, EF2, EF3 are the emission factors for the respective seasons (in tons per hectare).

The harvested rice areas for different seasons and regions were determined based on rice cropping intensity using remote sensing technology. The emission factors were obtained from published data.

For the years 2015 and 2020, harvested rice area estimates were based on MODIS data (with a spatial resolution of 500 meters), covering the majority of rice-producing regions, including 23 countries (see Table S1). From 2021 onward, we improved the spatial resolution to 10 meters using Sentinel-1A/B synthetic aperture radar (SAR) and Sentinel-2A/B data, covering:

- 2021: 8 countries,
- 2022: 25 countries,
- 2023: 35 countries (see Table S1).

This refined approach accounts for approximately 32%, 94%, and 96% of global rice production for 2021, 2022, and 2023, respectively, based on FAOSTAT 2022 data.

From 2015 to 2021, emissions estimates were refined by national emission factors (EFs), (see Tables S2). Subsequently, for 2022 and 2023, emission factors were further customized for three countries—China, Vietnam, and Thailand—where sub-national EFs or higher temporal frequencies were available. These country-specific factors were applied to capture local variations in rice cultivation practices (Katoh, 1999; Thoung Vo, 2020; Sun, 2020). The sub-national EFs used for these countries are detailed in Tables S3 to S5.

2. Supplementary materials

Table S1 The different spatial resolutions for modeled countries by year. 500m = MODIS modeling approach. *10m* = Sentinel-1A/B and -2A/B modeling approach. A country with a "N/A" for a specific year, or for any country not shown, used FAOSTAT to estimate rice emissions for that specific country and year.

Country	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Bangladesh	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Brazil	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Cambodia	500m	500m	500m	500m	500m	500m	*10m*	*10m*	*10m*
China	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Ecuador	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*10m*
Egypt	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*10m*	*10m*
Ethiopia	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*10m*	*10m*
Guyana	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*10m*
India	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Indonesia	500m	500m	500m	500m	500m	500m	*10m*	*10m*	*10m*
Iran (Islamic Republic of)	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Italy	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Japan	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Korea (the Democratic People's Republic of)	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Korea (the Republic of)	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Lao People's Democratic Republic (the)	500m	500m	500m	500m	500m	500m	*10m*	*10m*	*10m*

Country	2015	2016	2017	2018	2019	2020	2021	2022	2023
Madagascar	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*10m*
Malaysia	500m	500m	500m	500m	500m	500m	*10m*	*10m*	*10m*
Mexico	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*10m*
Myanmar	500m	500m	500m	500m	500m	500m	*10m*	*10m*	*10m*
Nepal	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Pakistan	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Peru	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*10m*
Philippines (the)	500m	500m	500m	500m	500m	500m	*10m*	*10m*	*10m*
Russia	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*10m*
Spain	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Sri Lanka	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Suriname	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*10m*
Taiwan (Province of China)	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Thailand	500m	500m	500m	500m	500m	500m	*10m*	*10m*	*10m*
Turkey	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*10m*
United Republic of Tanzania	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*10m*
United States of America (the)	500m	500m	500m	500m	500m	500m	500m	*10m*	*10m*
Uruguay	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*10m*
Viet Nam	500m	500m	500m	500m	500m	500m	*10m*	*10m*	*10m*

Tables S2 Seasonally integrated methane (CH4) emission factors (EFs) in various conditions and locations of the world that were used in this study. Mean emission factors and standard deviation (SD) are provided.

Country	**ISO3 country**	**Mean CH_4 Emission (kg CH_4/ha/season)**	**SD CH_4 Emission (kg CH_4/ha/season)**	**References**
Bangladesh	BGD	168.2	80.4	(Islam *et al.*, 2020)
Brazil	BRA	430.1	149.6	(Camargo *et al.*, 2018; Zschornack *et al.*, 2018)
Cambodia	KHM	145.3	31	(Vibol and Towprayoon, 2010)
Ecuador	ECU	430.1	149.6	Brazil EF
Egypt	EGY	183.6	51.04	(Mboyerwa, 2022)
Ethiopia	ETH	183.6	51.04	(Mboyerwa, 2022)
Guyana	GUY	430.1	149.6	Brazil EF
India	IND	81	42.5	(Bhatia *et al.*, 2005; Kritee *et al.*, 2018; Oo *et al.*, 2018)
Indonesia	IDN	339.8	102.1	(Setyanto *et al.*, 2018)
Iran (Islamic Republic of)	IRN	81	42.5	India EF
Italy	ITA	292	116	(Lagomarsino *et al.*, 2016; Mazza *et al.*, 2016; Meijide *et al.*, 2017)
Japan	JPN	469.8	302.4	(Camargo *et al.*, 2018; Toma *et al.*, 2019)
Korea (the Democratic People's Republic of)	PRK	349.4	93	Korea (the Republic of) EF
Korea (the Republic of)	KOR	349.4	93	(Gutierrez, Kim and Kim, 2013; Lim *et al.*, 2021)
Lao People's Democratic Republic (the)	LAO	78.3	31.6	Thailand EF
Madagascar	MDG	183.6	51.04	(Mboyerwa, 2022)
Malaysia	MYS	178.3	118.5	(Fazli and Man, 2014)
Mexico	MEX	202	121.9	USA EF

Country	ISO3 country	Mean CH_4 Emission (kg CH_4/ha/season)	SD CH_4 Emission (kg CH_4/ha/season)	References
Myanmar	MMR	30.1	12.5	(Win *et al.*, 2020)
Nepal	NPL	81	42.5	India EF
Pakistan	PAK	81	42.5	India EF
Peru	PER	430.1	149.6	Brazil EF
Philippines (the)	PHL	258	192.7	(Alberto *et al.*, 2014; Sander, Samson and Buresh, 2014; Sibayan *et al.*, 2018)
Russia	RUS	81	42.5	India EF
Spain	ESP	405.7	202.9	(Moreno-García, Guillén and Quílez, 2020; Martínez-Eixarch *et al.*, 2021)
Sri Lanka	LKA	81	42.5	India EF
Suriname	SUR	430.1	149.6	Brazil EF
Taiwan (Province of China)	TWN	112	91.4	(Chang, 2001)
Turkey	TUR	81	42.5	India EF
United Republic of Tanzania	TZA	183.6	51.04	(Mboyerwa, 2022)
United States of America (the)	USA	202	121.9	(Hatala *et al.*, 2012; Humphreys *et al.*, 2019; Della Lunga *et al.*, 2021; Karki *et al.*, 2021)
Uruguay	URY	430.1	149.6	Brazil EF

Table S3 summarizes emissions factors and their standard deviation for five regions in China (Sun 2020). For regions where it is common to have multiple rice harvests, unique emissions factors were provided to help illustrate seasonal variation. These emissions factors were applied to modeled harvested area estimates to characterize annual methane emissions.

Table S3 China subnational EFs reported in Sun (2020)

Region	Season	Mean (kg CH4/ha)	Standard Deviation
South China	Early Season	50.5	83.41
	Late-rice	182.3	156.65
	All Rice	116.4	146.14
Southwest China	Single Rice	244	220.36
	All Rice	244	220.36
Yangtze River	Early Season	99.2	140.68
	Late-rice	224.8	224.03
	Single Rice	188.5	173.32
	All Rice	174	188.75
Northeast	Single Rice	74.4	133.62
Huang-Huai-Hai	Single Rice	43.2	15.41

Table S4 Thailand subnational estimated seasonal rice field methane rates. Major and second refers to “wet season rice cropping” and “dry season rice cropping”, respectively (Katoh, 1999). Table modified from Katoh (1999). Blank cells indicate no value given. Asterisk with numbers refer to citations- *1 = Yagi et al. (1994), *2 = Katoh et al. (1999a), and *3 = Katoh et al. (1999b). A season with a “N/A” indicates no value provided.

Site	Year	Rice cultivation	Flooding period (day)	CH4 flux (mg m-2 hr-1)	Estimated seasonal emission (g m-2 season-1)	
					Second	**Major**
Khon kaen	1991	Major *1	97	16.4	N/A	50.8
		Second *1	109	19.4	38.2	N/A
Khlong Lugang	1991	Second *1	83	3.1	6.1	N/A
Chai Net	1991	Major *1	94	1.1	N/A	2.5
Bang Khen	1992	Major *2	106	21.8	N/A	55.5
		Second *2	120	4.3	12.4	N/A
	1994	Second	118	6.7	19	N/A
Phitsanulok	1992	Major *3	98	7.4	N/A	17.4
	1993	Second *3	113	6.6	17.9	N/A
San Pa Thong	1993	Major *3	103	16.1	N/A	39.8
	1994	Second *3	101	8.8	21.3	N/A
Phtae	1993	Major *3	128	22.2	N/A	68.2
	1994	Second *3	127	15.9	48.5	N/A
Khon Kaen	1994	Major *3	129	19.8	N/A	61.3
	1995	Second *3	96	15.1	34.8	N/A
Surin	1994	Major *3	123	13.3	N/A	39.3
	1995	Second*3	120	15.4	44.4	N/A
Mean					***26.9***	***41.8***

Table S5 Vietnam subnational emission factors reported in Thoung Vo (2020). In each of these regions, rice production involved multiple harvests. Unique emissions factors were provided to help illustrate seasonal variation in emissions across successive harvests. These emissions factors were applied to modeled harvested area estimates to characterize annual methane emissions.

Region of Vietnam	Season	Average emissions (kg ha^{-1} $season^{-1}$)	Standard Deviation
North	Early	271	150
	Late	404	173
Central	Early	321	237
	Middle	321	237
South	Early	174	82
	Middle	277	116
	Late	356	481

(a) Rice cropping intensity across 35 countries

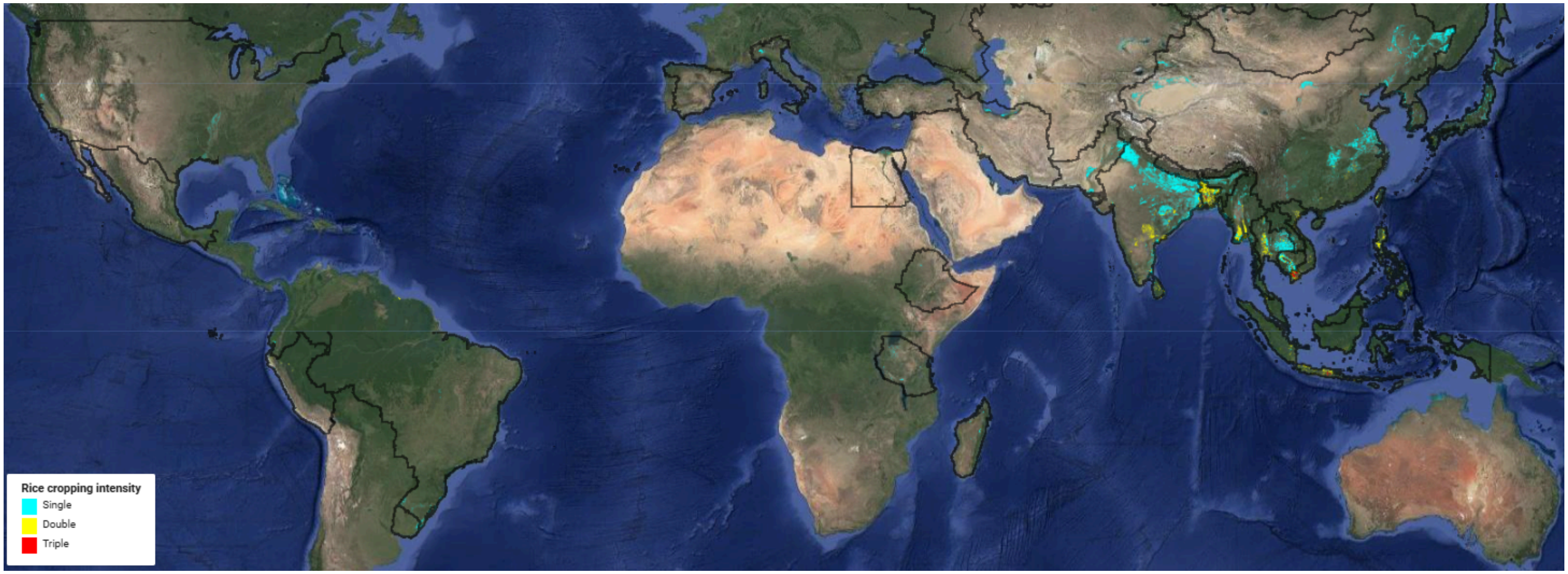
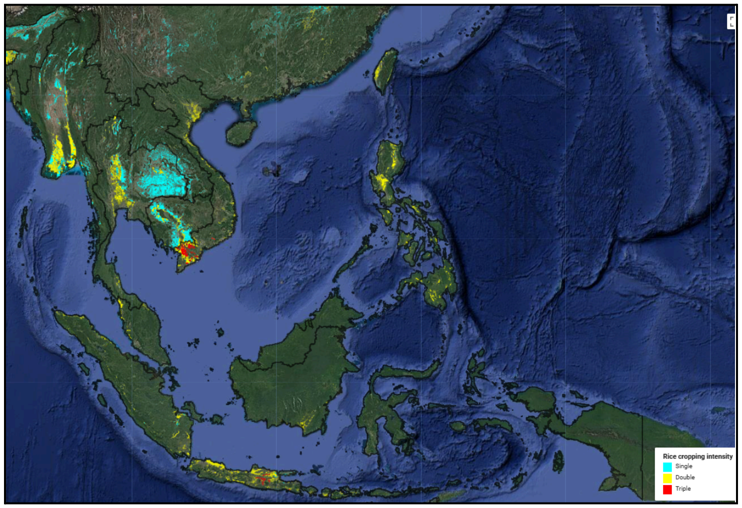
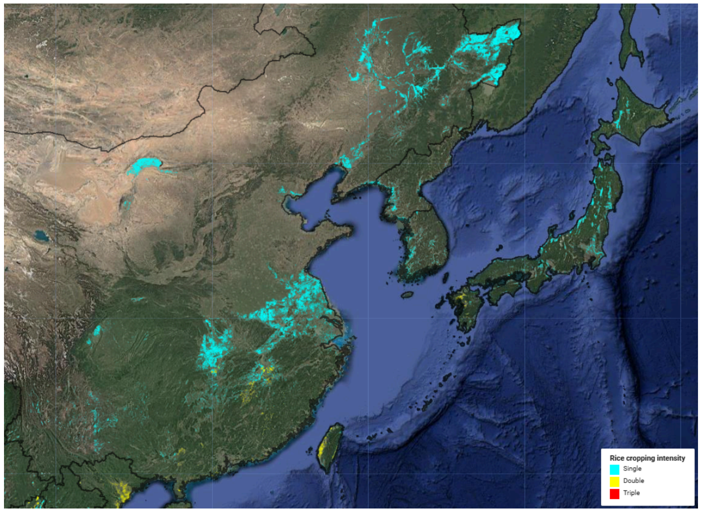


Figure S1 illustrates the spatial distribution of rice cropping intensity for 2023 across different regions: (a) 35 key rice-producing countries. Figure S1 continues below and shows the following regions: (b) Southeast Asia, (c) East Asia, (d) South Asia, (e) the USA, (f) South America, and (g) Africa. The data is derived from Sentinel-1 and Sentinel-2A/B imagery with a 10m spatial resolution. In Southeast Asia, which is situated in the tropical zone, there is significant variation in cropping intensity, ranging from single (light blue) to double (yellow) and triple (red) rice cropping. In contrast, most other regions are predominantly characterized by single cropping intensity, mainly due to climatic conditions.

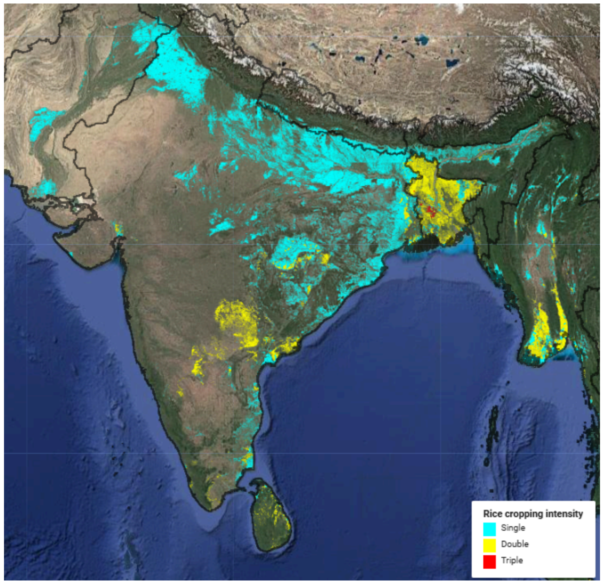
(b) Southeast Asia



(c) East Asia

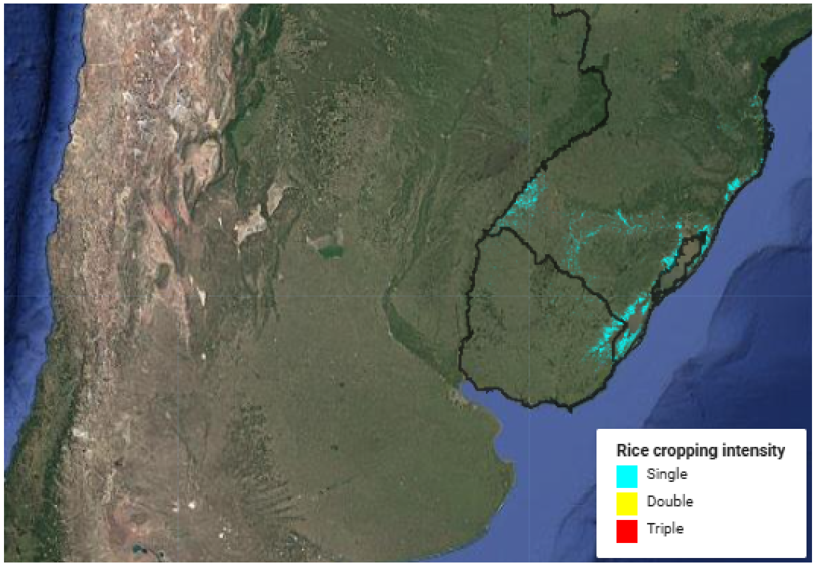


(d) South Asia



(e) USA (California, Arkansas, Missouri, Mississippi, Louisiana, Texas)

(f) South America (South regions of Brazil and Uruguay)



(g) Africa (Tanzania and Madagascar)

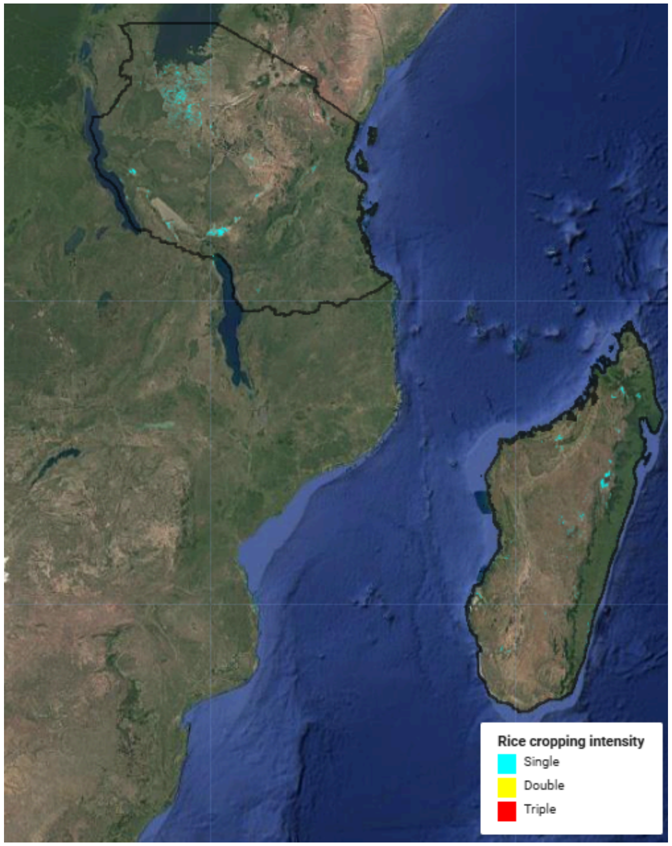


Figure S1 continued. Spatial distribution of rice cropping intensity for the year 2023 in (a) 35 countries as the main rice producer, (b) Southeast Asian, (c) East Asian, (d) South Asian, (e) USA, (f) South America and (g) Africa countries derived from Sentinel-1 and Sentinel-2A and -2B at (10m spatial resolution). Colors indicate rice cropping: single (light blue), double (yellow), and triple (red).

Figure S2 presents a dot plot of the annual harvested rice area for 2023 across 35 countries, derived from calculations based on the rice cropping intensity shown in Figure S1a. The total harvested rice area for 2023 amounts to 155,811,388 hectares. This dot plot highlights significant disparities among major rice-producing nations. India leads with a harvested area of 52,900,000 hectares, followed by China with 30,167,322 hectares, underscoring the dominance of these two countries in global rice production. Thailand and Bangladesh also stand out, with harvested areas of 12,120,200 and 11,000,000 hectares, respectively. Other notable contributors include Myanmar (9,369,727 hectares) and Indonesia (8,176,372 hectares). The data indicates that Southeast Asian countries, particularly those in the tropical region, have substantial harvested areas, reflecting their favorable climatic conditions for rice cultivation. In contrast, countries like the USA, Brazil, and several European nations exhibit significantly lower harvested areas, highlighting their lesser reliance on rice as a staple crop.

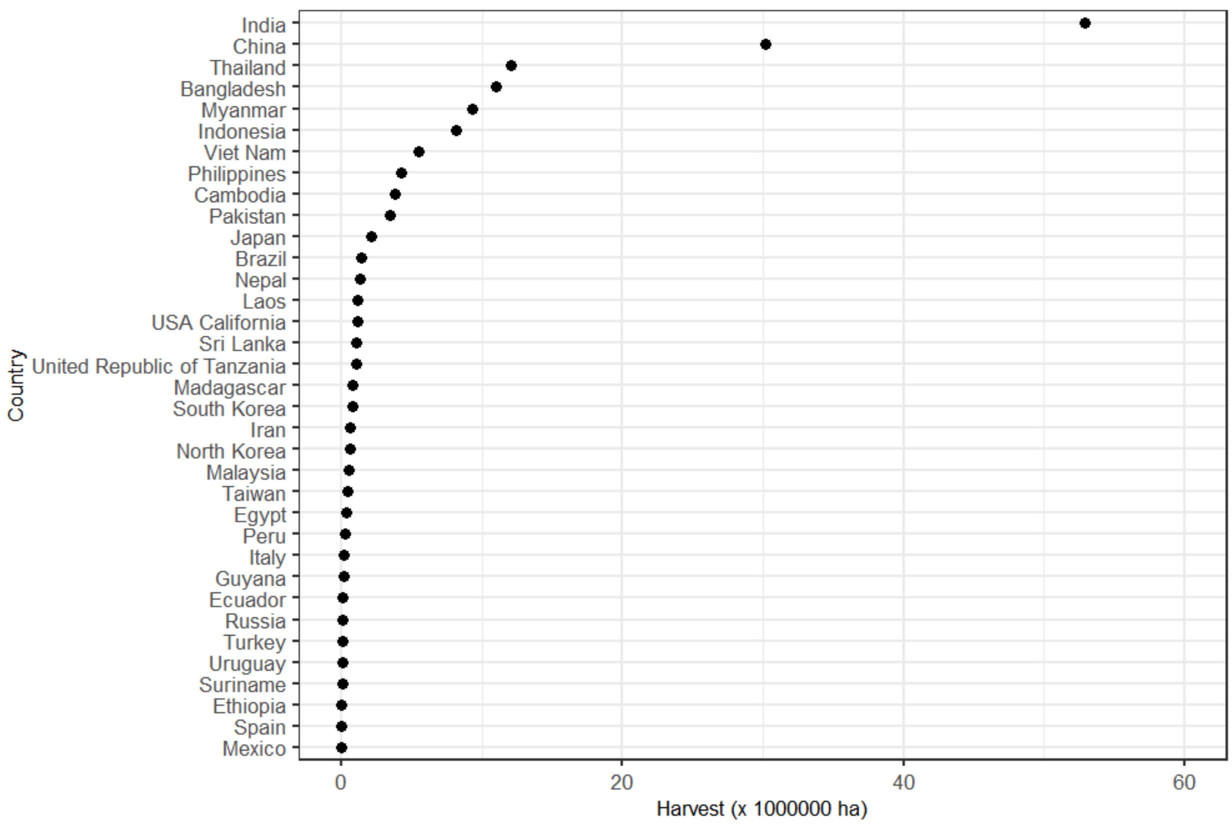


Figure S2. Annual harvested rice area for 2023 across 35 countries, derived from calculations based on rice cropping intensity shown in **Figure S1a**. FAOSTAT data is not available for 2023.

Based on the provided data comparing harvested rice areas in 2022 from both Paddy Watch and FAO in **Figure S3a**, significant variations are evident among the 25 countries listed. The total harvested rice area reported by Paddy Watch across these countries is 153,261,495 hectares, while the FAO reports a total of 136,160,346 hectares. This discrepancy is primarily attributed to the estimated harvested area in India, where Paddy Watch reports 52,500,000 hectares, significantly higher than the FAO's estimate of 46,400,000 hectares. The remaining countries exhibit relatively similar harvested rice areas across both sources. **Figure S3b** shows the correlation between harvested rice areas reported by Paddy Watch and FAOSTAT for 2022. There is a strong positive linear relationship between the two data sources, with an R^2 value of 0.99. However, the notable divergence in India's figures emphasizes the challenges of obtaining consistent agricultural data and illustrates how different methodologies and data sources can lead to varying estimates of harvested rice area.

Figure S3 continued

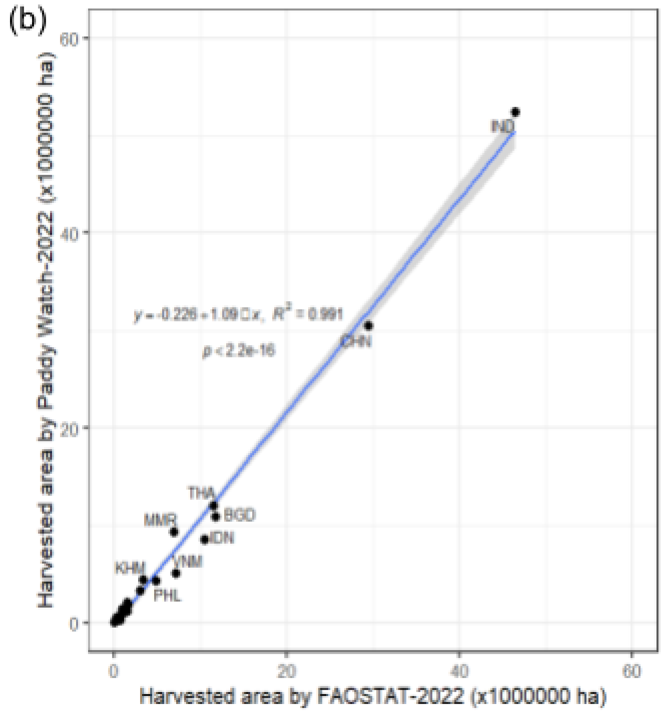
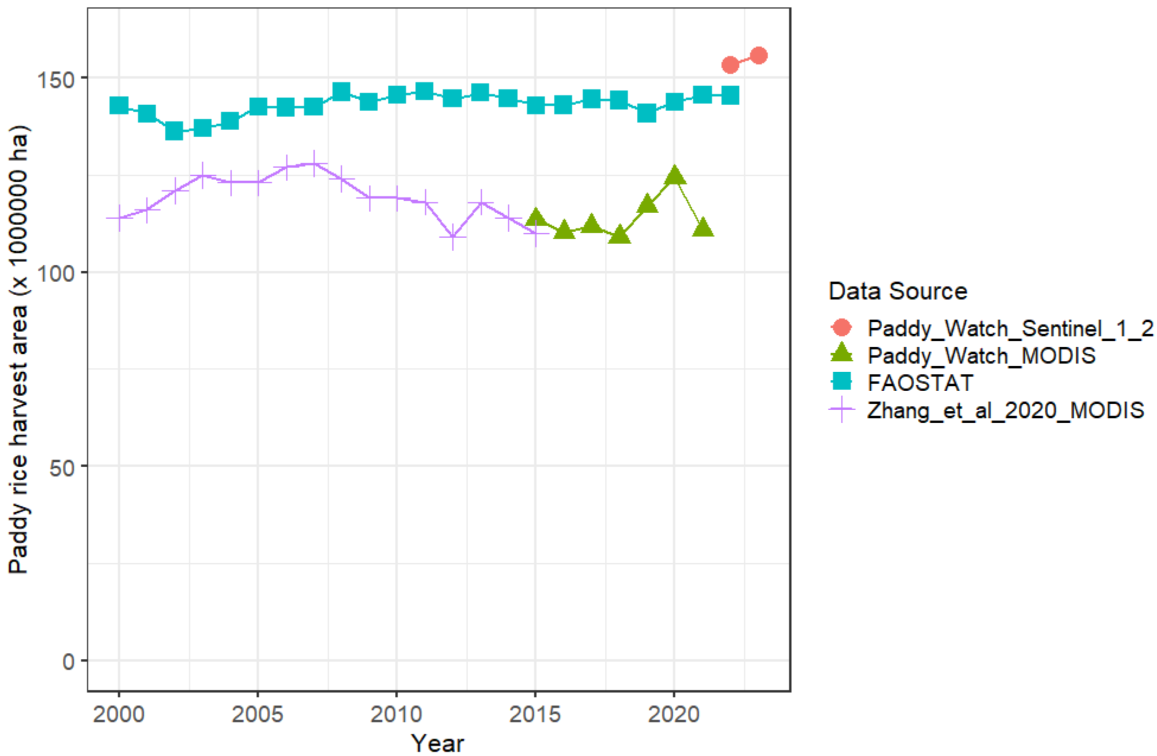


Figure S3. (a) Annual harvested rice area for 2022 across 25 countries; (b) Correlation analysis of annual harvested area between Paddy watch and FAOSTAT data for 2022. Shaded area represents the 95% confidence interval.

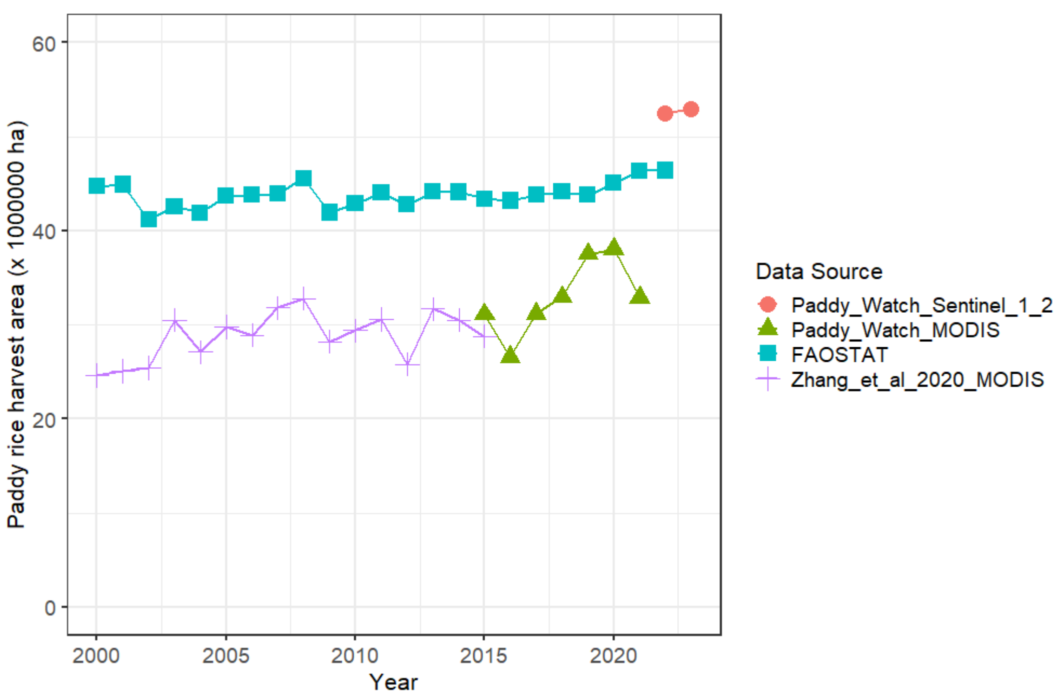
Figure S4 illustrates the annual harvested paddy rice area derived from multiple data sources, showcasing trends from 2015 to 2023. Panel (a) presents data for 23 countries within the Asian monsoon region, integrating information from Paddy Watch using MODIS (2015-2021) and Sentinel-1 and Sentinel-2 (2022-2023), alongside FAOSTAT data for the years 2000 to 2022 and Zhang et al. (2020) for 2000 to 2015. Panel (b) focuses specifically on India, while panel (c) highlights data for China. These figures are larger than the harvested rice area recorded from MODIS data for 2020, which was 124,271,392 hectares, and also exceed the FAOSTAT estimate of 145,408,328 hectares. This increase can be attributed to not only the inclusion of additional countries but also the enhanced spatial resolution, which improves from 500 meters with MODIS to 10 meters with Sentinel-1/2. This finer resolution allows for more accurate capture of smaller rice fields typically found across Asia.

For India (**Figure S4b**), there is a significant difference between the estimates from Paddy Watch (Sentinel-1/2) and FAOSTAT. Paddy Watch reported a harvested rice area of 52,500,000 hectares for 2022, while FAOSTAT provided a lower estimate of 46,400,000 hectares for the same year. This discrepancy underscores the variability in data sources and methodologies used for estimating agricultural production.

(a) 23 countries and Asian monsoon countries



(b) India



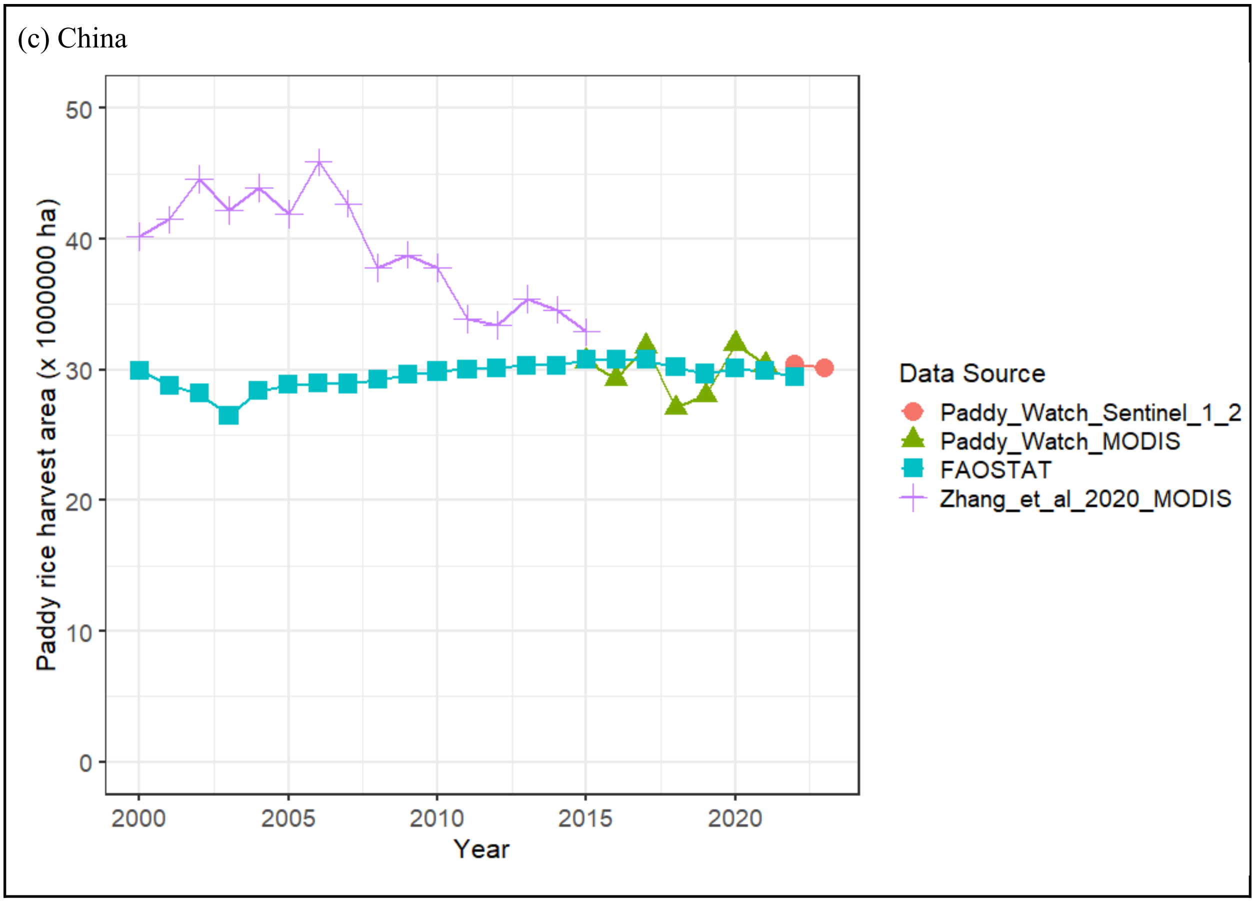


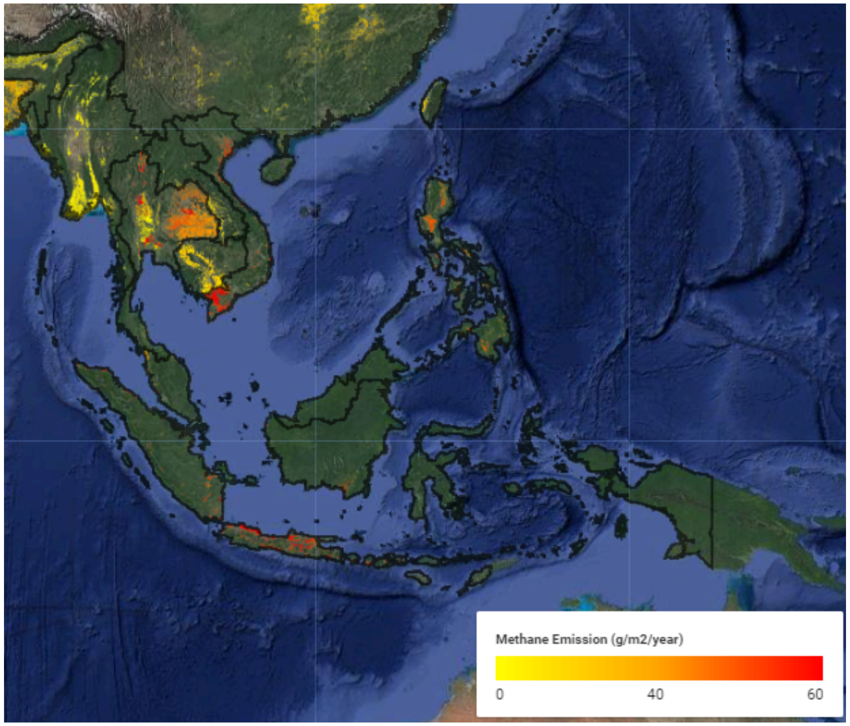
Figure S4. Annual harvested paddy rice area based on Paddy Watch using MODIS (2015 - 2021) and Sentinel-1 and 2 (2022-2023); FAOSTAT data (2000 - 2022) and Zhang et al. (2020) (2000 - 2015) for (a) 23 countries and Asian monsoon countries, (b) India and (c) China.

Figure S5 illustrates the spatial distribution of annual CH4 emission estimates for the year **2023** from rice cultivation across different regions and countries. The data focuses on 35 of the main rice-producing countries, grouped into several geographic categories: Southeast Asia, East Asia, South Asia, the USA, South America, and Africa.CH_4 emissions from rice cultivation across 35 countries for 2023, derived from calculations based on the spatial distribution of CH_4 emissions from rice cultivation shown in **Figure S6**. In 2023, China and India emerged as the top contributors to CH4 emissions from rice cultivation, with emissions of 4,712,261 tons and 4,286,663 tons, respectively, highlighting their roles as leading rice producers. Southeast Asian countries, including Thailand (4,001,391 tons), Indonesia (2,778,604 tons), and Bangladesh (1,850,612 tons), also significantly contribute to global emissions due to similar agricultural practices. Moderate contributors such as Vietnam (1,687,665 tons) and the Philippines (1,107,668 tons) further emphasize the region's importance. The notable emissions from Japan (1,009,923 tons) and emerging contributors like Brazil (609,785 tons) and Cambodia (558,655 tons).

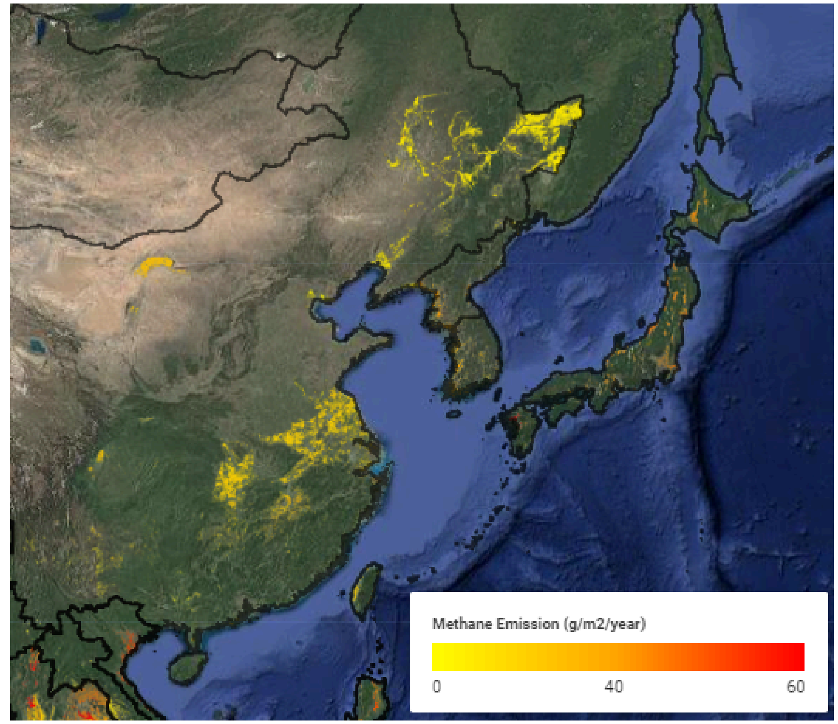
(a) Emission for 36 countries

Figure S5. Spatial distribution of annual CH_4 emission estimates for the year 2023 from rice cultivation in (a) 35 countries as the main rice producer and, continued below, for specific regions: (b) Southeast Asian, (c) East Asian, (d) South Asian, (e) USA, (f) South America and (g) Africa countries derived from Paddy Watch using Eq. (1). Yellow colors = lower CH_4 emissions and redder (warmer) colors indicate higher CH_4 emissions.

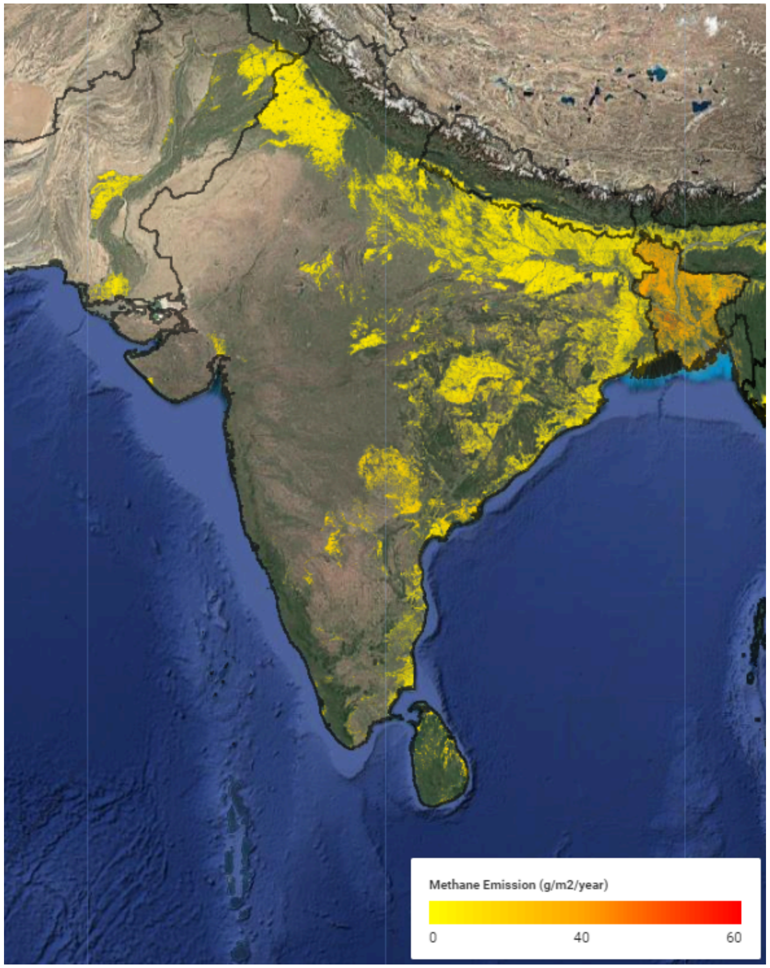
(b) Southeast Asia



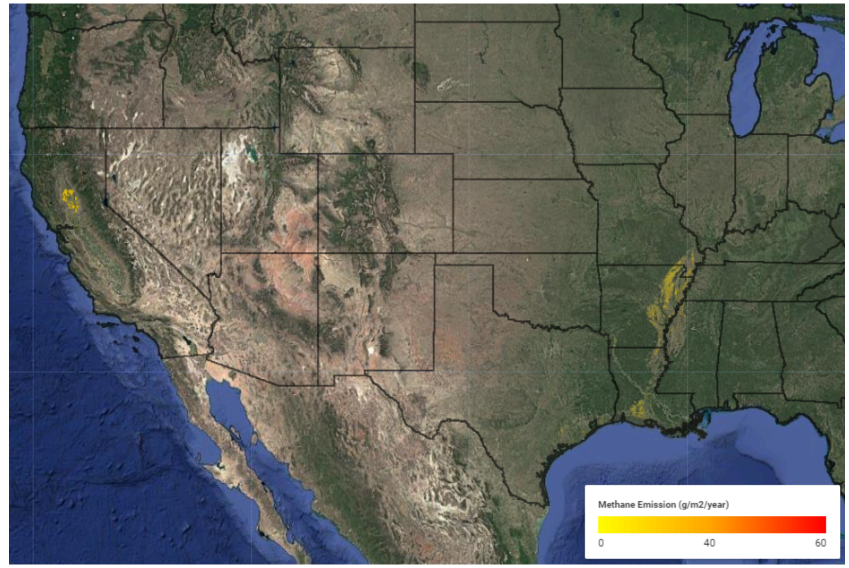
(c) East Asia



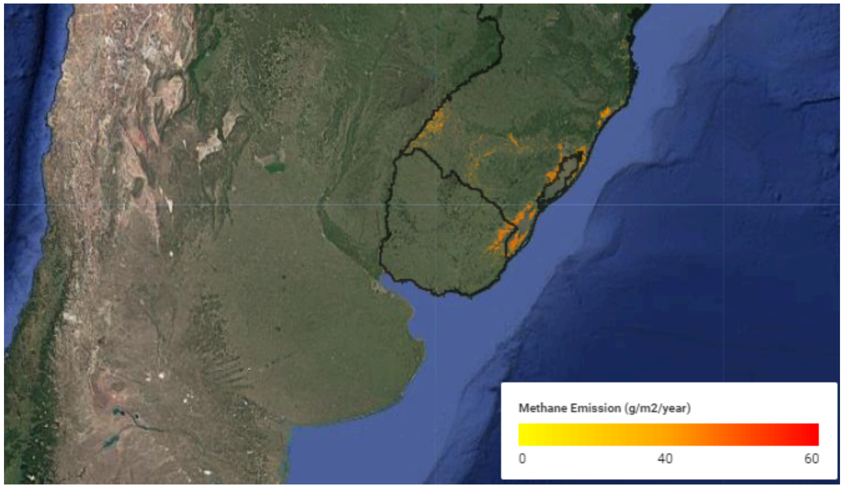
(d) South Asia



(e) USA (California, Arkansas, Missouri, Mississippi, Louisiana, Texas)



(f) South America (South regions of Brazil and Uruguay)



(g) Africa (Tanzania and Madagascar)

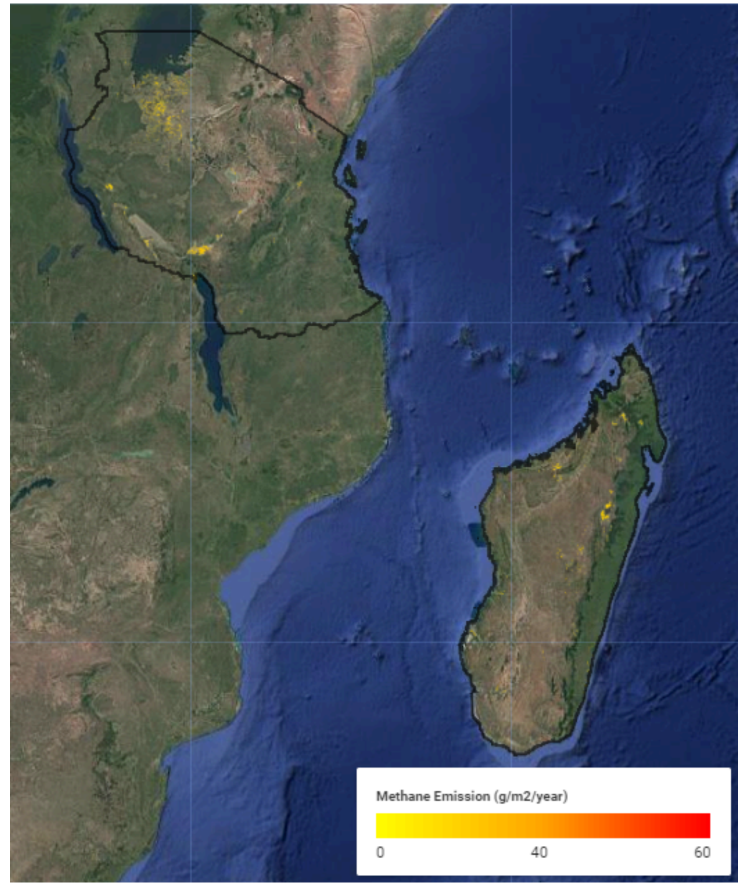


Figure S5 continued. Spatial distribution of annual CH_4 emission estimates for the year 2023 from rice cultivation in (a) 35 countries as the main rice producer, (b) Southeast Asian, (c) East Asian, (d) South Asian, (e) USA, (f) South America and (g) Africa countries derived from Paddy Watch using Eq. (1). Yellow colors = lower CH_4 emissions and redder (warmer) colors indicate higher CH_4 emissions.

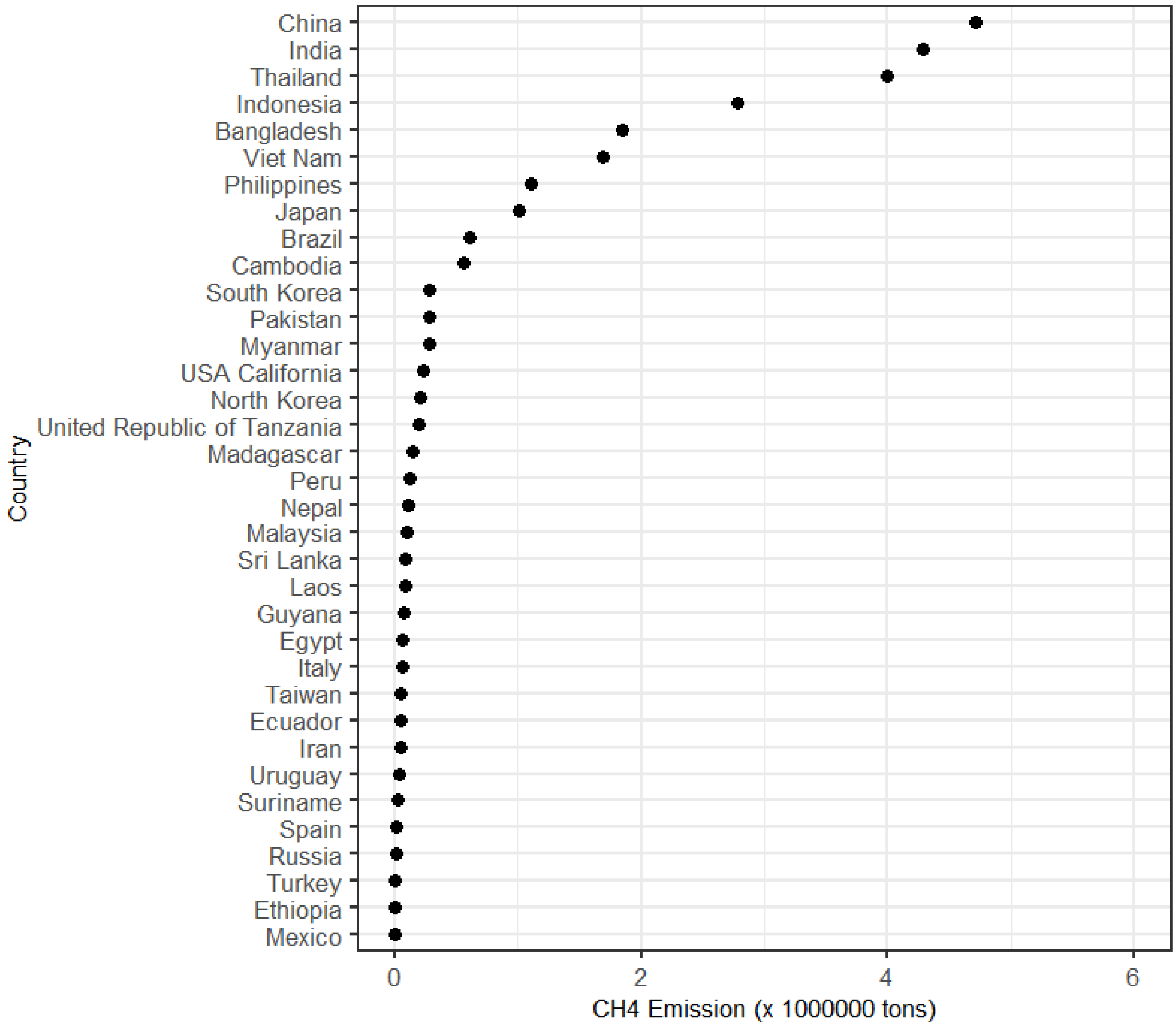
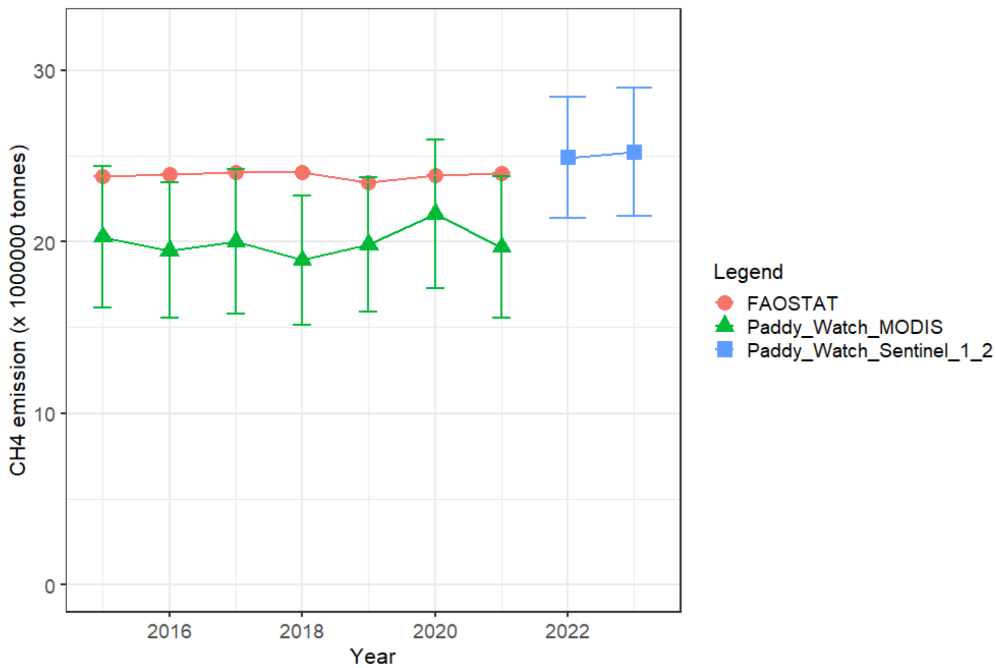


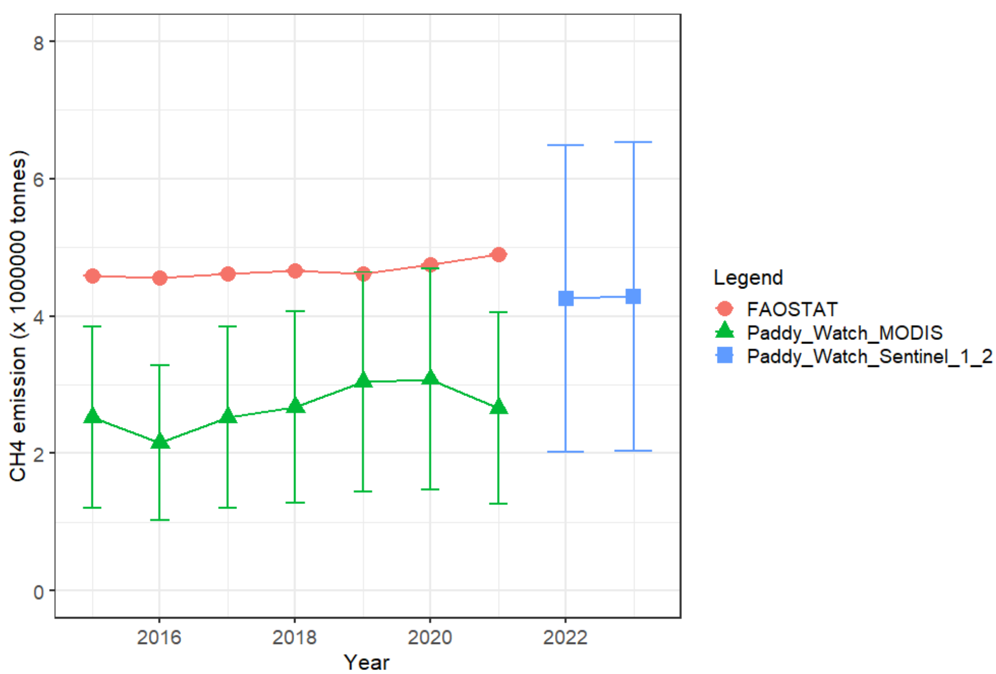
Figure S6. CH_4 emissions from rice cultivation across 35 countries for 2023, derived from calculations based on the spatial distribution of CH_4 emissions from rice cultivation shown in **Figure S5a**.

Figure S7 illustrates annual CH4 emissions from rice cultivation, integrating various data sources across different time periods. The emissions are derived from Paddy Watch using MODIS (2015-2021) and Sentinel-1 and Sentinel-2 (2022-2023), alongside FAOSTAT data (2000-2022) and Zhang et al. (2020) (2000-2015), divided into three key segments: (a) a comprehensive overview of 23 countries, including those influenced by the Asian monsoon; (b) a focused examination of emissions in India; and (c) a detailed analysis of emissions in China. The total CH4 emissions from rice cultivation are 24,906,589 tons and 25,223,626 tons for 2022 and 2023, respectively, derived from Sentinel-1/2 data, which exceed the MODIS estimate of around 20,000,000 tons for 2015-2020. A similar pattern is observed for India (Figure S8a). Conversely, CH4 emissions from rice cultivation in China are reported at 4,712,261 tons for 2023, lower than the MODIS estimate of approximately 7,000,000 tons for 2015-2020. These discrepancies are attributed not only to differences in harvested rice area but also to the use of different emission factors (EFs). Despite these variations, the estimates still fall within the confidence intervals.

(a) 23 countries and Asian monsoon countries



(b) India



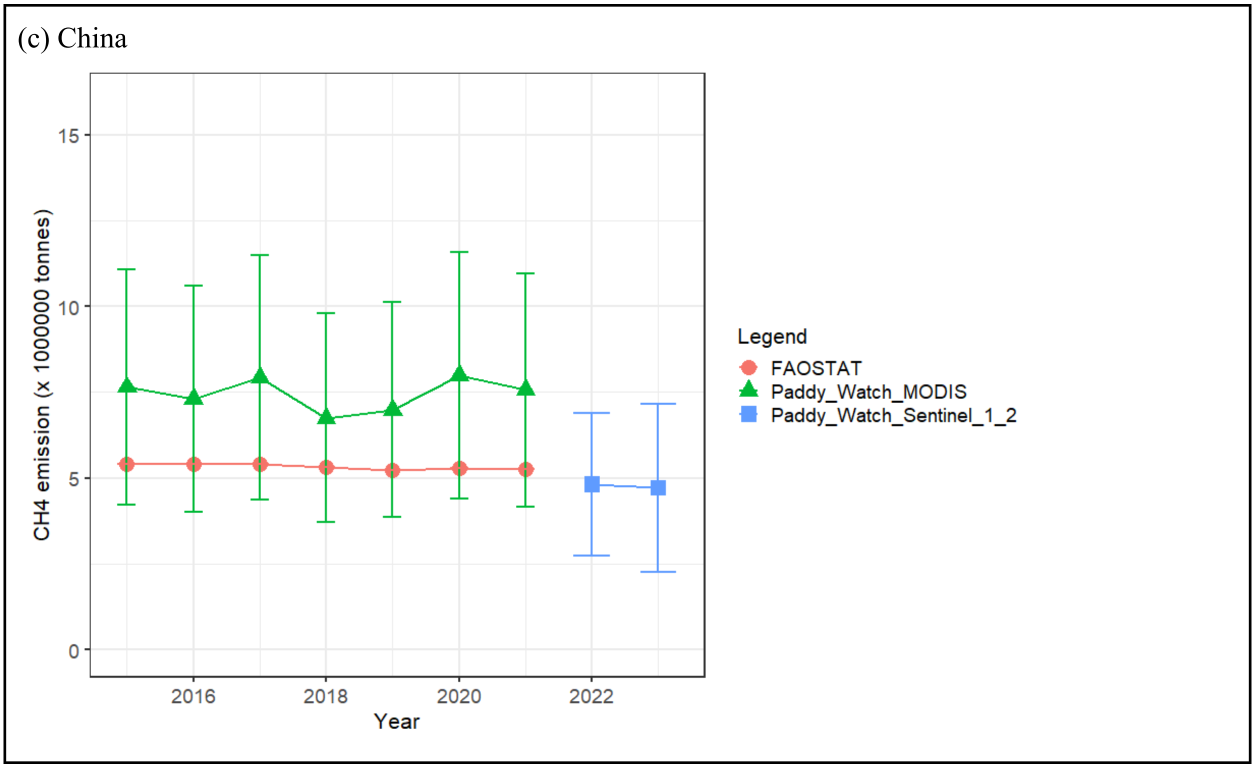


Figure S7. Annual CH_4 emission from rice cultivation based on Paddy Watch using MODIS (2015 - 2021) and Sentinel-1 and 2 (2022-2023); FAOSTAT data (2000 - 2022) and Zhang et al. (2020) (2000 - 2015) for (a) 23 countries and Asian monsoon countries, (b) India and (c) China.

Metadata section

The Agriculture sector: “Rice Cultivation Emissions Estimates using Sentinel-1A and -2A/B” reports the following data on the Climate TRACE website:

- Country-level CH_4, and 20 and 100 year GWPs emissions from rice cultivation.

Emissions estimates were reported for years 2021 to 2023 for select countries, with previous years combined with MODIS-generated and/or FAOSTAT generated emissions data (see Table S1). Other approaches to estimate rice emissions are in the Climate TRACE GitHub methodology repository. The data generated here has been combined with the other approaches to estimate rice cultivation emissions globally. All data is freely available on the Climate TRACE website (https://climatetrace.org/). A detailed description of what is available is described in Table S6. Note, uncertainty definitions are defined in Table S2 and S3, the standard deviation associated with each country. Confidence definitions are in the tables below.

Table S6 Metadata for Rice Cultivation Emissions Estimates.

General Description	Definition
Sector definition	*Country-level rice cultivation emissions*
UNFCCC sector equivalent	*3.C Rice Cultivation*
Temporal Coverage	*2021 – 2023 (see Table S1)*
Temporal Resolution	*Annual (original); Monthly (on website, see Temporal Disaggregation of Emissions Data for the Climate TRACE Inventory)*
Data format	*CSV*
Coordinate Reference System	*None. ISO3 country code provided*
Number of assets/countries available for download	*8 to 35 countries, varies by year (see Table S1)*
Ownership	*Country*
What emission factors were used?	*IPCC CH. 10 and 11 EFs*
What is the difference between a "0" versus "NULL/none/nan" data field?	*"0" values are for true non-existent emissions. If we know that the sector has emissions for that specific gas, but the gas was not modeled, this is represented by "NULL/none/nan"*
total_CO2e_100yrGWP and total_CO2e_20yrGWP conversions	*Climate TRACE uses IPCC AR6 CO_2e GWPs. CO_2e conversion guidelines are here: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FullReport_small.pdf*

Confidence values are based on the level of information detail used to estimate emissions, which is defined as the following:

- Subgroup 1: 10m resolution, regional EF
- Subgroup 2: 10m resolution, country level EF
- Subgroup 3: 10m resolution, Tier 1 EF or EF from neighboring country
- Subgroup 4: 500m resolution, country level EF
- Subgroup 5: 500m resolution, Tier 1 EF or EF from neighboring country
- Subgroup 6: backfilled by Climate TRACE

Low to very high confidence values for each group are shown in Table S7 and country specific confidences are shown in Table S8.

Table S7 Confidence definitions for rice cultivation emissions by subgroup number.

Data attributes	Definitions	Subgroup 1	Subgroup 2	Subgroup 3	Subgroup 4	Subgroup 5	Subgroup 6
type	Not used; NA						
capacity_description	Not used; NA						
capacity_factor_description	Not used; NA						
activity_description	Area harvested	High	High	High	Medium	Medium	Low

Data attributes	Definitions	Subgroup 1	Subgroup 2	Subgroup 3	Subgroup 4	Subgroup 5	Subgroup 6
CO2_emissions_factor	Not used; NA						
CH4_emissions_factor	T CH_4 per harvested ha	High	Medium	Low	Medium	Low	Low
N2O_emissions_factor	Not used; NA						
other_gas_emissions_factor	Not used; NA						
CO2_emissions	Not used; NA						
CH4_emissions	T CH_4	High	Medium	Medium	Medium	Medium	Low
N2O_emissions	Not used; NA						
other_gas_emissions	Not used; NA						
total_CO2e_100yrGWP	Based on CH_4 emissions	High	High	High	Medium	Medium	Low
total_CO2e_20yrGWP	Based on CH_4 emissions	High	High	High	Medium	Medium	Low
other_1	Area of single crop	Very High	Very High	Very High	Very High	Very High	Not used; NA
other_2	Area of double crop	Very High	Very High	Very High	Very High	Very High	Not used; NA
other_3	Area of triple crop	Very High	Very High	Very High	Very High	Very High	Not used; NA

Table S8 Country specific confidence definitions for rice cultivation emissions.

Country	ISO3	Sub group	capacity	capactiy_ factor	activity	CO2_ emissions_ factor	CH4_ emissions_ factor	N2O_ emissions_ factor	other_ gas_ emissions_ factor	CO2_ emissio ns	CH4_ emissions	N2O_ emissions	other_gas_ emissions	total_CO2e_ 100yrGWP	total_CO2e 20yrGWP	other_ 1	other_ 2	other_ 3
China	CHN	1	NA	NA	High	NA	High	NA	NA	NA	High	NA	NA	High	High	Very High	Very High	Very High
Vietnam	VNM	1	NA	NA	High	NA	High	NA	NA	NA	High	NA	NA	High	High	Very High	Very High	Very High
Thailand	THA	1	NA	NA	High	NA	High	NA	NA	NA	High	NA	NA	High	High	Very High	Very High	Very High
Bangladesh	BGD	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Brazil	BRA	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Spain	ESP	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Indonesia	IDN	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
India	IND	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Iran (Islamic Republic of)	IRN	3	NA	NA	High	NA	Low	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Italy	ITA	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Japan	JPN	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Cambodia	KHM	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Korea (the Republic of)	KOR	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Lao People's Democratic Republic (the)	LAO	3	NA	NA	High	NA	Low	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Sri Lanka	LKA	3	NA	NA	High	NA	Low	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Myanmar	MMR	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Malaysia	MYS	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Nepal	NPL	3	NA	NA	High	NA	Low	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Pakistan	PAK	3	NA	NA	High	NA	Low	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Philippines (the)	PHL	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Korea (the Democratic People's Republic of)	PRK	3	NA	NA	High	NA	Low	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High

Country	ISO3	Sub group	capacity	capactiy_ factor	activity	CO2_ emissions_ factor	CH4_ emissions_ factor	N2O_ emissions_ factor	other_ gas_ emissions_ factor	CO2_ emissio ns	CH4_ emissions	N2O_ emissions	other_gas_ emissions	total_CO2e_ 100yrGWP	total_CO2e _20yrGWP	other_ 1	other_ 2	other_ 3
Taiwan (Province of China)	TWN	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
United States of America (the)	USA	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Ethiopia	ETH	5	NA	NA	Mediu m	NA	Low	NA	NA	NA	Medium	NA	NA	Medium	Medium	Very High	Very High	Very High
Egypt	EGY	5	NA	NA	Mediu m	NA	Low	NA	NA	NA	Medium	NA	NA	Medium	Medium	Very High	Very High	Very High
Turkey	TUR	3	NA	NA	High	NA	Low	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Madagascar	MDG	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Tanzania	TZA	2	NA	NA	High	NA	Medium	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Uruguay	URY	3	NA	NA	High	NA	Low	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Surinam	SUR	3	NA	NA	High	NA	Low	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Peru	PER	3	NA	NA	High	NA	Low	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Guyana	GUY	3	NA	NA	High	NA	Low	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Ecuador	ECU	3	NA	NA	High	NA	Low	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Russia	RUS	3	NA	NA	High	NA	Low	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Mexico	MEX	3	NA	NA	High	NA	Low	NA	NA	NA	Medium	NA	NA	High	High	Very High	Very High	Very High
Backfilled Countries		6	NA	NA	Low	NA	Low	NA	NA	NA	Low	NA	NA	Low	Low	NA	NA	NA

Citation format: Rudiyanto and Minasny, B. (2024). *Agriculture sector- Rice Cultivation Emissions Estimates using Sentinel-1A and -2A/B.* Universiti Malaysia Terengganu, Malaysia, Climate TRACE Emissions Inventory. https://climatetrace.org [Accessed date]

Geographic boundaries and names (iso3_country data attribute): The depiction and use of boundaries, geographic names and related data shown on maps and included in lists, tables, documents, and databases on Climate TRACE are generated from the Global Administrative Areas (GADM) project (Version 4.1 released on 16 July 2022) along with their corresponding ISO3 codes, and with the following adaptations:

- HKG (China, Hong Kong Special Administrative Region) and MAC (China, Macao Special Administrative Region) are reported at GADM level 0 (country/national);
- Kosovo has been assigned the ISO3 code 'XKX';
- XCA (Caspian Sea) has been removed from GADM level 0 and the area assigned to countries based on the extent of their territorial waters;
- XAD (Akrotiri and Dhekelia), XCL (Clipperton Island), XPI (Paracel Islands) and XSP (Spratly Islands) are not included in the Climate TRACE dataset;
- ZNC name changed to 'Turkish Republic of Northern Cyprus' at GADM level 0;
- The borders between India, Pakistan and China have been assigned to these countries based on GADM codes Z01 to Z09.

The above usage is not warranted to be error free and does not imply the expression of any opinion whatsoever on the part of Climate TRACE Coalition and its partners concerning the legal status of any country, area or territory or of its authorities, or concerning the delimitation of its borders.

Disclaimer: The emissions provided for this sector are our current best estimates of emissions, and we are committed to continually increasing the accuracy of the models on all levels. Please review our terms of use and the sector-specific methodology documentation before using the data. If you identify an error or would like to participate in our data validation process, please contact us.

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