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

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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/B 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 and, in some cases, 2021. This highest resolution approach is documented in detail in the publications, "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) and "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).
- 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 the first approach, estimating rice cultivation emissions using Sentinel-1A/B and-2 A/B data.

1. Overview

The Climate TRACE coalition provides rice cultivation emissions estimates using three different methods. For the approach described here, rice cultivation emission estimates were produced using Sentinel-1A/B synthetic aperture radar (SAR) and Sentinel-2A/B time-series data and applied to map rice field extents, rice growth patterns, and number of plantings in rice producing regions globally for years 2021 to 2022 at a 10m spatial resolution. Using regional, sub-regional, and seasonal emission factors (EFs), rice emissions estimates were derived which reflect rice growing practices at the country and sub-national level (see Tables S1 to S4).

The application of these satellite measurements to map rice fields and growth was piloted in Malaysia and is documented in detail in the publication in Rudiyanto et al. (2019) and Fatchurrachman et al.(2022). The Universiti Malaysia Terengganu, in partnership with Climate TRACE, have expanded these modeling approaches to include eight additional countries in 2021 and 25 countries in 2022, shown in Table S5. These countries represent the majority of rice producing regions globally. To estimate rice cultivation emissions, the rice field and number of plantings were used with IPCC (1997) approaches to estimate emissions at the 10m spatial resolution, then aggregated to produce total country-level emissions for years 2021 to 2022.

2. Supplementary materials

Table S1 documents the EFs used to estimate each country's rice cultivation emissions. Included are the mean emissions and standard deviation associated with each EF.

Tables S1 Seasonally integrated methane 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)
China	CHN	249.4	112.1	(Wang *et al.*, 2021)
Egypt	EGY	183.6	51.04	(Mboyerwa, 2022)
Ethiopia	ETH	183.6	51.04	(Mboyerwa, 2022)
Spain	ESP	405.7	202.9	(Moreno-García, Guillén and Quílez, 2020; Martínez-Eixarch *et al.*, 2021)
Indonesia	IDN	339.8	102.1	(Setyanto *et al.*, 2018)
India	IND	81.0	42.5	(Bhatia *et al.*, 2005; Kritee *et al.*, 2018; Oo *et al.*, 2018)
Iran (Islamic Republic of)	IRN	81.0	42.5	India EF
Italy	ITA	292.0	116.0	(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)

Cambodia	KHM	145.3	31.0	(Vibol and Towprayoon, 2010)
Korea (the Republic of)	KOR	349.4	93.0	(Gutierrez, Kim and Kim, 2013; Lim *et al.*, 2021)
Lao People's Democratic Republic (the)	LAO	78.3	31.6	Thailand EF
Sri Lanka	LKA	81.0	42.5	India EF
Myanmar	MMR	30.1	12.5	(Win *et al.*, 2020)
Malaysia	MYS	178.3	118.5	(Fazli and Man, 2014)
Nepal	NPL	81.0	42.5	India EF
Pakistan	PAK	81.0	42.5	India EF
Philippines (the)	PHL	258.0	192.7	(Alberto *et al.*, 2014; Sander, Samson and Buresh, 2014; Sibayan *et al.*, 2018)
Korea (the Democratic People's Republic of)	PRK	349.4	93.0	Korea (the Republic of) EF
Thailand	THA	78.3	31.6	(Maneepitak *et al.*, 2019)
Taiwan (Province of China)	TWN	112.0	91.4	(Chang, 2001)
United States of America (the)	USA	202.0	121.9	(Hatala *et al.*, 2012; Humphreys *et al.*, 2019; Della Lunga *et al.*, 2021; Karki *et al.*, 2021)
Viet Nam	VNM	296.4	192.9	(Vo *et al.*, 2020)

EFs at the subnational level and or higher temporal frequencies were applied to three countries where more detailed information was available. Those countries include China (Sun 2020), Vietnam (Thoung Vo 2020), and Thailand (Katoh 1999). These subnational EFs were applied to these countries for years 2015 to 2022. Table S2 to Table S4 summarize the EFs used.

Table S2 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 S2 China subnational EFs reported in Sun (2020)

Region	Season	Mean (kg CH_4/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 S3 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).

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		50.8
		Second *1	109	19.4	38.2	
Khlong Lugang	1991	Second *1	83	3.1	6.1	
Chai Net	1991	Major *1	94	1.1		2.5
Bang Khen	1992	Major *2	106	21.8		55.5
		Second *2	120	4.3	12.4	
	1994	Second	118	6.7	19	
Phitsanulok	1992	Major *3	98	7.4		17.4
	1993	Second *3	113	6.6	17.9	
San Pa Thong	1993	Major *3	103	16.1		39.8
	1994	Second *3	101	8.8	21.3	
Phtae	1993	Major *3	128	22.2		68.2
	1994	Second *3	127	15.9	48.5	
Khon Kaen	1994	Major *3	129	19.8		61.3
	1995	Second *3	96	15.1	34.8	
Surin	1994	Major *3	123	13.3		39.3
	1995	Second*3	120	15.4	44.4	
Mean					***26.9***	***41.8***

Table S4 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 CH4 ha-1 d-1)	Standard Deviation
North	Early	2.213	1.22
	Late	3.894	1.664
Central	Early	3.097	2.218
	Middle	3.097	2.218
South	Early	1.718	0.8807
	Middle	2.797	1.168
	Late	3.583	4.838

Table S5 provides a summary of the modeled spatial resolution applied to each country for each year. N/A values represent years where harvested area estimates relied on FAOSTAT data rather than modeling.

Table S5 The different spatial resolutions of 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
Bangladesh	500m	500m	500m	500m	500m	500m	500m	10m
Brazil	500m	500m	500m	500m	500m	500m	500m	10m
China	500m	500m	500m	500m	500m	500m	500m	10m
Spain	500m	500m	500m	500m	500m	500m	500m	10m
Egypt	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10m
Ethiopia	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10m
Indonesia	500m	500m	500m	500m	500m	500m	10m	10m
India	500m	500m	500m	500m	500m	500m	500m	10m
Iran (Islamic Republic of)	500m	500m	500m	500m	500m	500m	500m	10m
Italy	500m	500m	500m	500m	500m	500m	500m	10m
Japan	500m	500m	500m	500m	500m	500m	500m	10m
Cambodia	500m	500m	500m	500m	500m	500m	10m	10m
Korea (the Republic of)	500m	500m	500m	500m	500m	500m	500m	10m
Lao People's Democratic Republic (the)	500m	500m	500m	500m	500m	500m	10m	10m
Sri Lanka	500m	500m	500m	500m	500m	500m	500m	10m
Myanmar	500m	500m	500m	500m	500m	500m	10m	10m

Malaysia	500m	500m	500m	500m	500m	500m	10m	10m
Nepal	500m	500m	500m	500m	500m	500m	500m	10m
Pakistan	500m	500m	500m	500m	500m	500m	500m	10m
Philippines (the)	500m	500m	500m	500m	500m	500m	10m	10m
Korea (the Democratic People's Republic of)	500m	500m	500m	500m	500m	500m	500m	10m
Thailand	500m	500m	500m	500m	500m	500m	10m	10m
Taiwan (Province of China)	500m	500m	500m	500m	500m	500m	500m	10m
United States of America (the)	500m	500m	500m	500m	500m	500m	500m	10m
Viet Nam	500m	500m	500m	500m	500m	500m	10m	10m

The Agriculture sector: Rice Cultivation Emissions Estimates using FAOSTAT reports the following data on the Climate TRACE website:

- Country-level enteric fermentation CH_4, and 20 and 100 year GWPs emissions from rice fields

Emissions estimates were reported for years 2021 to 2022, with previous years combined with MODIS-generated and/or FAOSTAT generated emissions data. 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.

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	*2015 – 2022*
Temporal Resolution	*Annual*
Data format	*CSV*
Coordinate Reference System	*None. ISO3 country code provided*
Number of assets/countries available for download	*250 countries*
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*

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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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