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Satellite-Based Quantification of Methane Emissions from Wetlands and Rice Paddies Ecosystems in North and Northeast India

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Abstract: Methane is produced by various natural processes that directly or indirectly contribute to the entire Earth's methane budget. If the Earth's overall methane budget becomes imbalanced, CH_4 has an impact on climate change. Wetlands, rice fields, animals, factories, and fossil fuels are major sources of methane emissions. Among all the resources, wetlands and rice fields are more prominent factors in methane emission, dependent on the water table, temperature, and vegetation. Our study employed the GIS remote sensing technique to analyze methane emissions from 2003 to 2021 in the northern part of India, East Uttar Pradesh and Bihar, and the northeast region of India that is Assam. We also predicted the water table, temperature, and vegetation as raw materials for methane creation. Water table, temperature, and vegetation are essential for wetland ecosystem life, particularly for methanogenic organisms; however, the water table and temperature are critical for rice plant growth and development. With the help of GIS remote sensing, India's monthly rainfall pattern and the water table, vegetation, and temperature pattern over 41 years were analyzed. Our key findings highlight the importance of GIS remote-sensing-based monitoring of methane gas emissions from wetlands and rice fields for their management.

Keywords: methane; climate change; GIS remote sensing; methanogens; vegetation

1. Introduction

Methane (CH_4) is a prominent greenhouse gas contributing to one third of worldwide emissions among all greenhouse gases [1]. Significant sources of CH_4 emission are agricultural activities, waste management, energy use, biomass burning, wetland, livestock, landfills, and rice cultivation [2–4]. Additionally, CH_4 is the most abundant reducing compound in the atmosphere that plays a direct key role in the earth's carbon cycle, and the carbon cycle has maintained the continuous balance of carbon transformation between the inorganic and organic pools in the atmosphere, hydrosphere, terrestrial biosphere, and geosphere [5]. A fully oxidized form of carbon in the atmosphere is carbon dioxide (CO_2), which is fixed by the marine and terrestrial biosphere. During the degradation of organic material, biomass carbon matter can be converted into CH_4 [5,6]. This conversation of organic matter into methane is dependent on environmental conditions. Methane gas is 30 times stronger in absorbing infrared radiation than another greenhouse gas, carbon dioxide. It absorbs the infrared radiation emitted from the earth after it gets energized and starts emitting heat in the atmosphere in all directions [7,8]. Because methane is present in less amount in the atmosphere than CO_2 and has a short life span of approximately eight years, it does not affect more, but a small change in its amount can make a big impact on global warming [9]. Oxidation of CH_4 occurs in two ways: first, photochemically in the atmosphere; second, biologically in the terrestrial and aquatic regions. On earth, some biological systems act as a sink, which means they store the methane, for example, in ocean, grasslands, and desert, while some act as sources to produce CH_4, like wetlands, rice fields, the grazing land of animals, and landfills [10]. Two major sources produce methane among all these sources: wetlands and rice fields. These two sources also require some essential components for methane production like the water table, temperature, and organic material. Wetland and rice farming depend on water; if water is unavailable, wetland ecosystem survival and rice farming are impossible. Temperature is directly related to the soil temperature of wetland and rice fields, and soil temperature is an essential component that influences methane emissions because the growth and development of methane-producing organisms require certain media, nutrients, and temperatures [11–14]. In the controlled conditions in the laboratory, the optimum range of temperature can be determined for methanogenesis, methanotrophy, and soil respiration, but the same temperature-related interpretation is not possible in field conditions [15,16].

Several researchers have examined microbial populations in ephemeral stream banks and hydrologically variable regions next to lakes and rivers, but the effects of hydrologic conditions and variability on the associated soil and CH_4-cycling microbial communities are not well characterized for seasonally saturated wetlands. Collectively, these studies suggest different microbial populations form in "wet" (predominantly anoxic) and "dry" (predominantly oxic) soil conditions [17]. Researchers have discovered that CH_4-cycling microorganisms can colonize a wide range of soil hydrologic conditions and that patterns in their relative abundance, diversity, and activity are not always as expected. For instance, it was discovered that permanently saturated soils support a larger but less diverse methanogen population and that wetter littoral wetland soils harbor a greater abundance and more diverse methanotroph population [18]. Soils that went through frequent wet-dry cycles were also found to have soil microbial communities that were more diverse, distinct, and highly adaptable than soils that did not experience such fluctuations in hydrologic conditions. Seasonally saturated wetland habitats were predicted to host a diverse soil- and CH_4-cycling microbial population due to the fluctuating hydrological conditions along the edges of these wetlands throughout the year [19,20]. The primary purpose of the previous study was to provide a description of the soil and CH_4-cycling microbial population typically found in seasonally saturated wetlands and to establish the connection between soil hydrologic conditions and the distribution and composition of these microbial populations [21]. The optimum temperature in the temperate zone is between 25 °C and 40 °C and in cold subarctic conditions is 20 °C to 25 °C [22–24]. The effect of temperature on the emission of CH_4 depends on carbon availability, microbial activity, and respiration of underground plant organs [22,25]. In some cases, methanogens' activity is also reported at 0 °C where the soil surface freezes and released gas is trapped under or in ice [25,26]. Organic material is a key factor in the development of plants and microbes. Organic matter in the soil is one of the largest carbon reservoirs in ecosystems that affect soil properties [27–29]. Soil organic matter (SOM) is formed by decomposition of plant and animal cells and tissue by soil microbes by various microbial biological activities [25]. The SOM decomposition rate in soil depends on the quality and quantity of SOM [30]. In wetlands, the soil is mainly saturated with water and the soil decomposition rate is slow because of the lack of available atmospheric oxygen that is important for biological and chemical oxidation [31–33]. Many scientific studies have shown an increase in the amount of soil organic matter enhancement of CH_4 production and thus a potential increase in CH_4 efflux from the soil into the atmosphere [30]. This type of condition was observed in the coastal marsh regions and rice fields [34]. Vegetation in wetlands also influences CH_4 production [35]. Through photosynthesis and decomposition, the biomass of plants can provide carbon compounds as nutrient fuel for methanogenesis activity to methanogens [36–38]. Vegetation helps transport oxygen via aerenchyma into anoxic soil layers and passes through toxic soil layers that support rhizosphere methane oxidation [39,40].

In contrast to unreliable and problematic census data, remote sensing technology can provide more precise, spatially explicit information on methane emissions from wetlands and paddy fields [41]. The vast amounts of data collected by various sensors about our planet are invaluable to researchers keeping tabs on spatial information in real time [42]. Many studies over the past 50 years have made use of remote sensing technology to learn more about wetlands, including (1) land use/cover changes or mapping in wetland regions, (2) the carbon cycle and climate warming in wetland environments, (3) the release of carbon by peatland fires, and (4) hydrology processes. The use of remote sensing in wetland research has been widespread, and numerous studies and reviews have examined this method [41,43–51]. Rundquist et al. [52] examined the issues of wetland identification, classification, change detection, and biomass and discussed them all in detail in a review of wetland remote sensing. Keeping this in view, the present study was conducted for the analysis and estimation of India's monthly rainfall, temperature, and vegetation pattern over 41 years. The monthly growth pattern of methane emission over 19 years was also determined. The data of this study is helpful for the management of methane emissions from wetlands and rice fields.

2. Materials and Methods

2.1. Site Description

UP East, Bihar, and Assam

The locations selected for the present study are Eastern Uttar Pradesh, Bihar (25°05′45.87″ N 85°18′47.23″ E), and Assam (26°12′02.18″ N 92°56′15.27″ E) (Figure 1). Eastern Uttar includes 19 cities, and all these cities produce rice as a major crop. Chandauli, Kushinagar, and Varanasi are high-productivity districts (>2500kg/ha) in Eastern Uttar Pradesh [53]. In Bihar, rice is cultivated in 37 districts, among which 25 are low-productivity districts (1000–1500kg/ha), 4 are medium-productivity districts (2000–2500kg/ha), 4 are medium-low-productivity districts (1500–2000kg/ha), 3 are very low productivity districts (<1000kg/ha), and 1 is a high-productivity district (>2500kg/ha) [53]. Ramgarh Taal (26°43′55.38″ N 83°24′20.32″ E) in Gorakhpur is only one wetland in Eastern Uttar Pradesh (Figure 2a) (TOI, 2018). In Bihar, one wetland is Kabartal Wetland (25°37′ N 086°08′ E) (Figure 2b) [54]. In Assam, rice is the main crop that grows three times in a year, which are autumn, winter, and summer. In Assam, 23 districts produce rice and, among them, 11 districts come under medium-low productivity (1500–2000kg/ha), another 11 are low-productivity districts (1000–1500kg/ha), and 1 district is a very low productivity district (<1000kg/ha) [36]. Deepor Beel is a wetland (26°07′ N 091°39′ E) situated in Assam (Figure 2c).

Although there are also some local wetlands in UP East, Bihar, and Assam, they are not officially recognized as Ramsar wetland sites.

2.2. Datasets

Satellite Data

This study collected the methane emission data from 2003 January to December 2021. To evaluate the wetlands and rice fields, we selected 3 parts of India: Uttar Pradesh East, Bihar, and Assam. The result findings were obtained from AIRS ascending (AIRX3STM) Level-3 data.

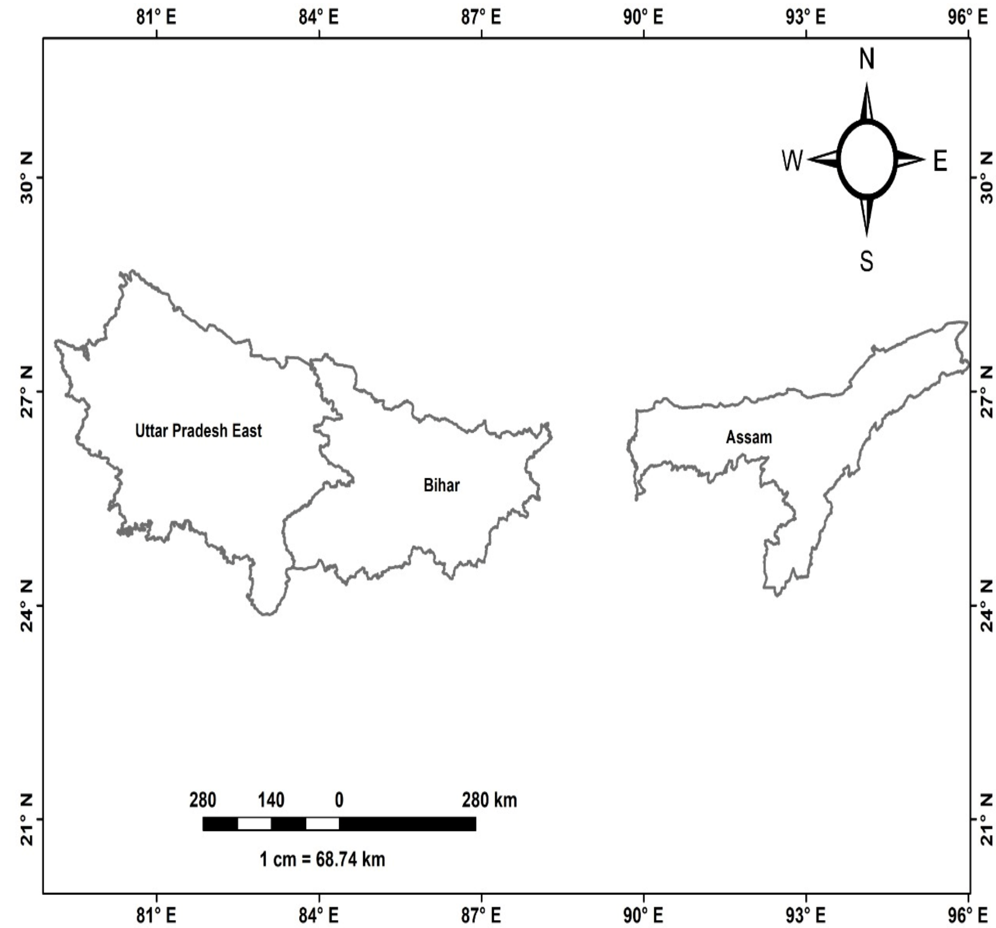

Figure 1. Location map of the study area in the northern part of India, East Uttar Pradesh, Bihar, and the northeast region of India that is Assam.

Figure 2. Diagrammatic representation of wetlands situated in (**a**) UP East, Ramgarh Taal (26°43′55.38″ N 83°24′20.32″ E); (**b**) Bihar, Kabartal (25°37′N 086°08′ E); and (**c**) Assam, Deepor Beel (26°07′N 091°39′ E).

3. Results and Discussion

3.1. Methane Emission in UP East, Bihar and Assam

Water table, temperature, and vegetation are required for wetland ecosystem survival, especially for methanogen organisms. On the other hand, water table and temperature are key elements for the growth and development of rice plants. Water table, temperature, and vegetation are the major sources responsible for methane emissions in wetlands and rice fields. In this study, methane emission was recorded in the years from 2003 to 2021 in different states such as UP East, Bihar, and Assam and the impact of temperature, rainfall, and vegetation on methane emission rate and the biogeochemical methane cycle are studied [55]. Figure 3a illustrates the methane emission for 19 years from 2003 to 2021 in UP East, Bihar, and Assam. The methane emission ranged from 1796.1 to 1907.7 in UP East and Bihar (Figure 3b), while in Assam, it is recorded from 1811.8 to 1904.3 ppbv (Figure 3c). The subsequent months viz methane emission was observed from 2003 to 2021 in UP East, Bihar, and Assam (Figure 3b,c). Similarly, IPCC report 2021 [56] also showed a similar trend of methane emission, as well as an increase in temperature over the years. Methane emission was measured in day and night time in these two study areas (Figure 3d,e). However, there was not any such difference observed in methane emission during both time periods (day and night). Monthly methane emissions declined from May to August during day and night, as represented in Figure 3d,e. It was also observed that CH_4 emission increased from September to next April in UP East Bihar and Assam (Figure 3d,e). A similar finding was observed by Zhang et al. [57].that seasonal wetland area variability was found to be statistically significantly related to an increase in CH_4 emission. The increment of methane from September to April in UP East, Bihar, and Assam was dependent on rainfall, temperature, and vegetation in rice fields and wetlands [35,58].

3.2. Monthly Rainfall Pattern and Methane Emission

In our study, average rainfall data was recorded for 41 years all over India along with UP East, Bihar, and Assam (Figure 4). This showed that, in March and November, average rainfall was observed, the lowest rainfall was observed in April and May, and the highest was observed for June to September. Our finding shows that the rate of methane also increased after the monsoon from September to April (Figure 3b,c) in UP East, Bihar, and Assam because the rice cultivation in UP East, Bihar, and Assam started in July and was harvested in late October, and in wetlands areas, the highest methane emission rate started from the rainy season [59–61]. During the rainy season, an increase in the emission of methane was recorded, along with an increase in rice and wetland plant biomass [61,62]. A dependence of methane emission on biomass has also been reported by other authors [61,63]. Some reports also support our finding that, in the monsoon season, the seasonal wetlands and wetlands emitted a higher rate of methane than in the dry days from April to August (Figures 3b,c and 4) [35,64]. All these statements suggested that the cultivation of rice and the growth and development of wetlands ecosystems require a certain water level and increasing or decreasing the rainfall can directly affect the availability of water for rice cultivation and the growth and development of wetlands ecosystems, affecting the methane emission [65].

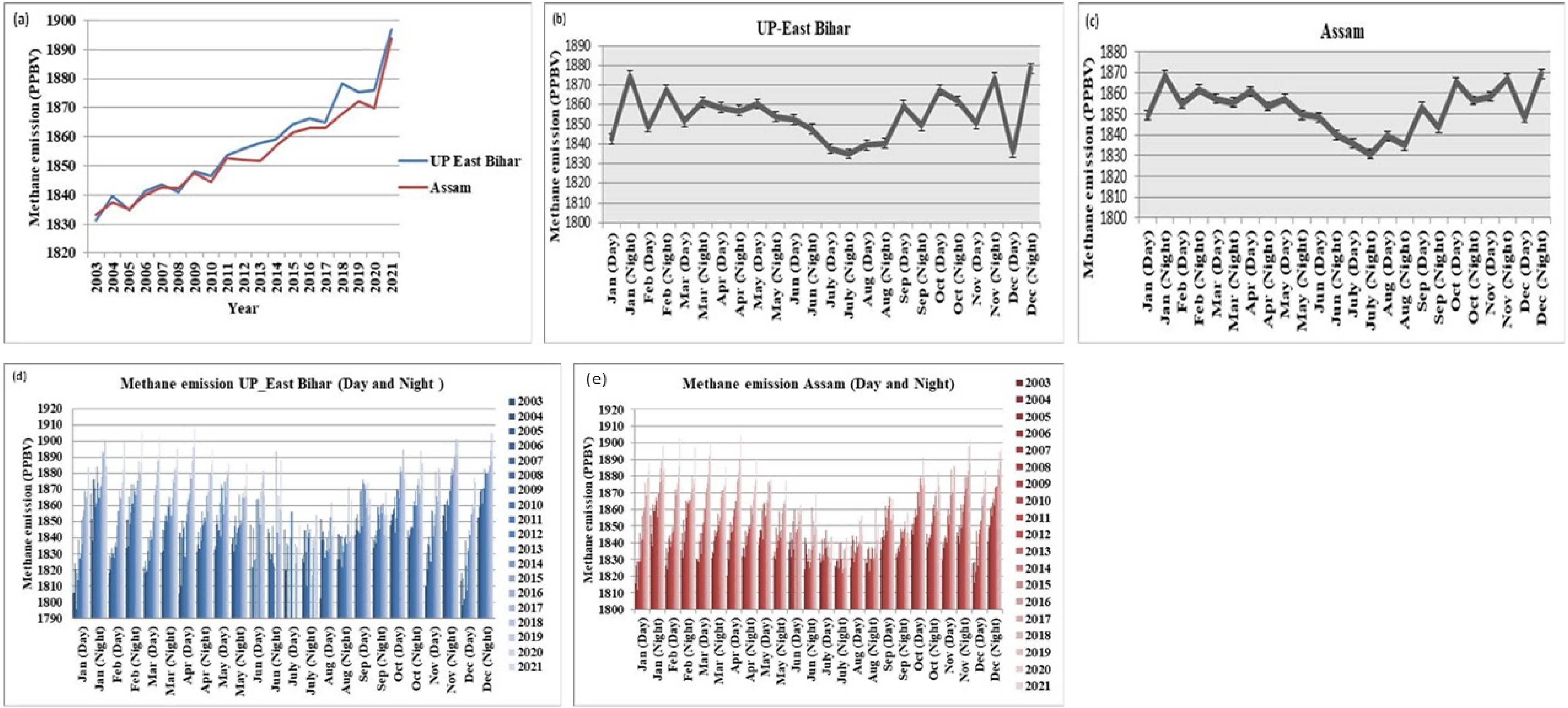

Figure 3. (**a**) Yearly methane emission of UP East, Bihar, and Assam over 19 years, (**b**) monthly methane emission of UP East and Bihar over 19 years, (**c**) monthly methane emission of Assam over 18 years, (**d**) monthly and yearly comparative methane emission pattern of UP East and Bihar over 19 years, and (**e**) monthly and yearly comparative methane emission pattern of Assam over 19 years.

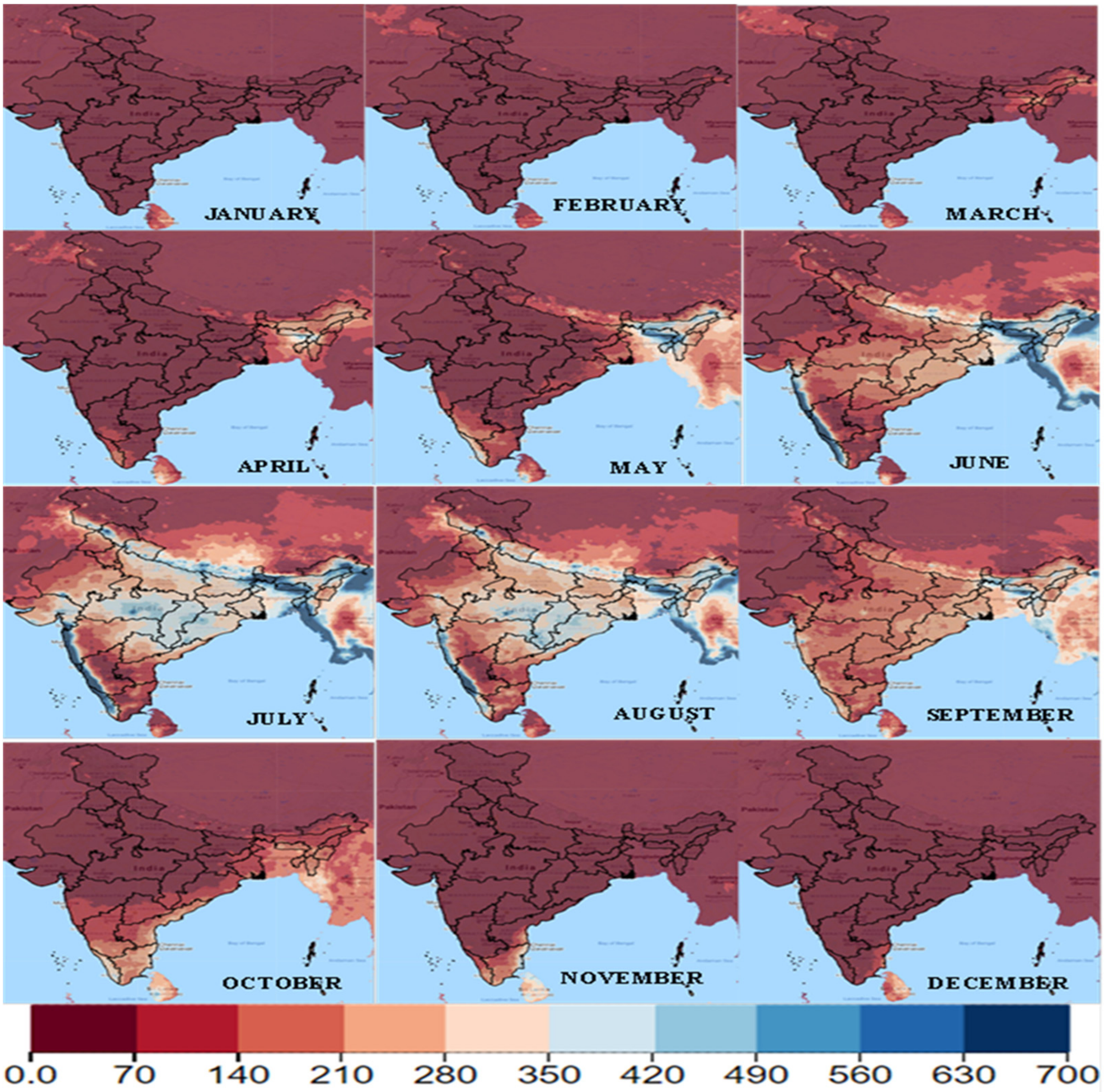

Figure 4. Satellite data of the monthly rainfall pattern of India over 41 years.

3.3. *Monthly Vegetation Pattern and Methane Emission*

Figure 5 shows 41 years of vegetation data of India, including UP East, Bihar and Assam, and also shows the lowest vegetation from April to July and the highest from August to October. The vegetation is dependent on the raining pattern. As we discussed earlier, the months of March and November show average rainfall, the lowest rainfall is observed in April and May, and the highest is observed from June to September. During the lowest rainfall from April to May, it shows less vegetation, and from June to September, higher rainfall increases the rate of vegetation, mainly from August to October (Figure 5). Similarly, increasing the rate of vegetation from August to October supports an increment in the methane emission rate, which started to increase from September to April in UP East, Bihar, and Assam (Figure 3d,e). Higher growth of rice plants and wetlands ecosystem plants was identified after August and many studies support our finding that the higher rate of vegetation after the monsoon increased the rate of methane emission (Figures 3d,e and 5) [66–68].

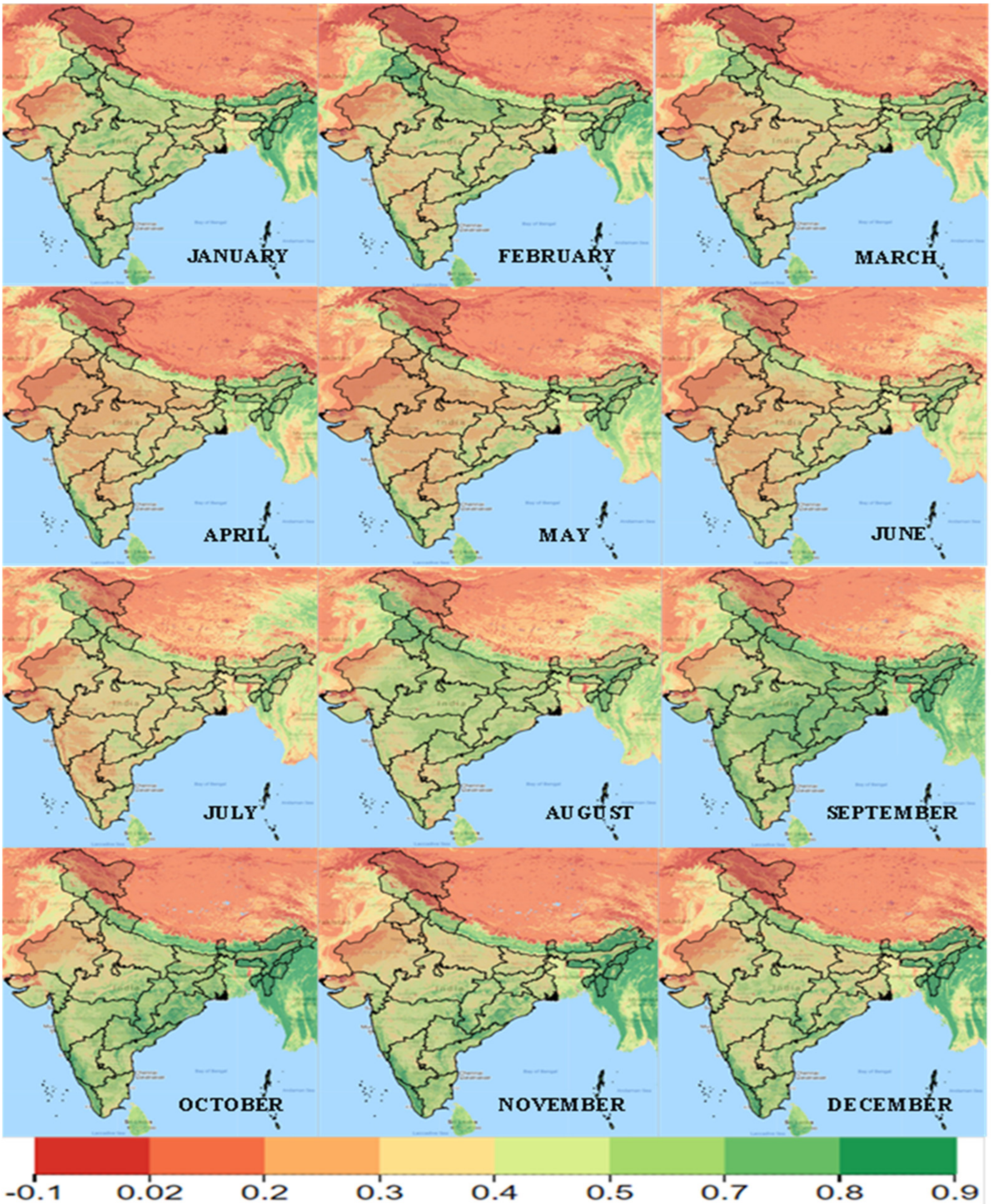

Figure 5. Satellite data of the monthly vegetation pattern of India over 41 years.

3.4. Monthly Temperature Pattern and Methane Emission

The temperature data of 41 years on average show the highest temperature recorded from April to August (Figure 6) and the lowest from September to March, which is optimal for rice growth. Thus, it was observed that the activity of methanogens is influenced by rainfall, temperature, and the amount of vegetation present in a given area [68]. A decrease in methane emission is influenced by methanogen activity in rice and wetlands [69]. Many scientific studies have shown an increase in the amount of soil organic material enhancement of CH_4 production and thus a potential increase in CH_4 efflux from the soils into the atmosphere [30]. Thus, the presence of organic matter plays an important role in methane emissions by methanogenesis [6].

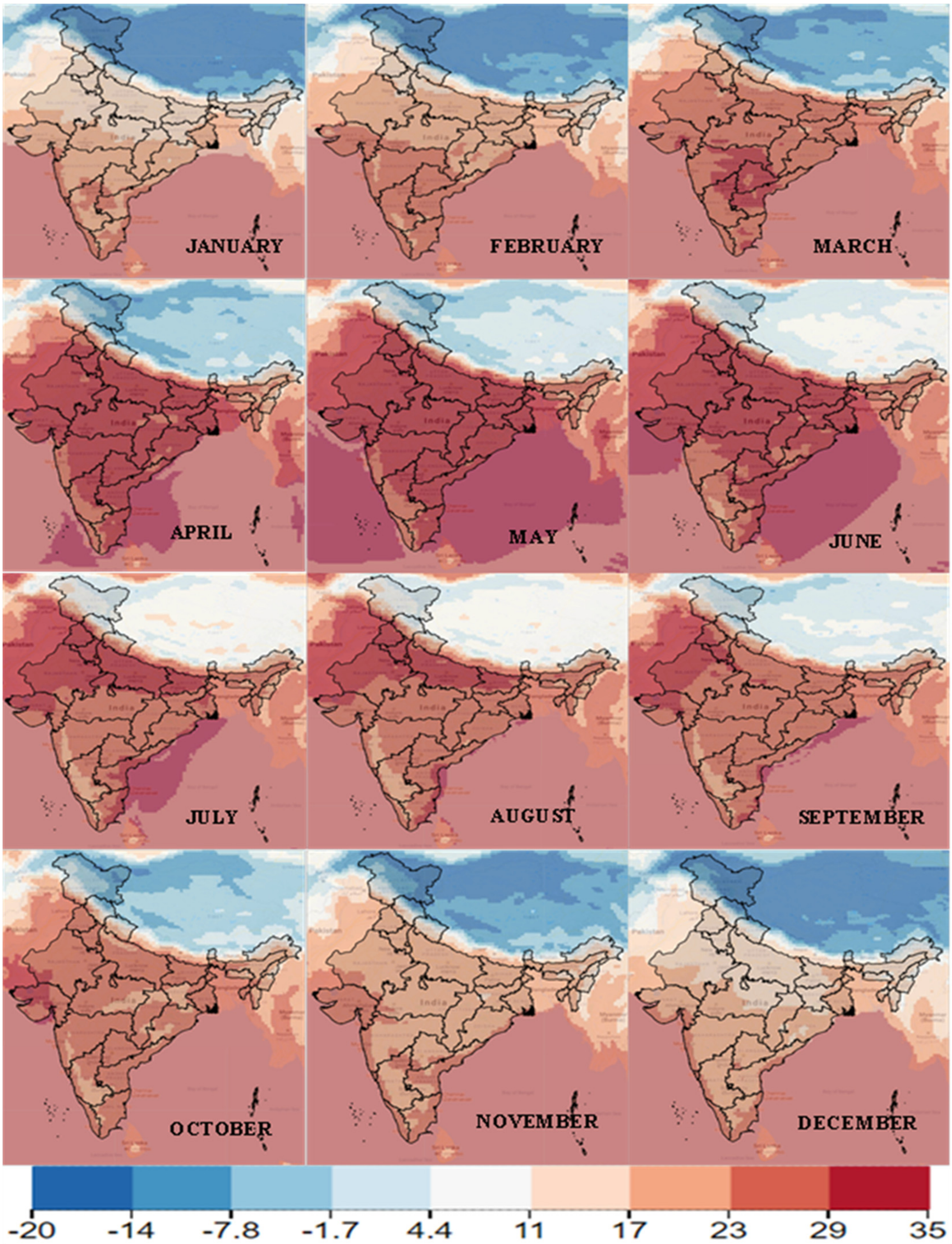

Figure 6. Satellite data of the monthly temperature pattern of India over 41 years.

During the higher temperature months, which is the April to August period, vegetation was low, leading to a decline in methanogen activity. Rainfall is also an important factor for methanogens as, according to this study, low rainfall occurs from November to March. An increase in temperature and low rainfall leads to a decrease in wetland areas, and during this time rice is not cultivated, thus decreasing the activity of methanogens and causing low methane emission [4,70,71]. Methane emission through methanogens is not solely affected by a single environmental factor but by various other environmental factors simultaneously.

4. Conclusions and Prospects

The current study describes the impact of temperature, rainfall, and vegetation affecting methane emission through paddy fields and wetlands. Various strategies have been employed to mitigate methane emissions without decreasing productivity. Short-term pre-digestion of green manure soil before flooding into paddy fields can be a good soil management strategy to mitigate methane emission [72]. The combined application of biochar and slow release of fertilizers can minimize methane emissions and maximize rice yield [73]. Methanotrophs' application in paddy fields can decrease methane emission by 60% and increase grain yield by 35% [74]. Selection of suitable rice varieties with high grain yield and a lower rate of CH_4 emission can be a feasible option for reduction of CH_4 emissions from rice agriculture. Bharali et al. [75] identified the Kolong, Lachit, and Dikhow rice varieties as low CH_4 emitters. The rice + Azolla with moderate N fertilizer had the lowest yield-scaled methane emissions in the double cropping system [76]. Bioanode is aided as a source of electron acceptors and reduced methane emission, competing with methanogens for carbon and electrons [77]. The complex interaction in rice fields suggests a multifactorial farming practice for reduced methane emissions. GIS remote-sensing-based methane emission monitoring can be used to make strategies for rice cropping and wetland management [78].

Significant changes in soil microbial communities were observed after environmental watering, and we hypothesize that these changes were associated with changes in greenhouse gas emissions, illustrating the significance of soil microorganisms in wetland and paddy field management. Soil oxygen levels in wetlands and paddy fields may be affected by several factors, including diurnal temperature swings and fluctuations in water levels, both of which, in turn, may affect the diversity of microorganisms involved in the decomposition of soil organic carbon [79]. The dynamics of carbon storage and release in wetlands are complex to quantify because they vary depending on the environment. In general, compared to terrestrial ecosystems, wetland ecosystems exhibit accelerated plant growth (vegetation) and slower rates of decomposition, both of which promote carbon storage that creates anaerobic conditions; however, anaerobic wetlands could result in higher methane (CH_4) emissions [79,80]. We propose that changes in greenhouse gas emissions were associated with the watering condition, availability of carbon sources for the nutrition of methanogen bacteria that come in wetlands from the decomposition of plant materials, and temperature conditions. We observed the highlighting of the significance of soil microorganisms in wetland management plans. Overall, the environmental watering programmed in this wetland ecosystem has resulted in benefits for the reduction of methane emissions. Determining the precise magnitude of the impacts of different water and fertilizer practices on soil and CH_4 emissions in paddy fields is crucial for future efforts to slow the rate at which the planet warms [81]. Water-efficient irrigation not only reduced soil CH_4 emissions but also increased rice yield, as we summarized using a large database. Both methane emissions and rice harvests benefited greatly from fertilization. Sustainable development in agricultural ecosystems can be achieved through studies that focus on the interactions between fertilizers, intermittent irrigation, and the associated microbial mechanisms, leading to higher rice yields while reducing soil CH_4 emissions. Application of nano-fertilizer and biochar show potential for the mitigation of methane emission from soil that helps in methane emission management in rice paddy fields [82].

New rice varieties have been found to have varying effects on greenhouse gas emissions, particularly that of methane, in several of the field studies [83,84]. Rice plants' physiology controls methane emissions by providing carbon for methanogenic substrates in the roots (including exudates) and by transporting CH_4 emissions through the aerenchyma [85–88]. The emission levels of various rice cultivars have been shown to differ in a series of studies. Growing and measuring emission levels from five cultivars commonly grown by smallholder farmers and five high-yielding improved varieties throughout an entire growing season allowed us to determine how different rice genotypes affect CH_4 emissions [89]. In contrast to conventional cultivars, which showed abundant vegetative growth associated with an increase in GHG emissions, the improved high-yielding varieties had lower emission levels [88].

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