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Maximum entropy modelling for predicting the potential distribution of methanogens in Sundarban mangrove ecosystem, India

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The production of methane (CH_4) by methanogens (*Mgen*) in mangrove sediments is known to contribute significantly to global warming. In such an estuarine environment, the abundance and population assemblage of *Mgen* are not well understood. Recently, there has been an increase of interest to understand about the properties of habitat distribution and the main environmental factors that influence mangrove suitability. Here, we used a maximum entropy (Maxent) species distribution model and a geographic information system (GIS) to determine the current habitat suitability distribution of *Mgen* in the Sundarban mangrove ecosystem in India. The Worldclim elevation (*elev*), precipitation (*precp*), solar radiation (*srad*), average temperature (t_{avg}), maximum temperature (t_{max}), minimum temperature (t_{min}), water vapor pressure (*vap*) and the wind speed (*wind*) data and 36 spatially well-dispersed species occurrence points were used to predict the potential distribution of *Mgen* in the 14,317 km^2 study area. The results indicated that *Mgen* has a high potential distribution at the deforested areas adjacent to the riverine system in the Indian Sundarban mangrove ecosystem. Jackknife test was used to evaluate the importance of the environmental variables for predictive modeling. The *prcp* is the most important environmental variable which influences the distribution of *Mgen* in mangrove sediments. With an AUC (area under curve "Sensitivity vs. Specificity") of 0.826, the Maxent model was extremely accurate. The study shows that Maxent could be a useful tool for species rehabilitation and biodiversity conservation planning in the face of climate change.

Keywords: methane, entropy, maxent model, ecological niche.

УДК 579.266

Моделирование методом максимальной энтропии для прогнозирования потенциального распределения метаногенов в экосистеме мангровых зарослей Сундарбан в Индии

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Известно, что производство метана (CH_4) метаногенами (*Mgen*) в опаде мангровых зарослей вносит значительный вклад в глобальное потепление. В среде таких эстуариев численность и состав популяций *Mgen* изучены недостаточно. В последнее время возрос интерес к пониманию свойств распределения основных факторов окружающей среды, влияющих на пригодность мангровых зарослей для обитания метаногенов. В данном исследовании модель максимальной энтропии (Maxent) распространения видов и техника географической информационной системы (ГИС) были использованы, чтобы определить текущее распределение пригодности среды обитания *Mgen* в экосистеме мангровых зарослей Сундарбан в Индии. Для прогнозирования потенциального распространения видов *Mgen* на изучаемой территории площадью 14 317 км^2 были использованы сведения из базы данных Worldclim о высоте местности над уровнем моря (*elev*), количестве осадков (*precp*), солнечном излучении (*srad*), средней (t_{avg}), максимальной (t_{max}) и минимальной температуре воздуха (t_{min}), давлении водяного пара (*vap*), скорости ветра (*wind*), а также данные по 36 пространственно хорошо рассредоточенным местам обитания этих видов. Результаты показали, что *Mgen* имеют высокий потенциал распространения на обезлесенных территориях, прилегающих к речной системе в мангровой экосистеме Сундарбан в Индии. Для оценки значимости переменных окружающей среды для прогностического моделирования использовался тест методом «складного ножа». Наиболее важным параметром окружающей среды, влияющим на распределение *Mgen* в опаде мангровых зарослей, является количество осадков. При значении площади под кривой «специфичность–чувствительность» AUC = 0,826 модель Maxent оказалась чрезвычайно точной. Исследование показывает, что метод Maxent может быть полезным инструментом для планирования восстановления видов и сохранения биоразнообразия в условиях изменения климата.

Ключевые слова: метан, энтропия, модель максимальной энтропии, экологическая ниша.

Methane (CH_4) is the key gas produced in the anaerobic environments, which is the second most abundant greenhouse gas (GHG) associated with climate change [1]. In terms of GHG emissions, the CH_4 is approximately 25 times more effective than the CO_2 [2]. The source of global CH_4 emissions is unclear, but microbial processes in anoxic environments such as termites, natural wetlands, ocean, gas hydrates, paddy fields, ruminants, landfills, and sewage treatment lead to 69% of CH_4 emissions [3]. Wetlands are the world's largest natural source of CH_4 emission, contributing for around 25% of the global CH_4 budget [4], of which 50–60% is contributed by natural tropical wetlands [5].

Mangroves are typical example of mesophilic and moderately halophilic environmental niches [6]. Mangroves are one of the most productive habitats on the planet, providing a wide range of benefits to the society. The diverse microbial communities of mangroves play an important role in the cycling of nutrients in the environment [7]. The *Mgen* belong to the Euryarchaeota phylum of the Archaea domain which comprises six phylogenetically distinct orders, *Methanobacteriales, Methanococcales, Methanomicrobiales, Methanocellales, Methanopyrales,* and *Methanosartinales,* as well as 33 genera based on 16S rRNA gene sequences [8]. The *Mgen* contains three major methanogenesis pathways: hydrogenotrophic, acetoclastic, and methylotrophic [3]. Across the river-bay spectrum, where continental freshwater meets oceanic water, methanogenic ecosystems are vulnerable to such stenohaline environment. It is crucial to point out major players involved in CH_4 production to understand the spatial and seasonal variability of *Mgen* in the river-bay system.

The drivers of *Mgen* from the mangrove beds are highly dynamic, which influences the emission process. So far, no such study on the distribution model of *Mgen* from mangrove system has been found under the huge body of literature. Therefore, the present work is probably a novel attempt to study the Maxent modeling of the *Mgen* distribution from the mangrove ecosystem. Predictive modeling of species spatial distributions based on environmental conditions at established occurrence sites is a useful technique in analytical biology, with applications in conservation and reserve planning, ecology, invasive species management, and other fields [9]. The Maxent modeling was used to predict the current *Mgen* distributions in the Sundarban mangrove ecosystem using a comprehensive array of geo-referenced occurrence records and recent surveys to evaluate the properties of habitat distribution and environmental factors shaping habitat suitability.

Material and methods

Study sites. The study area is the Indian part of Sundarbans delta comprising blocks of the North and South 24 Parganas districts in the state of West Bengal. It lies between 21º27′06″N to 21º50′18″N latitude and 88º14′26″E to 88º53′05″E longitude. The Sundarbans are located in the Bay of Bengal, on the delta formed by the Ganges, Brahmaputra, and Meghna rivers. The total annual precipitation ranges from 1500 to 2000 mm. The seasonal minimum and maximum temperatures range from 12 to 24 ºC and 25 to 35 ºC, respectively [10]. All along the forests, land reclamation activities for hotels, resorts, and plantations, both agricultural and aquaculture, have sprouted. The dominant species among the halophytes are *Avicennia marina, A. alba, Porteresia coarctata, Exoecaria agallocha, Ceriops decandra, Acanthus ilicifolius* and *Derris trifoliate* [1].

Data sources of CH_4 emissions. The *Mgen* records were obtained from previously published literature in the Indian portion of the Sundarban mangrove ecosystem for this research. The last ten years presence only data of *Mgen* were collected from the authenticated research papers [11–18]. Google Earth was used to gather record coordinates for those data which were not collected through literature. Duplicate records were manually deleted, and records with apparent geocoding errors were discarded. Finally, the Sundarban mangrove ecosystem generated 36 *Mgen* distribution records.

Data sources of environmental variables. The most influential variables associated with

Mgen distribution were identified using eight environmental variables with a spatial resolution of 10 minutes (1 km), downloaded from the WorldClim dataset (Version 2.0, www.worldclim.org) [19].

The environmental variables such as elevation (m) (*elev*); precipitation (mm) (*precp*); solar radiation ($kJ/(m^2 \cdot d)$) (*srad*); average temperature (°C) (*tavg*); maximum temperature (°C) (*tmax*); minimum temperature (°C) (*tmin)*; water vapor pressure (kPa) (*vap*); and wind speed (m/s) (*wind*) were retained to simulate the current and future distributions of *Mgen* in Sundarban mangrove ecosystem. The spatial data layers for the model run were generated using ArcMap 10.3. The permutation importance and percent contribution are essential factors in determining the importance of environmental variables. The permutation value was based on the final output of the model rather than the direction taken in a single run.

Model description. In the information theory, entropy is a basic principle. Shanon [20] described entropy as "a measure of how much 'choice' is involved in the selection of an event". As a result, a distribution with a higher entropy has more choices. The principle of the Maxent method is to ensure that approximation meets all constraints on unknown sites, which means that the approximate probability of an unknown distribution has less constraints but more choices [21]. The model can be defined by the following equation:

$$H(\hat{\pi}) = -\sum_{x \in X} \hat{\pi}(x) \ln \hat{\pi}(x),$$

whereas $H(\hat{\pi})$ – *Mgen* probability distribution, X – set of pixels in the study area, $\hat{\pi}(x)$ – non-negative probability to each point x.

Maxent (version 2.1) was used through http://www.cs.princeton.edu for scientific research. The training data consisted of 75% of the sample data, chosen at random. The test data consisted of the remaining 25% of the sample data. The regularization multiplier value was 0.1 to avoid over-fitting the test results [22]. The number of background points used here was restricted to 5,000. The goodness-of-fit of the model was measured using the area under the receiving operator curve (AUC). The model with the highest AUC was considered the best performer. The contributions of each variable to habitat model of *Mgen* were calculated using the jackknife test as built-in function of the software. The habitat suitability curves of each variable were calculated. The jackknife test (systematically eliminating each variable) was used to decide the climatic variables were the most relevant in assessing potential distribution of species. Limiting factor mapping was also used to investigate how the climatic factors that have the greatest influence on predictions differ across the study region. The final potential species distribution map had a range of values from 0 to 1 that were regrouped into three potential habitat classes: high potential (0.62–1.00), moderate potential (0.23–0.61), and least potential (0.00–0.22).

Results and discussion

The habitat suitability curves for each environmental variable are shown in Figure 1 (see color insert III). The *Mgen* prediction accuracy was found to be "excellent" during the current period (AUC mean = 0.826) (Fig. 2a, see color insert IV). The results of the jackknife test revealed that the selected variables accurately represented the current *Mgen* distribution (Fig. 1j). According to model, prediction among the eight environmental variables, the *precp* contributes 46.3%, the *vap* contributes 29.5%, the *srad* contributes 9.3%, the t_{min} contributes 7.4%, the *wind* contributes 4.3%, the *elev* contributes 1.7%, the t_{max} contributes 0.8% and the t_{avg} contributes 0.7%. Considering the importance of permutation, the *precp* (74.8%) was much higher than others, and played a vital role in predicting the probable distribution of *Mgen*.

Microorganisms play a significant role in the global biogeochemical cycling of estuarine environments [23]. Several environmental variables and important factors influence *Mgen* population in estuarine sediments [24]. The spatial changes in sediment temperature were negligible in Sundarban, but the temporal changes are important. Despite the fact that the temperature was slightly lower during the monsoon than during the summer, methanogenesis was significantly higher. As a result, it can be said that seasonal temperature fluctuations have little impact on methanogenesis.

During the monsoon season (July–October), the tropical mangrove ecosystem receives more rainfall. The *Mgen* density peaked during the rainy season, and plunged by two orders of magnitude during the season [25]. Increased freshwater production during the rainy season provided favorable conditions for *Mgen* proliferation. The condition mobilizes mangrove sediment, which then releases the nutrient that acts as a substrate for the *Mgen* [26]. Thus, episodic rain has a significant impact on the *Mgen* population. The rate of CH_4 production was found to

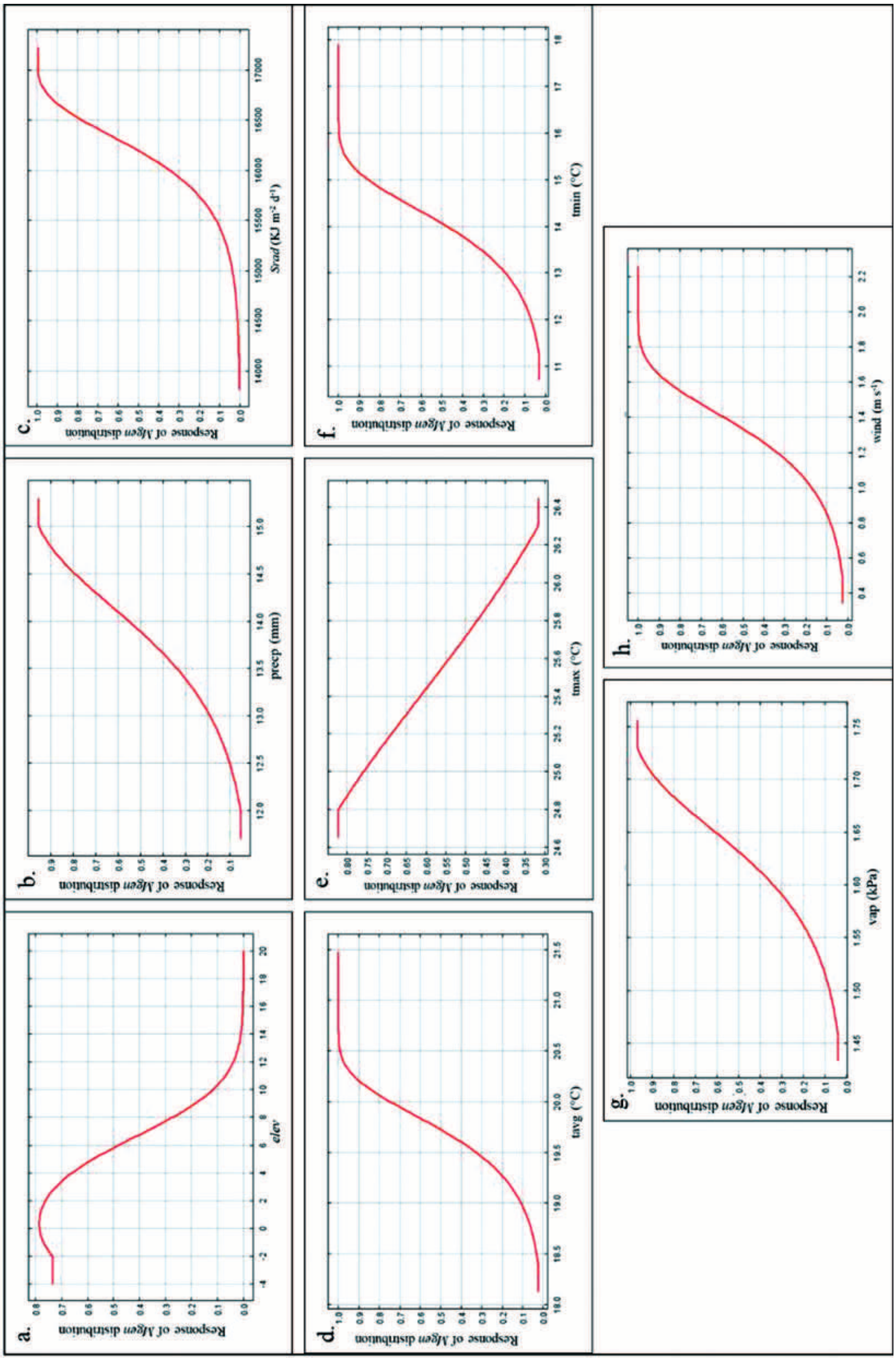

Fig. 1. Mgen's SDM response curves for significant environmental predictor variables.
Mgen response curve for (a) *elev*, (b) *precp*, (c) *srad*, (d) t_{avg}, (e) t_{max}, (f) t_{min}, (g) *vap*, (h) *wind*

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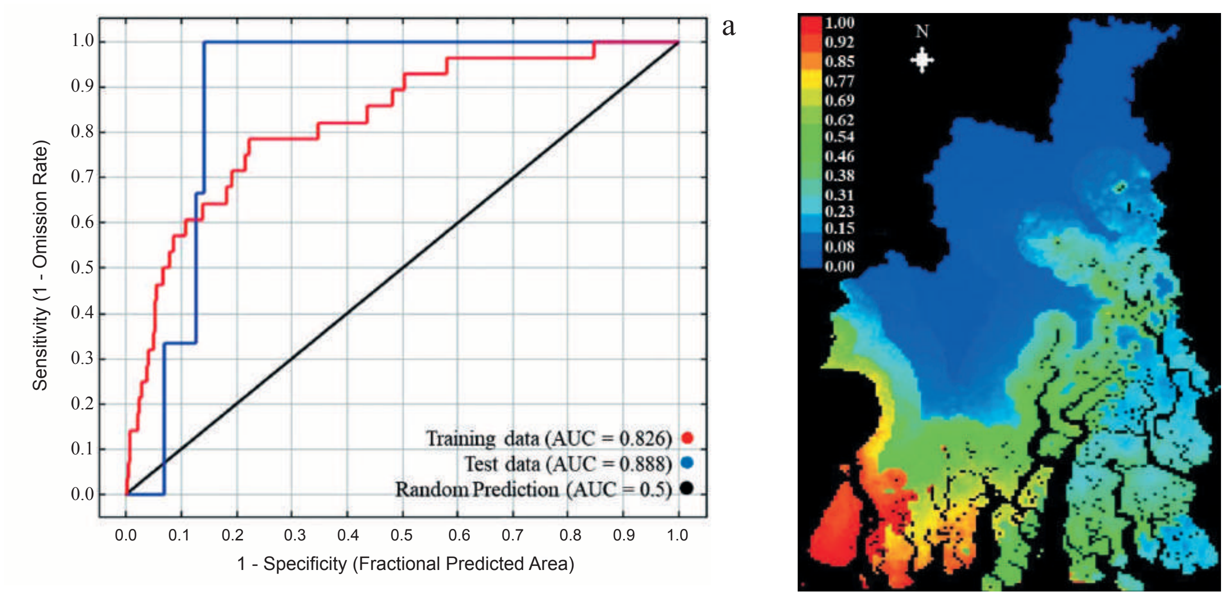

Fig. 2. Under the current time, the ROC curve and AUC value after 10 replicated runs (a) and Jackknife test of variable importance for *Mgen* distributions (b)

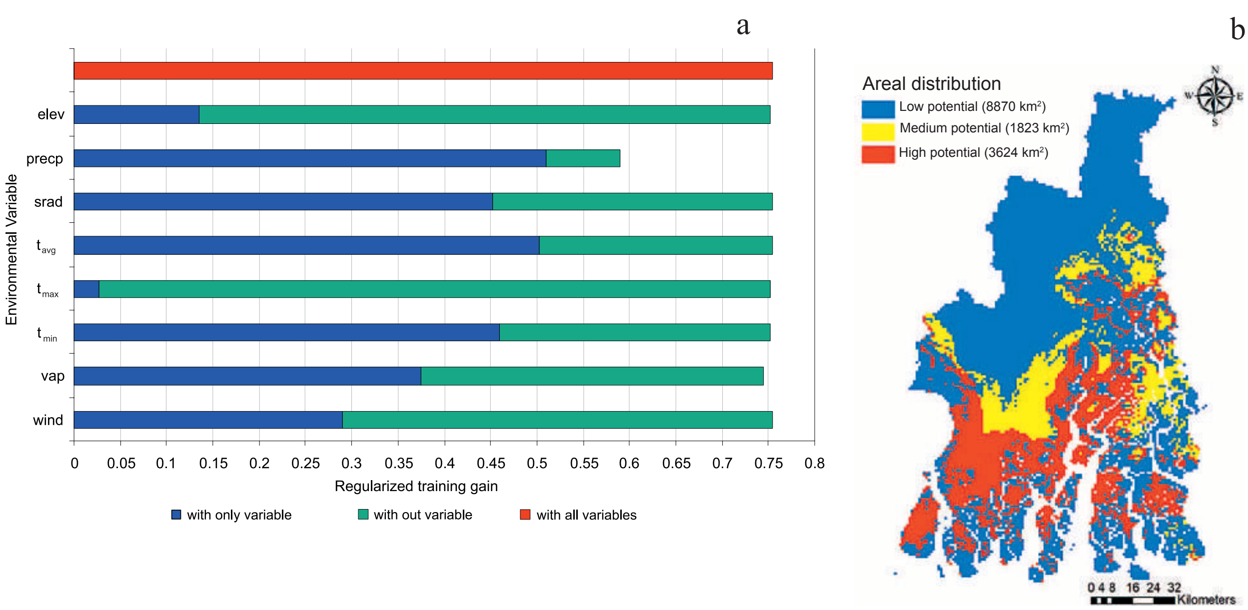

Fig. 3. Current suitable climatic distribution of *Mgen* in Sundarban mangrove ecosystem, India (a), Areal distribution of *Mgen* in Sundarban mangrove ecosystem, India (b)

be positively associated with the population of *Mgen*, suggesting that *Mgen* plays a significant role in CH_4 production [27]. *Mgen* abundance from hydrogen and acetate increased during the rainy season under low sulfate concentrations. Hydrogen contributes 33% methanogenesis when carbohydrates or related organic matter are degraded, making it essential in environments with high sedimentation rates (approximately 10 cm/yr) and organic carbon supplementation [28]. The recurrence of *Mgen* was most likely due to their ability to use a range of electron donors in an environment with a steady supply of organic matter from rivers and run-off from surrounding mangroves [29]. In both acidic and alkaline conditions, methanogenesis will occur [30]. It was corroborated that the existence of generalist groups within the methanogens vary with the change in estuarine conditions [31].

The potential distribution of *Mgen* based on observed occurrences and current environmental conditions projected by the Maxent model is shown in Figure 3a (see color insert IV). From the total 14,317 km^2 of distribution area, 3,624 km^2 was highly suitable, 1,823 km^2 was moderately suitable, and 8,870 km^2 was least suitable for *Mgen* distribution in the Sundarban mangrove ecosystem (Fig. 3b, see color insert IV). The results showed that the highly suitable habitats (where, the presence probability was greater than or equal to 62%) for *Mgen* were primarily located in coastal South-West and central part of Sundarban mangrove ecosystem, mainly including Kakdwip, Patharpratima, Sagar, Namkhana, Kulpi, Kultali, Mathurapur II, Basanti, Gosaba, Canning I block (administrative division of the district) and central middle part of Sundarban national park of South 24 Parganas.

The Maxent model predicted that different species will have different distributions of potentially suitable areas. Previously, it was claimed that the *Mgen* population benefited from a more favorable climate [32]. It was concluded that methanogenesis thrived in lower salinity environments, the concentration of *Mgen* in riverine sediments was significantly higher than in estuarine sediments [33]. Under current conditions, *Mgen* was more likely to be found in the south-west portion of the Sundarban mangrove ecosystem, along the Hooghly River and adjacent creeks. Polluted wetlands have higher *Mgen* distribution and CH_4 emission rates than unpolluted wetlands [34]. The Hooghly estuary is flanked by a large number of factories, which have been directly or indirectly emptying trade effluents, as well as domestic and waste-water into the estuary, and this waste has been used by *Mgen* as a source of nutrients [35, 36]. Human activities, such as industrial and residential wastewater, discharge relatively high levels of nutrients into riverine sediments, which could serve as methanogenesis substrates [37]. The highly deforested and polluted administrative blocks of South 24 Parganas surrounding 3624 km^2 area of the Hooghly River such as Kakdwip, Patharpratima, Sagar, Namkhana, Kulpi, Kultali, Mathurapur II, Basanti, Gosaba, Canning I blocks and central-middle part of Sundarban national park has higher potential distribution of the *Mgen*. On the other hand, potentially distributed *Mgen* populations was found mostly in the central part of the Sundarban along the Malta estuary with 1,823 km^2 area including Mandirbazar, Jaynagar I, Jaynagar II and Mathurapur I blocks of South 24 Parganas and Basirhat I block of North 24 Parganas and upper part of the Sundarban national park. These areas were free from such industrial pollution, thus the distribution of *Mgen* was moderate. The population distribution of *Mgen* was low in mostly afforested part surrounding 8,870 km^2 area of the North and South 24 Parganas with less riverine systems except the high and moderately distributed blocks.

It was important to consider the impact of a global climate change scenario on *Mgen* distribution. Converting mangrove forest land into a cultivation area, where the methanogenesis and oxidation processes are in equilibrium, may increase net CH_4 emissions even further [38]. Anthropogenic activities that add more greenhouse gases in the future, especially from deforested areas, could affect the interaction between *Mgen* and methanotrophs. Mangroves that had not been disturbed released less CH_4 than crop fields and anthropogenically damaged mangrove forests, according to studies [39]. The mangrove forest conservation would help to preserve the CH_4 flux dynamics in a long-term way.

Conclusions

The sensitive environmental variable for *Mgen* distribution was considered to be precipitation (*precp*). Under the scenario of an urbanized deforested area surrounding the Hooghly River, the suitable habitat for *Mgen* tends to increase. The predicted spatial and temporal range trend of *Mgen* will be helpful in designing forest management and conservation strategies. Therefore, determining the causes of species distribution allows us to devise potential methods for preventing, slowing, or reversing negative patterns.

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