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RESEARCH ARTICLE

Species distribution modelling of *Cephaleuros parasiticus* Karst in India using the maximum entropy model

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Abstract **-** *Cephaleuros parasiticus* Karst, a parasitic green alga that causes severe damage to agricultural and horticulture crops needs a critical understanding of its dispersion patterns to develop an effective management strategy. This work aimed to examine the potential distribution of *C. parasiticus* Karst in India using maximum entropy (MaxEnt) modelling strategy. The species occurrence data were gathered from several places across India. Using MaxEnt, these occurrence records were linked with environmental characteristics such as climatic, topographic indicators to create a predictive distribution model. The model's performance was assessed using the Area Under the Curve (AUC) and visualized using distribution maps. This algal pathogen is most commonly found in tropical and subtropical areas with high humidity and warm temperatures; and in our study, the MaxEnt model accurately anticipated the algal parasite's potential distribution, suggesting its appropriateness for ecological niche modelling. The most relevant environmental variables were observed to be slope, Mean Diurnal Range (BIO2), Land Use and Land Cover (LULC), Precipitation seasonality (BIO15) and Annual precipitation (BIO12), providing insights into the species' ecological requirements and preferences. In addition, the analysis highlighted possible high-risk areas in Assam, West Bengal, Tamil Nadu, Kerala, Karnataka and Eastern and south western coastal lines of India for this algal parasite invasion, highlighting places that require immediate attention for prevention and management techniques. The results of this research will be beneficial in the management of ecological impacts of *C. parasiticus* Karst in India and other regions with similar environmental conditions.

Keywords: *Cephaleuros parasiticus* Karst, Habitat distribution, MaxEnt modelling, Parasitic algae, Algal pathogen

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1. INTRODUCTION

Parasitic algae, like *Cephaleuros parasiticus* Karst, embody the intricate relationship of reliance and exploitation in the plant world, as they weave their colourful threads into their unsuspecting hosts, absorbing nutrients and manipulating their physiology. This pathogenic alga, is a subaerial filamentous green alga that poses a significant threat to a wide range of plant species including economically important crops such as tea, coffee, guava, clove, magnolia, etc. (Jose and Chowdary, 1980; Chapman and Henk, 1986; Nelson, 2008; Hasan et al., 2014; Suto et al., 2014). This algal pathogen, which is a member of Division Chlorophyta, Class Ulvophyceae, Order Trentepohliales, and the family Trentepholiaceae, is well recognized as the causal organism of diseases such as red rust of tea, algal spot disease of Guava (Sunpapao et al., 2016; Guiry and Guiry, 2023). Since its initial discovery in the early 19th century, *C. parasiticus* Karst has been found in a wide range of locations throughout the world, mainly in tropical and subtropical climates, and may be found spreading its green tentacles over Southeast Asia, India, Australia, and South America (Cunningham, 1879; Mann and Hutchinson, 1907; Joubert and Rijkenberg, 1971; Brooks, 2004; Ponmurugan et al., 2010). Its prevalence in these areas can be attributed to the favourable environmental conditions that promote its growth and survival.

The algal parasite prefers leaves and tender shoots of the host plants as its habitat and in the case of tea plants, *C. parasiticus* Karst primarily infects the leaves, leading to the formation of distinct reddish-brown rust-like lesions, hence the name "red rust" (Joubert and Rijkenberg, 1971; Bhattacharyya et al., 2016). These lesions can negatively impact the photosynthetic capacity of the tea plant, ultimately affecting its growth and productivity, as well as can spread rapidly within tea plantations, facilitated by wind, rainwater, and even human activities (Ponmurugan et al., 2010). Subsequently, this particular green alga is extremely adaptable, making it an excellent parasite, which further makes it highly detrimental to its host plants in terms of environmental consequences (Borah et al., 1978; Chapman and Good, 1983). It not only depletes the tree's nutrition and energy, but also lowers the tree's capacity to photosynthesize, restricting growth and fruit output (Ponmurugan et al., 2010). This parasite causes stunted development, poor health, and lower nutritional content in the fruit, all of which contribute to decreased agricultural yield (Suto and Ohtani, 2009). Besides agricultural issues, it may have a harmful influence on the ecosystem, where its establishment on trees reduces chlorophyll content thus depleting the tree's capacity to photosynthesize and to function as a carbon sink (Borah et al., 1978; Himel et al., 2021). Hence, the presence of the pathogen not only leads to economic losses in the forestry and agricultural sectors but also may pose a significant threat to global carbon sinks, making its management a critical and pressing issue.

However, due to the highly adaptive nature and rapid colonizing ability of the algal parasite, it has been proved to be quite difficult to control its growth (Sunpapao et al., 2016). In recent years, the incidence of infections in Indian tea plantations has shown an alarming increase, necessitating a comprehensive analysis of its potential distribution. Therefore, a mix of approaches, including pruning and removal of affected regions, water management, and the application of fungicides or suitable fertilizers as well as accurate knowledge of the geographical distribution of *C. parasiticus* Karst is essential for developing effective disease management strategies. It will enable the implementation of targeted interventions and preventive actions, limiting the pathogen's negative effects on the economy and the environment.

To study about habitat distribution of an organism, researchers employ various techniques and tools, including Species Distribution Models (SDMs), which utilize available species distribution data and pertinent environmental information to anticipate suitable geographic areas and evaluate and prioritize influential environmental factors (Li et al., 2023). These include MaxEnt (maximum entropy model), ENFA (ecological niche factor analysis), GLM (generalized linear model), GAM (generalized additive model), GARP (genetic algorithm for rule-set prediction), BIOCLIM, and CLIMEX (Ngarega et al., 2022). Among these types, MaxEnt modelling has been extensively used for ecological studies, where MaxEnt based analysis helps in predicting the species distribution through incorporating crucial environmental factors, that is especially useful when there is a very limited data available on species occurrences (Phillips and Dudík, 2008; Ngarega et al., 2022; Ejaz et al., 2023; Wang et al., 2023). Consequently, the habitat suitability maps produced from MaxEnt based analysis provide valuable insights into the ecological niche and potential distribution of a given species, thus helping the researchers to have a better understanding of the ecology of these species as well as their significance in a particular location (Peterson, 2006).

For examining the distribution of different plant diseases and their causative agents, researchers have found great success with MaxEnt models (Ngarega et al., 2022; Ejaz et al., 2023; Wang et al., 2023). For example, MaxEnt modelling has been applied in predicting the potential distribution of *Phytophthora ramorum*, the causal agent of sudden oak death, under environmental factors like temperature and precipitation (Lin and Ye, 2020). Through a similar approach, *Puccinia komarovii* var. *glanduliferae* displayed a global distribution, largely concentrating in temperate European regions and the southern Himalayas, nevertheless, areas such as the Pacific Northwest and Southeastern Australia showed lower suitability (Humbeek, 2023). In case of China, another study predicted the potential distribution of three pine species and *Bursaphelenchus xylophilus*, with precipitation as one of the most influential environmental factors. Furthermore, MaxEnt based analysis of a vector-borne pathogen *Xylella fastidiosa*, the causal agent of various plant diseases, highlighted the impact of climate change on its expansion (Raffini et al., 2020). Thus, in this context, by integrating species occurrence records with environmental data, MaxEnt modelling may also help assess the potential habitat distribution of algal pathogens. In this paper, our study uses a MaxEnt-based approach to investigate the distribution status and potential habitat distribution of *C. parasiticus* Karst in India and to analyse the key environmental factors affecting the natural distribution of this parasitic species. By integrating climatic and topographic indicators, and being locally focused, we provide a comprehensive understanding of the factors that influence the pathogen's distribution, with maximal relevance for the areas most affected by it. This comprehensive approach will further elicit a more nuanced understanding of the ecological requirements and preferences of *C. parasiticus* Karst.

2. MATERIALS AND METHODS

2.1. Study Area

With its wide range of geographical and climatic conditions, India is a perfect area to study species distribution modelling of *C. parasiticus* Karst using the MaxEnt model. India, which spans latitudinal coordinates from 8°4' to 37°6' North and longitudinal coordinates from 68°7' to 97°25' East (Fig 1), is home to a diverse array of habitats and experiences monsoonal climate fluctuations, which is marked by seasonal variations in temperature and precipitation. These diversity supports varied bioclimatic regions, which are crucial for understanding the distribution of the algal pathogen.

Meanwhile, as the causative agent of red rust in tea and a pathogen that thrives best in tropical and subtropical regions, *C. parasiticus* Karst is a crucial player in the management and production of tea in the case of Indian scenario (Suto et al., 2014). India serves as an ideal study area for this algal pathogen due to its prominent tea industry in Assam, West Bengal, Tamil Nadu, Kerala and Karnataka and diverse geographical regions conducive to tea cultivation. According to the report of Indian Tea Association, India's primary tea growing regions include Assam, followed by Darjeeling, Dooars and Terai, Kangra, Nilgiri, Anamallais, Wayanad, Karnataka, Munnar and Trancore.(https://www.indiatea.org/tea_growing_regions).

Therefore, as one of the world's largest producers and consumers of tea, India may face substantial economic losses attributed to diseases like red rust. Investigating the prevalence and distribution of this pathogenic algal strains across the Indian subcontinent can provide valuable insights into disease management strategies that are adapted to the unique agronomic and environmental circumstances of the area.

2.2. Collection of occurrence data

The occurrence data for *C. parasiticus* Karst was gathered from various sources. The Global biodiversity Information Facility (GBIF, http://www.gbif.org/), which offers a thorough collection of data on any species distribution was consulted. To collect data on occurrences, field surveys were also carried out in the four agro-climatic regions consisting of the Brahmaputra Valley, Assam, India which

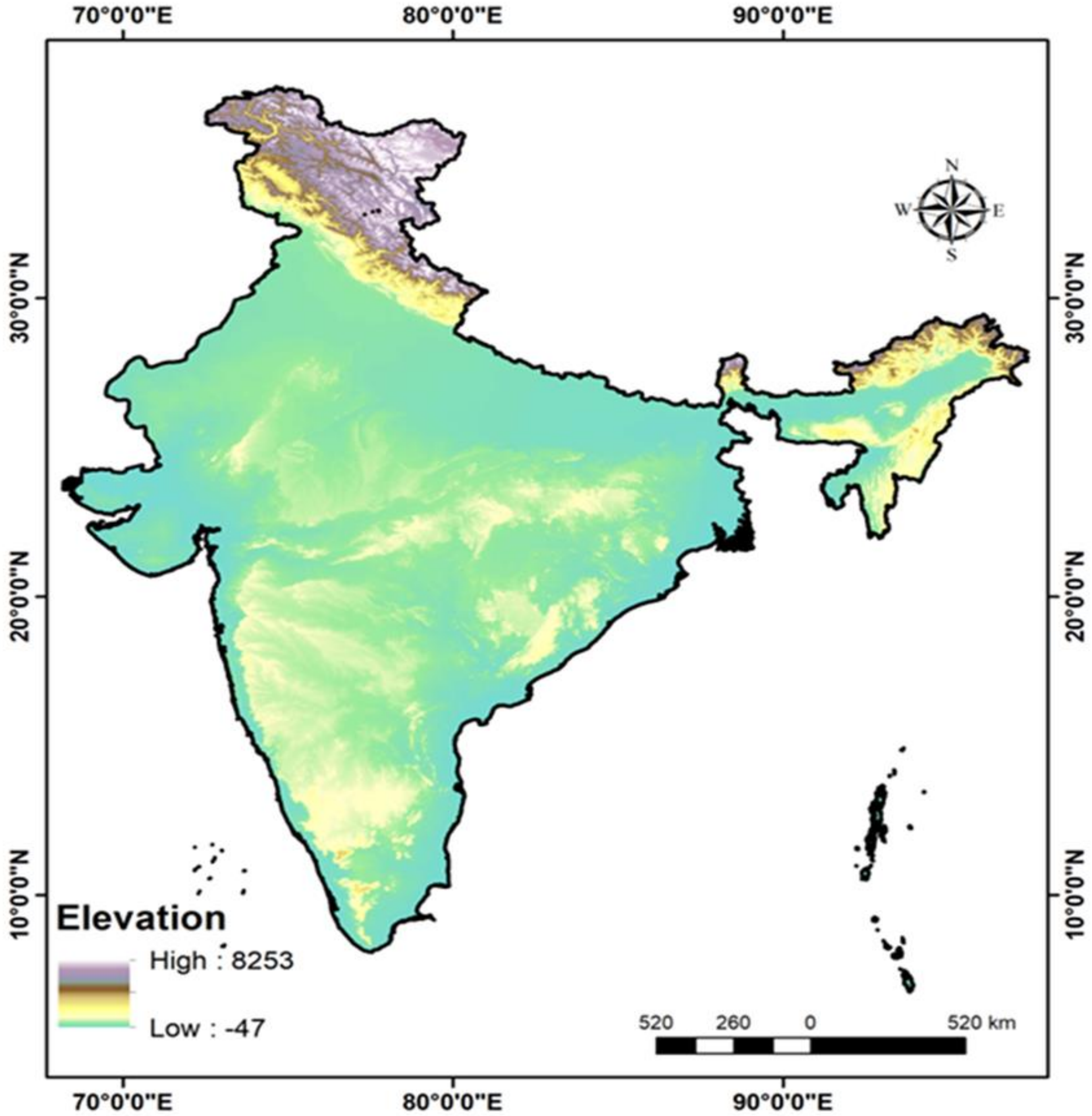

Fig 1: Location map of India

is one of the major tea growing areas in India and from each region, the samples were collected randomly. Following the protocol suggested by Wan et al. (2020), *the alga's* presence and geographic distribution described in pertinent articles were also consulted for the literature review and for modelling inputs also (Borah et al., 1978; Ponmurugan et al., 2010; Ramya et al., 2013; Hasan et al., 2014; Bhattacharyya et al., 2016; Devarajan et al., 2018; Himel et al., 2019). In instances where precise geographic coordinates were unavailable for a particular record, we employed Google Earth (http://ditu.google.cn/) to ascertain the latitude and longitude by referencing the provided geographic location description. Data from these sources were combined to produce a solid dataset) that aided in the later MaxEnt analysis of the spread of *C. parasiticus* Karst habitat (S1).

2.3. Environmental variables

The environmental variables are biologically important indicators that indicate how climate affects ecosystems and organisms' niches. To carry out the MaxEnt analysis nineteen environmental variables were downloaded from worldclim.org (Fick and Hijmans, 2017), and the Terra Aqua combined Moderate Resolution Imaging Spectroradiometer (MODIS), MCD12Q1 (Friedl and Sulla-Menashe, 2019) land cover type was used for the land use raster. A multicollinearity test was conducted between the nineteen environmental variables along with elevation, slope, land use and aspect, and those with a cross-correlation of 0.8 or more were excluded from the model (Mehmud et al., 2022) (Fig 2, Table 1, S2, S3). In addition, the Shuttle Radar Topographic Mission (SRTM) (Rodríguez et al., 2005) elevation raster was utilized in the study area.

2.4. Ecological modelling and validation

The MaxEnt version used in this study is 3.4.0. we have used 70 percent presence records used for training, 30 percent for testing. We used 10 replicated run. The maximum iteration is 500. The model validation is done on AUC values. As the output format is in logistic and giving a range of 0 to 1 (S3). The threshold values selected as 0 - 0.2 (least potential), 0.2 -0.4 (moderate), 0.4-0.6 (good), 0.6 -0.99 (high potential).

Table 1: Environmental variables used in the model

BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3 = Isothermality (BIO2/BIO7) (×100)
BIO4 = Temperature Seasonality (standard deviation ×100)
BIO12 = Annual Precipitation
BIO14 = Precipitation of Driest Month
BIO15 = Precipitation Seasonality (Coefficient of Variation)
BIO16 = Precipitation of Wettest Quarter
BIO17 = Precipitation of Driest Quarter
Aspect
LULC
Slope

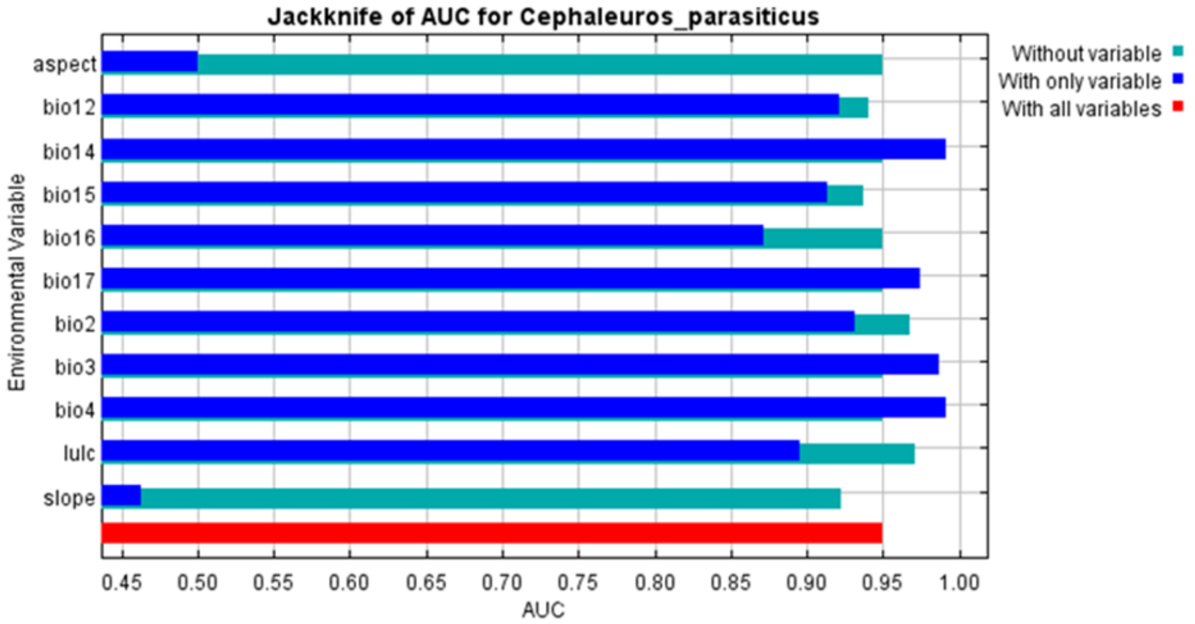

Fig 2: Jackknife test of environmental values for studying *Cephaleuros parasiticus* Karst's habitat distribution

3. Results and Discussion

The training AUC is 0.953 and the test AUC is 0.950 for the model. This provides the model with a very high acceptance. A total of 20 occurrence points were collected. Spatial autocorrelation and spatial thinning were performed to ensure robust modelling results. Initially, 8 presence records were used for training, with 3 reserved for testing. In subsequent replicated runs, we employed various methods, including cross-validation, subsampling, and bootstrapping. Bootstrapping was particularly favoured, especially given the small sample size in the Indian context. The resulting map aligns with major tea-producing states in India: Assam, West Bengal, Tamil Nadu, Kerala, and Karnataka. This alignment is significant because the species under study are associated with tea plantations. Thus, the map's reliability is supported by field data.

Here, the slope has a 33.7 percent contribution. BIO2 has 30.7, LULC 26.3. Other notable contributors are BIO15 and BIO12. The model suggests that the Moderate, good and high potential area covers 10.38, 5.93 and 2.50 percent of the total geographical area. As the output format is in logistic and giving a range of 0 to 1. The threshold values selected as 0 - 0.2 (least potential), 0.2-0.4 (moderate), 0.4-0.6 (good), 0.6-0.99 (high potential). The remaining 81.18 percent area has the least potential.

C. parasiticus Karst has been known to infect the leaves, stems and other parts of the plants that it infects. It has been known to cause considerable damage to Tea plantations and other economically important plants. The results of this study add to thorough quantitative estimations of the spatial extent of the distribution range of this algal parasite throughout India as determined by various categories of suitability threshold. The analysis showed that *C. parasiticus* Karst is distributed throughout South, Southwest and Southeast India, along with A few North Eastern states like Assam, a few parts of Manipur and Tripura. This is consistent with its well-known presence in tropical rainforest regions, as expected (Fig 3).

Analysis of environment variables suggests that topographic slope plays an important role in determining the habitat suitability for *C. parasiticus* Karst. The topographic slope emerged as a crucial factor with maximum contribution, indicating that certain slope characteristics create favourable conditions for the growth and establishment of this parasitic alga. Areas with specific slope attributes are likely to provide suitable microhabitats for this algal colonization. Furthermore, temperature patterns (BIO2- Mean diurnal range) were found to have a substantial influence on the habitat distribution. This suggests that specific temperature ranges play a critical role in determining the species' occurrence and persistence. Optimal climatic conditions characterized by suitable temperature regimes are likely to support the growth and development of *C. parasiticus* Karst. Moreover, the type and composition of land use and land cover in a given area have been found to play a role in the shaping of its habitat suitability. Moreover, precipitation seasonality (BIO15) and annual precipitation (BIO12) showed noteworthy contributions to predicting the habitat distribution of this particular alga. These variables highlight the importance of precipitation in the growth and development of the alga. Optimum climatic conditions characterized by suitable precipitation levels and a specific pattern of seasonality are likely to enhance the proliferation and survival of *C. parasiticus* Karst.

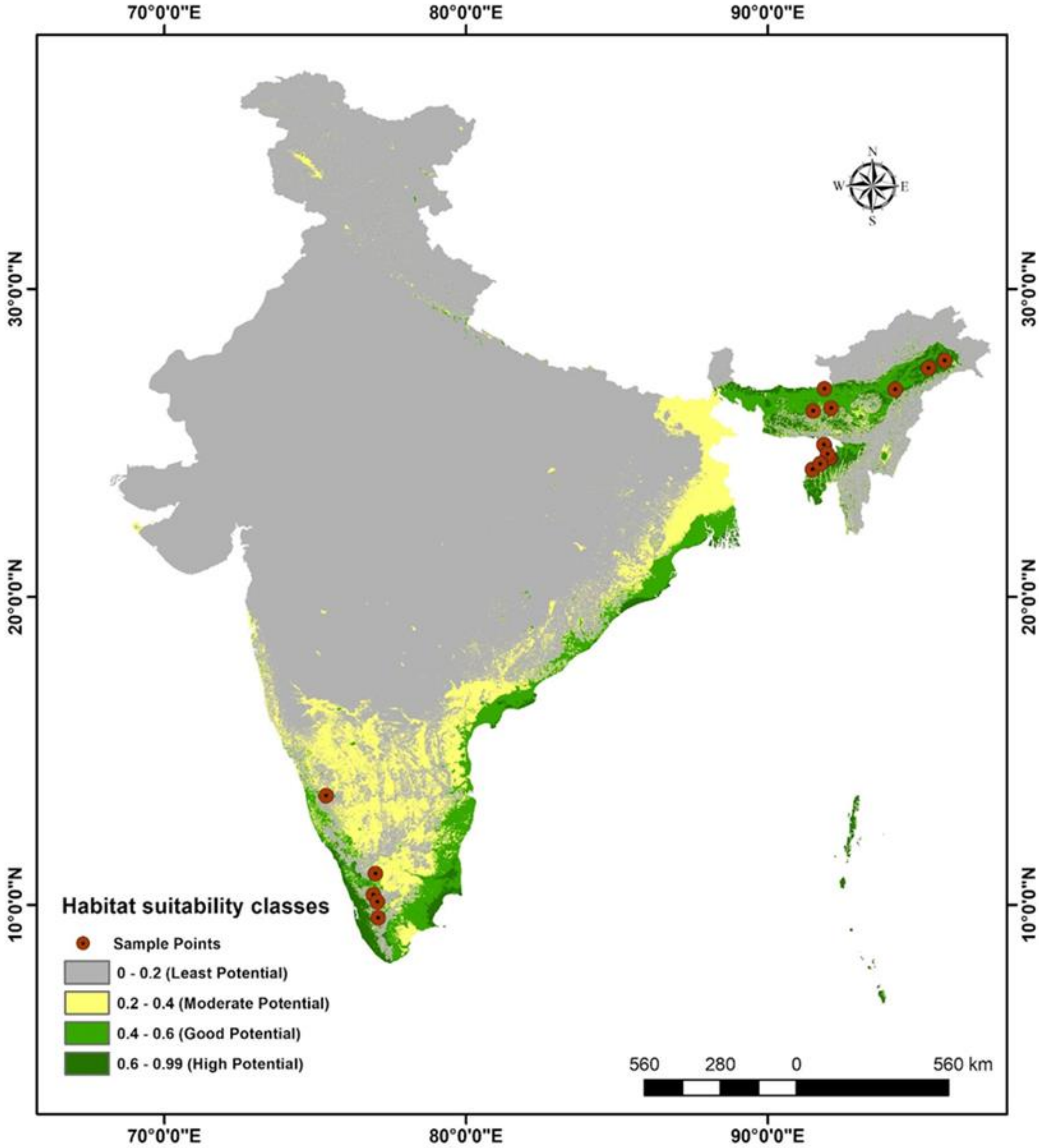

Fig 3: Habitat suitability classes of *Cephaleuros parasiticus* Karst in India.

Our results are in alignment and contribute to the results of several studies that have used MaxEnt modelling to explore the habitat distribution of other plant pathogens in apparently similar environmental conditions. For instance, the one conducted on *Phytophthora ramorum*, the pathogen causing sudden oak death, showed that parts of the landscape with some slope attributes had a higher probability of being infected by the pathogen (Lin and Ye, 2020; Kozanitas et al.,2022). Another study done on the pathogen of apple canker, *Valsa mali*, revealed that topographic variables including slope ranked as one of the most important factors influencing the distribution of the pathogen (Xu et al., 2020). These studies show that slopes govern drainage and retention of water in such a way that microhabitats are developed in favour of the proliferation of the pathogen. In our study on *C. parasiticus* Karst, topographic slope was, therefore, observed to be the key factor in habitat suitability.

Lin and Ye (2020) emphasized the role of temperature and precipitation in defining the potential distribution of *Phytophthora ramorum*. Humbbeek (2023) described the distribution of the rust fungi (*Puccinia komarovii* var. *glanduliferae*) as mainly affected by the necessities of the climate, especially in temperate climates. In the same manner, Wang et al. (2019) applied MaxEnt to predict the potential distribution of Asian citrus psyllid caused by *Diaphorina citri* (Kuwayama). It was found that temperature was the fundamental factor in determining the suitability of the environment. Tang et al. (2021) cited precipitation as the key factor influencing the distribution of *Bursaphelenchus xylophilus* in China. Our study agrees with these results, finding that the particular temperature ranges and precipitation patterns are necessary factors that determine the distribution of the algal parasite, implying that there is a common reliance on climate for the different pathogens

Several studies have pointed out that land use and land cover changes are an important influential factor in conducting MaxEnt modelling for habitat distribution studies of pathogens. For example, one study on the distribution of malaria vectors, namely *Anopheles arabiensis*, in Sudan and Upper Egypt, pointed to the importance of changes in land cover (Fuller et al., 2019) Similarly in the case of oak wilt caused by *Bretziella fagacearum*, land cover may contribute to the establishment and spread of the plant disease (Gearman and Blinnikov, 2019). These results further agreed with the *C. parasiticus* Karst habitat distribution study, in which land use and land cover and the topographic slope were the two factors that greatly supported the growth and establishment of this parasitic alga.

4. Conclusions

In this study, we have investigated the current distribution as well as the potential habitat suitability of *C. parasiticus* Karst throughout India. This study is the first to use MaxEnt modelling to map the distribution of the algal parasite based on various environmental variables. The model identifies the most suitable areas of *C. parasiticus* Karst are located mainly in the North-Eastern region as well as the eastern and western coastal region, with topographic slope, temperature, land use and land cover and precipitation as the critical environmental variables influencing the habitat suitability of the algal pathogen. Identification of influencing environmental factors provides useful recommendations for policymakers and practitioners. For instance, targeted monitoring within high-risk areas, proper land use planning and the development of climate-resilient agricultural practices are some of the potential measures, that can be opted for mitigating the distribution of the algal pathogen. However, reliance on environmental data quality and the lack of temporal and biotic interaction considerations including the development of crop varieties resistant to *C. parasiticus* Karst point towards the vast areas for future research. Meanwhile, higher information resolution data, longitudinal studies and integration of biotic interactions will enable better understanding and management strategy. In addition, integrated pest management, educational and awareness programmes among practitioners and collaborative research are very important for the control and prevention of the spread of this algal pathogen.

Author Contribution

PD, PPB, NK, DS: Conceptualization. PD: Data collection. NK: Methodology and analysis. PD, PPB, NK, DS: Discussed the results and reviewed the manuscript. All authors have read and agreed to the final version of the manuscript.

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