

Annual assessment of mangrove defoliation by *Hyblaea puera* (Cramer, 1777) around Thane Creek, India using field observations and Sentinel-2 imagery from 2018 to 2022

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ABSTRACT

Mangroves are salt-tolerant trees thriving in coastal and brackish waters, adapting to harsh conditions with features like aerial roots and salt filtering. Out of 64 global mangrove species, 11 are endangered. In Maharashtra, mangroves are concentrated around Mumbai, with an estimated 54.5 square kilometers in Thane Creek, where *Avicennia marina* shows signs of infestation. This current research used Sentinel-2 data from 2018 to 2022 to assess defoliation caused by *Hyblaea puera*, the teak defoliator. Ground-truth observations from 2020 to 2022 confirmed the extent of defoliation and identified varying infestation levels categorized as very highly infested, highly infested, moderately infested, low infested, very low infested, and uninfested. NDVI analysis examined these levels in relation to meteorological factors such as rainfall, temperature, humidity, and wind speed. The analysis revealed an extended peak infestation both spatially and temporally, along with severe defoliation during the study period. Six categorical infestation hotspots were identified and compared with meteorological parameters, revealing that *Hyblaea* outbreaks were more common during low wind speeds and moderate temperatures, with peak infestations occurring after heavy rainfall and under moderate relative humidity. The study suggests further research to explore outbreak causes, insect preferences for specific mangrove species, and the broader implications of defoliation.

1. Introduction

Mangroves, which are trees and shrubs, thrive in coastal and brackish water environments of tropical and subtropical regions between 30°N and 30°S latitude (Giri et al., 2011). They are also known as halophytes because they grow in harsh environmental conditions such as high salinity conditions (Giri et al., 2011; Alongi, 2014a). Mangroves have morphological and physiological adaptations, including complex aerial root systems and salt filtering capabilities to combat saltwater inundation and wave action (Linneweber, 2013; Parida and Bhavanath, 2010). They experience saturated soil conditions and regular flooding, allowing them to grow in extreme climates and even under anoxic conditions (Adam, 2011). Mangroves yield many ecosystem services, such as provisioning, regulating, culturing, and supporting services.

Provisioning services such as food, timber, fuelwood, etc., provide economic benefits and security to local coastal communities (Uddin et al., 2013). Regulating services became popular and well-recognized after the 2004 Asian tsunami (Barbier, 2016) and 2011 global climate change mitigation (Donato et al., 2011) due to tsunami wave attenuation and blue carbon storage and sequestration capacity of mangroves, respectively. Cultural services include tourism, education, cultural heritage, and esthetic values for local communities and visiting tourists (James et al., 2013; Thiagarajah et al., 2015). Mangroves improve coastal water quality by stabilizing fine sediments and absorbing pollutants, including heavy metals (Analuddin et al., 2017). Mangroves provide crucial ecosystem services but are rapidly disappearing (Alongi, 2002; Duke et al., 2007) and are among the most endangered ecosystems globally (Ivan Valiela et al., 2010). Over 64 mangrove species are

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known, with 11 listed as endangered on the IUCN Red List (Polidoro et al., 2010). However, in 2022, hybrids were removed the list (Spalding et al., 2010). Their decline results from human activities such as deforestation, aquaculture, agriculture, urban development, and palm oil production (Richards and Friess, 2016), as well as natural factors like climate change impacts, including rising sea levels, increasing temperatures, and stronger storms (Ward et al., 2016).

In general, herbivory in mangroves is a minor means of organic matter transfer, and insect herbivores generally cause only moderate damage, accounting for no more than 5 % of leaf area (Erickson et al., 2004; Faraco and Da Cunha Lana, 2004; Offenberg et al., 2004). The teak defoliator, scientifically referred to as *Hyblaea puera*, is indigenous to South Asia and Southeast Asia but is widely distributed in Australia, India, Sri Lanka, Malaysia, South Africa, and many parts of East Africa. It causes periodic defoliation and its seasonal outbreaks on mangrove species such as *Avicennia* spp., including *A. marina*, *A. schaueriana*, and *A. germinans* (P R and V Mahajan, 2012). So far, scant mangrove herbivory studies have offered in-depth insights into the implications of defoliation events (Anderson and Lee, 1995; Burrows, 2003; Duke, 2002; Gara et al., 1990; Tong et al., 2006). However, evidence shows that heavy defoliation caused by insects negatively impacts mangrove reproduction due to leaf loss and direct damage to flowers and buds (Anderson and Lee, 1995). Consequently, attacks by the teak defoliator moth pose a serious threat to this already vulnerable ecosystem.

In this context, highly accurate, valid, and updated information with high spatial and temporal resolution on characteristics of mangrove ecosystems, such as the extent of mangroves, location, type, distribution of species and communities, carbon stocks, pest infestation, is essential for their conservation, sustainable management, and policy and decision making to acquire their ecosystem. Remote sensing is an excellent and effective tool widely used in providing high-resolution spatial and temporal information on mangrove ecosystem distribution, species differentiation, health conditions, and variations in mangrove populations (Tong et al., 2003; Blasco et al., 1998; Dahdouh-Guebas, 2002; Giri et al., 2008). Sentinel-2 (hereafter S2) imagery, with its high-resolution multispectral data (10–60 m spatial resolution, 5-day revisit, 13 bands), is ideal for monitoring mangrove ecosystems, including defoliation caused by *Hyblaea puera*, offering valuable insights into vegetation health and changes over time (Malenovsky et al., 2012; Ghorbanian et al., 2021; Wang et al., 2010). Mangrove ecosystems, particularly *Avicennia marina* in urban estuarine environments like Thane Creek, Mumbai, are increasingly threatened by biotic stressors such as insect-induced defoliation. Among these stressors, the insect *Hyblaea puera* (Cramer, 1777) has been observed to cause significant canopy loss in mangroves; however, its impact remains largely understudied in India (Nakhawa et al., 2023; P R and V Mahajan, 2012; Raja Rishi, 2021; Raja Rishi and Sundararaj, 2020; Sathish et al., 2021). Addressing this gap, the present study aims to investigate the occurrence, spatial distribution, and inter-annual variability of mangrove defoliation while exploring its potential linkages with meteorological parameters. S2 optical data with 10 m resolution and a maximum likelihood classification in ArcGIS were used to identify mangroves and associated features such as tidal flats, salt pans, and water bodies, while NDVI (Normalized Difference Vegetation Index) served as a proxy to quantify the loss in green density and detect defoliation, validated through field observations. This integrated remote sensing and field-based approach represents the first detailed spatial assessment of insect-induced mangrove defoliation in the region. The findings aim to enable better spatio-temporal analysis of mangrove defoliation, identify infestation hotspots, examine meteorological influences, and support effective mitigation and conservation strategies. Future efforts will focus on refining detection techniques and extending this framework to other vulnerable mangrove ecosystems along the Indian coast.

2. Study area

The study was conducted in a mangrove-covered area around Thane Creek along the Eastern Arabian Sea. Thane Creek is 26 km long, named after the adjacent Thane city to its north. It joins the Ulhas River through a small connection at Kasheli and connects to Mumbai Harbour to its south. The Creek extends from longitude 72.967° E to 73.033° E and latitude 19.233° N to 19.067° N (Siddhesh Bhawe et al., 2015), as shown in Fig. 1. The Creek is shallow and narrow at the river end and more profound and broader towards the sea, and salt pans and stretches of mangroves surround its border. The Creek has alluvial soil or coastal saline soil due to its mangrove-rich catchment area. Most of the mangrove forests in Maharashtra are located near urban areas, especially in Mumbai and its suburbs. According to a report submitted by the Indian Institute of Space Sciences and Technology (IIST), Thiruvananthapuram, to the Mangrove Foundation, Mumbai, the mangrove forests of Maharashtra cover an area of approximately 353 square kilometres (Gnanappazham and Pillai, 2022). *Avicennia marina* is one of the most common and dominant mangrove species in Maharashtra's mangrove regions. It is found to be infested by defoliating insect pests during the SW Monsoon season, especially in the post-monsoon season (P R and V Mahajan, 2012) and (Raja Rishi and Sundararaj, 2020).

Thane Creek harbours 15 species of mangroves dominated by *Avicennia marina acutissima* and *Acanthus ilicifolius* across the creek and is one of the most important bird habitats, including Thane Creek Flamingo Sanctuary (Shri, 2020). A few ecological facets of *Hyblaea* infestations within the Mangrove ecosystem of Thane Creek were presented by (P R and V Mahajan, 2012).

3. Data and methodology

3.1. Ground truthing

Annual field works were conducted from 2020 to 2022 to study the year-to-year variability of *Hyblaea puera*-induced defoliation of mangroves on the banks of the creek and away from the creek using boat and best access routes. In the field survey, primarily, an abundance of mangrove defoliation was observed visually in various spots in the study region, and the same was done through photographic evidence and ground truthing of the respective locations was also done by collecting Ground Truth Points (GTPs) using Handheld Garmin Global Positioning System (GPS). GTPs of mangrove areas and their associated features, such as water bodies/aquaculture ponds, salt pans, tidal and mudflats, barren land, etc, were collected to identify them in satellite images as well as to check the accuracy estimation of Land Use Land Cover (LULC) classification. Caterpillars of the moth have been observed over the last few years systematically defoliating thousands of acres of mangroves along with three creeks (P R and V Mahajan, 2012). During boat surveys at high tide, larvae and pupae of *Hyblaea puera* on defoliating leaves of *A. Marina* trees were observed, collected, and photographically captured, as shown in Fig. 2, and it was also observed that the severity of infestation varied from spot to spot, and some sites had no infestation at all. A tidal effect on infestation can also be observed, in which plant infestation begins above the high tide water level, and some plants away from the creek or landward boundary of the mangrove area have no defoliation; however, those plants belong to the *Avicennia* genre. Based on the physical observations, mangrove trees that have at least 40–50 % defoliation were considered infested for this study. In this context, the degree of defoliation, i.e., the percentage of infested plant area in each quadrat of 15 × 15 m, was visually assessed and rated by comparing invaded and un-invaded plants. In this study, the degree of infestation was categorized into six levels, as outlined in Table 1.

Trees in each quadrant with over 75 % infestation were classified as 'very highly infested,' those with 50–75 % infestation were deemed 'highly infested,' while trees with 25–49 % infestation were labelled as 'moderately infested' Trees with 10–24 % infestation were categorized

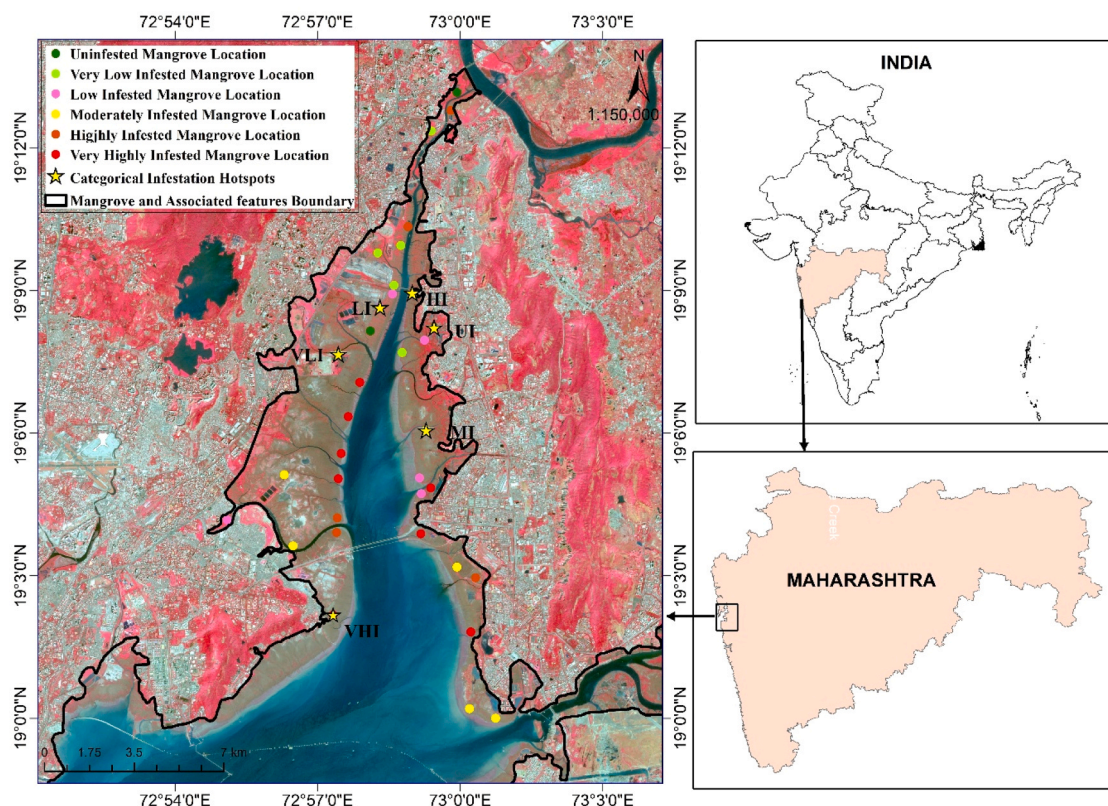


Fig. 1. Study area map of Thane Creek, Maharashtra, showing field sampling sites marked by colored dots representing mangrove infestation categories, from uninfested (green) to very highly infested (red). The black boundary outlines mangrove and associated feature extents. Insets show the study area's location within India and Maharashtra. Yellow stars indicate categorical infestation hotspots selected for comparison with meteorological parameters (air temperature, wind speed, rainfall, and relative humidity).

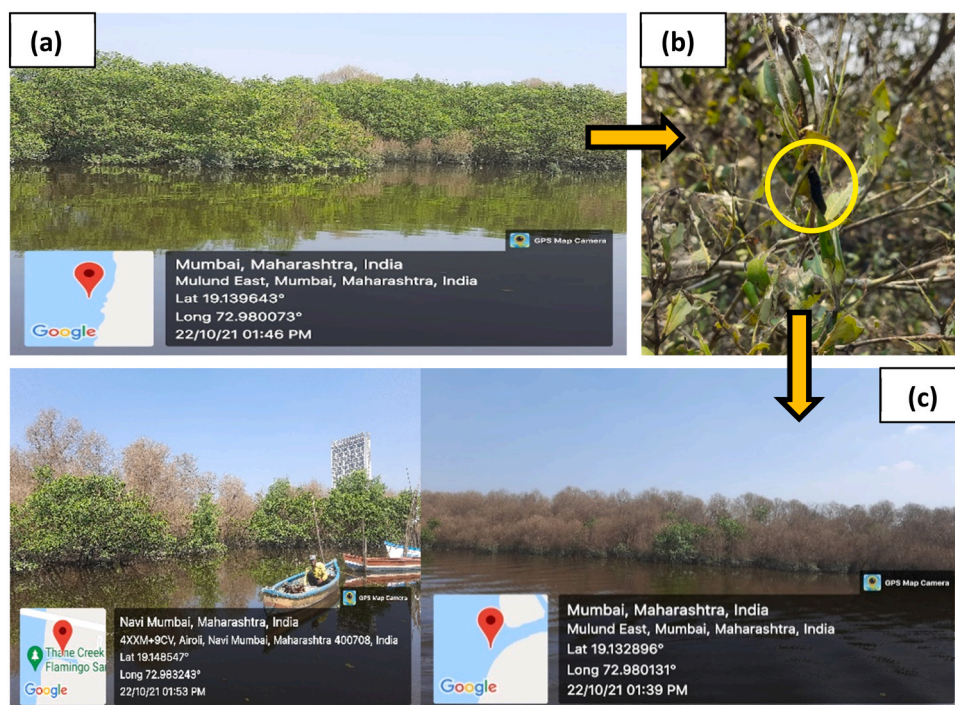


Fig. 2. Ground thruthing using boat and best access routes (a) uninfested mangroves in the study area; (b) *Hyblaea Puera*, caterpillar (larvae) feeding on *Avicennia marina* leaves; (c) infested mangroves after the attack.

Table 1

Infestation categories determined by severity of infested plant area in each quadrant.

S. No.	Category	% of infested plant area in each quadrant of 15 × 15 m	Description
1	Very highly infested	> 75	Almost all plants are infested
2	Highly infested	50 – 75	Most of the plants are infested
3	Moderately infested	25 – 49	More than half plants infested
4	Low infested	10 – 24	Few plants infested
5	Very low infested	01–09	Very few plants infested
6	Uninfested	0	No plants infested

as 'low infested,' those with 1–9 % infestation were referred to as 'very low infested,' and trees without any infestation were designated as 'uninfested' mangroves. Only some sampling sites for each category were selected from the study region.

3.2. Satellite imagery

S2, part of the Copernicus program, provides high-resolution multi-spectral imaging with a spatial resolution of 10–60 m and a five-day revisit cycle (Malenovsky et al., 2012). Its 13 spectral bands, ranging from visible to shortwave infrared, make it ideal for monitoring vegetation, including mangrove ecosystems. While S2 data has been extensively applied in various fields such as agriculture, urban planning, and forest monitoring (Otunga et al., 2019; Pesaresi et al., 2016), its application in mangrove studies remains comparatively limited. Notable applications in mangrove research include mapping mangrove extent (Ghorbanian et al., 2021; Wang et al., 2010), assessing canopy density (Wachid et al., 2017), and monitoring vegetation stress and health (Manna and Raychaudhuri, 2020, 2019), with some studies also focusing on mangrove species composition (Pham et al., 2019; Selamat et al., 2020). In this study, cloud-free S2 imagery was downloaded from the Copernicus Open Access Hub (<https://scihub.copernicus.eu/>) for the months of January, February, March, April/May, October, November, and December in the years 2018 through 2022. S2 data of April/May, October, and December of each year were used to compare defoliation levels before, during, and after an infestation of mangroves, respectively, and the S2 image of January 2020 is used for LULC to classify the other associated features on land using ArcGIS tool. In the present study, the flow chart of satellite image processing, including downloading S2 data, applying TOA corrections, preprocessing (layer stacking, band clipping, etc.), using supervised classification (maximum likelihood) technique for LULC map preparation and NDVI for *Hyblaea* classification and its intensity map preparation as shown in Fig. 3. After downloading S2 images, TOA reflectance corrections were applied to surface reflectance. Then, layer stacking of the same spatial resolution bands, such as 8,4,3,2, to obtain FCC (False Colour Composition) or NCC (Natural Colour Composition), followed by band clipping for the study area as the S2 coverage is usually more extensive and takes more computational time. One of the most widely used indices for vegetation health assessment is NDVI (Karnieli et al., 2010), calculated as the normalized ratio between the red and near-infrared (NIR) bands:

$$NDVI = \frac{NIR - R}{NIR + R}$$

In the context of detection of defoliation, the greenness of the NIR reflectance is a more accurate indicator of plant stress compared to visible greenness (Rullan-Silva et al., 2013; Townsend et al., 2012; Wang et al., 2010). Consequently, NDVI is considered a robust and widely tested method for estimating vegetation cover and defoliation intensity (Rullan-Silva et al., 2013). In this study, mangrove trees with 40–50 % defoliation were considered infested based on field surveys. NDVI values

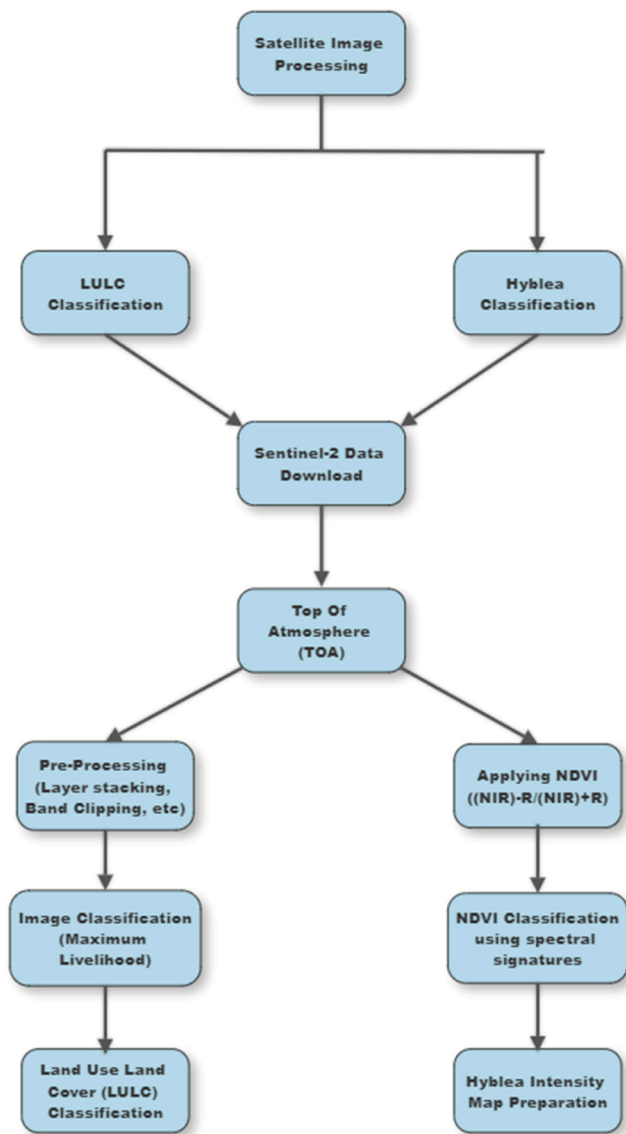


Fig. 3. Flow chart illustrating the sequence of steps in Sentinel-2 image processing for Land Use and Land Cover (LULC) and *Hyblaea* classification.

were then categorized into six infestation levels: very highly infested, highly infested, moderately infested, low infested, very low infested, and uninfested, by comparing spectral signatures from invaded and uninvaded mangrove areas within 15 × 15 m quadrats. The specific NDVI thresholds that define these infestation levels were derived from these comparisons and validated with field data and photographic evidence, ensuring a reliable assessment of defoliation severity using NDVI.

4. Results

4.1. Field work analysis

Fieldwork, conducted annually from 2020 to 2022, involved using boats and the most convenient routes during high tide to evaluate the presence of *Hyblaea puera* infestations in the mangroves near Thane Creek. Furthermore, this study also examined infestations from 2018 and 2022 by integrating satellite imagery analysis with on-site field observations. The present estimate of mangrove coverage near Thane Creek is approximately 54.42 square kilometers (Gnanappazham and Pillai, 2022). In this ecosystem, records indicate the presence of mangrove species like *Avicennia marina*, *A. officinalis*, *Acanthus ilicifolius*,

Aegiceras corniculatum, *Cerriops tagal*, *Excoecaria agallocha*, and *Sonneratia apetala*, accompanied by associated mangrove varieties such as *Derris trifoliata*, *Volkameria inermis*, *Sesuvium portulacastrum*, and *Salvadora persica*. The dominant species within the ecosystem is *A. marina*, followed by *S. apetala*, *A. officinalis*, and others. Various benthic fauna were observed in the study site. *Sesamid*, *grapsid*, and *Ocypodid crabs* dominate the benthic fauna in mangrove forests, coexisting with associated features like tidal areas, mud flats, ponds or water bodies, and salt pans. *Hyblaea puera*, commonly called the teak defoliator, was first described by Pieter Cramer in 1777. It has a wide distribution outside its native South and Southeast Asia, including Australia, India, Sri Lanka, Malaysia, South Africa, and some parts of East Africa. Recent reports have documented its presence in Central America and Africa, with its caterpillar posing a significant threat not only to teak, resulting in approximately 44.1 % loss in plant increment volume (Tripathy et al., 2018), but also to various other tree species, including mangroves like *A. marina*, *A. schaueriana*, and *A. germinans* (Faraco et al., 2019; Fernandes et al., 2009; Mehlig and De Menezes, 2005; Nakhawa et al., 2023; P R and V Mahajan, 2012; Sathish et al., 2021), establishing it as a prominent global pest. In addition to mangroves, the teak defoliator moth has been documented on 45 different host tree species (Peres-Filho et al., 2002). In teak plantations, *Hyblaea* caterpillars primarily pupate within the leaf litter on the ground, whereas in mangroves, their pupation occurs exclusively on tree branches (P R and V Mahajan, 2012). Reports from teak plantations indicate that *Hyblaea* completes its life cycle in about a month, with the potential for up to twelve generations per year (Javaregowda, 2005). Research conducted in Faizabad, Uttar Pradesh, on the biology of *Hyblaea puera* in teak plantations revealed that the egg stage lasts for 2.8 days, followed by five instar stages with an average duration of 11.2 days when developed on teak foliage under net house conditions, and a subsequent average pupal period of 5.4 days. The adult moth has a brief lifespan, lasting approximately 5.06 days for females and 3.6 days for males. Females lay an average of 205 eggs during their lifetime, with a sex ratio of 1:2.1. In Odisha, Tripathy et al., (2018) investigated the population dynamics of *Hyblaea puera* and observed the migration of *Hyblaea puera* from teak plantations into nearby mangrove areas. Chandrasekhar et al. (2005) examined that migrating moths from distant teak plantations contribute to localized teak defoliator outbreaks, highlighting the need to control epicenter populations to prevent larger infestations. Lee (1991) observed less than 5 % leaf damage in *Kandelia candel* in Hong Kong, while Burrows (2003) reported herbivore-induced leaf losses of up to 13 % in *Rhizophora stylosa* and 36 % in *A. marina*. In our study, certain areas experienced almost 100 % leaf loss in *A. marina* due to herbivory without causing plant mortality.

In most of the mangrove cover, various levels of infestation on *A. marina* plants by *Hyblaea puera* have been observed in 2020, 2021, and 2022. *Hyblaea* outbreaks in mangroves of different nations often align with the transition between rainy and dry seasons. March and July in Equatorial Brazil (Mehlig and De Menezes, 2005; Menezes and Ariane Luna, 2009), May to August (Hong Kong), winter months June to August (mangroves of Port Curtis in Central Queensland, NE Australia) and (Kamruzzaman et al., 2019) documented a bimodal leaf litterfall pattern in the Sunderbans of Bangladesh, with the highest levels occurring in December and May. However, in India, the timing of outbreaks varies from place to place within a single year and from one year to the next in the exact location. For instance, P R and V Mahajan, (2012) noted outbreaks that occurred from September and January 2006–2009, whereas Raja Rishi and Sundararaj, (2020) and Sathish et al. (2021) reported attacks limited to August and September and July to October, respectively, in 2018 and 2019. In the present study, the peak infestation was observed during October and persisted till November in 2020 and 2021. In contrast, in 2022, the infestation commenced in September, October and continued in November with little break and reached its peak infestation in December, leading to extensive defoliation. During fieldwork in 2022, comparatively numerous caterpillars were found on each

infested plant, and most of the *A. marina* plants were extensively defoliated, with a few remaining untouched, especially towards Navy Mumbai. No infestation was identified within the remaining mangrove species and their associated vegetation, predominantly composed of *S. apetala*, *A. officinalis*, and *A. ilicifolius*. Additionally, *A. marina* was observed in specific areas. Moreover, during the fieldwork conducted from 2020 to 2022, there was a marked increase in the severity, spatial extent, and temporal duration of defoliation. Following the infestation period each year, all the plants exhibited signs of recovery, characterized by the emergence of new buds and the subsequent growth of green, fully-developed leaves. The current findings regarding the peak incidence of *Hyblaea puera* align with the studies by Raja Rishi and Sundararaj, (2020) and Sathish et al. (2021). In the case of 2022, they closely follow the pattern of Kamruzzaman et al. (2019). Furthermore, it was observed that the leaf fall rate increased during the pre-monsoon dry period (March, April, and May) almost every year due to the rising temperature, salinity levels, decreased relative humidity, and freshwater inflow from the rivers. *Hyblaea puera* has adapted its life-history habits to match the mangrove ecosystem's conditions and pupates merely on mangrove tree branches (P R and V Mahajan, 2012). The possible reason for *Hyblaea* instances in the study area may be due to environmental stress, decreased availability of the primary host plant, and the proximity of alternative hosts, which have led the moths to adapt and move from Teak plants in Sanjay Gandhi National Park (SGNP) near Mumbai to adjacent mangroves. This shift underscores the need for ongoing ecosystem monitoring and a better understanding of landscape dynamics in rapidly evolving environments.

Additionally, different insect species have been found to cause significant herbivory in mangroves in several other nations. These include the defoliation of *A. marina* in Queensland, Australia (West and Thorogood, 1985), *Excoecaria agallocha* in Indonesia (Whitten and Damanik, 1986), *A. alba* in Thailand (Piyakarnchana, 1981), and *A. marina*, *E. agallocha*, and *Aegiceras corniculatum* in Singapore (Murphy, 1990). Every summer in Hong Kong, Nephopterix syntaract caterpillars cause severe herbivory on *A. marina*, leading to complete defoliation within three months, with all cases attributing the herbivorous activity to lepidopteran larvae (Anderson and Lee, 1995). Everitt et al. (1996) assessed mangrove damage in Texas, USA, using GPS, GIS, and airborne color infrared video imagery. Meanwhile, Paraná, Southern Brazil, Faraco et al. (2019) documented the infestation of *A. schaueriana* by the invasive moth *Hyblaea puera*, impacting 20,000 ha of mangroves. Jenoh et al. (2016) quantified *S. alba*-induced infestation of two wood-boring species in mangrove embayments, such as Gazi and Mida. In India, various authors, including Nakhawa et al. (2023); P R and V Mahajan, (2012); Raja Rishi and Sundararaj, (2020), conducted similar studies in the vicinity of Thane Creek, Mumbai, based on field observations and satellite data. Moreover, (Sathish et al., 2021) investigated defoliation in Dharamtar Creek using S2 multispectral satellite imagery, revealing varying levels of infestation intensity across different years. Raja Rishi and Sundararaj, (2020) studied Mumbai's mangroves, reporting sporadic infestation in 2018 and epidemic infestation in 2019.

4.2. NDVI analysis

In the current study, multispectral S2 data with better resolution (10 m x 10 m) than several other contemporaneous non-commercial space-borne satellites was used in conjunction with field observations to assess the infestation of mangroves. The study focused exclusively on an entire designated mangrove region and utilized NDVI analysis to estimate green cover variations during the months of January, February, March, April/May, October, November, and December every year, as shown in Fig. 4. Nonetheless, the monsoon months from June to September were omitted due to extensive cloud cover, although they were also assessed through field observations. The analysis of monthly NDVI variations for each year from 2018 to 2022 shows significantly the stages of mangrove infestation by *Hyblaea puera*, including the pre-

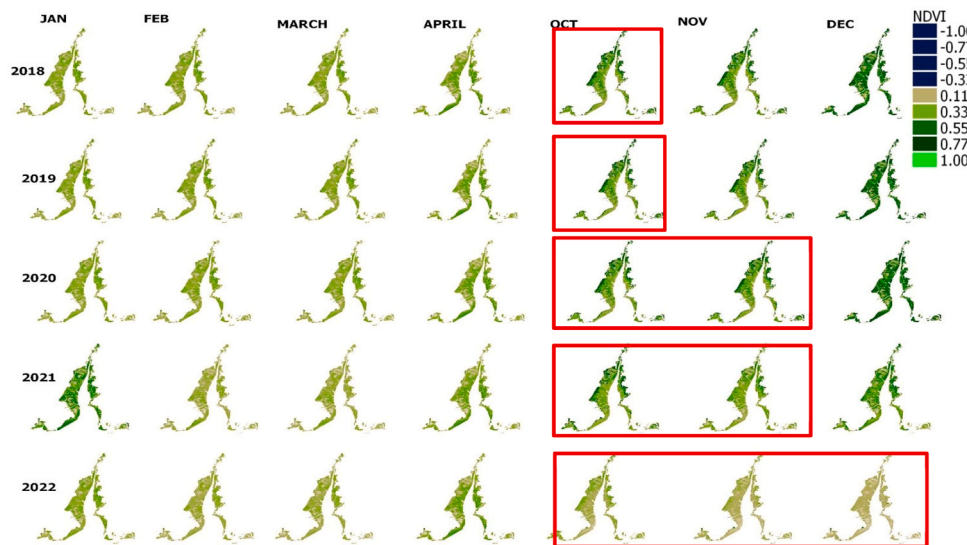


Fig. 4. Spatiotemporal NDVI variations from 2018 to 2022 depict vegetation conditions before infestation, during peak infestation, and after infestation of mangroves by *Hyblaea puera*. Red boxes highlight the peak infestation periods in each year.

infestation, the peak infestation, and the post-infestation.

Typically, NDVI values fall from -1.0 – 1.0 , where zero to negative values signify bare soil, land, clouds, and water. In contrast, zero to positive values indicate varying levels of vegetation density, from sparse to dense. Spectral signatures were used in NDVI classification to generate *Hyblaea* intensity maps during the peak infestation period of each year, depicting the severity of infestation. The observed infestation across the entire Thane Creek mangrove area was categorized into distinct levels: very highly infested, highly infested, moderately infested, low infested, very low infested, and uninfested. *Hyblaea* intensity maps, along with definite infestation and associated features of mangroves, were generated using S2 images during the peak infestation periods of each year, specifically on October 20, 2018; October 5, 2019; October 29, 2020; October 4, 2021; and December 3, 2022, shown in Fig. 5. These intensity maps reveal how infestation levels are distributed across the entire mangrove cover during the peak infestation period in each year. Persistent locations characterized by a categorical infestation can be identified through these maps, allowing for a comprehensive analysis of meteorological parameters, including rainfall, relative humidity, air temperature, and wind speed, in conjunction with the occurrences of *Hyblaea* attacks at these specific sites.

In the course of fieldwork conducted from 2020 to 2022, it was observed that the peak infestation period and its duration showed year-to-year variability. These observations correspond with the analysis of monthly NDVI variations for each year from 2018 to 2022, showcasing the distinct phases of mangrove infestation induced by *Hyblaea*, including the pre-infestation, peak infestation, and post-infestation stages. However, low NDVI values were also observed due to the stress induced by dry conditions in pre-monsoon months. In the present study, Infestation commenced as early as August in both 2018 and 2019 (Raja Rishi and Sundararaj, 2020; Sathish et al., 2021). Subsequently, the infestation rate progressively increased, reaching its peak in October, characterized by lower NDVI values, attributed to extensive defoliation by *Hyblaea puera*. Leaf regrowth then started in late October, followed by progressive development in the following months, extending up to December in both 2018 and 2019. In 2020 and 2021, NDVI values showed their lowest values during both October and November, with only minor differences between the two years. In 2020, the peak infestation occurred in late October and extended into early November, while in 2021, it reached its peak in early October. Subsequently, in late November, regrowth commenced, reaching its peak in December 2020. Likewise, in 2021, regrowth initiated in early December, gradually

attaining maximum greenery in the following months. In 2022, the infestation period lasted for approximately three months, with only a short pause in between, reaching its peak in December and followed by regrowth in the subsequent months. Monthly NDVI analysis across all years reveals a variable peak infestation period, shifting from October in 2018 and 2019 to November in 2020 and 2021 and finally to December in 2022. Additionally, the duration of the peak infestation also fluctuates, lasting one month in 2018 and 2019, nearly two months in 2020 and 2021, and extending to approximately three months in 2022. The variation in spectral signatures in satellite images of infested and non-infested mangroves during their respective peak periods can be due to differences in leaf and canopy morphology as well as variations in the background substratum within the study region. The ecology may be considerably impacted by nearly half a year of low NDVI each year, which consists of three months of stress induced by infestations and three months of stress induced by the dry pre-monsoon season (Sathish et al., 2021). The percentages of infested and uninfested areas for each category and year concerning the total mangrove area were summarized in Table 2. Furthermore, the areas of mangrove-associated features, such as tidal flats, mudflats, saltpans, and ponds/water bodies, are 5.08 sq. km., 7.79 sq. km., 1.82 sq. km., and 2.6 sq. km., respectively.

5. Discussions

5.1. *Hyblaea* intensity analysis

In 2018, most infestations fell within the moderately (26 %) to very low (36 %) infested category, suggesting a relatively moderate-to-low severity level. Conversely, in 2019, the predominant infestation ranges from moderately (50 %) to very highly (15 %) infested categories, indicating severe infestation. During 2020 and 2021, a substantial portion of the infested area, representing over 70 % of the total, was predominantly categorized as very highly, highly, and moderately infested, highlighting the extensive spatial reach and higher severity of the infestation, which has had notable adverse effects on plant growth. In 2022, a significant portion of the infected area, depicting more than 75 % of the total, was mainly categorized as very highly, highly to moderately infested, emphasizing the extensive and widespread nature of the infestation, along with its extreme severity and potential consequences for mangrove regrowth. In comparison, 2018 experienced a relatively less severe and geographically limited infestation, whereas 2022 marked an exceptional peak in severity and extensive geographical

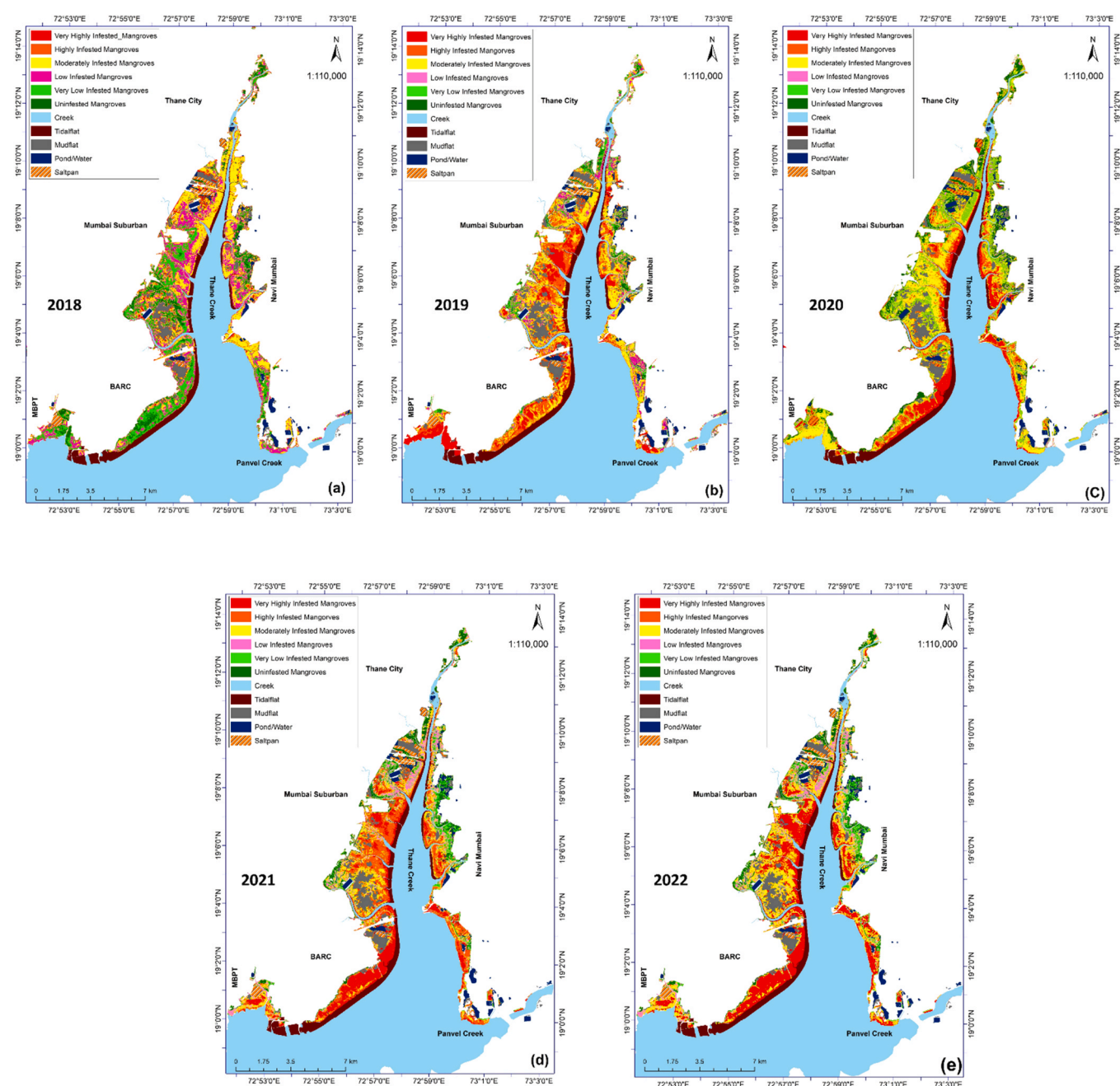


Fig. 5. *Hyblaea* intensity maps derived from NDVI spectral signatures illustrate the spatial distribution of six infestation categories: very highly infested, highly infested, moderately infested, low infested, very low infested, and uninfested mangroves, along with creeks, tidal flats, mudflats, ponds or water bodies, and salt pans across Thane Creek during the peak infestation periods on (a) 20 October 2018, (b) 5 October 2019, (c) 29 October 2020, (d) 4 October 2021, and (e) 3 December 2022.

Table 2

Various variable categories of infested mangroves with respect to total mangrove coverage in the vicinity of the Thane Creek from 2018 to 2022.

Class	% of area occupied by each class from the total study area				
	2018	2019	2020	2021	2022
Very highly infested	7	15	19	24	12
Highly infested	7	11	19	24	21
Moderately infested	26	50	35	28	46
Low infested	16	12	9	11	10
Very low infested	36	9	12	6	6
Uninfested	8	3	6	7	5

coverage; nevertheless, 2019, 2020, and 2021 also reported significantly high levels of infestation severity. The possible reason for the spatial and temporal extent of peak infestation and severe defoliation during the study period may be due to habitat changes, such as the expansion of mangrove cover on both sides of shrinking Thane Creek (Adluri et al., 2023). This expansion could make surrounding land more suitable for species like *Avicennia* and offer new food sources for *Hyblaea puer*, potentially leading the moths to migrate from declining Teak plants to the newly available mangroves.

To identify persistent infestation zones of specific categorical infestations within the study area, a few sampling locations that frequently say the same categorical infestation from the study region in all years were selected, resulting in six locations representing six distinct

infestations, as depicted in Fig. 1. Based on annual assessments of *Hyblaea* intensity during the peak infestation period for each year (Fig. 5), six infested hotspot zones, categorized by intensity, were identified. In the proximity of the BARC (Bhabha Atomic Research Centre) region, mangrove cover was consistently reported as 'very highly infested' in almost all years, designating it as a 'very highly infested' area. Similarly, the region adjacent to Aroli Bridge was consistently registered as a 'highly infested' region. The mangrove cover near Khanjurg was identified as 'moderately infested,' while that near Bhandup village was categorized as a 'low-infested' region. In the vicinity, the Koparkhairne Mangroves showed signs of 'very low infested,' while the Ghansoli Mangroves remained 'uninfested'. The annual estimation of infested areas reveals that most of the region experiences infestations ranging from very high to moderate levels. Notably, the southern and left portions of the creek have higher infestation levels than the northern and right sides. The area near BARC has very high infestation, while the Ghansoli mangroves remain uninfested throughout the years, highlighting hotspot zones of mangrove infestation.

5.2. Meteorological parameters analysis

The *Hyblaea* intensity analysis identified six sampling locations consistently showing nearly identical infestation categories across almost all years. These locations were subsequently labeled as VHI (Very Highly Infested), HI (Highly Infested), LI (Low Infested), VLI (Very Low Infested), and UI (Uninfested), aligning with the six infestation categories. Later, in an integrated approach, the analysis of annual instances of *Hyblaea* infestation, including events before, during, and after the attacks at six sampling locations covering six infestation categories, was combined with an analysis of meteorological variables comprising air temperature, rainfall, relative humidity, and wind speed, as depicted in Fig. 6, to investigate the relationship between *Hyblaea* attacks and meteorological parameters. Monthly rainfall data (in millimeters per month) from <https://indiawris.gov.in> were utilized for the study region from 2018 to 2022, while other parameters like air temperature, relative humidity, and wind speed were obtained from <https://power.larc.nasa.gov/data-access-viewer/>. The *Hyblaea* intensity fluctuates between different locations and from year to year, while meteorological parameters remain consistent across all locations but vary from year to year. Environmental conditions significantly trigger defoliation outbreaks in mangrove forests, with rainfall intensity and wind patterns as the primary drivers of these events (Nakhawa et al., 2023). Initially, the relationship between actual rainfall and *Hyblaea* intensity, measured through NDVI values at six designated locations representing all six infestation categories, was analyzed across all years, indicating the significant influence of rainfall on annual *Hyblaea* outbreak incidents, particularly in the VHI, HI, and MI categories (Fig. 6).

Severe *Hyblaea* outbreak occurrences, indicated by low NDVI values, were observed during years with substantial rainfall peaks, particularly in infestation categories ranging from VHI to LI. These observations support earlier findings that highlight an increased probability of outbreaks during high rainfall years (Nakhawa et al., 2023; Raja Rishi, 2021). Notably, the duration between the primary peak of rainfall and the rise of infestation in each year fluctuates, with the gap steadily increasing from 2018 to 2022. The average interval of over three months indicates a prolongation and shift in the occurrence of the peak infestation period from 2018 to 2022. Similarly, relative humidity signifies that peak infestation occurred in nearly all years and all locations under moderate humidity conditions. However, minor variations were observed concerning the year and the specific location. Regarding air temperature, most peak infestation events during the study period were observed under moderate temperature conditions. Nevertheless, it's important to note that *Hyblaea* intensity varies across different locations and categories. Finally, wind speed during the annual peak infestation events suggests that *Hyblaea* incidents likely occur during moderate to

low wind speed conditions, as higher wind speeds may reduce *Hyblaea* density in the mangrove cover. In locations with high infestation levels, ranging from VHI to MI, as shown in Fig. 6, NDVI consistently exhibited lower upper limit values across all years, signifying extensive defoliation. In contrast, locations with lower infestation levels, spanning from LI to UI, showed higher upper limit NDVI values, indicating minimal defoliation. Fig. 6 reveals that in these low to uninfested categories (LI to UI), NDVI values generally remain high across all years, suggesting limited impact of *Hyblaea* outbreaks. Although these regions are also exposed to similar meteorological conditions, such as seasonal rainfall peaks and fluctuations in temperature, humidity, and wind speed, the corresponding drops in NDVI are far less pronounced compared to highly infested locations. This indicates that despite the presence of conducive meteorological triggers, other local ecological or biotic or urbanization factors may suppress infestation severity in these zones. The analysis of meteorological parameters about *Hyblaea* attacks shows that these outbreaks are more frequent in conditions of low wind speed and moderate temperatures, combined with heavy rainfall and moderate humidity levels.

5.3. Ecological impacts and pest management strategies

Insect herbivores play a vital ecological role beyond causing plant material loss, influencing plant performance and ecosystem functioning (Cannicci et al., 2008). Though often seen as disruptors that affect forest productivity and nutrient cycling, they also contribute to essential ecosystem processes (Jenoh et al., 2016). Rapid larval feeding on both young and aging foliage leads to complete defoliation in mangrove nurseries and young plantations, triggering pest outbreaks and negatively impacting plant growth (Raja Rishi and Sundararaj, 2020). An eddy covariance flux study showed that insect disturbances can significantly alter forest carbon cycling, causing annual fluctuations in net ecosystem productivity and potentially shifting forests from carbon sinks to sources (Amiro et al., 2010). In this regard, repeated declines in vegetation health caused by *Hyblaea puera*, as reflected by sustained drops in NDVI during outbreak periods, may reduce the carbon sequestration capacity of mangrove ecosystems. Since mangroves are among the most efficient natural carbon sinks (Donato et al., 2011; Alongi, 2014b), such infestations can compromise their ability to capture and store carbon, with broader implications for climate change mitigation, as disturbances to mangrove carbon stocks can diminish their role in long-term atmospheric CO₂ regulation (Feller et al., 2010). Severe infestations can also impact local fishers' livelihoods, as many rely on mangrove crabs, prawns, and fish for food and supplemental income. Beyond the direct impact on *Avicennia marina*, defoliation by *Hyblaea puera* can affect the broader mangrove ecosystem. The loss of canopy alters microclimate, reduces organic matter input, and degrades habitat complexity, factors critical for many organisms. Sathish et al. (2024) reported a notable decline in crustacean diversity and abundance in defoliated mangrove patches in the Dharamtar Estuary, highlighting the vulnerability of benthic communities to vegetation loss. The study also observed increased estuarine catches of juvenile and sub-adult shrimps during severe defoliation periods in Maharashtra, likely driven by detritus-rich frass attracting them, which led to over-harvesting and a decline in stocks. It further noted indirect effects on fish species dependent on mangrove root zones and sediments for shelter and breeding. These findings underscore that defoliation events disrupt species interactions and ecosystem functioning, extending beyond just *A. marina*.

Despite the damage caused by *Hyblaea* caterpillars, their presence may also provide ecological benefits, such as promoting mangrove diversity, nutrient enrichment, and increased secondary production (Sathish et al., 2021). Their frass contributes significant organic matter to the forest floor, producing an ammonia-like odor and increasing fish availability (Fernandes et al., 2009; Mehlig and De Menezes, 2005; P R and V Mahajan, 2012). Our observations support P R and V Mahajan,

Categorical *Hyblaea* Intensity (bars) & Meteorological Parameters (lines) from 2018–2022

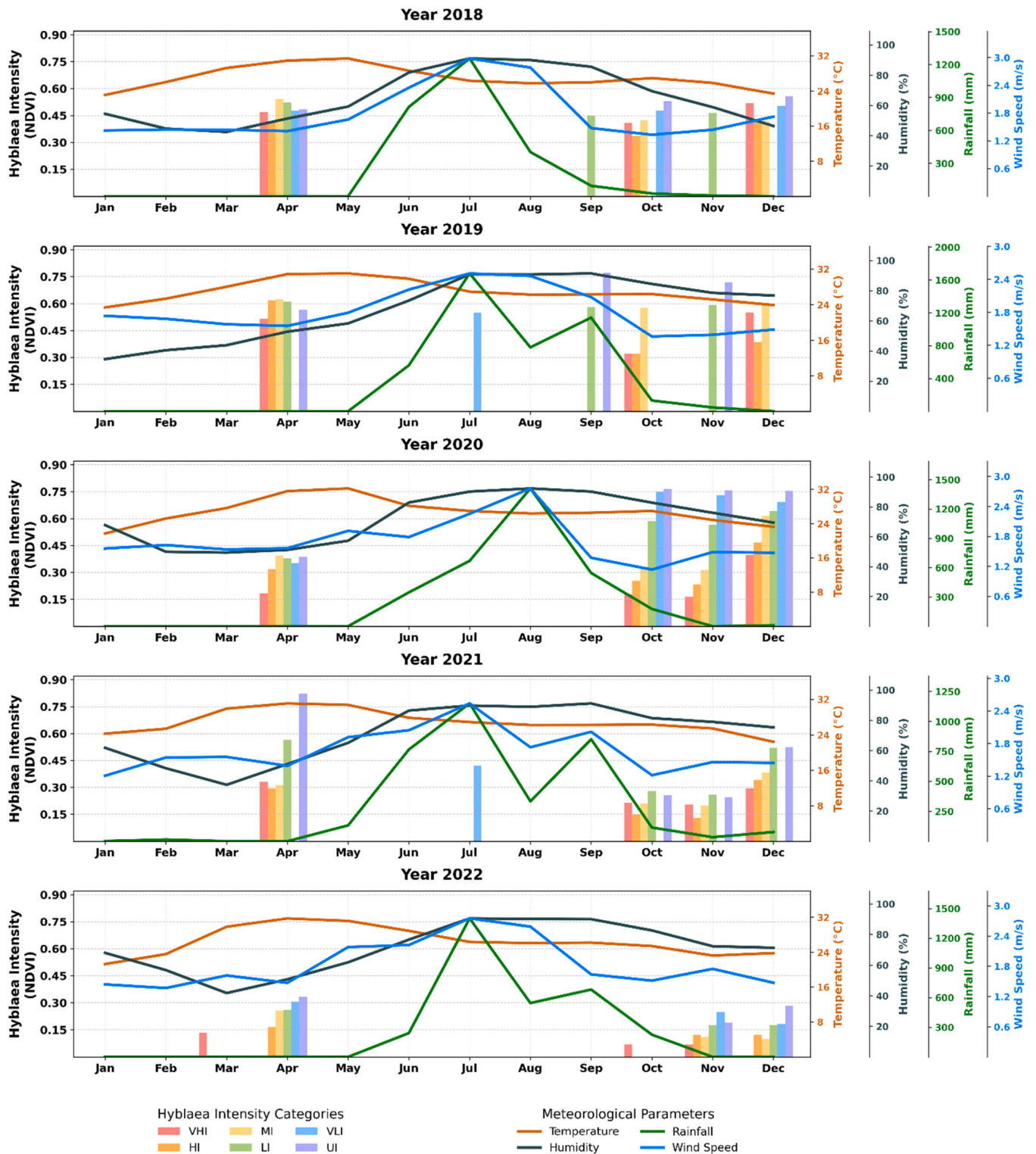


Fig. 6. Monthly variations of six categorical *Hyblaea* intensities (Very Highly Infested to Uninfested) across six categorized infestation hotspot locations (Fig. 1) for each year from 2018 to 2022, along with meteorological parameters (temperature, humidity, rainfall, and wind speed). Bar plots represent infestation levels before, during, and after the peak infestation period in each year, while overlaid line plots illustrate associated meteorological trends, highlighting their relationship with infestation dynamics.

(2012) findings that shrimp migrate inshore from offshore during infestations to feed on the frass, potentially leading to excessive shrimp harvesting in estuaries and creeks, as noted by local fishers. However, secondary data supporting this observation is currently lacking, and further efforts are underway to document it. Notably, a concurrent decline in mangrove crab populations was also observed, indicating the need for further investigation into how such infestations affect overall ecosystem functionality.

In the event of frequent pest outbreaks within short time frames (Faraco et al., 2019), an alternative approach suggested by Raja Rishi and Sundararaj, (2020) involves applying the botanical biopesticide Hy-ACT, which effectively achieves a 95 % larval mortality rate within 48 h in field conditions. Interestingly, no infestation was observed up to the area of *Avicennia* covered by high tide water levels, suggesting that saltwater may serve as a natural method for controlling *Hyblaea*. This finding highlights an important opportunity for future research to explore how saltwater influences *Hyblaea* control, potentially through sensitivity experiments such as sprinkling saltwater on *Avicennia marina* in subsequent field studies. To strengthen long-term management strategies, integrating meteorological monitoring into predictive models offers considerable potential. Although such models are widely used in forest pest management, such as BioSIM, which forecasts pest phenology based on climate data (Régnière et al., 2014), their application in mangrove ecosystems remains unexplored. Given the periodic outbreaks of *Hyblaea puera* in mangrove regions like Brazil (Faraco et al., 2019), developing early warning systems using key variables such as temperature, humidity, and rainfall could greatly improve preparedness. Similar frameworks have proven effective in predicting outbreaks of spruce budworm and gypsy moth in temperate forests (Gray, 2008; Logan et al., 2003). While mangrove-specific pest models are lacking, remote sensing and statistical tools have been applied to monitor mangrove health and landscape dynamics (Chen et al., 2013), and predictive datasets have informed carbon stock modeling and forest policy planning in mangrove areas (Bukoski et al., 2020). These approaches provide a foundation for designing pest-specific models that incorporate localized meteorological data and ecological feedbacks to guide timely mitigation efforts. Alongside these technical solutions, community-based management enhances local resilience by incorporating stakeholder observations to improve early defoliation detection and enable timely response. In parallel, continuous monitoring using drones or high spatiotemporal resolution satellite imagery can enhance early detection of pest outbreaks and enable rapid intervention. Furthermore, restoring degraded mangrove patches and strategically planting less-susceptible species offer long-term strategies to reduce vulnerability and improve overall ecosystem resilience.

6. Conclusions

To study the inter-annual variability of *Hyblaea puera*-induced mangrove defoliation in and around Thane Creek, annual fieldwork was conducted from October 2020 to October 2022 using boats through the most accessible routes. This was complemented by satellite observations collected between 2018 and 2022. The occurrence of *Hyblaea* in the study area may be due to environmental stresses, such as reduced availability of their primary host plants and the presence of nearby alternative hosts. These factors could have caused the moths to shift from Teak in Sanjay Gandhi National Park to the adjacent mangrove ecosystems. This shift underscores the need for ongoing ecosystem monitoring and understanding of rapidly evolving environments. S2 data were used to classify various infestation categories through NDVI analysis and assessments of infestation phases before, during, and after each year. Annual assessment of mangrove defoliation using field and S2 imagery data, revealed that the peak infestation was spatially extended and temporally prolonged and that infestation intensity increased from 2018 to 2022. *Hyblaea* Infestation classification indicates that the infestation level is mostly under moderate to low infestation, as well as

low occurrence of infestation in both spatial and temporal aspects in 2018. In contrast, in 2021 and 2022, there was a notable escalation in infestation, occurring extensively and frequently, reaching very high to very high levels. The observed increase in both the spatial and temporal extent of peak infestation, along with severe defoliation, may be attributed to habitat changes resulting from expanding mangroves around the shrinking Thane Creek (Adluri et al., 2023). This expansion could enhance habitat for *Avicennia* and provide new food sources for *Hyblaea puera*, potentially driving the moths to migrate into the newly available mangroves, particularly if their primary Teak host plants are declining. Over the five-year period, the estimation of infested area reveals that most of the region experiences very high to moderate levels of infestation each year, with the southern and left side of the creek showing dense and severe infestation compared to the northern and right side. Based on *Hyblaea* intensity analysis and field observations, this study identified six categorical infested hotspots corresponding to six infestation categories, exemplified by very high infestation near BARC and uninfested zones near the Ghansoli mangroves, suggesting future research to explore underlying causes. A comparison between annual *Hyblaea* outbreaks and meteorological parameters such as air temperature, rainfall, relative humidity, and wind speed reveals that outbreaks tend to occur during periods of lower wind speed and moderate temperature. However, the peak infestation generally follows peak rainfall and occurs during moderate relative humidity conditions. Further research into the relationships between these parameters and *Hyblaea* outbreaks could enhance early prediction of infestations using forecasts of these parameters. Beyond insect infestations and diseases, ecosystems can also experience compound disturbances triggered by natural events such as hurricanes and climate change, as well as human activities like logging. One type of disturbance, such as a hurricane, may even initiate another, such as an insect infestation, leading to complex, interacting disturbance patterns (Turner, 2010).

Insect herbivores such as *Hyblaea puera* play a complex ecological role in mangrove ecosystems, influencing not only plant health but also broader ecosystem dynamics. While their larval feeding activity can cause rapid and extensive defoliation of *Avicennia marina*, leading to reduced plant growth and forest productivity, the impacts extend well beyond vegetation. Defoliation alters the structural integrity of mangrove habitats, disrupts microclimatic conditions, and reduces organic matter input, all of which are critical for maintaining biodiversity. Sathish et al. (2024) reported a marked decline in crustacean diversity and abundance in defoliated patches of the Dharamtar Estuary, and also noted potential cascading effects on fish species that depend on mangrove root systems and sediment conditions for breeding and feeding. Additionally, our observations and earlier reports (P R and V Mahajan, 2012; Sathish et al., 2021) suggest that insect infestations may indirectly enhance nutrient cycling through frass deposition, which has been linked to increased shrimp activity near infested sites. However, this may be offset by concurrent declines in mangrove crabs, indicating trophic imbalances. These findings underscore the need to consider both the detrimental and potentially beneficial outcomes of insect outbreaks, and to evaluate their net impact on mangrove ecosystem functioning and associated livelihoods.

Frequent pest outbreaks in mangrove ecosystems call for integrated management approaches. Botanical biopesticides such as Hy-ACT have demonstrated high larval mortality under field conditions, while saltwater exposure may naturally suppress infestations. To improve preparedness, incorporating meteorological monitoring into predictive models widely used in forest pest management but yet to be applied in mangroves can enable early warning systems based on climate variables like temperature, humidity, and rainfall. Remote sensing and statistical tools have successfully monitored mangrove health and can support pest specific model development. Alongside these technical solutions, community-based management enhances resilience by involving local stakeholders in early detection and response. Continuous monitoring using drones and high-resolution satellite imagery further aids rapid

intervention. Additionally, restoring degraded mangrove patches and planting less susceptible species offer sustainable long term strategies to reduce ecosystem vulnerability.

Further research is needed to better understand the defoliator's characteristics and identify factors that make mangroves vulnerable. It is also important to explore how mangrove defoliation affects associated fauna, investigate why the teak defoliator prefers *A. marina* over other mangrove species, and develop effective management strategies. Based on the initial findings of this study, several research gaps remain, including the need for annual monitoring of *Hyblaea* outbreaks through both field observations and satellite data, identification of infestation hotspots, and evaluation of impacts on surrounding habitats and ecosystems. Installing covariance flux towers with rain gauges to monitor heat, moisture, radiation, and other meteorological factors is recommended to improve understanding of *Hyblaea* dynamics and habitat suitability. These insights can guide adaptive management strategies such as saltwater treatment trials and targeted conservation efforts in persistently infested zones.

CRedit authorship contribution statement

Adluri Mr. Anjaneyulu: Software, Investigation, Data curation, Writing – review & editing, Resources, Funding acquisition, Conceptualization, Validation, Methodology, Formal analysis. **Borra Sivaiah:** Writing – review & editing, Validation, Methodology, Conceptualization, Writing – original draft, Supervision, Investigation, Visualization, Software, Formal analysis. **Manas Manjrekar:** Resources, Formal analysis, Data curation. **C Sathish:** Investigation, Writing – review & editing, Formal analysis, Supervision, Conceptualization. **P.S.N. Acharyulu:** Visualization, Formal analysis, Validation, Supervision. **Naidu V.S:** Visualization, Supervision, Writing – review & editing, Formal analysis. **Nadaf Mahaboob Dastagir:** Formal analysis, Software, Data curation, Resources. **Sudheer Joseph:** Visualization, Formal analysis, Validation, Writing – review & editing, Supervision. **Kumar M Nagaraja:** Supervision, Writing – review & editing, Formal analysis, Visualization. **Hari Kumar R:** Visualization, Formal analysis, Validation, Writing – review & editing, Investigation. **T.M. Balakrishnan Nair:** Investigation, Writing – review & editing, Formal analysis, Supervision.

Authors Statement

Anjaneyulu A. led the conceptualization of the study and contributed to data collection, methodology development, literature review, preparation of figures, fieldwork, manuscript review, and validation. Sivaiah B. contributed to the conceptualization, authored the original manuscript and its review, and was involved in the literature review, data handling, methodology development, figure preparation, analysis, and validation. Manas Manjrekar and Mahaboob Nadaf assisted in fieldwork activities. Sathish C., P.S.N. Acharyulu, and V.S. Naidu contributed through manuscript review and scientific discussions. Sudheer Joseph, M. Nagaraja Kumar, R. Hari Kumar, and Balakrishnan Nair T.M. provided scientific guidance, suggestions, and overall support. All authors have read and approved the final version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

- Adam, Paul, 2011. The energetics of mangrove forests. e18-e19.
- Adluri, Anjaneyulu, Manjrekar, Manas, Karve, Harshal, Simhadri Naidu, V., 2023. Study of decadal variations in width and mangrove cover of the Thane Creek, Maharashtra, India, using remote sensing. *Current Science* (00113891) 124 (3).
- Alongi, D.M., 2002. Present state and future of the world's mangrove forests. *Environ. Conserv.* <https://doi.org/10.1017/S0376892902000231>.
- Alongi, Daniel M., 2014a. Mangrove forests of timor-leste: ecology, degradation and vulnerability to climate change. *Mangrove Ecosyst. Asia Status Chall. Manag. Strateg.* 199–212.
- Alongi, Daniel M., 2014b. Carbon cycling and storage in mangrove forests. *Annu. Rev. Mar. Sci.* 6 1, 195–219.
- Amiro, B.D., Barr, A.G., Barr, J.G., Black, T.A., Bracho, R., Brown, M., Chen, J., Clark, K. L., Davis, K.J., Desai, A.R., Dore, S., Engel, V., Fuentes, J.D., Goldstein, A.H., Goulden, M.L., Kolb, T.E., Lavigne, M.B., Law, B.E., Margolis, H.A., Martin, T., McCaughey, J.H., Misson, L., Montes-Helu, M., Noormets, A., Randerson, J.T., Starr, G., Xiao, J., 2010. Ecosystem carbon dioxide fluxes after disturbance in forests of North America. *J. Geophys Res Biogeosci* 115. <https://doi.org/10.1029/2010JG001390>.
- Analuddin, K., Sharma, S., Jamili, Septiana, A., Sahidin, I., Rianse, U., Nadaoka, K., 2017. Heavy metal bioaccumulation in mangrove ecosystem at the coral triangle ecoregion, Southeast Sulawesi, Indonesia. *Mar. Pollut. Bull.* 125, 472–480. <https://doi.org/10.1016/j.marpolbul.2017.07.065>.
- Anderson, C., Lee, S.Y., 1995. Defoliation of the Mangrove *Avicennia marina* in Hong Kong: Cause and Consequences.
- Barbier, E.B., 2016. The protective service of mangrove ecosystems: A review of valuation methods. *Mar. Pollut. Bull.* 109, 676–681. <https://doi.org/10.1016/j.marpolbul.2016.01.033>.
- Blasco, F., Gauquelin, T., Rasolofoharino, M., Denis, J., Aizpuru, M., Caldaïrou, V., 1998. Recent advances in mangrove studies using remote sensing data. *Mar. Freshw. Res.* 49, 287–296. <https://doi.org/10.1071/mf97153>.
- Bukoski, Jacob J., Elwin, Angie, MacKenzie, Richard A., Sharma, Sahadev, Purbopuspito, Joko, Kopania, Benjamin, Apwong, Maybeleen, Poolsiri, Roongreang, Potts, Matthew D., 2020. The role of predictive model data in designing mangrove forest carbon programs. *Environ. Res. Lett.* 15 (8), 084019.
- Burrows, D.W., 2003. The role of insect leaf herbivory on the mangroves *Avicennia marina* and *Rhizophora stylosa*. *James Cook University*.
- Cannicci, S., Burrows, D., Fratini, S., Smith, T.J., Offenberger, J., Dahdouh-Guebas, F., 2008. Faunal impact on vegetation structure and ecosystem function in mangrove forests: A review. *Aquat. Bot.* <https://doi.org/10.1016/j.aquabot.2008.01.009>.
- Chandrasekhar, N., Sajeev, T.V., Sudheendrakumar, V.V., Banerjee, M., 2005. Population dynamics of the Teak defoliator (*Hyblaea puera* Cramer) in Nilambur teak plantations using Randomly Amplified Gene Encoding Primers (RAGEP). *BMC Ecol.* 5. <https://doi.org/10.1186/1472-6785-5-1>.
- Chen, Chi-Farn, Son, Nguyen-Thanh, Chang, Ni-Bin, Chen, Cheng-Ru, Chang, Li-Yu, Valdez, Miguel, Centeno, Gustavo, Thompson, Carlos Alberto, Aceituno, Jorge Luis, 2013. Multi-decadal mangrove forest change detection and prediction in Honduras, Central America, with Landsat imagery and a Markov chain model. *Remote Sens.* 5 (12), 6408–6426.
- Dahdouh-Guebas, F., 2002. Use Remote Sens. *Gis Sustain. Manag. Trop. Coast. Ecosyst.*
- Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M., Kanninen, M., 2011. Mangroves among the most carbon-rich forests in the tropics. *Nat. Geosci.* 4, 293–297. <https://doi.org/10.1038/ngeo1123>.
- Duke, N.C., 2002. Sustained high levels of foliar herbivory of the mangrove *Rhizophora stylosa* by a moth larva *Doratifera stenosa* (Limacodidae) in north-eastern Australia. *Wetl. Ecol. Manag.* 10, 403–419. <https://doi.org/10.1007/BF03263357>.
- Duke, N.C., Meynecke, J.-O., Dittmann, S., Ellison, A.M., Anger, K., Berger, U., Cannicci, S., Diele, K., Ewel, K.C., Field, C.D., Koedam, N., Lee, S.Y., Marchand, C., Nordhaus, I., Dahdouh-Guebas, F., 2007. A World Without Mangroves? *Science* 317 (1979). <https://doi.org/10.1126/science.317.5834.41b>.
- Erickson, A.A., Bell, S.S., Dawes, C.J., 2004. Does Mangrove Leaf Chemistry Help Explain Crab Herbivory Patterns?

- Everitt, H., Judd, F.W., Escobar, D.E., Davist, M.R., 1996. Integration of Remote Sensing and Spatial Information Technologies for Mapping Black Mangrove on the Texas Gulf Coast. Title. J. Coast. Res. 12, 64–69.
- Faraco, L.F.D., Da Cunha Lana, P., 2004. Leaf-consumption levels in subtropical mangroves of Paranaguá Bay (SE Brazil). Wetl. Ecol. Manag 12, 115–122. <https://doi.org/10.1023/B:WETL.0000021666.42546.c2>.
- Faraco, L.F.D., Ghisi, C.L., Martins, M., Ota, S., Schühli, G.S., 2019. Infestation of mangroves by the invasive moth *Hyblaea puera* (Cramer, 1777) (Lepidoptera: Hyblaeidae). Braz. Arch. Biol. Technol. 62, 1–7. <https://doi.org/10.1590/1678-4324-2019170516>.
- Feller, I.C., Lovelock, C.E., Berger, U., 2010. Biocomplexity in mangrove ecosystems. Annu. Rev. Ecol. Evol. Syst. 41, 1–22. <https://doi.org/10.1146/annurev.ecolsys.110308.120237>.
- Fernandes, M.E.B., Nascimento, A.A.M., Carvalho, M.L., 2009. Effects of herbivory by *Hyblaea puera* (Hyblaeidae: Lepidoptera) on litter production in the mangrove on the coast of Brazilian Amazonia. J. Trop. Ecol. 25, 337–339. <https://doi.org/10.1017/S0266467409005884>.
- Gara, R.L., Sarango, A., Cannon, P.G., 1990. Defoliation of an Ecuadorian mangrove forest by the bagworm, *Oiketicus kirbyi* Guilding (Lepidoptera: Psychidae). J. Trop. For. Sci.
- Ghorbanian, A., Zaghian, S., Asiyabi, R.M., Amani, M., Mohammadzadeh, A., Jamali, S., 2021. Mangrove ecosystem mapping using sentinel-1 and sentinel-2 satellite images and random forest algorithm in google earth engine. Remote Sens (Basel) 13. <https://doi.org/10.3390/rs1312565>.
- Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Masek, J., Duke, N., 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. Glob. Ecol. Biogeogr. 20, 154–159. <https://doi.org/10.1111/j.1466-8238.2010.00584.x>.
- Giri, C., Zhu, Z., Tieszen, L.L., Singh, A., Gillette, S., Kelmelis, J.A., 2008. Mangrove forest distributions and dynamics (1975/2005) of the tsunami-affected region of Asia. J. Biogeogr. 35, 519–528. <https://doi.org/10.1111/j.1365-2699.2007.01806.x>.
- Gnanappazham, L., Pillai, Nithin, 2022. Final Report of the project Monitoring the Health of Mangroves of Maharashtra State Using Near Real Time Satellite Remote Sensing Data Mangrove and Marine Biodiversity Conservation Foundation of Maharashtra Office of the Additional Principal Chief Conservator of Forests Mumbai. Indian Institute of Space Sciences and Technology (IIIST), Thiruvananthapuram.
- Gray, David R., 2008. The relationship between climate and outbreak characteristics of the spruce budworm in eastern Canada. Clim. Change 87 (3), 361–383.
- James, G.K., Adegoke, J.O., Osagie, S., Ekechukwu, S., Nwilo, P., Akinyede, J., 2013. Social valuation of mangroves in the Niger Delta region of Nigeria. Int J. Biodivers. Sci. Ecosyst. Serv. Manag 9, 311–323. <https://doi.org/10.1080/21513732.2013.842611>.
- Javaregowda, B., 2005. Studies on the Seasonal Incidence Biology and Management of Teak defoliator *Hyblaea puera* Cramer Hyblaeidae Lepidoptera In Uttara Kannada District of Karnataka.
- Jenoh, E.M., Robert, E.M.R., Lehmann, I., Kioko, E., Bosire, J.O., Ngisange, N., Dahdouh-Guebais, F., Koedam, N., 2016. Wide ranging insect infestation of the pioneer mangrove *Sonneratia alba* by two insect species along the Kenyan coast. PLoS One 11. <https://doi.org/10.1371/journal.pone.0154849>.
- Kamruzzaman, M., Basak, K., Paul, S.K., Ahmed, S., Osawa, A., 2019. Litterfall production, decomposition and nutrient accumulation in Sundarbans mangrove forests, Bangladesh. For. Sci. Technol. 15, 24–32. <https://doi.org/10.1080/21580103.2018.1557566>.
- Karnieli, A., Agam, N., Pinker, R.T., Anderson, M., Imhoff, M.L., Gutman, G.G., Panov, N., Goldberg, A., 2010. Use of NDVI and land surface temperature for drought assessment: Merits and limitations. J. Clim. 23, 618–633. <https://doi.org/10.1175/2009JCLI2900.1>.
- Lee, S.Y., 1991. Herbivory as an ecological process in a *Kandelia candel* (Rhizophoraceae) mangal in Hong Kong. J. Trop. Ecol.
- Linneweber, Volker, 2013. Mangrove ecosystems: function and management. Springer Science & Business Media.
- Logan, Jesse A., Régnière, Jacques, Powell, James A., 2003. Assessing the impacts of global warming on forest pest dynamics. Front. Ecol. Environ. 1 (3), 130–137.
- Malenovsky, Z., Rott, H., Cihlar, J., Schaepman, M.E., García-Santos, G., Fernandes, R., Berger, M., 2012. Sentinels for science: Potential of Sentinel-1, -2, and -3 missions for scientific observations of ocean, cryosphere, and land. Remote Sens Environ. 120, 91–101. <https://doi.org/10.1016/j.rse.2011.09.026>.
- Manna, S., Raychaudhuri, B., 2019. Stress mapping of Sundarban mangroves with Sentinel-2 images using Discriminant Normalised Vegetation Index (DNVI) and Fuzzy classification technique. J. Geomat.
- Manna, S., Raychaudhuri, B., 2020. Mapping distribution of Sundarban mangroves using Sentinel-2 data and new spectral metric for detecting their health condition. Geocarto Int 35, 434–452. <https://doi.org/10.1080/10106049.2018.1520923>.
- Mehlig, U., De Menezes, M.P.M., 2005. Mass defoliation of the mangrove tree *Avicennia germinans* by the moth *Hyblaea puera* (Lepidoptera: Hyblaeidae) in Equatorial Brazil. Ecotropica 11, 87–88.
- Menezes, L.F.T. de, Ariane Luna, Peixoto, 2009. Leaf damage in a mangrove swamp at Sepetiba Bay, Rio de Janeiro, Brazil. Braz. J. Bot. 32, 715–724.
- Murphy, D.H., 1990. The natural history of insect herbivory on mangrove trees in and near Singapore. Raffles Bull. Zool. 38, 119–203.
- Nakhawa, A.D., Chellapan, A., Akhilesh, K.V., Bhendekar, S., Kumar, R., Vase, V.K., Zacharia, P.U., 2023. Investigation of teak defoliator, *Hyblaea puera* (Cramer, 1777) outbreak on mangrove ecosystem in Mumbai metropolitan region using multi-spectral satellite data. Reg. Stud. Mar. Sci. 60. <https://doi.org/10.1016/j.rsma.2023.102828>.
- Offenberg, J., Havanon, S., Aksornkoae, S., MacIntosh, D.J., Gissel Nielsen, M., 2004. Observations on the Ecology of Weaver Ants (*Oecophylla smaragdina* Fabricius) in a Thai Mangrove Ecosystem and Their Effect on Herbivory of *Rhizophora mucronata* Lam. Biotropica 36, 344. <https://doi.org/10.1646/03158>.
- Otunga, C., Odindi, J., Mutanga, O., Adjorlolo, C., 2019. Evaluating the potential of the red edge channel for C3 (Festuca spp.) grass discrimination using Sentinel-2 and Rapid Eye satellite image data. Geocarto Int 34, 1123–1143. <https://doi.org/10.1080/10106049.2018.1474274>.
- P R, A., V Mahajan, M., 2012. Ecological Costs and Benefits of Teak Defoliator (*Hyblaea puera* Cramer) Outbreaks in a Mangrove Ecosystem. Mar. Sci. 2, 48–51. <https://doi.org/10.5923/j.ms.20120205.02>.
- Parida, Ashish Kumar, Bhavanath, Jha, 2010. Salt tolerance mechanisms in mangroves: a review. Trees 24 (2), 199–217.
- Peres-Filho, O., Dorval, A., Berti-Filho, E., 2002. Ocorrência de *Hyblaea puera* (Cramer, 1777) (Lepidoptera: Hyblaeidae) em teca no Brasil. Bragantia 61, 59–60.
- Pesaresi, M., Corbane, C., Julea, A., Florczyk, A.J., Syrris, V., Soille, P., 2016. Assessment of the added-value of sentinel-2 for detecting built-up areas. Remote Sens (Basel) 8. <https://doi.org/10.3390/rs8040299>.
- Pham, T.D., Yokoya, N., Bui, D.T., Yoshino, K., Friess, D.A., 2019. Remote sensing approaches for monitoring mangrove species, structure, and biomass: Opportunities and challenges. Remote Sens (Basel). <https://doi.org/10.3390/rs11030230>.
- Piyakarnchana, T., 1981. Severe defoliation of *Avicennia alba* BL. by larvae of *Cleora injectaria* Walker. ScienceAsia 7.
- Polidoro, B.A., Carpenter, K.E., Collins, L., Duke, N.C., Ellison, A.M., Ellison, J.C., Farnsworth, E.J., Fernando, E.S., Kathiresan, K., Koedam, N.E., Livingstone, S.R., Miyagi, T., Moore, G.E., Nam, V.N., Ong, J.E., Primavera, J.H., Salmo, S.G., Sanciangco, J.C., Sukardjo, S., Wang, Y., Yong, J.W.H., 2010. The loss of species: Mangrove extinction risk and geographic areas of global concern. PLoS One 5. <https://doi.org/10.1371/journal.pone.0010095>.
- Raja Rishi, R., 2021. Development of Integrated Pest Management (Ipm) Strategies Against the Major Defoliating Pests of Mangroves in the Thane District of Maharashtra Project Completion Report Mangrove Cell. Maharashtra Forest Department.
- Raja Rishi, R., Sundararaj, R., 2020. Record of an epidemic outbreak of *Hyblaea puera* Cramer (Lepidoptera: Hyblaeidae) on *Avicennia marina* in the mangroves of Maharashtra, India. J. Entomol. Zool. Stud. 9, 306–309.
- Régnière, Jacques, Rémi Saint-Amant, Ariane Béchard, Moutaoufik, Ahmed, 2014. BioSIM 10: User's manual. Laurentian Forestry Centre, Québec, QC, Canada.
- Richards, D.R., Friess, D.A., 2016. Rates and drivers of mangrove deforestation in Southeast Asia, 2000–2012. Proc. Natl. Acad. Sci. USA 113, 344–349. <https://doi.org/10.1073/pnas.1510272113>.
- Rullan-Silva, C.D., Olthoff, A.E., Delgado de la Mata, J.A., Pajares-Alonso, J.A., 2013. Remote monitoring of forest insect defoliation. A review. Syst. <https://doi.org/10.5424/fs/2013223-04417>.
- Sathish, C., Nakhawa, A.D., Bharti, V.S., Jaiswar, A.K., Deshmukhe, G., 2021. Estimation of extent of the mangrove defoliation caused by insect *Hyblaea puera* (Cramer, 1777) around Dharamtar creek, India using Sentinel 2 images. Reg. Stud. Mar. Sci. 48. <https://doi.org/10.1016/j.rsma.2021.102054>.
- Sathish, Chennuri, Sivaiah, B., Srinivas, K., Vidya Shree, Bharti, Jaiswar, A.K., Sudheer, Joseph, Geetanjali, Deshmukhe, 2024. Impact of mangrove defoliation by *Hyblaea puera* on diversity of associated crustaceans in the Dharamtar Estuary, Maharashtra, India. Indian J. Fish. 71 (3).
- Selamat, M.B., Mashoreng, S., Amri, K., Susetiono, Rappe, R.A., 2020. The use of sentinel 2A imageries to improve mangrove inventoryization at coremap CTI monitoring areas. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing Ltd. <https://doi.org/10.1088/1755-1315/564/1/012065>.
- Shri, M.M. Panditrao, 2020. Thane Creek Flamingo Sanctuary Manag. Plan.
- Siddhesh Bhav, Benjamin, S., Dr. Goldin Quadros, Vaz, J., Tripathi, A., Gujarpadhaye, P., 2015. Conducting baseline studies for Thane Creek Project report. Sálím Ali Centre for Ornithology and Natural History (SACON).
- Spalding, M., Kainuma, M., Collins, L., 2010. World Atlas of Mangroves. Routledge.
- Thiagarajah, J., Wong, S.K.M., Richards, D.R., Friess, D.A., 2015. Historical and contemporary cultural ecosystem service values in the rapidly urbanizing city state of Singapore. Ambio 44, 666–677. <https://doi.org/10.1007/s13280-015-0647-7>.
- Tong, Y.F., Lee, S.Y., Morton, B., 2003. Effects of artificial defoliation on growth, reproduction and leaf chemistry of the mangrove *Kandelia candel*. J. Trop. Ecol. 19 (4), 397–406.
- Tong, Y.F., Lee, S.Y., Morton, B., 2006. The herbivore assemblage, herbivory and leaf chemistry of the mangrove *Kandelia obovata* in two contrasting forests in Hong Kong. Wetl. Ecol. Manag 14, 39–52. <https://doi.org/10.1007/s11273-005-2565-0>.
- Townsend, P.A., Singh, A., Foster, J.R., Rehberg, N.J., Kingdon, C.C., Eshleman, K.N., Seagle, S.W., 2012. A general Landsat model to predict canopy defoliation in broadleaf deciduous forests. Remote Sens Environ. 119, 255–265. <https://doi.org/10.1016/j.rse.2011.12.023>.
- Tripathy, M.K., Tripathy, A., Manoj, C., Tripathy, K., Rout, M., 2018. Population dynamics of teak defoliator, *Hyblaea puera* Cramer at coastal Odisha, India. ~ 2378. J. Entomol. Zool. Stud. 6.
- Turner, M.G., 2010. Disturbance and landscape dynamics in a changing world.
- Uddin, M.S., de Ruyter van Steveninck, E., Stuij, M., Shah, M.A.R., 2013. Economic valuation of provisioning and cultural services of a protected mangrove ecosystem: A case study on Sundarbans Reserve Forest, Bangladesh. Ecosyst. Serv. 5, 88–93. <https://doi.org/10.1016/j.ecoser.2013.07.002>.
- Valiela, Ivan, Bowen, Jennifer L., York, Joanna K., 2010. Mangrove forests: One of the World's threatened major tropical environments. BioScience 51, 807–815.
- Wachid, M.N., Hapsara, R.P., Cahyo, R.D., Wahyu, G.N., Syarif, A.M., Umarhadi, D.A., Fitriani, A.N., Ramadanningrum, D.P., Widaymanti, W., 2017. Mangrove canopy

- density analysis using Sentinel-2A imagery satellite data. In: IOP Conference Series: Earth and Environmental Science. Institute of Physics Publishing. <https://doi.org/10.1088/1755-1315/70/1/012020>.
- Wang, J., Sammis, T.W., Gutschick, V.P., Gebremichael, M., Dennis, S.O., Harrison, R.E., 2010. Review of Satellite Remote Sensing Use in Forest Health Studies. *Open Geogr. J.*
- Ward, R.D., Friess, D.A., Day, R.H., Mackenzie, R.A., 2016. Impacts of climate change on mangrove ecosystems: a region by region overview. *Ecosyst. Health Sustain.* 2. <https://doi.org/10.1002/ehs2.1211>.
- West, R., Thorogood, C., 1985. Mangrove dieback in Hunter River caused by caterpillars. *Aust. Fish.* 44.
- Whitten, A.J., Damanik, S.J., 1986. Mass defoliation of mangroves in Sumatra, Indonesia. *Biotropica* 18, 176.