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Review

Indian Sundarbans mangrove forest considered endangered under Red List of Ecosystems, but there is cause for optimism

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ABSTRACT

Accurately evaluating ecosystem status is vital for effective conservation. The Red List of Ecosystems (RLE) from the International Union for the Conservation of Nature (IUCN) is the global standard for assessing the risk of ecosystem collapse. Such tools are particularly needed for large, dynamic ecosystem complexes, such as the Indian Sundarbans mangrove forest. This ecosystem supports unique biodiversity and the livelihoods of millions, but like many mangrove forests around the world is facing substantial pressure from a range of human activities. Holistic, standardised and quantitative environment risk assessment frameworks are essential here, because previous assessments have either been qualitative in nature, or have generally considered single threats in isolation. We review these threats and utilise the RLE framework to quantitatively assess the risk of ecosystem collapse. Historical clearing and diminishing fish populations drove a status of *Endangered* (range: *Vulnerable* to *Endangered*), and ongoing threats including climate change and reduced freshwater supply may further impact this ecosystem. However, considering recent change, the outlook is more optimistic. Mangrove extent has stabilised, and analysis of mangrove condition highlights that only a small proportion of the forest is degraded. Using the RLE provides an authoritative avenue for further protection and recognition of the issues facing this UNESCO World Heritage Site. We also identify knowledge and data gaps in the Sundarbans that are likely common to coastal systems globally. By articulating these and presenting opportunities and recommendations, we aim to further the conservation goals of the IUCN and the implementation of its new assessment framework.

1. Introduction

Many of the world's ecosystems are experiencing severe and sustained decline in extent and condition, with intergovernmental bodies suggesting we are experiencing unprecedented environmental loss and deterioration (IPBES, 2019). Such rates of environmental loss are expected to have myriad impacts on biodiversity (Maxwell et al., 2016) and ecosystem service provision (Rounsevell et al., 2010), with subsequent impacts on human populations. Recently, tools have been developed to chart environmental health (Logan et al., in press) and assess the risk of ecosystem collapse. One tool that has gained traction internationally is the International Union for the Conservation of Nature (IUCN)'s Red List of Ecosystems (RLE) framework (Keith et al., 2013). Analogous to the IUCN Red List of Threatened Species, the RLE provides criteria to identify the risk of collapse of assessed ecosystems. While there are a number of challenges with adapting a species framework to broader ecosystems (e.g. Boitani et al., 2015), the RLE has been widely discussed theoretically (Keith et al., 2013; Murray et al., 2017) and used empirically to assess the condition of various ecosystems and locations (Marshall et al., 2018; Ferrer-Paris et al., 2019). Consequently, the RLE

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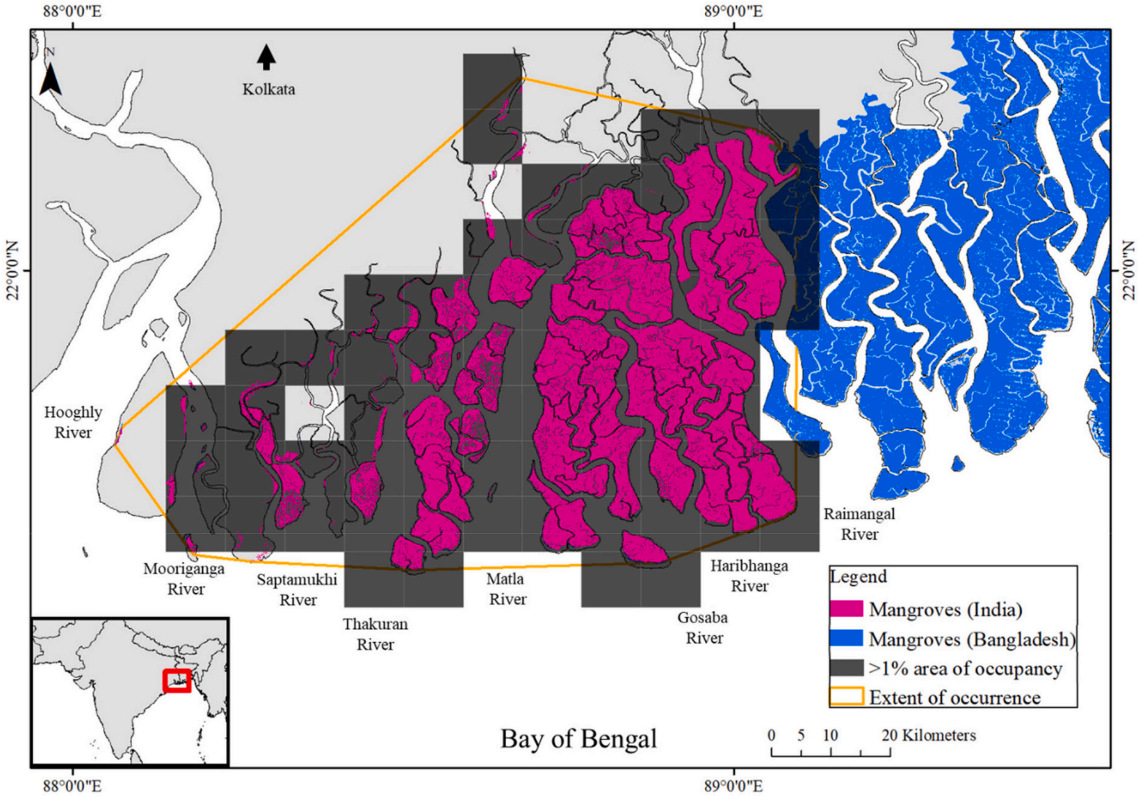

Fig. 1. Mapped distribution of the mangrove ecosystem of the Indian Sundarbans, showing the key rivers, the minimum convex polygon enclosing all occurrences of mangroves (orange line: extent of occurrence), and all occupied (> 1%) 10 × 10 km grid cells (dark grey cells: area of occupancy). Also shown is part of the mangrove ecosystem of the Bangladesh Sundarbans. Distribution data current at 2016 from the Global Mangrove Watch (https://data.unep-wcmc.org/datasets/45).

framework has been strongly promoted as assisting a shift from species-level to ecosystem-level conservation (Watson et al., 2020).

Conservation risk identification tools such as the RLE are particularly needed for large and dynamic ecosystems, such as the 4000 km^2 Sundarbans mangrove forest in East India, that are at risk from a diverse range of threats. The Indian Sundarbans are part of a large deltaic complex that extends to mangrove forests in Bangladesh, and are a key biodiversity hotspot, home to iconic species including the Royal Bengal tiger (*Panthera tigris*), the fishing cat (*Prionailurus viverrinus*), the Ganges river dolphin (*Platanista gangetica*), the Irrawaddy river dolphin (*Orcaella brevirostris*), and the lesser known mangrove horseshoe crab (*Carcinoscorpius rotundicauda*) (Gopal and Chauhan, 2006; IUCN, 2013). Four million people rely on the Indian Sundarbans for ecosystem services (Ghosh et al., 2015); in particular, wild fisheries are the second biggest source of employment within the Sundarbans (Ghosh, 2012). Therefore, conservation of the Indian Sundarbans mangrove forest is critical for both wildlife and people.

The Sundarbans are a changing system under strong environmental and anthropogenic influence. Natural dynamics of accretion and erosion contribute to annual gains and losses in mangrove area (Hazra et al., 2002). Mangrove erosion between 1984 and 2018 in the Sundarbans totalled 136.77km^2, with a progradation of 62.17km^2 (Bhargava et al., 2020). The land has a long history of mangrove clearing. Populated since the 8th century, intensification of land use and mangrove clearing escalated from the late 19th century and continued throughout the 20th century (Ghosh et al., 2015). Since the 1970s, the declaration of the area as a World Heritage Site, along with other management and conservation tools, has helped to stabilise the mangrove area (Ghosh et al., 2015). However, as the local population continues to increase, and the impacts from agriculture, hydrological changes, illegal fishing including shrimp farming, and climate change intensify, there is a need to monitor and identify the status and drivers of change of this important mangrove system.

A holistic, standardised and quantitative risk assessment framework is essential for the Indian Sundarbans, because previous assessments have either generally considered single threats to the mangrove forest in isolation (e.g. salinity and erosion; Islam and Gnauck, 2009, Bera and Maiti, 2019), or have been qualitative in nature. For example, the Indian Sundarbans National Park was assessed using qualitative information to assign a conservation outlook status of '*good with some concerns*' as part of the IUCN World Heritage Outlook (IUCN, 2017). However, quantitative tools are required to show transparency and set targets for future conservation interventions, and allow future changes in assessed variables to be rapidly incorporated into updated assessments when new data become available (Hill et al., 2016; McQuatters-Gollop et al., 2019). A holistic assessment is also required because the Indian Sundarbans face a range of threats that vary in their cause from the biophysical to the human, and originate both within and outside its borders. The RLE is a proven and transparent framework that has the ability to inform public policy (Alaniz et al., 2019; Bland et al., 2019), and can help the formulation of further conservation plans for the area.

This study represents the first quantitative and standardised environmental risk assessment for the Indian Sundarbans. The objectives of this study were to: (i) identify the defining ecological features of the ecosystem and review the key processes that threaten them, (ii) evaluate trends in key environmental and biotic variables relevant to the persistence of the ecosystem, (iii) assess the potential risk of ecosystem collapse, and (iv) evaluate the utility of the framework for assessing and managing coastal ecosystems.

2. Materials and methods

Classifying ecosystem boundaries is a key step and constraint of the RLE (Boitani et al., 2015). Assessments require detailed information on the target ecosystem, including its classification, spatial distribution, and descriptions of the abiotic and biotic environment, the ecosystem processes and the key threats acting upon the ecosystem (see Appendix A for the full assessment for the Indian Sundarbans).

2.1. Study site description

The Indian Sundarbans mangrove ecosystem - defined by the extent of mangrove vegetation (Fig. 1) - is classified as habitat type 12.7 *Marine Intertidal – Mangrove Submerged Roots* and 1.7 *Forest – Subtropical/Tropical Mangrove Vegetation Above High Tide Level* under the IUCN Habitats Classification (Version 3.1), and is part of the Bay of Bengal Marine Ecoregion of the World (Spalding et al., 2007). The deltaic complex of the rivers Ganga, Brahmaputra and Meghna covers 9630 km^2, with the Sundarbans mangrove forest shared between Bangladesh (62%) and India (38%). This assessment is on the Indian Sundarbans mangrove ecosystem (Fig. 1), the largest delta in the estuarine phase of the River Ganges. The major rivers in the Indian Sundarbans are the Hooghly, Mooriganga, Saptamukhi, Thakuran, Matla, Gosaba and Haribhanga, while the Raimangal divides the Indian and Bangladesh border (Fig. 1). Tidal range varies spatially, with an average amplitude between 2.5 (neap) to 4.8 m (spring) and waves reaching 7 m during storm surges. Moreover, significant freshwater flow from Hooghly and Mooriganga rivers strongly influences the western side of Indian Sundarbans, while the eastern side is tidally influenced except during seasonal monsoons (Durand et al., 2011).

The Sundarbans mangrove complex stretches across India and Bangladesh (Fig. 1), sharing similar social, ecological, chemical, and physical characteristics. Therefore, connectivity between these two portions is fundamentally important to the overall health and condition of the greater Sundarbans area. Currently, each country manages its forest independently (Ortolano et al., 2016), making each side of the forest a different system from the perspective of public policy. Since the RLE criteria can be instrumental in operationalising public policy (Alaniz et al., 2019), we conducted a focused assessment to inform relevant policy changes for the better management of the Sundarbans in India, but acknowledge that the condition of either side is inherently linked.

Similar to other mangroves, key drivers of diversity and productivity are temperature, salinity, freshwater flow, nutrients and tidal amplitude, all of which have been well quantified in the area (Manna et al., 2012). River-dominated settings are typically large deltas that receive substantial volumes of freshwater and sediment from upstream catchments, with hydrodynamics controlling the distribution of nutrients and salinity values along the estuaries of Sundarbans (Manna et al., 2012). Salinity strongly influences the Indian Sundarbans' ecology, as salinity tolerance can vary greatly among mangrove species (Mitra et al., 2010; Dasgupta et al., 2017).

The Indian Sundarbans are highly biodiverse, making up over 60% of India's total mangrove forest area and containing 90% of its mangrove plant species. Twenty-four true mangrove species from nine families occur in the Indian Sundarbans (Barik and Chowdhury, 2014; Appendix A). The ecosystem provides habitat for many charismatic, rare and threatened mammals, birds and reptiles (Chaudhuri and Choudhury, 1994; Gopal and Chauhan, 2006; Singh et al., 2015). There are also several hundred species of fishes and crustaceans that inhabit the Sundarbans, including many of commercial and recreational importance (Das, 2009; Danda et al., 2017). For a comprehensive list of the known wildlife found within the Sundarbans, see https://rsis.ramsar.org/ris/2370.

2.2. IUCN Red List of Ecosystem framework

We applied the RLE criteria according to IUCN guidelines (Bland et al., 2017), all of which assess the risk of ecosystem collapse. We assessed trends and status in the ecosystem under four of the five criteria (A through D). Like many RLE assessments (see Keith et al., 2013), criterion E was not assessed as this requires a sophisticated quantitative analysis to assess the future risk of ecosystem collapse. Criterion A identifies ecosystems that are undergoing declines in extent; Criterion B identifies ecosystems at risk due to restricted distributions; Criterion C assesses environmental degradation, and; criterion D assesses disruption of biotic processes or interactions. Criteria C and D require the relative severity of decline in key ecosystem indicators to be estimated and combined with the proportion of the ecosystem affected to determine the risk category (Bland et al., 2017). Where possible, criteria A, C and D were assessed over four time frames: the past 50 years (sub-criterion 1), a future 50-year time frame (sub-criterion 2a), any 50 year period including the past, present and future (sub-criterion 2b) and since 1750 (sub-criterion 3). Using these criteria, ecosystems are assigned a status based on the risk of ecosystem collapse, with levels akin to those popularised by the Red List of Threatened Species (*Critically Endangered, Endangered, Vulnerable, Near Threatened, Least Concern,* and *Data Deficient*). The final, overall status assigned to the ecosystem is the most severe category assigned to any one sub-criteria (i.e. the one-out-all-out principle; Bland et al., 2017).

2.3. Defining ecosystem collapse

Based on literature review, we summarise the most pressing threats for mangroves within the Indian Sundarbans (Table 1 and more comprehensively in Appendix A and Table S1) and create a conceptual model to inform indicators for ecosystem collapse (Fig. 2). To estimate risk from these threats, the endpoint of ecosystem decline must be defined (i.e. the point at which an ecosystem is considered collapsed). Within the RLE, “an ecosystem is collapsed when it is virtually certain that its defining biotic or abiotic features are lost from all occurrences, and the characteristic native biota are no longer sustained” (Bland et al., 2017). Across criteria in this study, collapse is defined as the loss of mangroves (complete loss of vegetation, or the absence of true mangrove plant species), key functions, processes, or the characteristic biota; similar to Marshall et al. (2018). Specifically, for criteria A and B, the ecosystem was considered collapsed when the extent of mangroves declines to zero (based on the best available spatial maps; Table 2). While it may be expected that a mangrove ecosystem may functionally collapse prior to this, there is a lack of information on how ecosystem function or service provision is impacted with decreasing extent, or at what percentage extent a tipping point occurs. For criterion C, collapse is assumed to occur when conditions within the ecosystem are no longer suitable to support characteristic biota (both mangrove flora and fauna; Table 2). For criterion D, collapse is assumed to occur when 100% of the mangrove area is considered degraded based on changes to vegetation metrics (see Section 2.4.4.) or the abundance of ecologically or economically important species/functional groups within mangrove habitats decline to zero (Table 2).

2.4. Data for the ecosystem assessment

2.4.1. Decline in distribution – criterion A

To estimate current changes in extent (sub-criterion A1), Landsat and Corona imagery data collated and analysed by Ghosh et al. (2015) were used (1968, 1989, 2001, 2014), as was a 2016 estimate for the region from the Global Mangrove Watch global extent (Bunting et al., 2018; https://data.unep-wcmc.org/datasets/45). We calculated both proportional and absolute rate of loss from these data (Bland et al., 2017). Future risk of collapse (sub-criterion A2a; A2b) was extrapolated from current rates of decline, using both proportional and absolute rate of loss, with variability expressed by estimating rates of loss for each time interval over the last 50 years of data (e.g. from 1966 to 2016, 1967–2016, …, 2015–2016). There are obvious assumptions and uncertainties involved in this extrapolation, and where needed, these are interpreted in the context of current environmental protections and we

Table 1

Summary of the key threats that influence the Sundarbans mangrove ecosystem. See Table S1 for a comprehensive review of the threats, sub-threats, impacts to the mangrove ecosystem, and bibliography. References provided are from study of the entire Sundarbans (India and Bangladesh), as processes and impacts are likely to be similar across countries.

Key threat	Brief description	References
Agriculture and aquaculture	Agriculture and aquaculture lead to direct land clearing and conversion, deplete wild fish and crustacean populations, alter water quality through various inputs such as feed and medicines, and extract water which influences soil and water salinity.	(Miah et al., 2011, Banerjee et al., 2012, Dubey et al., 2016, Mandal et al., 2019)
Biological resource use	The local human population relies on the mangrove ecosystem for a range of resources, such as food fish and crustaceans, honey cultivation, hunting and poaching of tigers, spotted deer and boar, as well as tree harvesting for building materials, firewood and paper production.	(Chandra and Sagar, 2003, Hoq, 2007, Chakrabarti, 2009)
Climate change	The Indian Sundarbans is vulnerable to coastal erosion and inundation, and enhanced salinisation, due to sea level rise. Increasing temperatures and an increase in the frequency and severity of cyclones and drought also threaten the ecosystem.	(Danda, 2010, Mahadevia Ghimire and Vikas, 2012, Raha et al., 2012)
Natural system modification	Modifications to the ecosystem largely centre around the construction of barrages, dams and embankments. Most prominent, the Farakka Barrage in 1975 substantially limited freshwater and sediment supply to the Sundarbans mangrove ecosystem as well as resulting in changes in salinity regime.	(Islam and Gnauck, 2009, Sarkhel, 2015, Rahman and Rahaman, 2018)
Pollution	A diverse range of agricultural, industrial and urban effluents such as sewage, nitrogen, pesticides, pharmaceuticals and heavy metals are transported into the mangrove ecosystem. Oil pollution, especially crude oil and its derivatives, are one of the most harmful pollutants that enter the mangrove forest from accidental spills during oil transportation or due to the extensive use of mechanised boats for carrying passengers and fishing.	(Zuloaga et al., 2013, Chowdhury and Maiti, 2016, Islam et al., 2017, Pozo et al., 2017)
Residential and commercial development	Forest clearing and land conversion for human developments began at least as early as the 1700s. Mangroves continue to be cleared for the construction of jetties and harbours, commercial shipping traffic is increasing, and the tourism industry is growing quickly.	(Islam et al., 2013, Ghosh et al., 2015, Hossain et al., 2018)

provide plausible bounds of confidence when necessary. Historical changes in extent (sub-criterion A3) were estimated by Ghosh et al. (2015) who analysed historical maps of the distribution of mangroves within the Indian Sundarbans in 1776 and 1873. Uncertainty can arise when extrapolating mangrove area trajectories compiled from different data sources (Friess and Webb, 2014; Mejía-Rentería et al., 2018), and this approach makes assumptions about compatibility of image precision and resolution across imagery types. Despite this limitation, compiling data from multiple studies to extract mangrove area trends is a well-used methodology (e.g. FAO, 2007) and the only way to analyse mangrove forest loss across the timescale required for the RLE.

2.4.2. Restricted geographic distribution – criterion B

The extent of occurrence (sub-criterion B1) was calculated as the area of a minimum convex polygon enclosing all mapped occurrences of the Sundarbans mangrove ecosystem. The area of occupancy (sub-criterion B2) was calculated as the number of 10 × 10 km grid cells that contained the ecosystem, excluding grid cells where mangroves were < 1% of cell area (Bland et al., 2017). To assign a status based on these two sub-criterion, an ecosystem must meet the thresholds that delineate threat categories, as well as at least one of three further sub-criteria that distinguish restricted ecosystems at appreciable risk of collapse from those that persist over long periods within small stable ranges (Keith et al., 2013). Briefly, these additional sub-criteria are (1)

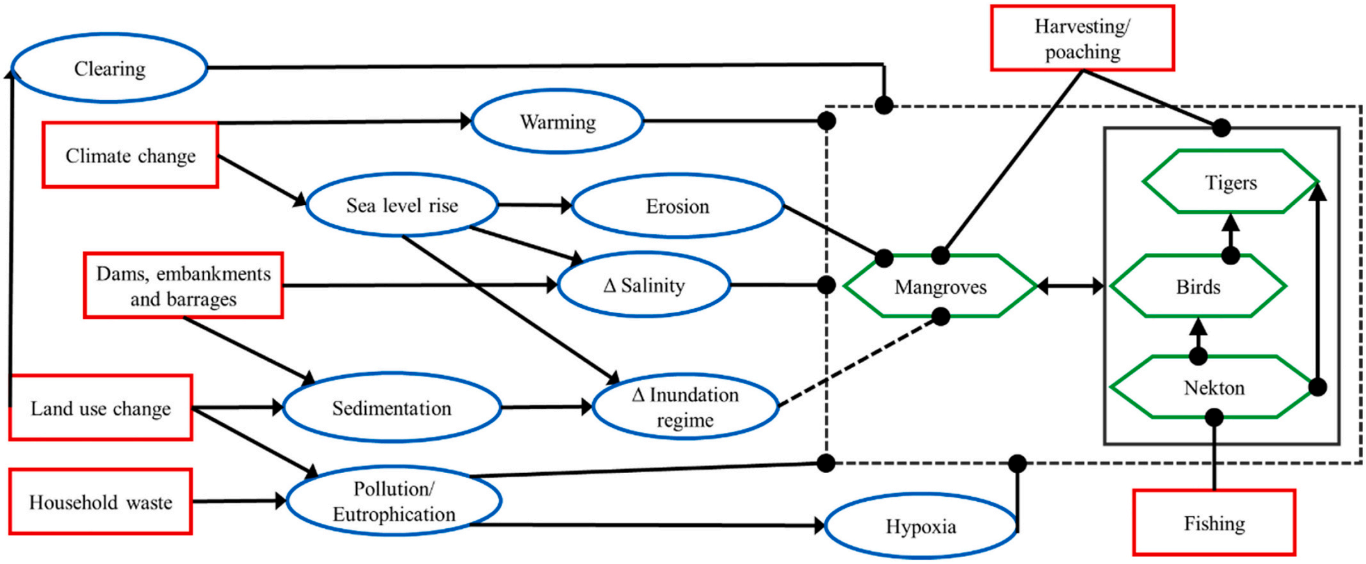

Fig. 2. Conceptual model of key threats and key processes (both abiotic and biotic) relevant to the risk assessment for the mangroves of the Indian Sundarbans. Only the most influential threats are shown. Red boxes represent threats, blue ellipses represent the abiotic environment and processes, green hexagons represent biotic components. The dashed box represents the entire ecosystem under assessment, and the solid box represents the fauna (with only key faunal groups shown). Pointed arrowheads indicate positive effects and rounded arrowheads indicate negative effects. The dashed line indicates the context-dependent effect of changes in inundation regime, which can positively or negatively affect the ecosystem. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Indicators used to assess the risk of collapse for the mangrove ecosystem of the Indian Sundarbans, including collapse thresholds.

Criterion	Indicator	Collapse threshold	Data
A (Decline in distribution)	Change in extent	0% extent remaining	Extent estimates from 1776, 1873, 1968, 1989, 2001, 2014 (Ghosh et al., 2015) and 2016 (Global Mangrove Watch; https://data.unep-wcmc.org/datasets/45)
B (Restricted geographic distribution)	Current distribution	0% extent remaining	2016 mangrove distribution from Global Mangrove Watch
C (Environmental degradation)	Sea-level rise	0% extent remaining	Modelling in Lovelock et al. (2015) and Bomer et al. (2020)
D (Disruption of biotic processes or interactions)	Mangrove canopy density and fragmentation	NA	Sahana et al., 2015
	Density of juvenile fish	Population declines to 0	Juvenile fish density during 2007–2016 (Mitra et al., 2017)
	Diversity of juvenile fish	Diversity declines to 0	Juvenile fish diversity during 2007–2016 (Mitra et al., 2017)
	Abundance of tigers	Population declines to 0	Population estimates from Jhala et al. (2019), Mallick (2013), Naha et al. (2016) and Roy Chowdhury et al. (2018)
	Changes in mangrove tree community	Complete loss of key mangrove species groups	Mukhopadhyay et al. (2018)
	Mangrove degradation	100% of the ecosystem degraded	Temporal changes in vegetation dynamics from Worthington and Spalding (2018)
E (Quantitative analysis of probability of collapse)	Quantitative risk model	NE	NE

an observed or inferred continuing decline in extent, environmental quality, or a measure of biotic disruption; (2) observed or inferred threatening processes that are likely to cause continuing declines in extent, environmental quality or biotic interactions within the next 20 years, and; (3) the number of threat-defined locations. We attempted to quantify the number of threat-defined locations (sub-criterion B3) from spatial management areas for the most significant threats likely to cause collapse over a short time period and comp (~20 years; Bland et al., 2017).

2.4.3. Environmental degradation – criterion C

Criteria C was evaluated with future sea level rise (SLR) as a proxy for increasing tidal inundation period and frequency, which pushes mangrove vegetation beyond species-specific thresholds of flooding tolerance (Ball, 1988). SLR risk was estimated based on two published projected models that were used to estimate the proportion of the mangrove ecosystem that would be functionally lost under SLR scenarios over the next 50–100 years (Criterion C2a). Payo et al. (2016) adapt the Sea Level Affecting Marshes Model (SLAMM) for use in the Bangladesh Sundarbans, which we assume responds similarly to SLR as the mangroves of the Indian Sundarbans. The SLAMM model is a dynamic model that simulates wetland area change with SLR and associated surface elevation thresholds and dynamics. Lovelock et al. (2015) produced a regional-scale model that encompassed the Indian Sundarbans, calculating the elevation capital of mangroves by projecting surface elevation rates derived from a relationship between field measurements of surface elevation change and suspended sediment measurements from satellite remote sensing. Model results were also compared to trends from field measurements of surface elevation change taken from the Bangladesh Sundarbans (e.g. Bomer et al., 2020).

Although measurements of water temperature, salinity, dissolved oxygen, and pH are collected as part of the Sundarbans Biological Observatory Time Series (SBOTS; Bhattacharjee et al., 2013, Choudhury et al., 2015; Fig. S1) next to Sagar Island in southern Sundarbans, their spatial resolution were insufficient for an assessment of the entire Indian Sundarbans. Further, direct relationships with environmental degradation are not fully understood. Given the dynamic nature of the system, a grid-based approach to assess these variables would be required. The current data do show, however, that these variables have all been steady over the last decade and freshwater flow strongly influences the measured variables (within seasonal fluctuations; Fig. S1).

2.4.4. Disruption of biotic processes or interactions – criterion D

Criterion D was assessed using a dataset on annual (2007–2016) juvenile finfish density and diversity – as a proxy for overall fish populations and communities – in the pre-, post- and during-monsoon seasons, in three regions of the Indian Sundarbans: 24 Parganas South district (Diamond Harbour: northern of the Sundarbans), 24 Parganas Sundarbans district (Sagar light house: southern Sundarbans) and Purba Medinipur district (Junput: east of theern Sundarbans) (Mitra et al., 2017). We assumed that these regions represent general trends across the entire ecosystem, and a linear mixed-effects model was fitted to these data (averaged across seasons, with year fitted as a fixed effect and site fitted as a random effect). Relative severity was calculated using range standardisation (Keith et al., 2013) under the assumption fish density and diversity in 2007 was similar to that 50 years ago. Plausible range was calculated based on 95% confidence intervals (Table 3).

Criterion D (D2b) was also analysed using the extent of ecosystem degradation, based on a global mangrove degradation dataset (Worthington and Spalding, 2018). Temporal changes in vegetation dynamics were used to classify degradation status across ~18 years. For each satellite image, four vegetation indices were calculated: Normalized Difference Vegetation Index, Soil-Adjusted Vegetation Index, Enhanced Vegetation Index and Normalized Difference Moisture Index, which represent vegetation condition and moisture content. To examine changes over time, the images were split into five timesteps:reference (earliest image in the collection – 2000), T1 (2000–2005), T2 (2005–2010), T3 (2010–2015), and T4 (2015 – latest image in the collection). For each timestep, three measures of central tendency were calculated: the median, the 10–90% interval mean and the 25–75% interval mean. Combined, the four vegetation indices and the three measures of central tendency provide 12 metrics of change. Degradation was assessed at the pixel level (30 m resolution). For a pixel to be classified as degraded, a significant ($> 40\%$) decline in any one of the timesteps relative to a pre-2000 baseline had to be identified. This decline had to be consistent (at least 10 out of 12) across the metrics of change. The degradation also had to be sustained and as such none of the 12 metrics of change could have a T4 value $\geq -20\%$ of the reference value, which would suggest regeneration of the mangrove forest. Future changes in the presence of key mangrove species and assemblages (Mukhopadhyay et al., 2018), changes in forest canopy density and fragmentation rates (Sahana et al., 2015), and population estimates for mangrove tigers (Mallick, 2013; Naha et al., 2016; Roy Chowdhury et al., 2018; Jhala et al., 2019) were also investigated to assess criterion D. For these metrics, indicator estimates are assumed to represent the entire ecosystem.

Although data or quantitative collapse thresholds for some relevant variables are unavailable, we discuss these under each relevant section (criteria C and D, and Appendix A) to highlight knowledge gaps and

Table 3

Application of the IUCN Red List of Ecosystems criteria for the mangrove ecosystem of the Indian Sundarbans. DD, *Data Deficient* (blue); LC, *Least Concern* (green); VU, *Vulnerable* (yellow); EN, *Endangered* (orange); NE, *Not Evaluated* (white). Categories in brackets indicate plausible bounds of status for each sub-criterion. Note there are only three sub-criteria for criterion B that are unrelated to timeframe.

Criterion	Declining distribution (A)	Restricted distribution (B)	Environmental degradation (C)	Biotic disruption (D)	Quantitative risk analysis (E)	Overall ecosystem status
Sub-criterion 1 (past 50 years)	LC	LC	DD	VU (VU-EN)	NE	EN (VU-EN)
Sub-criterion 2a (next 50 years)	LC	LC	LC	LC		
Sub-criterion 2b (any 50 year period including the past, present and future)	LC		DD	LC		
Sub-criterion 3 (since 1750)	EN (VU-EN)	LC	DD	DD		

guide future monitoring. Unless otherwise stated, data used are assumed to represent the entire ecosystem, so 100% ecosystem extent is used for assigning status based on the framework, though in reality vulnerability will show spatial variation.

3. Results

3.1. Decline in distribution – criterion A

Mangrove extent changed from 2307 km^2 (1968) to 1983 km^2 (1989), 1926 km^2 (2001), 1852 km^2 (2014), and 1851 km^2 (2016) (Fig. 3). The proportional and absolute rate of decline is 0.4% and 9.5 km^2 year^{-1}, respectively, representing a decrease in mangrove habitat of 20–21% over the last 50 years dependent on the method of calculation (proportional or absolute). Therefore, the ecosystem is assessed as *Least Concern* ($<$ 30% reduction) for sub-criterion A1. Linearly extrapolating 50 years into the future based on current rates of extent change (2066 predicted extent between 1376 and 1470 km^2), the ecosystem also meets the criteria for *Least Concern* ($<$ 30% loss) for sub-criterion A2a and sub-criterion A2b (Fig. 3; Table 3).

Historically, the area of mangroves was estimated to be 6588 km^2 in 1776 and 6068 km^2 in 1873 (Fig. 3). These estimates suggest that the extent of mangroves has declined by 71.9% from 1776 to 2016, classifying the ecosystem as *Endangered* (between 70 and 90% loss). However, no quantitative estimates of accuracy have been made on these historical sources, so a reasonable level of error can be assumed; thus, the ecosystem can be classified with a plausible range from *Vulnerable* to *Endangered* under sub-criterion A3 (Table 3).

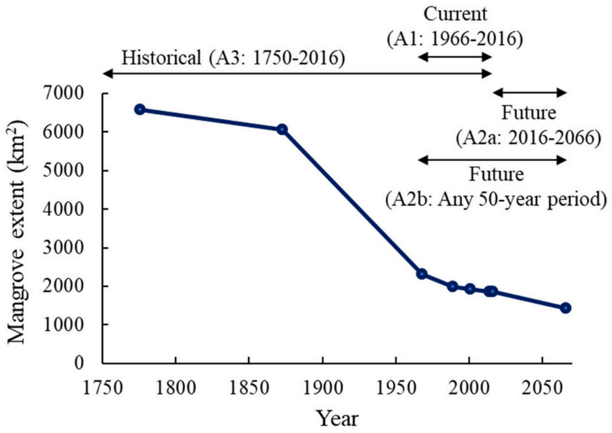

Fig. 3. Changes in extent of mangrove area used for the calculation of ecosystem status under sub-criteria A1 (current), A2a/b (future) and A3 (historical). Due to the mapping techniques used, no bounded estimates of uncertainty are available for past or current area estimates. For the 2066 prediction, uncertainty is able to be estimated, and is very small, ranging between 1376 and 1470 km^2.

3.2. Restricted geographic distribution – criterion B

The minimum convex polygon was 6365 km^2 in 2016 (i.e. *Endangered*; Fig. 1). Although some observed ecosystem loss drivers are likely to continue to influence the Sundarbans (see criterion C), there is not strong evidence to suggest further likely declines in distribution, environmental quality or biotic interactions within the next 20 years. Therefore, the ecosystem does not satisfy both criteria and is assessed as

Least Concern for sub-criterion B1. For criterion B2, there were 68 grid cells of 10 × 10 km that contain the ecosystem in 2016 (Fig. 1). The ecosystem is thus classified as *Least Concern* (> 50 grid cells occupied) for sub-criterion B2. We did not perform grid uncertainty analysis, as this would not alter the outcome, but acknowledge that the precise number of grid cells could be slightly different than 68.

The Indian Sundarbans Biosphere Reserve is split into core, buffer and transition zones, and a cluster of these areas are also defined as the tiger reserve, tourism zone and primitive zone (Ghosh, 2015). Although these zones are managed differently, the zones still respond to many of the key threats similarly (e.g. lack of sediment supply, SLR). There is no defensible way to specify the exact number of threat-based locations based on the RLE framework. However, since the key threats will not *likely* lead to *Critically Endangered* or *Collapsed* status within a very short time period (~20 years; a requisite of the framework), the ecosystem does not satisfy both criteria and is assessed as *Least Concern* for sub-criterion B3 (Table 3).

3.3. Environmental degradation – criterion C

Much of the research on the potential impact of SLR on the Sundarbans has been conducted on the Bangladesh side. Given processes and inputs are similar between the sides, these studies still inform our assessment. Although some research predicts significant losses of the Sundarbans under SLR (e.g. Loucks et al., 2010; Mukul et al., 2019), these studies ignore key geomorphological processes that influence how mangroves respond to SLR, such as sediment availability and landward migration, as well as resulting biological proxies influenced by SLR such as food availability and nature of organic carbon. Therefore, we deem these unsuitable for this assessment. These processes are critical to assess relative SLR (see Bomer et al., 2020), and when incorporated into predictions, the Sundarbans (both Indian and Bangladeshi sides) is under low threat from SLR before the end of the century (see Lovelock et al., 2015; Payo et al., 2016). Although we do not calculate relative severity, the ecosystem is assessed as *Least Concern* for SLR under sub-criterion C2a (Table 3) on the basis of previously published results from these comprehensive predictive models.

3.4. Disruption of biotic processes or interactions – criterion D

Declines in finfish density across the Sundarbans provide a calculated relative severity of 47% (Table 4; 95% CI range: 31.8–62.2; Mitra et al., 2017), giving the ecosystem a status of *Vulnerable* (30–50%) with a plausible range between *Vulnerable* and *Endangered* (Table 3). Mitra et al. (2017) also assessed fish diversity. Using the same methods as for density, the ecosystem is assessed as *Least Concern* based on fish diversity (sub-criterion D1: mean relative severity 3.3%; Table 3).

Table 4

Juvenile finfish density and Shannon diversity quantified annually between 2007 and 2016 in the pre-, post- and during-monsoon seasons, in three regions within and nearby the Indian Sundarbans (Mitra et al., 2017). Values for the years 2007 and 2016 are model estimates based on linear mixed models of annual density and diversity, averaged across seasons. Relative severity is calculated using range standardisation (Keith et al., 2013) under the assumption fish density and diversity in 2007 was similar to that 50 years ago. Coloured cells represent threat status based on an extent of 100%: orange – *Endangered* (50–80%); yellow – *Vulnerable* (30–50%), and; green – *Least Concern* (< 30%).

Variable	Year	Site A	Site B	Site C	Mean	Low 95% CI	High 95% CI
Density							
	2007	219.5	667.9	790.3			
	2016	149.8	320.9	338.2			
	Relative Severity	31.8	51.9	57.2	47	31.8	62.2
Diversity							
	2007	3.3	2.1	3.1			
	2016	3.3	2	2.9			
	Relative Severity	0.7	5.1	4.1	3.3	0.7	5.9

Degraded mangroves cover 0.83 km^2, and most of this area is along the fringing edge, suggesting that degradation is caused by erosion events. This represents less than 0.11% of the mangrove ecosystem extent, and thus well below the 30% required to elicit a threatened status (sub-criterion D1), even when extrapolated to cover a 50 year period (sub-criterion D2b), and is therefore of *Least Concern* (Table 3). It is questionable whether degradation of the entire ecosystem based on the definition from Worthington and Spalding (2018) would lead to conditions where biota could not be supported. However, various possible assumptions on severity (e.g. using 100% severity vs 1% severity) would not affect the outcome, because the extent component does not meet any category thresholds for threatened status.

It is difficult to assess changes in mangrove tiger abundance within the Indian Sundarbans (Mallick, 2013). Focusing on the more reliable method, tiger numbers were relatively stable from 1976 (181) to 2004 (249), peaking in 1989 (269) (Mallick, 2013). More recently using camera traps, an estimated 70–108 tigers inhabited the Indian Sundarbans at any one time between 2008 and 2018 (Naha et al., 2016; Roy Chowdhury et al., 2018; Jhala et al., 2019). Although listed as *Endangered* in the Red List of Threatened Species, without Sundarbans-specific population trends, the ecosystem is considered *Data Deficient* for mangrove tiger populations (sub-criterion D1; Table 3). Within the Sundarbans, an estimated 2400 + adult tigers were killed between 1881 and 1912 and substantial historical declines are assumed (see Chakrabarti, 2009). Despite a strong inclination of a justified threatened status, as population estimates from the Indian Sundarbans are not available or reliably estimated from ca 1750, the assessment is *Data Deficient* for historical losses of mangrove tigers under sub-criterion D3 (Table 3).

Biotic variables directly linked to forest structure such as tree density and fragmentation rates are likely relevant for assessing the likelihood of ecosystem collapse under criterion D. Sahana et al. (2015) calculated changes in forest density for patch, edge, perforated and core areas (classes) of the Indian Sundarbans between 1990 and 2011. Overall, the average forest canopy density within these fragmentation classes decreased by less than 4%. Concurrently, fragmentation analysis showed a decrease in patch area and a decrease in edge and perforated areas (Sahana et al., 2015). Combined, these relatively minor changes over 21 years suggest a status of *Least Concern*. However, these data are not amenable to calculating severities and quantitative collapse thresholds are largely unassessed in the literature. Therefore, sub-criterion D1 for mangrove trees is assessed as *Not Evaluated*.

There are also predicted changes in mangrove species in the future largely due to salinity changes. Net estimated change between 2015 and 2050 suggests a maximum loss for *Excoecaria-Heritiera* assemblages (of 20%) and a maximum gain for *Phoenix-Xylocarpus-Aegiceras* assemblages (of 25%; Mukhopadhyay et al., 2018). Given no losses are greater than 30%, we assess the ecosystem as *Least Concern* for mangrove community changes under sub-criterion D2a (Table 3).

4. Discussion

4.1. Conservation status of the Indian Sundarbans

The RLE framework allows the collation of current knowledge on the status of, and threats to, the mangrove ecosystem of the Sundarbans, India. We evaluate the utility of the framework for a dynamic coastal ecosystem. We show that long-term historic losses led to a status of *Endangered* with a plausible range between *Vulnerable* and *Endangered* for the ecosystem, and that continuing declines in juvenile fish populations are concerning. However, a significant slowing of past losses, limited areas of degraded mangrove, and recently stabilising tiger populations are overall cause for optimism.

The standardised RLE framework requires that the overall ecosystem status is determined by the most severe rating received by any one sub-criterion (Bland et al., 2017). As such, the Indian Sundarbans are considered *Endangered* because of historical declines in areal extent, even though recent ecosystem trends are more positive. This may be considered alarmist and prove challenging to gain the buy in of managers who have contributed to the recent positive trends. However, an assessment of *Endangered* is valid and important, even if it is based largely on historical trends. Historical changes are important for ecosystems that contain biota with long generation times and/or slow population turnover (as per the Red List of Threatened Species guidelines; Mace et al., 2008) and now have steady ecosystem extents, as historical changes may have predisposed it to additional threats and reduced its ability to absorb adverse changes (Folke et al., 2004). We are fortunate to have such historical data on the Sundarbans, which is rare for mangroves and unavailable for similar RLE assessments of mangrove ecosystems (e.g. Marshall et al., 2018; Ávila-Flores et al., 2020; Sievers et al., 2020). This should be taken into account when direct comparisons of overall threat status are made between this assessment and other mangrove assessments without sub-criterion A3.

Significant reductions in fish populations within and adjacent to the Sundarbans also elicited a threatened status and is cause for concern (Mitra et al., 2017). Fish are fundamentally important to the ecology of the ecosystem, but also for livelihoods, with wild fisheries the second biggest source of employment within the Sundarbans (Ghosh, 2012). Therefore, reductions in fish abundance of this magnitude will have considerable implications across socio-ecological systems. In addition, abstruse but non-trivial impacts are possible. For example, reduced fish numbers might increase the duration and intensity of fishing, which would lead to greater rates of by-catch (a current issue in the greater Sundarbans area; Ahmed and Troell, 2010). Thus, measures to mitigate and reverse observed trends are needed to ensure the integrity of the ecosystem and people's livelihood. As an example, owing to research by scientists at the University of Dhaka and Jadavpur University, the Government of West Bengal banned fishing for Hilsa shad (*Tenualosa ilisha*), helping to stabilise populations of this species (Ortolano et al., 2016).

Although a lack of data provides challenges to the quantitative assessment of climate change risk, continued monitoring of relevant indicators is vital, particularly when the threat of climate change is coupled with the multitude of additional threats present. Increasing temperatures, altered salinity profiles, and more severe and frequent extreme weather events are all likely to occur and impact mangroves (Ward et al., 2016). But quantifying collapse thresholds for the mangrove ecosystem is extremely challenging, particularly as changes occur over decades and centuries (potentially allowing adaptation; Hoffmann and Sgro, 2011). Continued warming has the potential to further exacerbate the observed declines in fish populations; a rise in SST in Bay of Bengal may change phytoplankton community structure in estuarine waters of the Sundarbans and increase the prevalence of harmful algal blooms, with significant consequences for nursery grounds of fisheries (Choudhury et al., 2015). Although SLR is not of immediate concern based on the most recent projections (Lovelock et al., 2015) and field observations (e.g. Lovelock et al., 2015; Bomer et al., 2020), these studies highlight the importance of allochthonous sediment supply, so river damming and reduction in fluvial sediment delivery to the coastal zone may increase the vulnerability of mangroves to SLR in the future. New quantitative approaches such as stable isotope ratio of carbon analysis with elevation can help track SLR in the challenging terrains of the Sundarbans (Sen and Bhadury, 2017). River damming is also likely to change fluvial nitrogen loads into the coastal zone in the future, with implications for coastal and marine ecosystem productivity (Akbarzadeh et al., 2019).

The outlook for the Indian Sundarbans is far from bleak, and given the aforementioned considerations when relying on changes in extent from 200+ years ago, there is cause for optimism;,mirroring the current global outlook for mangroves (Friess et al., 2020). Current protection and management of the Indian Sundarbans is considered good (IUCN, 2017). For instance, the Sundarban Tiger Reserve (STR) was launched in 1973 to save the Royal Bengal tiger (*Panthera tigris*) from extinction and continues to offer effective protection for tigers and the mangrove ecosystem (Roy Chowdhury et al., 2018). While the management of the site is laudable, ongoing and enhanced monitoring of ecologically and economically important wildlife is critical to track the health of the ecosystem and to inform future assessments. Funding and capacity issues have been highlighted as key barriers to achieve these and other goals (IUCN, 2017). Our work to highlight the importance of the Indian Sundarbans, articulate the key threats that are, or could, impact the system, and quantify risks using a standardised and respected framework should bolster support to fund these necessary endeavours.

4.2. The utility of the RLE framework for assessing the Indian Sundarbans

The RLE framework was highly applicable for the mangrove ecosystem of the Indian Sundarbans. Despite the comprehensiveness of our assessment, however, data on some indicators likely pertinent to the assessment of risk of collapse for the Sundarbans are not currently available (e.g. ecosystem functional metrics such as measures of productivity) or are difficult to assess using the RLE criteria (e.g. structural tree metrics). Similar outcomes exist for other RLE assessments of mangrove ecosystems. For instance, Sievers et al. (2020) found mangroves in Moreton Bay, Australia were *Least Concern* but did not have data on changes to the mangrove trees. Likewise, Ávila-Flores et al. (2020) rely on changes in mangrove extent and expert opinion to assess mangrove ecosystems in Mexico. Conversely, Marshall et al. (2018) used changes in NDVI to assess biotic degradation, but due to finding no clear relationship between this metric and mangrove degradation, assessed criterion D as *Data Deficient*. Given the mangrove degradation metric used here is now available globally (along with other global mangrove datasets; Worthington et al. 2020), all future assessments on mangroves can incorporate this metric under criterion D.

Although many useful indicators have not routinely been monitored throughout the world, new technologies including satellite imagery are allowing these types of data to be collected quickly, cheaply, and at high spatial and temporal resolution (Vuolo et al., 2016). For instance, changes in carbonate chemistry (ocean acidification) within the coastal Bay of Bengal, and in particularly in the Sundarbans, can strongly influence biological community structure and resulting mangrove ecosystem functioning; such changes that can now be monitored using satellite remote sensing and validated using robust in situ measurements (Land et al., 2019). We have greater capacity to calculate and interpret metrics from these big datasets as computers get faster and techniques get automated (e.g. pH, alkalinity, dissolved carbon), and we can use older satellite data to back calculate and derive trends for relative severity calculations for use within RLE. Now that the RLE has been adopted as a global standard for assessing ecosystems, there is benefit in developing monitoring programs that suit the needs of the framework for both remotely sensed indicators and those requiring more hands-on monitoring programs (e.g. SBOTS; Bhattacharjee et al., 2013, Choudhury et al., 2015).

For several other indicators, quantitative collapse thresholds – below which characteristic biota, ecological functions and/or processes are not supported – are largely unknown. This has formed a bottleneck in the RLE assessment process which can prevent accurate calculations of relative severity and the assignment of a threat status (Bland et al., 2018). We opted for caution here, choosing to not evaluate indicators for which no suitable thresholds could be estimated with confidence (e.g. salinity, water temperature). Through manipulative field and lab experiments, expert elicitation, modelling and meta-analyses, we can begin to quantify the level at which these indicators cause loss of ecological structure and function, and apply this information to the risk assessment process in future (also see Mukherjee et al., 2014). Alternatively, we can monitor when species die (particularly keystone species such as mangroves) and back-calculate collapse thresholds for abiotic indicators through species distribution models (Lovelock et al., 2017). Ultimately, as updated thresholds of collapse and additional datasets (for current or new indicators) become available, this assessment can be updated. However, an improved overall ecosystem status can only occur if the extent of mangroves increases, reducing the rate of historical decline.

The focus of our assessment on the Indian portion of the Sundarbans, for management and policy reasons, does not come without limitations. Improving policies based on standardised assessments of one side of the national boundary, for instance, might not be as effective as those that cover the entire Sundarbans. This is because the country border dividing the Sundarbans into its two parts is porous, meaning that the 'ecosystem' on both sides exchanges elements constantly, and spill-over from a less-well managed side will likely influence the other. Therefore, it is important to consider the outcomes of this assessment in relation to the area considered and the potential implications of managing only one part of a greater ecosystem. Further, as all people who rely on the Sundarbans for resources are a key part of the ecosystem, ensuring no one group feels marginalised when creating and actioning ecosystem management plans should help ensure long term social and thus biological management success (Christie, 2004). Despite a push for greater transnational research and management (Ortolano et al., 2016), we suggest that our current assessment will more readily allow and inform relevant policy changes for the management of the Indian Sundarbans. Given processes and threats are similar throughout the entire Sundarbans, information from this assessment might be useful to guide assessments of the Bangladesh side, and ultimately inform holistic management.

The RLE provides a robust framework to assess risks and inform management and policy, and was amenable to this highly dynamic ecosystem. The push to shift from species-level conservation to ecosystem-level conservation, partly under the proviso that the former is insufficient to sustain biodiversity and the benefits that humans derive from nature (Watson et al., 2020), means that more and more ecosystem RLE assessments will be produced in the near future. Given the RLE has been adopted within the Biodiversity Indicators Partnership and thus provides important information to track progress towards the Sustainable Development Goals (SDGs) and Aichi Targets (Bera and Maiti, 2019), such assessments have never been more important or influential. This RLE assessment, and the extensive supplementary material included in this study, contributes to the growing body of work highlighting the importance and fragility of the Indian Sundarbans ecosystem, and the need for its protection (e.g. Ghosh et al., 2015; IUCN, 2017).

5. Conclusions

Using a holistic, standardised and quantitative environment risk assessment framework, the Indian Sundarbans has been assessed as *Endangered* (with a plausible range between *Vulnerable* and *Endangered*), based primarily on substantial historical declines in extent. Despite this seemingly bleak outcome, there is cause for cautious optimism. Historically high rates of mangrove clearing have reduced, and management of the ecosystem, although under resourced, is laudable. However, the current optimistic trajectory is not guaranteed, and ongoing factors that threaten the ecosystem, as evidenced by some subcriteria, should not be ignored. In particular, impacts from hydrological modifications and sediment supply reduction, future climate change and agriculture need to be properly evaluated and monitored. Combined with several qualitative assessments and reviews, this assessment of the Indian Sundarbans using the IUCN Red List of Ecosystem framework provides important policy-relevant information for this significant and iconic mangrove ecosystem.

CRediT authorship contribution statement

RC, MS: Conceptualization; MS, AG, PB: Data curation; MS: Formal analysis, Visualization, Roles/Writing - original draft; MC: Data curation; All: Writing - review & editing.

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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