Scenario-based quantification of land-use changes and its impacts on ecosystem services: A case of Bhitarkanika mangrove area, Odisha, India

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Abstract

Mangrove habitats play a vital role in balancing the coastal ecosystems by providing an array of provisioning, regulating, cultural, and supporting ecosystem services. Despite several conservation measures taken to protect mangroves, they have been facing economic, socio-environmental, and climatic threats. There is a need to quantify the mangroves' ecosystem services (ES), especially in developing and under-developed nations, to fasten up the mangrove conservation. To address this issue, in the present study, we quantified the ES of the mangroves in Odisha State on the eastern coast of India. And we projected the changes in ES according to the plausible future land-use changes using scenario analysis. The plausible future scenarios (by 2030) have been generated based on the participatory surveys and key informant interviews from the stakeholders in the region. The scenarios encompass socio-economic development, infrastructural development, mangrove conservation, agriculture and aquaculture expansion, and climate change. Coastal blue carbon sequestration, sediment retention and export, and nutrient export were quantified using the InVEST (Integrated valuation of ecosystem services and trade-offs) model. Results indicate that disturbances to mangrove forests in Odisha can emit 2.16 Tg C back into the atmosphere by 2030. In an optimistic scenario, mangroves can sequester 1.55 Tg C from the atmosphere. An increase in mangrove and green cover has reduced sediment and nutrient export by a maximum of 24.9% and 7.6%, respectively. The findings will help in evidence-based decision-making about the socio-environmental systems comprising sensitive mangrove ecosystems.

Highlights

1. Major drivers threatening mangrove ecosystems were identified from the participatory survey instruments in Odisha, India.
2. We quantified the mangrove's blue carbon sequestration according to the future land-use scenarios in eastern Odisha.
3. Disturbances to mangrove forests in Odisha can emit 2.16 Tg C back into the atmosphere by 2030.
4. In an optimistic scenario, mangroves can sequester 1.55 Tg C from the atmosphere by 2030.
5. An increase in mangrove and green cover has reduced sediment and nutrient export by a maximum of 24.9% and 7.6%, respectively.
6. Proactive efforts to prioritize conservation and enhanced financing to restore degraded mangrove areas are urgently required.

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Introduction

Urbanization, economic development, and socio-cultural factors are dramatically changing the natural habitats across the world. The most productive and biologically diverse coastal habitats, including mangroves, are susceptible to these changes (Dou et al. 2021; Kadaverugu et al. 2021a). Besides the anthropogenic drivers, the climate variability induced tropical cyclones, storm surges, rising sea level, and coastal erosion threaten the coastal ecosystems (Servino et al. 2018). The increased frequency and intensity of these calamities are exasperating the already damaged coastal habitats globally (Sharma et al. 2020). Mangroves on the east coast of India, especially in Odisha State, are no exception to these stressors.

Coastal ecosystems should be conserved with utmost priority as they provide a multitude of nature's contributions, such as provisioning, regulating, and cultural ecosystem services for human wellbeing (Dasgupta et al. 2018; Kathiresan 2018; Kadaverugu et al. 2021a). Evidence shows that mangrove ecosystems protect the coastal human settlements from cyclones, tsunamis, and storm surges (Kadaverugu et al. 2021a). Also, mangroves foster marine biodiversity and fishing yield. Local people are dependent on mangrove forests for the direct provisioning services such as food, fodder, fuelwood, medicines, honey, fish, etc.

Coastal ecosystems are the top natural sinks of carbon (blue carbon) per unit area than other terrestrial ecosystems across the globe. On a global scale, blue carbon capture is about 1.3% (38.5 ± 19 TgC y^{-1}) of total terrestrial carbon sequestration but covers less than 0.4% of land area (Taillardat et al. 2018). Blue carbon sequestration in salt marshes is on an average 242 ± 26 gC $m^{-2}y^{-1}$ (Ouyang and Lee 2014), which is the highest, followed by mangroves (168 ± 36 gC $m^{-2}y^{-1}$ (Alongi 2012)), and seagrasses (83 gC $m^{-2}y^{-1}$ (Duarte et al. 2005)). Mangroves can accumulate organic carbon up to 900 Mg ha-1, which is nearly four times higher than that of salt marshes (600 Mg ha^{-1}) and seagrass meadows (200 Mg ha^{-1}) (Alongi 2014). They continually store large amounts of carbon in their sediments, creating vast reservoirs of sequestered carbon. Full utilization of blue carbon sequestration along the coasts will be a boon for achieving Nationally Determined Carbon (NDC) reduction targets according to the Paris Climate Agreement (2015) and recently concluded Glasgow Pact (2021). Disturbances to these coastal habitats expose the sediments and hence release the carbon back to the atmospheric carbon cycle, contributing to the impending global warming and climate change.

Mangroves also arrest sediments and nutrients entering the estuaries and ocean and help regulate coastal water quality. Conserved mangrove forests can accumulate approximately 2.5 mm y^{-1} of sediments (Breithaupt et al. 2012). Mangroves, with their peculiar root structure, help significantly arrest the sediment entering the estuaries and oceans. Mangrove forests also uptake a notable amount of nutrients in the form of biomass. Ray et al. (2021) estimated that the stock of macronutrients in the mangrove's biomass varied from 60–2717 Mg ha^{-1}, while micronutrient stock ranged from 0.003–37.7 Mg ha^{-1}. The spatial distribution of water pollution along a river from the point of sewage discharge to the estuary, where mangrove patches are present, indicates a significant reduction in pollution levels due to mangrove-mediated removal mechanisms (for ex. Lin and Dushoff 2004).

Mangroves in India are one the richest biological diverse mangroves patches in Asia. Their existence is threatened due to increasing anthropogenic and climatic drivers. There are chances that many of them may face a hidden collapse in the coming decades if appropriate proactive conservation policies and restoration efforts are not in place, and this is already observed in many areas. The East coast of Odisha is highly prone to increasing extreme climate events, mainly the increasing frequency and intensity of cyclones and sea-level rise. Though the mangroves of Bhitarkanika and Paradip play an essential role in coastal ecosystem regulation, very few studies have quantified their ecosystem services. From our regular field visits to these mangroves, it was observed that the fringes of mangrove patches are replete with agricultural fields and aquaculture farms that pose an imminent threat to the mangrove habitats. Moreover, very few studies integrated the scenario-based analysis with the ecosystem services assessment of mangroves. The scenario-based analysis is a powerful assessment tool for anticipating the long-term changes in socio-environmental systems with multiple uncertain factors (Hashimoto et al. 2018).

The present study explores scenario-based modeling with the ecosystem services quantification to better understand effective policy action. The ES of the mangroves in terms of carbon sequestration (blue carbon), sediment, and nutrient retention were quantified using the InVEST-v3.8.0 model (Sharp et al. 2020), which is widely applied in the quantification of ES (Gomes et al. 2021). The model is particularly suitable for policymakers and researchers in comparing multiple development scenarios and their trade-offs with ecosystem services. For instance, the model is applied for studying carbon sequestration (Babbar et al. 2021), sediment retention (Hamel et al. 2015), urban heat mitigation and energy conserved due to various land-use scenarios (Kadaverugu et al. 2021b), flood retention service from green and open spaces (Kadaverugu et al. 2020), among others. The present study used Coastal Blue Carbon (CBC), Nutrient Delivery, and Sediment Delivery sub-models of

InVEST-v3.8.0 suit. The data required for these modules consist of current land-use and land cover layer, and a biophysical variable for each land-use category. A proximity-based land-use change simulation module of the InVEST model was utilized to project future land-use changes according to the generated scenarios. The story-and-simulation approach (Dasgupta et al. 2018; Hashimoto et al. 2018) was followed in the study to develop future scenarios (by 2030) based on the participatory survey and key informant interviews of the stakeholders in the study region. Mainly, short-term scenarios have been considered in the study to quantify the imminent losses and benefits from the highly vulnerable and the most productive mangrove ecosystems for timely policy intervention. With this backdrop, the study attempts to address the following objectives:

1. to identify the significant drives of change affecting the mangroves in the region and to build the future scenario of land-use

2. to quantify the carbon sequestration, sediment retention and export, and nutrient export trends in the baseline and future scenarios

3. to draw a comparative analysis of the changes in these ecosystem services in the future scenarios

Study area

The study area consists of five administrative blocks (*tehsil,* equivalent to a county) which cover the mangroves in the coastal districts of Kendrapara and Jagatsinghpura in Odisha State, India. Mahakalpada (543.2 km^2) and Rajnagar (594.8 km^2) *tehsils* are from Kendrapara District, while Kujang (304.7 km^2), Ersama (392.2 km^2), and Balikuda (315.0 km^2) are from Jagatsinghpura District (Fig. 1). The study area (2150 km^2) extends between 19.96–20.76^0 N and 86.20–87.05^0 E, and the surface elevation ranges from 0–15 m above the mean sea level (MSL). The Brahmani and Mahanadi River systems have significantly shaped the
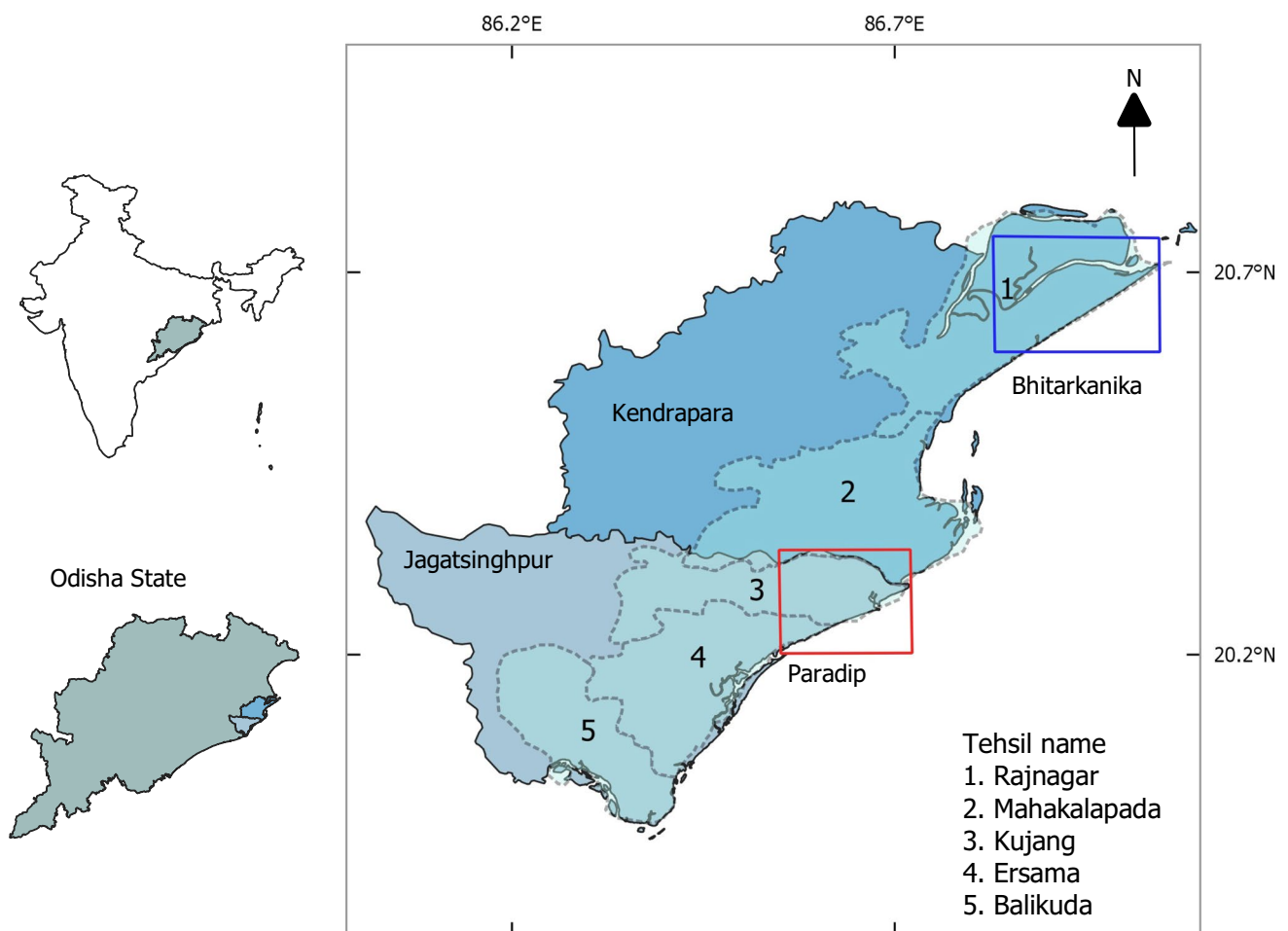

Fig. 1 Study area consists of five administrative *Tehsils* from Kendrapara and Jagatsinghpur Districts of Odisha State, India. The blue and red boxes cover the mangrove patches of pristine Bhitarkanika National Park and disturbed forests in Paradip, respectively

landscape of these districts with their sinuous banks and sediment deposition. The sediments in the Bhitarkanika mangrove forests are of Pleistocene deposits, consisting of clay, sand, and silt, with cemented pebbles and gravels (reddish-brown) (Banerjee and Rao 1990). According to the Harmonized World Soil Database (HWSD 2012), the soil in the region has a composition of 39% sand, 41% silt, and 20% clay. The average soil organic carbon in the dense mangrove forest area is reported as $0.57 \pm 0.09\%$ (Banerjee et al. 2018). The region experiences summer from March to June, monsoon from June to October, and winter from November to February. The region receives an annual rainfall of 1020 mm, mainly during the monsoon. May is the hottest month (32 ^{0}C average), while January is the coldest month (23 ^{0}C average).

The mangroves of Odisha are globally recognized for their rich biodiversity, consisting of 59 mangrove species from 28 families. *Sonneratia apetala, Heritiera fomes,* and *H. Littoralis* are dominant species in the region (Kathiresan 2018). The protected mangrove forests of Bhitarkanika National Park (BNP) are from Rajnagar *tehsil*, and other intact mangrove patches are present in Mahakalapada *tehsil.* The mangrove density varied between 3356 ± 680 trees/ha in Mahakalapada *tehsil* (Bhomia et al. 2016), and the soil organic carbon stock in Bhitarkanika protected area was around 25.3 Mg/ha (Hussain and Badola 2008). Whereas, the disturbed mangrove patches are present close to Paradip (industrial hotspot) in Kujang *Tehsil* (Fig. 1).

Nearly 1,50,000 people reside in the villages adjoining the BNP (Census 2011), depending directly and indirectly on the mangroves. Overall, 70% population in coastal districts is dependent on cultivation. Paddy is widely cultivated, jute is the main cash crop, while coconut is a crucial horticulture crop. The study area is covered with agricultural land, followed by vegetation (other than mangroves), river systems, water bodies, aquaculture ponds, and built-up areas. The Mahanadi and Brahmani Rivers are the primary sources of potable and irrigation waters.

The estuaries on the coasts and inland river banks, which are brackish, are safe havens for the mangroves. But, the mangrove habitats in the region are degraded due to the expansion of aquaculture and agriculture. Habitat fragmentation, expansion of aquaculture and agriculture along the fringes of mangroves, developmental activities like the construction of ports, jetties, and marinas, and promotion of tourism, among others, are some of the main factors affecting the mangroves in Odisha. Specifically, the mangroves of Odisha are more vulnerable due to the high intensity of frequent tropical cyclones, storm surges, and coastal erosion as the coast of Odisha has a shallow continental shelf that enhances the storm surges during the cyclones or tsunamis. Around 187 of 480 km stretch of Odisha's coast is exposed to high (40 km), medium (52 km), and low type of erosion (Ramesh et al. 2011). Hence, the state's coastal districts face a widespread loss of human lives, crops, and property. Spatio-temporal analyses shows that the overall mangrove in the state has increased by 12 km^2 from 2015–2017 and by 8 km^2 from 2017–2019; however, the highly-dense cover remained almost stagnant at 82 km^2 located in Kendrapara District (FSI 2019).

Materials and methods

The methodology followed in the study can be divided into a) participatory survey for identifying the drivers of change; b) developing future scenarios based on the aspects of economic and socio-cultural development and climate awareness; c) translation of the plausible future scenarios into the land-use and land cover (LULC) changes; d) quantification of different ES viz. blue carbon sequestration, sediment retention and export, and nutrient export due to the LULC changes using the InVEST model; and e) comparative analysis of the ES over multiple scenarios according to the administrative zones. The overall methodology is presented in Fig. 2 as a flow diagram and discussed in detail in the following subsections.

Participatory survey

The participatory survey was conducted on several regional stakeholders to assess the significant drives of change. Participatory Rural Appraisal (PRA) tools, including Focus Group Discussion (FGD) and Key Informant Interviews (with open-ended questions) were used

Fig. 2 Methodology followed in the study
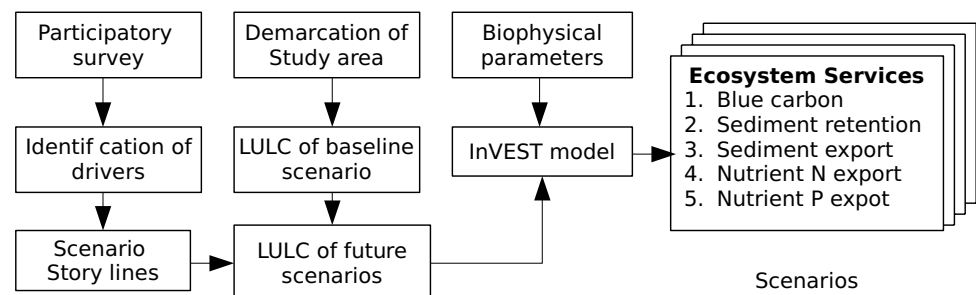
initially, followed by a short questionnaire survey of local inhabitants living or working in and around Bhitarkanika and Paradip Port regions (n = 84). We first conducted three exploratory FGDs and several Key Informant Interviews (n = 15) from 5-10th March and later from 6-7th August 2019.

The PRA exercises were carried out in villages viz. Gupti, Dangmal, Paradip, and surrounding areas. In total, four FGDs were carried out with local farmers (15 participants), forest department local staff (five participants), women, and boat owners (eight participants). This was followed by the key informant interviews of 42 locals from the study area, majorly men from diverse occupational backgrounds (including farmers, homestead owners, teachers, government employees, business people, etc.). The first and second authors and other volunteers conducted these interviews. During the interviews, respondents were asked about their socio-economic background and sought information on the direct and indirect drivers of mangrove loss (based on IPBES Asia Pacific Regional Assessment Report 2018) in Bhitarkanika. As per the IPBES Global Assessment for Biodiversity and Ecosystem Services report, five direct drivers of biodiversity loss are changing use of sea or land, direct exploitation of organisms, climate change, pollution, and invasive non-native species. The two indirect drivers are people's disconnect with nature and lack of value and importance of nature (IPBES 2019). These drivers were addressed under various sub-headings which included direct drivers such as population growth, land use changes, aquaculture, deforestation, agriculture intensification, unsustainable harvesting, urban sprawl, tourism, natural disasters, human-wildlife conflict, invasive species; and indirect drivers such as local socio-economic conditions, coastal policies by the government, local culture, technological innovations, etc.

In our study, we have also tried to understand the significant impact of the potential drivers on Bhitarkanika mangroves. During the interviewing exercise, the first and second authors observed the narratives and encouraged discussion by probing further questions. Based on the directed content analysis and the highest repetitions, the region's potential drivers of mangrove loss were listed, which were later verified through personal observations on the field. The empirical data were gathered in each step with an experienced local interpreter. The summary of the stakeholder responses was further analyzed to identify specific drivers related to (a) the loss of mangroves in the region, (b) forest conservation practices, and (c) local efforts to reduce the impact to reduce disaster risks. Additional information from recent scientific papers, government policy documents, and reports was also taken to strengthen the evidence from the above analysis.

Scenario development

Many respondents agreed that the local people are directly or indirectly dependent on the mangrove forest produce, and the pressure has been building recently due to the population growth resulting from rural–urban migration. Changes in land use, expansion of the built-up area, and extensive construction activities significantly affect the local hydrology. The effect of industries along the coasts, ports, and jetties is not to be ignored when polluting the surrounding environment. Uncontrolled tourism causes plastic pollution, pressurizes the solid and hazardous waste management systems in the localities, and stresses local resources. Several stakeholders have also reported clearing mangroves for aquaculture and agricultural farms. Most participants believe with high certainty that expansion of aquaculture and agriculture is also a significant cause of the degradation of mangrove habitats. Along with that, most of the participants believe with very high certainty that deforestation and habitat fragmentation are also some of the significant concerns for mangrove habitat degradation.

The participants believe with high certainty that local socio-economic factors drive mangrove degradation. For instance, tourism, firewood collection, fishing, poaching, extraction of medicinal plants, etc., have been identified as some of the significant issues directly related to the socio-economic conditions of the people in the region. Further, it emerged from the discussion that there are mixed responses on the role of governmental agencies and implementing authorities in mangrove conservation. Most of the respondents believe that the government's protective measures have helped check the deforestation and degradation of mangroves. However, a few voices expressed dissatisfaction with slack in policy implementation and reported a few instances of violation of coastal protection rules. Remarkably, most of the participants believe that through the implementation of technology, using remote sensing and GIS-based surveying, the mangroves will be protected through increased ecosystem monitoring, management, and resource conservation. Also, specific coastal conservation structural measures are believed to help reduce the impact of storm surges and cyclones on the mangroves. The frequency and intensity of these natural disasters have been increasing in the last decades due to climate change. Most of the participants believe with high certainty that tsunamis, tropical cyclones, and sea-level rise are affecting the mangrove habitats. The summary of the discussion is presented in Table 1.

The farmers in the region recognize the nutrient retention service of the mangroves. And most of them were willing to pay a higher price for getting the agricultural land adjoining mangroves. The productivity of various crops bordering mangrove forests within 0–1 km was relatively higher than faraway crops within 1–3 km (Hussain and Badola 2008).

Table 1 Summary of the participatory survey on mangrove habitats

Major factors	Ramifications
Uncontrolled economic development	Increase in built-up, aquaculture and agriculture farms, and tourism. Leads to pollution. Decline in mangrove habitats
Conservation measures	Checks deforestation and habitat fragmentation. Use of technology for mangroves monitoring and coastal protection
Socio-economic factors	Lack of education and environmental awareness. Dependency on forest produce, disturbs pristine forests Climate change mitigation

The majority in the study have favored the mangrove restoration, hoping that mangroves will improve the agricultural land fertility. Evidence by Reddy et al. (2021) also supports the higher bio-availability of nutrients in the Bhitarkanika region. These findings are especially interesting because they might be a motive for the agriculture and aquaculture expansion in the vicinity of mangroves.

Scenario analysis, if employed efficiently, can improve decision-making through various phases of the policy cycle (Hashimoto et al. 2018). Three scenarios were imagined in the present study according to the stakeholder perceptions of the future landscape of the region.

Scenario-1 would be a case where economic development is given utmost importance. Expansion of built-up areas, agricultural farms, and aquaculture would be emphasized without concern for protecting coastal blue carbon ecosystems like mangroves. Conversion of mangroves at the fringes of the intact habitats is possible. The land occupied with other vegetation and water bod-

ies will be converted into a built-up area. This scenario is particularly favorable for economic development, but with the slightest concern for protecting the mangrove habitats, the worst-case scenario. This scenario orients with most stakeholders' concerns about unscrupulous economic development at the cost of mangrove habitats. The conversion of land use according to the storyline of this scenario was created using the InVEST model with a sequential run of proximity-based land-use scenario generator model. The rule set for the land-use conversion and the steps followed is shown in Table 2.

Scenario-2 would be a case where economic development is given priority and the conservation of mangroves is also taken care of. In this scenario, economic growth is encouraged in terms of expansion of the built-up area, but the encroachment of existing mangrove patches is not allowed to be converted into agriculture or aquaculture farms. This scenario captures the belief of the majority of the respondents in the survey who agreed that mangroves provide favorable conditions

Table 2 Scenario description and the respective land use transition from the baseline

	Description	Focus land use	Convertible land use	Replacement land use
Scenario-1	Economic development, without concern to protecting mangroves Expansion in built-up, aquaculture, and agriculture	Built-up	Mangroves, other vegetation, and water bodies	Built-up
		Aquaculture, and mangroves	Mangroves, other vegetation, and water bodies	Aquaculture
		Mangroves	Mangroves and other vegetation	Agriculture
Scenario-2	Economic development with concern to mangrove protection Expansion of built-up area, but prohibiting the expansion of agriculture and aquaculture that are adjacent to mangroves	Built-up	Agriculture, and other vegetation	Built-up
Scenario-3	Improved socio-economic factors and concern on climate change Encouraging people to explore alternative sources of income, making them less dependent on mangroves. Conversion of adjacent aquaculture and agriculture farms back to mangrove forests. Existing built-up area is not disturbed	Mangroves	Aquaculture, agriculture, other vegetation, and water bodies	Mangroves

for the overall productivity of the surroundings, hence the land occupied with agriculture or other vegetation types is allowed to expand built-up, but mangroves are not disturbed (Table 2).

Scenario-3 would be a more optimistic case where mangrove forest cover will increase along the fringes by converting aquaculture, agriculture, and other vegetated areas. This scenario will reflect the improved socio-environmental awareness, and the local people will appreciate the protective role of mangroves in mitigating climate-related hazards. Studies show that the productive lifespan of aquaculture ponds on the fringes of mangroves is relatively short (see Aslan et al. 2021). In such cases, the abandoned ponds or uneconomical ponds can be restored into mangrove plantations after necessary amendments. Similar instances with the agricultural lands help expand the extent of mangroves under this scenario. Padhy et al. (2021) argue that mangroves have less global warming potential (by 63%) compared with wetlands/rice production (0.26 mg m^{-2} h^{-1} methane emission), yet, the former has high carbon sequestration potential (by 38%) than the latter. Conversion of unproductive agricultural land to mangrove plantations would be a greener alternative with multiple benefits of high carbon sequestration with lower greenhouse gas (GHG) emissions (methane and nitrous oxide).

Land-use land cover classification

Google Earth Engine (GEE) and QGIS-v3.16 models were used to analyze the Sentinel-2 (Multi-Spectral Imagery) and Sentinel-1 (Synthetic Aperture Radar) imageries with 10 m spatial resolution. The Red, Green, Blue, and Near Infrared (NIR) bands of Sentinel-2 (MSI) were used to create true color and false color combinations for visualization. The Random Forest machine learning algorithm was trained from the Sentinel-2 bands to classify the pixels into six different LULC classes (code), including waterbodies (1), aquaculture (2), other vegetation (3), built-up (4), agriculture (5), and mangroves (6). The pixels with no data or not classified are represented with code 0. From this supervised LULC output, it was observed that the aquaculture class was getting confused with waterbodies and agriculture. To improve the LULC accuracy, we have applied the microwave satellite imagery of Sentinel-1. The VV and VH polarization bands (V = vertical, H = horizontal) of Sentinel-1 were used in the form of Dual Polarized Water Index, Shadow Difference Water Index (SDWI), Eq. 1, for enhancing the identification of water bodies from the image. A threshold of pixel values greater than 0.3 was applied for the identification.

$$SDWI = ln(10 \times VV \times VH) - 8 \tag{1}$$

Modelling mangrove ecosystem services

The coastal blue carbon, sediment, and nutrient retention services of the mangrove habitats were estimated using the InVEST-v3.8.0 suite of models. The input layers for the models were prepared using the QGIS-v3.16 software. More details on the model description and data needs are provided in the following subsections.

InVEST—coastal blue carbon model

In the present study, the coastal blue carbon model was used for quantifying the carbon sequestered or released (in Mg C/ha) from the mangroves till 2030 due to the land-use changes. Three carbon pools (p) consisting of mangrove biomass (both above ground and below ground), litter, and sediments (carbon stored in the soil) were considered, denoted by $S_{p,t}$. The carbon stock in the standing mangrove forests was assigned to 100 Mg C/ha in biomass, 0.59 Mg C/ha in the litter, and 134 Mg C/ha in soil based on our literature survey. The accumulation rates of carbon in biomass and sediments (or soil) were considered to be 1.789 and 3.35 Mg C/ha/y, respectively. The differential amounts of carbon captured by 2030 due to the land-use changes (as per the scenarios) were estimated by the model. The annual carbon accumulation rate (three pools) and half-life of exponential decay (biomass and soil) were obtained from the previous studies on Bhitarkanika/Mahanadi mangroves (Table 3). The model calculates the transition of land-use categories by comparing the baseline land use with the future land use (according to the scenarios). The transition of mangroves into a non-coastal blue carbon land use will cause disturbances to the mangroves and thus emit the sequestered carbon from various pools back to the atmosphere. In contrast, for no change in mangrove land use, the model will accumulate the carbon stocks as per the rate of accumulation in each pool (Eq. 2). The level of disturbance ($M_{p,s}$) to the mangroves can be assigned in the model in three categories viz., less, medium, and high intensity.

The disturbances to mangroves by land-use conversion from agriculture and built-up were treated as 'high-impact-disturbance' category, whereas conversion to aquaculture was treated as 'medium-impact-disturbance.' It is considered that due to high-impact disturbances, mangroves will lose 100% of biomass and 50% of the carbon stored in the soil. In contrast, 50% biomass and 50% soil carbon will be lost due to medium-impact disturbances. These percentages vary according to the study area; hence the default values presented in the InVEST manual are considered (after Murray et al. 2011).

Table 3 Carbon stock values and accumulation rates used in InVEST coastal blue carbon model (the values in boldface are considered in the model from multiple references)

Parameter	Value	Unit	Reference	Study area
Standing carbon stock in mangrove biomass	89.1 ± 8.9	Mg C/ha	Sahu et al. (2016)	Mahanadi mangrove wetland
	100 ± 11	Mg C/ha	Bhomia et al. (2016)	Bhitarkanika conservation area
Standing carbon stock in litter in mangrove forests	0.59 ± 0.20	Mg C/ha	Bal and Banerjee (2019)	Bhitarkanika Wildlife Sanctuary
Standing carbon stock in the sediments of mangrove forests	54.3 ± 3.0 (upto 30 cm)	Mg C/ha	Pattnayak et al. (2019); Sahu et al. (2016)	Bhitarkanika National Park; Mahanadi mangrove wetland
	134 ± 17 (upto 100 cm and beyond)	Mg C/ha	Bhomia et al. (2016)	Bhitarkanika conservation area
Half-life of C decomposition from biomass	15	Years	Murray et al. (2011)	
Half-life of C decomposition from sediments	7.5	Years	Murray et al. (2011)	
Accumulation rate of C by mangrove forests	1.789	Mg C/ha/y	Sahu et al. (2015)	Swamps and littoral forests of Odisha
Accumulation rate of C by sediments	0.69–6.02 (average **3.35**)	Mg C/ha/y	MacKenzie et al. (2016)	Viet Nam and global average
	4.00–5.00	Mg C/ha/y	Liu et al. (2020)	China

The blue carbon model integrates all these factors of land-use changes, level of disturbance, and carbon accumulation or emission rates and quantifies the changes in carbon sequestration across the years of land-use changes. See the InVEST model manual (Sharp et al. 2020).

$$S_{p,t} = S_{p,t-1} + N_{p,t} \tag{2}$$

where $N_{p,t}$ represents the differential carbon either gained (accumulated, $A_{p,t}$) or lost (emissions, $-E_{p,t}$) in year t. The above equations represent the biomass and soil pools, whereas the litter stocks are considered to be only accumulating linearly according to the defined rate of accumulation. The model follows the exponential decay of carbon pools according to the half-life ($H_{p,s}$) defined (Eq. 3), where s represents the year of transition, and $D_{p,s}$ is the total carbon released over time due to the land-use transition on a grid (as time tends to infinity), which is represented by Eq. 4.

$$E_{p,t} = D_{p,s} \times \left(0.5^{\frac{(1-(s+1))}{H_{p,s}}} - 0.5^{\left(\frac{(t-s)}{H_{p,s}}\right)} \right) \tag{3}$$

$$D_{p,s} = S_{p,s} \times M_{p,s} \tag{4}$$

InVEST—sediment delivery model

The sediment delivery model calculates the sediment volume generation using the revised universal soil loss equation (RUSLE), using Eq. 5. The input data layers of surface elevation (m), LULC, rainfall erosivity factor (R) (MJ mm (ha h y)$^{-1}$), and soil erodibility (K) (t ha h (MJ ha mm)$^{-1}$) were prepared for the study area using QGIS software. Digital Elevation Model (DEM) data of 30 m spatial resolution was obtained from the Shuttle Radar Topography Mission. The values of land cover-management factor (C) (unit-less) and support practice factor (P) (unit-less) required for each land-use category were sources from the literature (Table 4). The C-factor varies between 0 and 1, which compares the effectiveness of soil cover and management practices that affects soil erosion for various land uses (including crops) with respect to a bare fallow area (control plot). The practices include tillage, planting of cover crops, spreading of plant residues, etc. In contrast, support factor (P) reflects contouring and strip cropping practices. Determining the P and C values based on the locally measured field experiments will reduce the uncertainty in the soil loss estimations. However, the C and P factor values can also be estimated through

Table 4 Crop cover management factors (C) and support practice factors (P) used in the InVEST sediment retention model

Land use	C *	P #
Water bodies	0	1.0
Aquaculture	0	1.0
Other Vegetation	0.030	0.8
Built-up	0	1.0
Agriculture	0.400	0.5
Mangroves	0.004	1.0
	* Chatterjee et al. (2014)	# USDA handbook (1981) / Naqvi et al. (2013)

remote sensing methods (for ex. Almagro et al. 2019). The model calculates the terrain slope length-gradient factor (LS) (unit-less) internally using the DEM data. Terrain slope gradient (S) and length (L) are directly proportional to the soil erosion, which is jointly represented through the topographic factor (LS), which can be determined using GIS software with the DEM layer. See Chatterjee et al. (2014) for more information on the calculation of LS from DEM.

The watershed vector layer was required for channelizing the stormwater flow from the catchments and for the sediment transport. The watershed layer was prepared using the void-filled DEM layer. The rainfall erosivity raster layer for the study area was sourced from the Global Rainfall Erosivity dataset (Panagos et al. 2017). The K factor value was calculated according to the empirical relation provided in the InVEST manual (Renard et al. 1997), which is 0.06643. The soil texture and organic content data have been sourced from the HWSD-v1.21. The soil texture, according to USDA, is of loam type, with sand, silt, clay fractions of 39%, 41%, and 20%, respectively. The average soil organic carbon in the study area according to the HWSD is 0.9%. The K values considered by Chatterjee et al. (2014) in Jharkhand State, which is on the north of Odisha State, are 0.062–0.068 for soil types with sand in the range of 20–50%. Whereas, K value obtained from the Ontario Ministry of Agriculture, Food and Rural affairs factsheet is around 0.05 for the loamy soils (http://www.omafra.gov.on.ca/english/engineer/facts/12-051.htm). Soil erodibility (K) signifies soil susceptibility to erosion and its transportability with respect to a particular rainfall input (Chatterjee et al. 2014).

$$A = R \times K \times LS \times C \times P \tag{5}$$

Based on the input data layers, the model calculates the amount of sediment that is exported into the streams in the watershed. For that, the model first computes the connectivity index (IC) at each pixel based on Borselli et al. (2008). The IC value (unit-less) at a pixel describes the extent of linkage between the sources of sediment upstream (D_{up}) and the sinks or streams downstream (D_{dn}). In general terms, higher IC values indicate a more likely situation of sediments making their way into the streams. Dense vegetation and lower slopes result in lower IC values and vice-versa. Based on the IC values and further calculations, the model calculates the amount of sediments (estimated using RUSLE) reaching the streams (called sediment export, E_i in t ha^{-1} y^{-1}) according to Eqs. 6–8. Where SDR_i is the sediment delivery ratio (Eq. 9) using the calibration parameters from the SDR-IC relationship. For more details on the methodology for calculating sediment retention, refer to the InVEST manual (Sharp et al. 2020). The parameters k and IC_0 that define the curve's properties between SDR and connectivity index (IC) were kept at their default values of 2 and 0.5, respectively. The maximum threshold of SDR_{max}

at any pixel was set at 0.8 (a default value prescribed in the InVEST model).

$$IC = log\left(\frac{D_{up}}{D_{dn}}\right) \tag{6}$$

$$E = \sum E_i \tag{7}$$

$$E_i = USLE_i \times SDR_i \tag{8}$$

$$SDR_i = \frac{SDR_{max}}{\left(1 + exp\left(\frac{(IC_o - IC_i)}{k}\right)\right)} \tag{9}$$

InVEST—nutrient delivery model

The nutrient delivery model calculates the amount of nutrients (both dissolved and sediment attached) released from a land use using a simple mass-balance approach. The released nutrients, majorly as agriculture run-off, are arrested by the coastal or riparian vegetation and prevents contamination of water bodies. The dynamics of nutrient export and retention are computed across all pixels in accordance with the hydrology of a watershed (derived using Digital Elevation Model data), which results in the overall nutrient delivery or retention service provided by the vegetation land-use.

The nutrient delivery model adopts a similar approach, inspired by the sediment delivery model, in calculating the export of nutrients from various land uses in the upstream area into the streams (Eq. 10 and 11). Nutrient loading of Nitrogen and Phosphorus (kg/ha/y) has to be assigned for different land use classes from which the model estimates the nutrient load is making into the streams from both surface and sub-surface (groundwater) pathways. In the present study, only the surface pathway has been considered; however, the quantity of nutrients leached out of the system will not be affected. Precipitation data obtained from WorldClim (https://www.worldclim.org) was considered a surrogate variable that drives the nutrient erosion in the system. Model parameters on critical length factor (K_c), nutrient loading, and retention values are presented in Table 5. The InVEST nutrient retention model parameters viz. threshold flow accumulation, Borselli k parameter, critical length of (N and P), and maximum nutrient retention (N and P) were set to 1000, 2, 30, and 0.8, respectively. More details on the model are presented in Vigiak et al. (2012) and InVEST manual (Sharp et al. 2020).

$$NE_{total} = \sum NE_i \tag{10}$$

$$NE_i = NLoad_i \times NDR_i\left(D_{up}, D_{dn}, eff_{dn}\right) \tag{11}$$

Table 5 Nutrient loading values used in the InVEST nutrient export model

Land use	N load (kg/ha)	P load (kg/ha)	Retention efficiency, N and P (%)	Critical length for N and P (m)
Water bodies	0	0	0	0
Aquaculture	0	0	0	0
Other Vegetation	1.4	1.4	0.8	30
Built-up	2.1	2.1	0.26	30
Agriculture	21.27	9.42	0.48	30
Mangroves	0	0	0.9	15

where the NDR is calculated in similar lines with the SDR as described in "Modelling Mangrove Ecosystem Services" section, and eff$_{dn}$ is the effective downslope retention.

Comparative analysis of the ES

The zonal statistics of ES in the study area were summarized according to the *tehsil* administrative boundaries for each scenario. R program (R Core Team 2017) was used for summarizing the results, change analysis, and plotting.

Results and discussion

land-use and land cover — Scenarios

The accuracy of LULC analysis was determined with the standard Kappa coefficient = 0.86, which is acceptable. According to the analysis (Fig. 3), the predominant land use in the study area is agriculture, followed by other vegetation, mangroves, waterbodies, built-up, and aquaculture as of 2020 (Table 6). The total mangrove cover in the study area is estimated to be 194 km^2, out of which nearly 74% is in Rajnagar and 23% is in Mahakalapada *tehsils*. The land-use transition analysis indicates that, in scenario-1, the expansion of built-up (+5% with respect to baseline land-use), aquaculture (+5%), and agriculture (+5%) due to the conversion of water bodies (-4.6%), other vegetation (-4%), and mangroves (-6.6%), is a result of economic development without concern for the mangroves or other vegetation. The total mangrove cover in this scenario would be 53 km^2 after losing nearly 90% and 66% of mangrove cover from Mahakalapada and Rajnagar *tehsils*, respectively. In scenario-2, the economic development is more balanced than that of scenario-1, where conversion of mangroves is totally restricted, however agricultural land (-4.5%) and other vegetation (-0.6%) land is marginally allowed for the expansion of built-up area (+5%). In scenario 3, the focus is more oriented towards the development of climate resilience of the coastal systems by promoting the expansion of the mangrove forests. This scenario emerges due to the development in socio-cultural and socio-economic conditions of the society that appreciates the ecosystem services and multiple other benefits of the mangroves and other natural ecosystems. Here, there is an increase in mangrove cover (+5%), which is marginally converted from agriculture (-0.1%), aquaculture (-0.1%), water bodies (-1%), and other vegetation (-1.3%) at the fringes. The total mangrove cover extends from 194 (baseline) to 301 km^2, with the highest increment of 52 km^2 in Mahakalapada followed by 29 km^2 in Rajnagar *tehsil*. The summary of the land-use transitions is graphically represented using a Sankey plot (Fig. 4).

Coastal blue carbon

The standing BC stored in biomass, litter, and sediments of mangrove ecosystems in the study area is estimated to be 4.55 Tg C as of 2020. In scenario-1 (increased economic activity with no commitment to mangroves and other vegetation), net carbon emissions will be due to the loss of mangroves (Fig. 5). It is estimated that 2.16 Tg C will be emitted back into the atmosphere due to anthropogenic disturbances to the mangrove patches, and the standing carbon stock in scenario-1 will remain at 2.39 Tg C. The highest carbon loss will be from Rajnagar and Mahakalapada *tehsils* at 1.42 and 0.66 Tg C, respectively, which are commensurate with the loss of mangrove cover (Fig. 6 and Table 7). On the other side, in scenarios 2 and 3, there will be no change in mangrove cover and increased mangrove cover, respectively. In the former case, the increase in carbon stock is due to the sequestration rate in the mangroves (biomass, litter, and sediments), and the stocks are estimated to reach 5.55 Tg C by 2030. Whereas, in the latter case, 6.10 Tg C will be the total carbon stock in the mangroves due to both expansion of mangrove patches and net C sequestration rates. The net carbon sink will be 0.74 and 0.23 Tg C in Rajnagar and Mahakalapada *tehsils*, respectively, compared with the baseline land use. These changes are commensurate with the changes in land use and the level of disturbances caused to the mangroves.

Mangrove biomass is directly proportional to the accumulated soil and sediment carbon pools with a correlation
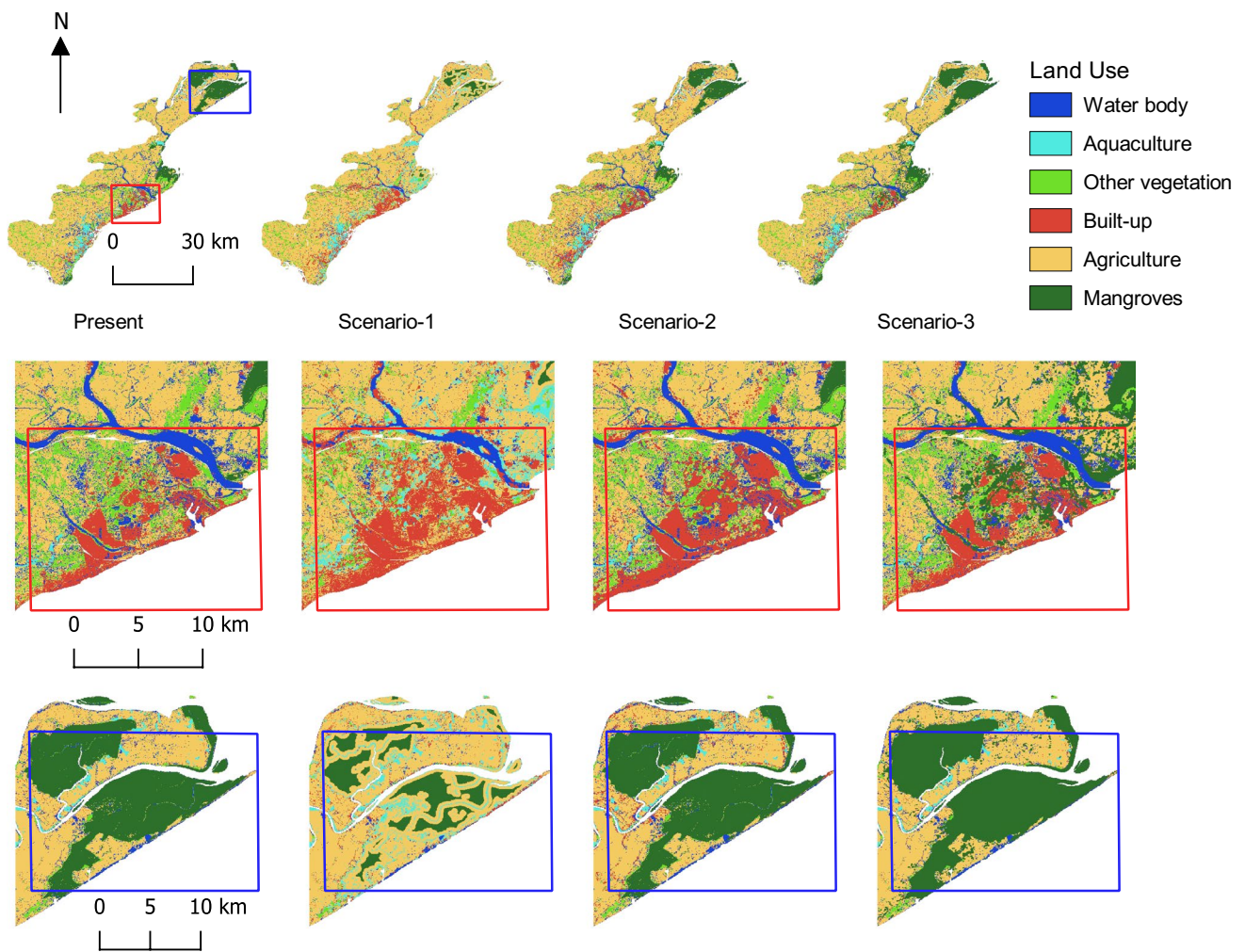
Fig. 3 Land-use and land cover in the present year (2020) and future scenarios 1–3. The inset boxes cover the mangroves of Bhitarkanika (blue) and Paradip (red) areas in Odisha State

Table 6 Summary of land use percentages in baseline and future scenarios (study area is 2150 km.^{2})

Land use (code)	Present Scenario (%)	Scenario-1 (%)	Scenario-2 (%)	Scenario-3 (%)
Unclassified	4.7	4.7	4.7	4.7
Water body (1)	8.1	3.5	8.1	7.1
Aquaculture (2)	2.8	7.8	2.8	2.7
Other vegetation (3)	11.5	7.5	10.9	10.2
Built-up (4)	4.5	9.5	9.5	4.5
Agriculture (5)	59.4	64.4	54.9	56.7
Mangroves (6)	9.1	2.5	9.1	14.1

of 0.87 (Sahu et al. 2016). This indicates the vital role of mangrove vegetation in building the sediment carbon pools. Apart from quantifying the standing carbon stocks, understanding the rate of C accumulation is also essential (Murray et al. 2011; Jennerjahn 2020), which signifies the climate change mitigation potential. According to the sediment core sample analysis by Liu et al. (2020), the organic carbon accumulation rate in sediments is approximately 400 to 500 g m^{-2}y^{-1}, substantially higher than globally reported sediment accumulation rates. The downward fluxes of C into

Fig. 4 Land-use and land cover change Sankey plot for three future scenarios in comparison with the baseline or present land-use of 2020

6=Mangroves

5=Agriculture

4=Built-up
3=OtherVegetation
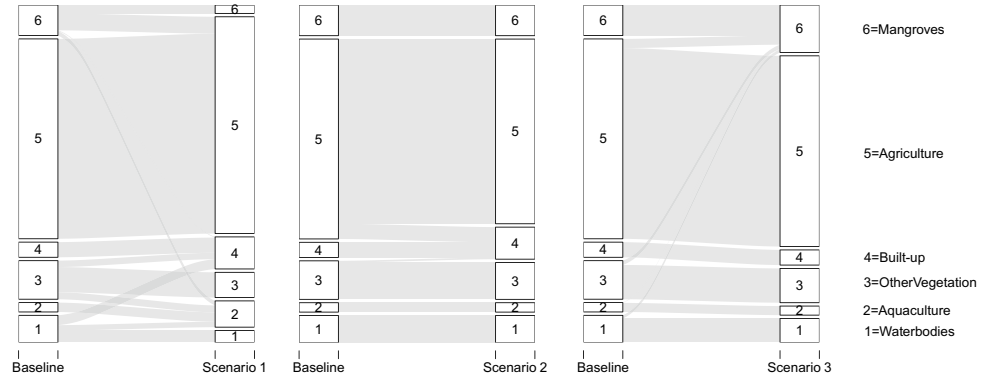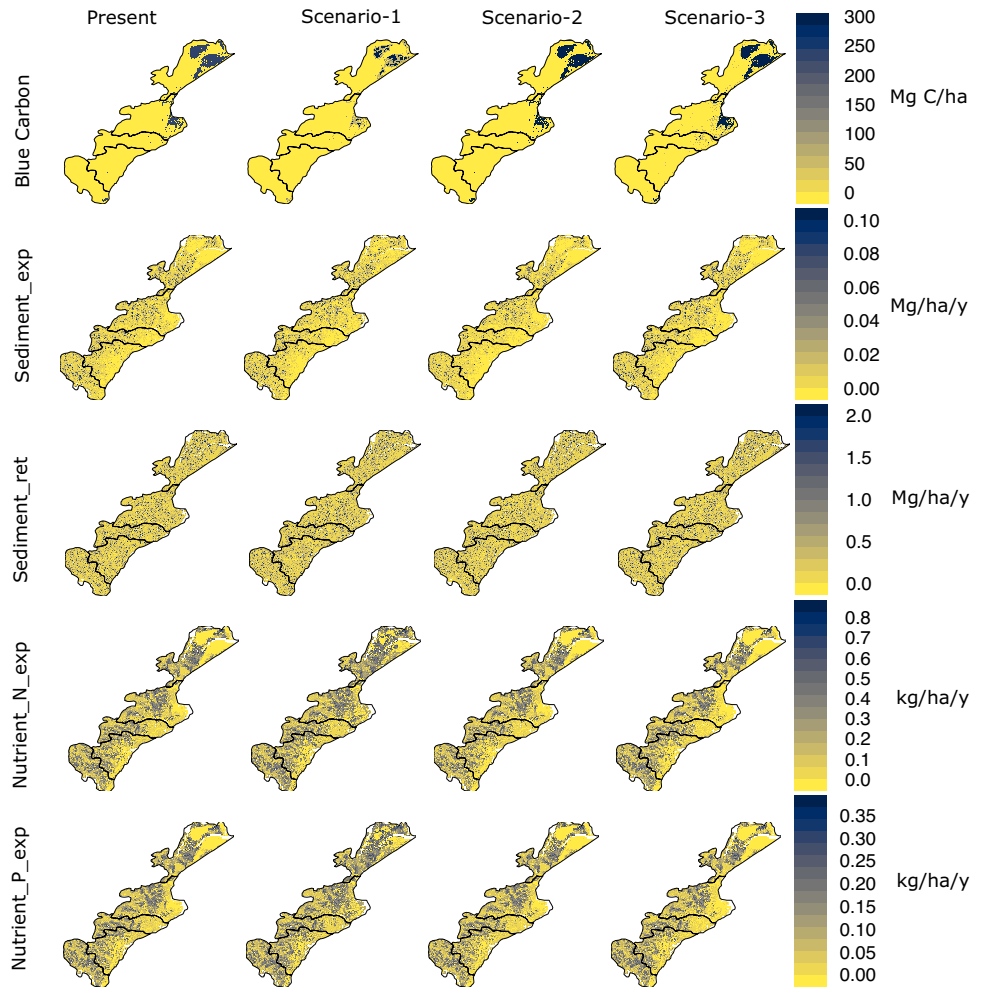2=Aquaculture
1=Waterbodies

Fig. 5 InVEST model simulated coastal blue carbon, sediment export and retention, nutrient export spatial maps for baseline and future scenarios


the deeper sediment layers are being unvalued, which otherwise would contribute to higher C accumulation. Modeling results by Jennerjahn (2020) also agree with Liu et al. (2020) findings.

Field experiments by Pérez et al. (2018) demonstrate that the carbon accumulation capacity of mangroves varies depending on the type and degree of impact. They further argue that the carbon sequestration rate apparently increases due to stressors like anthropogenic effluents, natural storms, and floods. Further studies are required to establish the range of carbon accumulation rates within which the positive correlation between the disturbance and carbon accumulation is valid. Sharma et al. (2020) observed that nearly 60% of ecosystem carbon is lost due to mangrove degradation. The availability of field-level data specific to the study area is not straightforward. The lack of data standardization on carbon

Fig. 6 Blue carbon stock (Tg C), Sediment export (Gg/y), Sediment retention (Gg/y), Nutrient export (Mg/y)
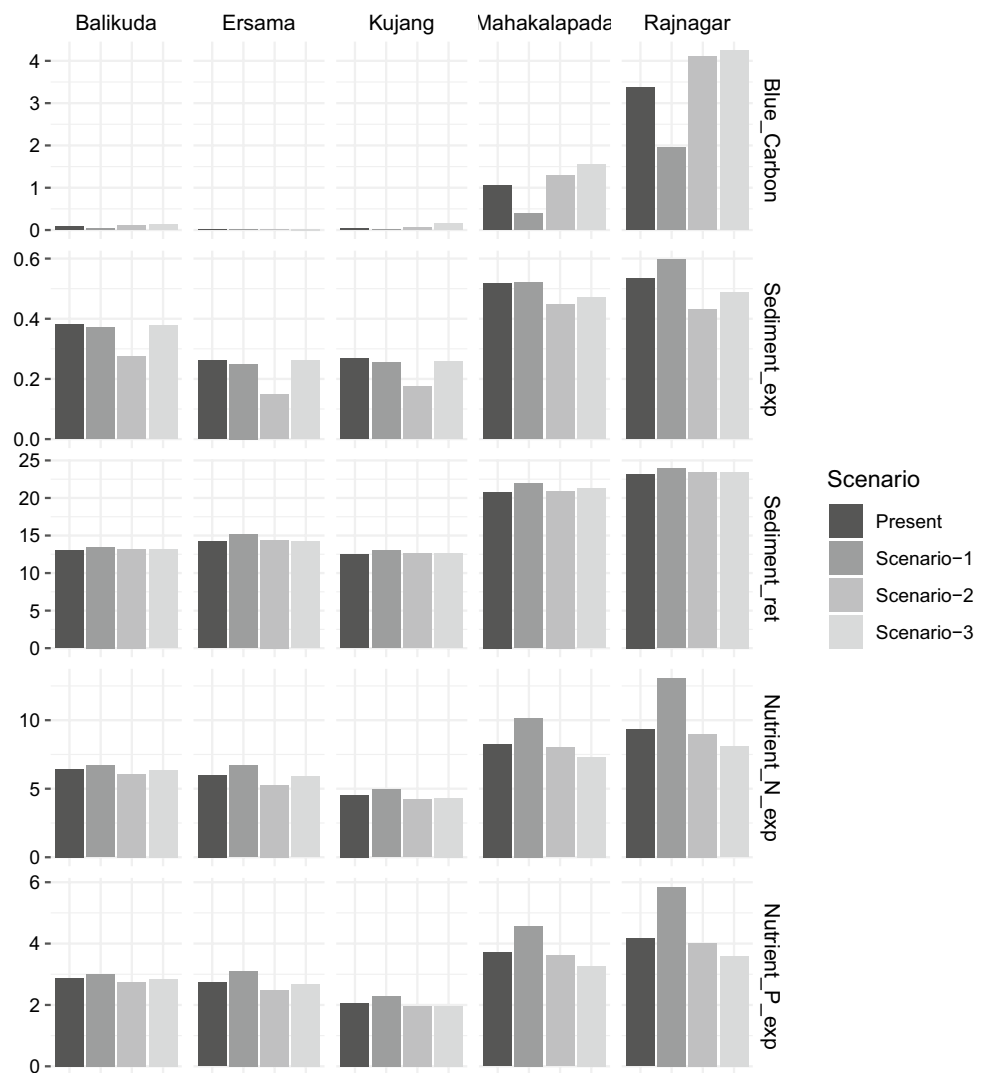
Sediment delivery

The study area has mostly a flat terrain owing to the deltaic formation by the Brahmini and Mahanadi River systems. Flat landscapes have a relatively less tendency for soil erosion. The combined effect of the variables in RUSLE along with the land management practices reflected through C and P values determines the sediment delivery ratio.

Results indicate that the sediment export in the study area for the baseline scenario is estimated to be 1.96 Gg/y (Fig. 5). In scenario-1, the sediment export marginally increased to 1.99 Gg/y, mainly due to the loss of mangroves. The increase in sediment export is maximum in Rajnagar by 11.49%, which is correlated with the highest loss in mangrove cover in the *tehsil* (Fig. 6). Whereas the sediment export in the study area has dropped to 1.48 and 1.86 Gg/y

in scenarios-2 and 3, respectively, when compared with the baseline, as there is a significant increase in the mangrove cover. In various scenarios, the sediment retained in the study area has not changed much, which remained in the range of 83.65 to 87.41 Gg/y.

The interplay of several factors, including high-intensity rainfall, overgrazing, and vegetation clearance on steep slopes, and increasing human and livestock populations, exacerbates the soil loss. Overland soil erosion is rampant due to land-use changes and modifications in natural vegetation and, to a significant extent, affected by the rainfall intensity. The streams in a watershed carry the sediment loads into rivers, reservoirs, and estuaries. Similarly, the nutrients released from the crops wash down into the streams and rivers in a catchment.

Mangroves, with their peculiar root structure, can retain sediments and nutrients. Similar estimates of sediment losses across non-socio-ecological landscapes indicate the highest soil losses of 1.23 and 0.88 Mg/ha/y from agricultural and

Table 7 InVEST model projected coastal blue carbon, sediment, and nutrient export in the baseline and projected scenarios. Percent change with respect to baseline is shown in brackets (%)

Variable	Unit	Tehsil	Baseline	Scenario-1	Scenario-2	Scenario-3
Blue carbon	Tg C	Balikuda	0.09	0.03 (-68.55)	0.10 (21.91)	0.13 (53.66)
		Ersama	0.01	0.00 (-65.87)	0.01 (21.91)	0.02 (231.54)
		Kujang	0.04	0.01 (-67.37)	0.05 (21.91)	0.15 (237.17)
		Mahakalapada	1.06	0.40 (-62.28)	1.29 (21.91)	1.56 (47.17)
		Rajnagar	3.36	1.94 (-42.15)	4.10 (21.91)	4.24 (26.27)
		Total	4.55	2.39 (-47.60)	5.55 (21.91)	6.10 (34.03)
Sediment export	Gg/y	Balikuda	0.38	0.37 (-2.84)	0.27 (-28.17)	0.38 (-0.76)
		Ersama	0.26	0.25 (-4.79)	0.15 (-43.52)	0.26 (-0.35)
		Kujang	0.27	0.25 (-5.47)	0.18 (-34.45)	0.26 (-3.43)
		Mahakalapada	0.52	0.52 (0.63)	0.45 (-13.73)	0.47 (-9.19)
		Rajnagar	0.54	0.60 (11.49)	0.43 (-19.46)	0.49 (-8.76)
		Total	1.96	1.99 (1.36)	1.48 (-24.89)	1.86 (-5.47)
Sediment retention	Gg/y	Balikuda	13.04	13.46 (3.24)	13.22 (1.41)	13.14 (0.74)
		Ersama	14.20	15.12 (6.46)	14.38 (1.25)	14.23 (0.20)
		Kujang	12.43	13.01 (4.62)	12.58 (1.17)	12.56 (1.05)
		Mahakalapada	20.80	21.93 (5.44)	20.93 (0.62)	21.27 (2.26)
		Rajnagar	23.18	23.89 (3.09)	23.38 (0.86)	23.47 (1.27)
		Total	83.65	87.41 (4.49)	84.49 (1.00)	84.68 (1.22)
Nutrient N export	Mg/y	Balikuda	6.43	6.68 (4.03)	6.08 (-5.44)	6.36 (-1.07)
		Ersama	5.99	6.71 (12.06)	5.26 (-12.16)	5.90 (-1.49)
		Kujang	4.55	4.95 (8.79)	4.23 (-6.98)	4.32 (-5.00)
		Mahakalapada	8.28	10.15 (22.53)	8.00 (-3.36)	7.31 (-11.67)
		Rajnagar	9.35	13.09 (40.08)	8.98 (-3.93)	8.08 (-13.56)
		Total	34.59	41.58 (20.22)	32.55 (-5.90)	31.97 (-7.57)
Nutrient P export	Mg/y	Balikuda	2.88	3.01 (4.54)	2.75 (-4.47)	2.85 (-1.08)
		Ersama	2.73	3.10 (13.73)	2.48 (-9.06)	2.69 (-1.54)
		Kujang	2.07	2.30 (10.77)	1.96 (-5.40)	1.96 (-5.32)
		Mahakalapada	3.71	4.57 (23.18)	3.61 (-2.65)	3.27 (-11.75)
		Rajnagar	4.16	5.85 (40.50)	4.02 (-3.30)	3.60 (-13.57)
		Total	15.56	18.83 (21.05)	14.83 (-4.65)	14.37 (-7.61)

artificial areas, respectively, in Maritsa basin (Ozsahin et al. 2018). In contrast, the soil loss from wetlands and water bodies were found to be 0.001 and 0.003 t/ha/y, respectively. In the upper Blue Nile basin, the soil erosion rates of 37–246 t/ha/y were observed (Adimassu et al. 2014; Ebabu et al. 2019). In the present study, the soil loss was estimated to be 9.11 kg/ha/y (in the baseline scenario), which is significantly lower than that of other landscapes.

Changes in land use due to climatic and anthropogenic drivers may dramatically affect the sediment export into the streams and thereby affect aquatic life and water quality. Globally, sediment yield in water bodies has become a significant challenge for water managers and reservoir management. Measuring soil erosion at multiple spatial scales is a challenge; hence it is typically estimated with the help of erosion models, including both empirical models and process-based models. The Revised Universal Soil Loss Equation (RUSLE, Renard et al. 1997) is a widely used empirical

model for soil erosion estimation (Kebede et al. 2021; Fenta et al. 2020).

Nutrient retention

According to the land-use change scenarios in the study area, the export of nutrients N and P into the streams varied significantly. In the baseline scenario, N and P exports into streams are estimated to be 34.59 and 15.56 Mg/y, respectively (Fig. 5). In scenario-1, with a significant loss in mangrove cover, the N and P nutrient exports have increased to 41.58 and 18.83 Mg/y, respectively. Whereas, in scenarios 2 and 3, the N and P nutrient exports are projected to be lower than the baseline scenario (Table 7). Experimental plot studies by Kothyari et al. (2004) in the central Himalayan region quantified that annual N, P, and K losses from predominant land uses ranged from 0.30–21.27 kg/ha, 0.14–9.42 kg/ha, and 0.12–11.31 kg/ha, respectively.

Due to nutrient retention in mangrove sediments, higher quantities of total nitrogen (2.9 Mg/ha), phosphates (28.11 Mg/ha), and potassium (1.56 Mg/ha) were observed in the areas surrounding the mangroves in Bhitarkanika (Hussain and Badola 2008). Nutrient-rich soils around the mangroves favor the conversion of land use into agriculture. Nutrient resorption and nitrogen-use efficiency of mangroves with the angiosperms is the highest, as mangroves are characteristically flexible in their ability to opportunistically use the nutrients when they are present (Reef et al. 2010).

The adjacent areas of mangrove patches are typically dominated by agriculture and aquaculture fields. Fertilizer run-off from agriculture fields, sewage from human settlements and tourism units, and aquaculture wastes (rich in nutrients) are the primary sources of artificial nutrients in the mangrove ecosystems. Wet and dry deposition of ambient air pollutants is also a source of nutrient load. For instance, Mitra (2020) observed mangroves near the highly urbanized and industrial pockets of the Hooghly and Haldia regions are affected by air pollution.

Tam and Wong (1993) demonstrated through column experiments that the pollutant retention in mangrove sediments has increased with wastewater's strength. Notably, the study showed that the first 4 cm of the column retained most of the pollutants, with negligible downwards migration, which suggests that mangrove sediments trap the nutrients (N and P) (immobilization) and heavy metals (Cu, Mn, Zn, and Cd). The sediments rich in the organic content act as a substrate for the microbial communities, hence regulate the biogeochemistry of the contaminants and nutrient storage (Banerjee et al. 2018). Due to strong cohesive forces, the organic carbon forms a coating around the clay and silt particles in the sediments, but is not quite strong enough on sand particles. Mangrove sediments rich in clay and silt are an excellent storehouse for the sediment organic carbon.

Anthropogenic influxes to some degree affect the rate of carbon assimilation in coastal ecosystems. Sediment accretion and organic carbon sequestration by mangroves are affected by the nutrient load (Wilkinson et al. 2018), damming of inland rivers and hydrological regime (Pérez et al. 2018), which fluctuate the estuarine salinity, and plastic pollution (Van Bijsterveldt et al. 2021), etc. Further, Pérez et al. (2018) observed an increase in sediment accretion and carbon accumulation rates in the mangroves sites impacted by the anthropogenic effluents, twofold and fourfold, respectively. The nutrient-rich effluent conditions trigger exponential growth in algae and cyanobacteria in the water and sediments (Atwood et al. 2017), which positively enhances the organic carbon accumulation (Bournazel et al. 2015). Further, Pérez et al. (2018) argue that mangrove sites affected by frequent flooding and storms accumulate higher sediments and carbon than the conserved mangroves. Due to dense root systems of mangroves, the areas prone to these hydrological

disturbances trap material like litter, fallen vegetation, and mud. The carbon accumulation rate of conserved mangroves, 160 $gm^{-2} y^{-1}$ (Breithaupt et al. 2012), can reach up to 1000 $gm^{-2} y^{-1}$ (Alongi 2014) receiving nutrient loads from domestic effluent and aquaculture ponds. This proves that mangrove habitats are excellent carbon sinks from the atmosphere and water column even when they are stressed. However, the long term behavior of increased carbon accumulation due to anthropogenic factors is to be assessed with field experiments.

Evidence shows that increasing the nutrient loading in mixed mangrove stands has enhanced growth in some species like *A. germinans* compared with others (Weaver and Armitage 2020). Carbon and nutrient accumulation is higher in this species. Further, Sen and Bhadury (2017) observed that nutrient enrichment has severely affected benthic organisms as increased bacterial degradation in the water column rises hypoxia. Along with the nutrient enrichment, the addition of Potential Toxic Elements (PTE) and heavy metals from industrial wastewater sources also impacts the biota. Anthropogenic factors in nutrient enrichment and the climate and sea-level rises will shape the mangrove stands' habitats and species diversity. Long-term studies are required to accurately capture the effects of excess nutrient enrichment on mangrove biodiversity and functioning.

Limitations

Lack of uniformity in the methods for estimation of C pools through sample collection leads to biases in sampling, which affects the spatial extrapolation of the C in biomass and soil of coastal blue carbon ecosystems. The collection of sediment samples and their accretion rates is a challenging task. Uncertainty in sampling, analysis, spatial extrapolation (errors in remote sensing and LULC classification), etc., will be reflected in the model projections. The positive effect of anthropogenic disturbances on enhanced mangrove carbon and nutrient accumulation, as argued by Pérez et al. (2018), is not yet widely reported from the Bhitarkanika mangroves, and hence not considered in the present study.

Policy recommendation

Mangroves are one of the highly functional coastal ecosystems, and their conservation and restoration should be prioritized. Based on the results, we advocate that policymakers and stakeholders mainstream the benefits of mangroves in blue carbons sequestration, sediment and nutrient retention, and other invaluable ecosystem services.

At present, the data on mangrove forests are obtained from diverse sources and field conditions. In order to

harmonize the studies on mangroves ES estimation, there is a need to coordinate the global research programs with standardized methodologies and objectives to assess the spatio-temporal behavior of the forests. This integration will help policymakers and stakeholders visualize the future of the socio-ecological systems, and imminent damages to the sensitive ecosystems can be minimized (Arowolo et al. 2018). Understanding the role of anthropogenic drivers in shaping natural habitats is also vital for sustainable decision-making to balance development and environmental degradation. Scenario-based analysis of socio-environmental systems (SES) involving mangroves and people's decisions will be a rational approach to comprehending the plausible alternative futures due to the drivers of change, as demonstrated in the present study. Evidence shows that socio-cultural, demographic, and economic aspects, government policies, among others, where human behavior is likely to be influenced significantly modify the ES of natural habitats (Hauck et al. 2013). One among them is the LULC changes which are translated from the above-mentioned factors and directly interfere with the natural ecosystems.

Zoderer et al. (2016) demonstrated a link between the cultural and socio-demographic background of the people. Apart from the LULC changes simulated by the models, the intertwined factors of people's socio-cultural values and economic background also play an essential role in the valuation of ES. The perceived values of ES vary with the socio-cultural background of the people (Zoderer et al. 2016). Engaging all stakeholders in the co-development of future scenarios of change is essential for accommodating their perceptions and knowledge for efficient policymaking. Scenario-based assessment of future impacts on the ES of mangroves considering the potential changes in LULC due to multiple drivers of change provides science-based evidence for effective policymaking.

Although coastal ecosystems, including mangroves, arrest the loss of sediments and nutrients, adoption of soil retention practices is required to minimize the soil and nutrient losses on a regional scale. Soil erosion and nutrient loss are two major drivers of land degradation, which can impact the region's economic development. Arresting soil erosion should be on top priority for policymakers. India stands just next to China in terms of land degradation rates in Asia, and the rates of coastal land degradation are massive. It is estimated that 5.3 billion t of soil is eroded annually in India, out of which nearly 8 Mt are nutrients (Tandon 2007). Loss of nutrients through soil erosion is widening the existing nutrient gap in the agriculture scenario of India.

The economic benefits from mangroves are substantial, for instance, Trégarot et al. (2021) estimated that ES of mangroves in French overseas amount to nearly EUR 1.6 billion/y, out of which 60% is through carbon sequestration, followed by coastal protection (28%), water purification

(7%), and fish biomass (6%). Similar studies on mangrove ES valuation in the Indian context are very few, which needs to be mainstreamed into active coastal zone regulation (CZR) planning for reaping the maximum benefits from the mangroves. Studies show that mixed mangrove forests have approximately 20% higher carbon stocks than monotypic forests (if a single genus of mangrove occupies more than 75% of the ecosystem) and have higher sediment accretion rates (Pérez et al. 2018). To get sustainable long-term benefits, we advocate for the mixed plantation of mangroves while restoring the degraded aquaculture or agriculture areas into mangrove forests.

Improving the socio-ecological status of the people directly dependent on the mangroves, imparting the climate awareness, mainstreaming the benefits of the coastal ecosystems in local actions, use of technology (drones, remote sensing products, sensors) for near real-time monitoring of the mangrove environment, involving local people in the conservation of the mangroves, and through responsible tourism activities, the state of affairs with the mangroves in a socio-ecological landscape can be significantly improved. There is also a need for enhanced financial support from the corporate sector as part of their Corporate Social and Ecological Responsibility (CSR and CER) to achieve restoration goals.

Conclusions

Mangrove ecosystems play a vital role in regulating coastal habitats through a multitude of ecosystem services. These habitats are facing the direct impact of anthropogenic stresses in terms of urbanization, expansion of agriculture, and aquaculture farms in the vicinity of the mangrove patches. Construction of ports, jetties, and marinas near the mangrove patches are polluting these habitats and hence affecting the natural regeneration and growth. In the present study, we have quantified the ecosystem services of mangroves in Bhitarkanika and Paradip of Odisha State of India, which were facing direct threats from a multitude of anthropogenic and climate forces. Coastal blue carbon sequestration, sediment, and nutrient retention services were quantified using the InVEST model, and the changes in these ecosystem services were projected according to plausible future scenarios.

Three possible future land-use and socio-ecological scenarios were imagined in this study based on the participatory survey and focus group discussions with the stakeholders. The main drivers are – unscrupulous economic development and conservation of the mangroves in light of improved socio-cultural and climate awareness of the local people. Results indicate that disturbances to mangrove forests in Odisha can emit 2.16 Tg C back into the atmosphere by

2030, which is certainly not desirable according to the global carbon budget to limit the temperature rise $< 1.5\ ^0C$. In an optimistic scenario, mangroves can sequester an additional 1.55 Tg C from the atmosphere. The decline in mangrove cover has resulted in higher sediment and nutrient export, and vice-versa.

Scenario-based analysis of the ecosystem services of the mangroves in the region is not attempted earlier. We believe that our study is the first of its kind that has integrated the interdisciplinary knowledge of the socio-environmental system (mangrove habitats and people's interaction with the ecosystem), people's perception, empirical models on ecosystem services, and scenario analysis. The results presented in the study will guide in shaping the policies for achieving overall human wellbeing and sustainable development.

Authors contribution **Rakesh Kadaverugu:** Conceptualization, Methodology, Investigation, Writing-Original Draft, Visualization **Shalini Dhyani:** Investigation, Writing-Original Draft **Vigna Purohit:** Data Curation **Rajarshi Dasgupta:** Writing-Review & Editing **Pankaj Kumar:** Writing-Review & Editing **Shizuka Hashimoto:** Writing-Review & Editing, Funding acquisition **Paras Pujari:** Project administration **Rajesh Biniwale:** Project administration.

Data availability The data could be made available if requested.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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