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Drivers of mangrove ecosystem service change in the Sundarbans of Bangladesh

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Mangroves are now well known to provide a range of ecosystem services that benefit local populations, though such ecosystem services are at risk from mangrove deforestation and degradation across much of the tropics. This study aimed to identify the natural and anthropogenic drivers of change that affect ecosystem services of the Sundarbans mangrove forest. Secondary data analysis and primary fieldwork were conducted in three districts in the Sundarbans region of Bangladesh to understand ecosystem service usage and the perceptions of local resource users. Time series data for a range of ecosystem services and biophysical, socio-economic variables were analyzed to identify the range of trends and the significant drivers of change. Also, community perceptions were consulted to elicit how these changes are felt and how they affected the local ecosystem services users. Results show that most of the ecosystem services of the Sundarbans experienced negative changes over the last two decades. Time series analysis and community perceptions held a number of drivers responsible for these changes. Climatic change, rapid environmental change, demand for mangrove products on the global market, major infrastructure development and governance failure were identified as primary drivers leading to the degradation of ecosystem services of the Sundarbans. The study calls for a transformation in the stewardship of ecosystem services of the Sundarbans and other mangroves across the tropics, to escape the situation where negative environmental impacts might be difficult to reverse.

Keywords: Ecosystem services, the Sundarbans mangrove, Bangladesh

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Introduction

The Millennium Ecosystem Assessment (MEA) (2005) highlighted the crucial role that ecosystem services contribute to mankind, and the current state of degradation of many of these ecosystem services around the world. According to the MEA (2005), around 60 per cent of the world's ecosystem services are being degraded or used in an unsustainable manner. Mangroves are widely recognized as highly productive (sub-) tropical tidal wetland ecosystems that offer a variety of ecosystem services including provisioning, e.g., timber production (Palacios & Cantera, 2017), regulating, e.g., wave attenuation (Bao, 2011), carbon sequestration and storage (Donato *et al.*, 2011) and spiritual functions, e.g., sacred forest (Mukherjee *et al.*, 2014). Though the importance of mangrove ecosystem services is now well known, mangroves continue to be lost across the tropics (Hamilton & Casey, 2016) and are increasingly threatened by conversion to aquaculture and agriculture, infrastructure development, pollution, overharvesting and anthropogenic climate change (UNEP, 2014; Lovelock *et al.*, 2015; Richards & Friess, 2016; Islam & Hossain, 2017; Thomas *et al.*, 2017). These combined and interlinked threats to mangroves are rising, while at the same time, the dependence on mangrove goods and services will increase. At the beginning of this century,

an estimated 100 million people were living within 10 km of a mangrove, and this number was predicted to increase to 120 million by 2015 (UNEP, 2014). The majority of the mangrove-dependent communities live in the developing countries of Asia and Africa, where millions of people rely directly on mangrove ecosystem services for food, income and overall well-being (MEA, 2005; UNEP, 2014).

The increased demand for, and exploitation of, mangrove products raises the issue of the sustainability of mangroves and the need for effective management. The role of ecosystem services is often ignored in management decisions which may cause continued degradation and destruction of mangroves (Barbier, 2006). In many parts of the world, mangroves have historically been viewed negatively as muddy wastelands spreading diseases (Horowitz *et al.*, 2012; Friess, 2016). Many stakeholders are not aware of the true value of mangroves, and even when they are, evaluating goods and services provided by mangroves is a difficult exercise (Vo *et al.*, 2015). The assessment of ecosystem services involves multiple dimensions (ecological, social, cultural and economic), and many of the services are not marketable, thus cannot be quantified in strictly monetary terms (Mukherjee *et al.*, 2014). To overcome these challenges, evaluating ecosystem goods and services might help decision makers to comprehend the actual value to society and to anticipate the potential costs of mangrove loss (Clavel *et al.*, 2011; Ruckelshaus *et al.*, 2013). There is a significant need for a better understanding of the value of mangroves and their associated ecosystem services for policy and decision-making (Mukherjee *et al.*, 2014; Vo *et al.*, 2015).

One area where a greater understanding of ecosystem value and management options is needed is the Sundarbans. This area is often considered the largest single tract mangrove forest in the world, covering approximately 10000 km^2 and straddling Bangladesh and India respectively by 60 per cent and 40 per cent (FD, 2010; Hossain *et al.*, 2016). The entire Sundarbans was declared a Reserve Forest in 1869 and is often considered the first scientifically-managed mangrove ecosystem in the world. Since then, the physical boundary of the Bangladesh Sundarbans has remained mostly unchanged, but the quality and quantity of ecosystem services are at risk. Though the Sundarbans is an indispensable element for Bangladesh, the forest and its associated resources are subject to rapid degradation due to several natural and anthropogenic drivers that degrade the capacity of the forest to deliver ecosystem services that are critical for millions of people in Bangladesh (Inman, 2009; Swapan & Gavin, 2011; Hossain *et al.*, 2016).

Though different scientific studies have addressed ecological or social issues related to the Sundarbans, there are very few studies that combine the analysis of both social and natural systems to address rapid environmental changes and associated impacts on ecosystem services. In-depth studies are required to identify the trend of environmental changes and status of ecosystem services of the Sundarbans regarding which factors are most responsible for triggering the changes and which factors interact to further deteriorate the situation. In this study, we take a mixed-methods approach, with primary data on local community perceptions of mangrove ecosystem services and threats supplemented by various secondary data sources, including forest product inventories and meteorological data.

Methods

Study site description

The Sundarbans mangrove forest is composed of three wildlife sanctuaries (Sundarbans West, East and South) which are classified as International Union for the Conservation of Nature (IUCN) category IV protected areas. It is situated in the ancient delta of the Ganges River in south-west coastal Bangladesh and stretches across Satkhira, Khulna and

Bagerhat districts. The Sundarbans was declared a Ramsar site in 1992 and UNESCO listed the three wildlife sanctuaries as a World Heritage Site in 1997 (Uddin *et al*., 2013). The Sundarbans mangrove serves as a breeding and nursery ground for a variety of fish and shellfish, including many commercial species (MEA, 2005; Food and Agriculture Organization, 2010; Supporting Information 1). The Bangladesh Sundarbans harbour a variety of terrestrial and aquatic species which includes large and small trees, shrubs, herbs, birds, fishes, reptiles, amphibians, cetaceans and 16 molluscs which altogether represent about 35 per cent of the total fauna of Bangladesh (Chaffey *et al*., 1985; FD, 2010; Table 1). The Sundarbans is also globally well known as the home of the endangered Bengal Tiger *Panthera tigris* ssp. *Tigris* (Linnaeus, 1758) (440 in number) (FD, 2010). About 90 per cent of commercial fishes and 35 per cent of all fish species from the Bay of Bengal utilize the Sundarbans as the nursery ground for their early life stages. Rural communities living within 20 km (known as the impact zone) of the forest boundary are largely dependent on mangrove forest resources for the maintenance of their livelihood (Rouf & Jensen, 2001; Islam & Chuenpagdee, 2013). Additionally, approximately 18 per cent of households of the southwestern coastal zone are dependent on resources of the Sundarbans, for example, fish, shrimp, molluscs, crabs and medicinal plants (Rahman & Rahman, 2013).

Field interviews

Fieldwork was conducted for six months (July to December 2015) within three fishing communities of the Sundarbans, situated in the southwestern part of Bangladesh. For primary data collection, a number of qualitative tools such as individual interviews, focus group discussions with various groups of stakeholders, key informant interviews with knowledgeable persons and oral history were employed in three fishing villages in the three districts of Khulna division that included Burigoalini in Satkhira, Kamarkhola in Khulna, and Chila in Bagerhat district (Figure 1).

Using a semi-structured questionnaire (Supporting information 2), 90 individual interviews with mangrove dependent communities (fish, crab, shrimp/bivalves, snail and oyster harvesters, and *Nypa* palm collectors) were conducted (Table 2). The 29 questions focused on the following themes: 1) socio-economic profile of the respondents; 2) extent of their perceived dependency on mangrove ecosystem services; and 3) perceptions of natural and anthropogenic environmental changes in the forest, and how this affects livelihood outcomes. In total, each interview took approximately 45 minutes to complete. In addition to the 90 individual interviews above, six focus group discussions sessions with resource users (where each group size consisted of

Table 1. Species distribution in the Bangladesh Sundarbans.

Type of species	Total Number	Source
Mangrove large tree species	10	Chaffey *et al*. (1985)
Mangrove small tree species	20	
Shrubs	25	
Herbs (including 2 fern species)	10	
Birds (including 84 migratory)	315	FD (2010)
Terrestrial fauna	289	
Aquatic fauna	678	
Cetaceans	11	
Amphibians	8	
Molluscs	16	
Fishes	210	

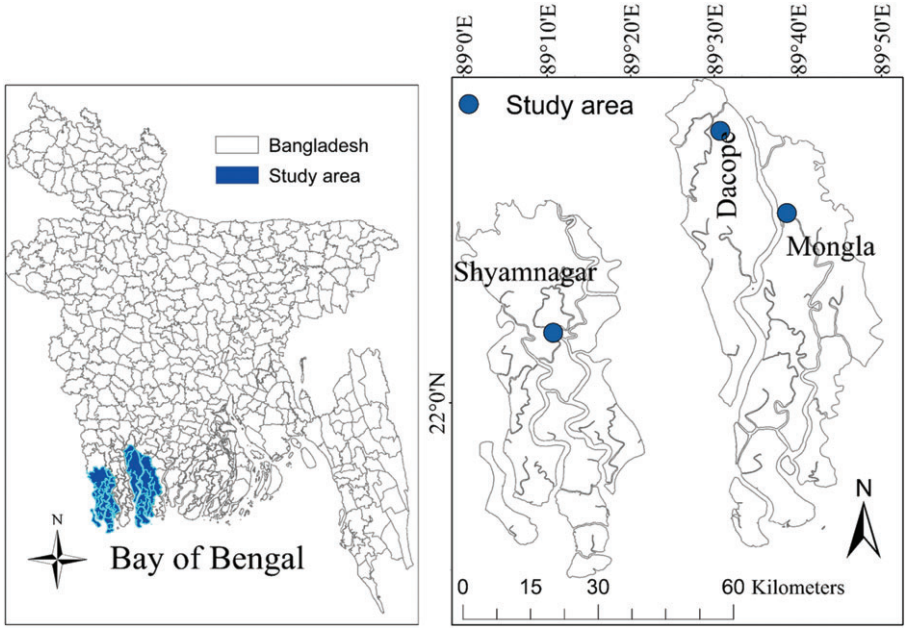

Figure 1. *Location of the study areas in the Sundarbans namely Burigoalini (Shyamnagar, Satkhira), Kamarkhola (Dacope, Khulna) and Chila (Mongla, Bagerhat) in south-west Bangladesh.*

8–10 persons) were conducted. Finally, 15 key informant interviews or cross-check interviews with local entrepreneurs, NGO personnel working on mangrove issues and forest officials were conducted to collect and verify or necessary information (Table 2). For analysis of qualitative data, content analysis method was employed; themes were identified and classified into manageable categories of different variables, such as provisioning services, drivers of changes of ecosystem services, etc.

Secondary data collection on ecosystem services and threats

Several datasets were collected to validate environmental changes and threats that were highlighted in the interviews. Meteorological data were collected from the Meteorological Department of the Bangladesh Government. Production data on forest products and the number of tourists visiting the Sundarbans were collected from the office of the Chief Conservator of Forest, Department of Forest of the Bangladesh Government.

Results and discussion

Status of ecosystem services from the Sundarbans mangrove forest

Interviews and secondary data suggested that three types of ecosystem services are primarily derived from the Bangladesh Sundarbans. These include provisioning services (benefits that people obtain directly, e.g., timber and food products such as fish), cultural services (non-material benefits, e.g., mangrove tourism), and regulatory services (benefits obtained from regulation of ecosystem processes, e.g., carbon sequestration and protection from cyclones). Of these services, provisioning and cultural services directly affecting the everyday lives of the Sundarbans-dependent communities were

Table 2. Source of primary information, methods, sample size, categories, and characteristics of the surveyed communities.

District (Sub-district)	Village or community	Location/ Geographical coordinates	Distance from the physical boundary of the Sundarbans (m)	Tools/ methods and sample size (number)		
				Individual interviews	Focus group discussion	Key informant interview
Satkhira (Shyamnagar)	Burigoalini	22°15′18.5"N 89°13′41.9"E	200-400	30	2	5
Khulna (Dacope)	Kamarkhola	22°29′18.1"N 89°30′12.9"E	50-200	30	2	5
Bagerhat (Mongla)	Chila	22°22′57.5"N 89°38′30.5"E	250-500	30	2	5
Total	3 villages			90	6	15

the most discussed and were the easiest for local communities in which to perceive changes. Hence the present study focused on these two services.

Provisioning services (fish, shrimp, honey, wax, wood, medicinal plants, fodder etc.)
The Sundarbans mangrove fishery resources consist of fishes, crustaceans (e.g., prawn, shrimp, crabs, lobsters) and molluscs (e.g., bivalves, clams, mussels, oysters) (Supporting Information Table 4). One respondent fisher said

> '…from the forest no one returns empty handed, if you have no other income earning option, at least you can make a living from the mangrove forest. This is the case for many households living adjacent to the Sundarbans'.

The communities harvest white fish, crabs, post larvae of shrimp and prawns. Harvested white fish are usually sold as fresh, although some high-valued fish as well as trash fish and shrimp are sold dried. Crabs are mainly exported live to foreign markets, particularly in Southeast Asia. It is estimated that 75 per cent of the exported shrimp are cultivated in Khulna, Bagerhat and Satkhira districts where the Sundarbans are situated (Islam *et al*., 2015). Post larvae of shrimp collected from the rivers of the Sundarbans enjoy higher preference than hatchery-produced post larvae, since the former has a higher survival rate and is considered superior quality. More than 0.7 million people are employed either directly or indirectly in shrimp farming and other related occupations (Banks, 2003; Figure 2). A significant proportion of these jobs will be dependent on the presence of the mangrove forest, due to the strong evidence suggesting that mangroves enhance fisheries yields in many situations, as they act as a fish nursery area (Mumby *et al*., 2004; Carrasquilla-Henao & Juanes, 2017).

The Bangladesh Sundarbans are also utilized for non-timber forest products. The Giant Honey Bee (*Apis dorsata* Fabricius, 1793) is a resident species in the Sundarbans. According to one key informant forest official, the Sundarbans produces about 50 per cent of the total volume of honey produced in Bangladesh. In addition, a variety of non-wood plant materials are collected by local communities for a variety of purposes such as thatching materials, fodder for domestic animals, medicinal purposes, foods

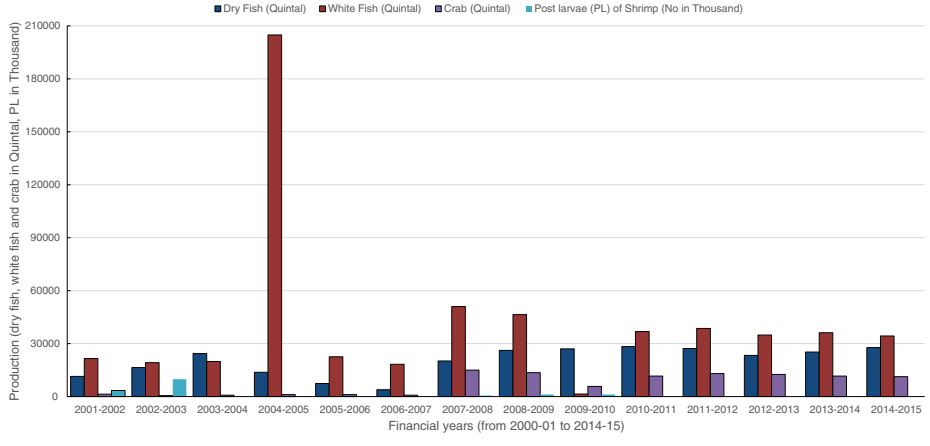

Figure 2. *Production of fish, shrimp and crabs from the Sundarbans, Bangladesh over the past 15 years (from 2000–01 to 2014–15).*
Source: **Data from FD, 2016.**

Table 3. Ecosystem services (ES) from the Sundarbans mangrove forest (based on respondents' interviews).

Ecosystem services	Brief description of ES categories (categories according to the Common International Classification of Ecosystem Services (CICES) v4.3 (http://cices.eu/))
	CICES categories of ES: Provisioning services
Foods and drinks	• Fish and shellfishes as food. • Fruits of Keora *(Sonneratia apetala)* and Ora (*Sonneratia caseolaris L*) used as food and culinary additions, young shoot of *Phoenix paludosa* freshly eaten as raw food, juice and fruits from *Nypa fruticans.* • Baoli lata (*Sarcolobus globosus* Wall.) are edible and consumed as raw or cooked food.
Fisheries	• The Sundarbans provides shelter to 678 aquatic species (of which 210 species are fish, 59 reptiles, 8 amphibians, 11 cetaceans and 16 molluscs).
Honey and wax	• About 50 % of total honey produced in Bangladesh.
Fodder	• Leaves of *Avicennia alba* Blume, *Avicennia marina* (Forssk.) Vierh, *Avicennia officinalis* L., Keora, *Sonneratia apetala* Buch. Ham., *Sonneratia caseolaris* (L.) Engl. *Excoecaria agallocha* L., *Hibiscus tiliaceus* L., Gang *Clerodendrum inerme* (L.) Gaertn., *Eriochloa procera* (Retz.) C.E.Hubb. and *Cyperus javanicus* Houtt., 1782 are used as fodder.
Thatching materials	• *Nypa fruticans* Wurmb, *Phoenix paludosa* Roxb., *Cyperus javanicus* Houtt., 1782, *Typha elephantine* Roxb., *Imperata cylindrica* L. P. Beauv., *Phragmites karka* (Retz.) Trin. ex Steud. *Acrostichum aureum* L. are mainly used as thatching materials for light construction, boat roofing, weaving and walls of cottage.
Medicine	• Leaves of *Phoenix paludosa* are used for the treatment of ringworm and sore throat. • Young shoots of Tiger fern (*Acrostichum aureum* L.) for fever, constipation, aches, pains, malnutrition, cooling the body, believes to helpful to diabetic patents. • Young leaves *Acanthus ilicifolius* L. for treatment of cough, asthma, indigestion, rheumatism and neuralgia; and *Sarcolobus globosus* Wall. as antiseptic, to stop bleeding and curing of skin injury. • Leaves of *Clerodendrum inerme* (L.) Gaertn to cure diarrhoea of cattle /goats (livestock). • Bark of *Xylocarpus moluccensis* (Lam.) M. Roem. to treat dysentery (*Amasoya*), gastric pain and diabetes.
Fire wood/ fuel wood	• Dead stems/wood/ Branches /trimmed parts of various mangrove species like *Bruguiera gymnorhiza* (L.) Lam., *Ceriops decandra* (Griff.) Ding Hou, *Bruguiera sexangula* (Lour.) Poir., *Heritiera fomes* Buch. Ham., *Cynometra ramiflora* L., *Aglaia cucullata* (Roxb.) Pellegr., *Phoenix paludosa* Roxb., *Lumnitzera racemosa* Willd., *Sonneratia apetala* Buch. Ham, *Avicennia alba* Blume, *Avicennia marina* (Forssk.) Vierh., *Avicennia officinalis* L., *Excoecaria agallocha* L. etc. are abundantly used as firewood.

Table 3. Continued

Ecosystem services	Brief description of ES categories (categories according to the Common International Classification of Ecosystem Services (CICES) v4.3 (http://cices.eu/))
Timber (construction and furniture wood)	• Mature stems of various high-priced taxa for instance *Heritiera fomes* Buch. Ham., *Xylocarpus moluccensis* (Lam.) M. Roem, *Xylocarpus granatum* K.D. Koenig, *Bruguiera gymnorhiza* (L.) Lam., *Bruguiera sexangula* (Lour.) Poir., *Ceriops decandra* (Griff.) Ding Hou, *Aglaia cucullata* (Roxb.) Pellegr., *Avicennia alba* Blume, *Avicennia marina* (Forssk.) Vierh., Gang jhapa, *Clerodendrum inerme* (L.) Gaertn., *Rhizophora apiculata* Blume, *Rhizophora mucronata* Lamk., *Cynometra ramiflora* L., *Excoecaria agallocha* L., *Lumnitzera racemosa* Willd. are used in construction (pole, house, hunts, boat construction, fences etc.) and furniture.
	CICES categories of ES: Cultural services
Ecotourism and recreation	• From 2001-2002 to 2014-2015, 1 439 806 tourists visited the Sundarbans (of which 1 409 410 are local and 30 386 are foreign). Total revenue collected by forest department was USD 1 087 599.
Aesthetic value and religious importance	• The Sundarbans is a centre of belief and rituals for local Hindu communities. • An annual religious festival called 'Rash Mela' has also been held in the Sundarbans (Dublar Char) during the full moon in mid-November (Purnima Tithi of Bengali month Katric) for approximately over 200 years, and which is attended by thousands Hindu devotees. • The 'Shaker Tek Kali Mondir' or Temple of Shaker Bari was built approximately 650 years ago by a Hindu landlord. Now it is a touristic place for its historical and archaeological importance. • The fable of 'Gazi Kalu Campabati: Gazi' was brought to the Sundarbans approximately over 500 years ago. The famous story is that every tiger and ferocious animal of the Sundarbans obeys the commands of Gazi.
Other cultural services	• The face of the Bengal Tiger, *Panthera tigris* ssp. *tigris* (Linnaeus, 1758) is used as the emblem of Bangladesh National Cricket Team. Biodiversity of the Sundarbans appeared on several postage stamps of the Bangladesh government. Biodiversity of the Sundarbans also appeared in different handicrafts of the region. • Kapalkundala, a Bengali romance novel (the first ever novel in Bengali literature based in the Sundarbans forest, published in 1866) written by Bankim Chandra Chattopadhyay. • Various types of indigenous or traditional occupations exist in the Sundarbans, for instance bawalis (timber, firewood & thatch cutter), jalley/chunery (fish, crab, shrimp/bivalves, snail & oyster harvester), moualis (honey extractor/collector), and ghasal (harvester of grasses). A number of indigenous occupations no longer in existence (extinct in nature, but are recorded in museums) from the Sundarbans, among which bagh-hungor-kumir shikari (tiger-shark and crocodile hunter), horin-banor-shikari/mrigaya-shikari/gasal-shikari (hunter of monkey and deer), saap-terkel-guishaap-shikari/shapuria (snake and lizard

Table 3. Continued

Ecosystem services	Brief description of ES categories (categories according to the Common International Classification of Ecosystem Services (CICES) v4.3 (http://cices.eu/))
	hunter), mongoli (making business of earthen made utensils used in salt production industry), kagoji (people engaged to produce hand-made paper from gewa wood, *Excoecaria agallocha* L.), dhali (experts in fighting with traditionally-made weapons (dhal-sorki) to defend against criminal gangs of mog (a tribe community) and purtugiz-olandaz, sana (community leader employed for maintenance (caretaker) of the dike or embankment by the government).

and culinary to consume and drinks (Table 3). A number of respondents also highlighted the important role of the Sundarbans as sources of medicinal plants that serve as medicine for communities living in the remotely located region.

The extraction of non-timber forest products from mangroves is relatively understudied, with only one review of traditional and medicinal uses of mangrove plants (Bandaranayake, 1998). However, the interview data gained in this study echoes that of other limited studies conducted in South Asia that have shown the importance of honey for local livelihoods. Getzner and Islam (2013) showed that 9 per cent of households in their study site in the Bangladesh Sundarbans were actively engaged in honey production. Honey production shows a particularly interesting trend; while this study and others have shown that is now an important non-timber forest product, this has only been the case in the last 20 years, with the honey production being very low in the Sundarbans in the 1970s-80s, at <100 tonnes per year (Hossain *et al.*, 2016).

Commercial harvesting of timber such as Sundri (*Heritiera fomes* Buch.Ham.), Goran (*Ceriops decandra* (Griff.) Ding Hou) and Bean (*Avicennia officinalis* L.), was the primary economic product of the Sundarbans until the late 1980s (Figure 3). A reduction in growing stock due to over-exploitation forced the government to impose a forestry

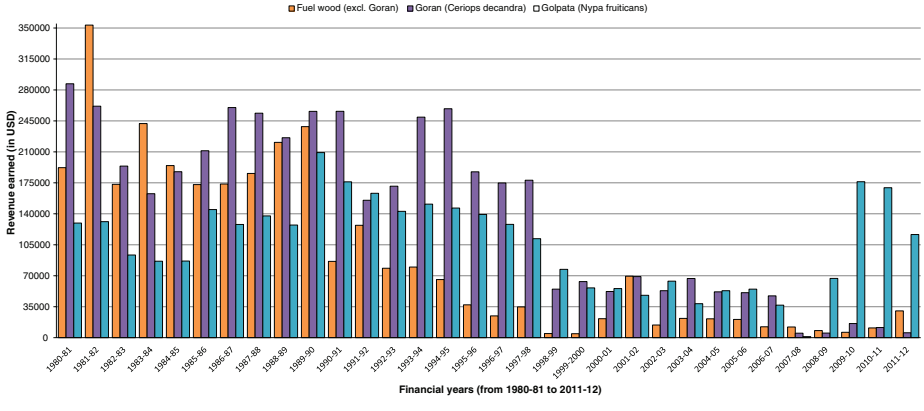

Figure 3. *Production scenarios of fuel wood, Goran (Ceriops decandra) and Nypa Palm (Nypa fruiticans) from the Sundarbans, Bangladesh over past 30 years (from 1980–81 to 2010–11).*
Source: Data from FD, 2016.

moratorium in 1989 to restrict large-scale timber harvesting, eventually leading to the banning of all timber harvesting – including fuel wood collection – by 1995. However, many mangrove taxa are still used by the community for a variety of purposes such as firewood, construction (pole, house, hunts, boat construction, fences, etc.), furniture (chairs, tables, shelves, fishing equipment, etc.) and wood (Tables 3 and 4).

Cultural services

The cultural and spiritual value of mangroves remains very difficult to convert into monetary values, but the Sundarbans is a culturally important ecosystem for dependent communities and beyond. A part of the forest is declared as a UNESCO World Heritage Site, thus making it globally significant. The scenic beauty, river cruises, wildlife observation and jungle trail activities of the Sundarbans attracts thousands of tourists each year. From 2001-2002 to 2014-2015, 1 439 806 tourists visited the Sundarbans (of which 1 409 410 are local and 30 386 are foreign). Total revenue collected by forest department was USD 1 087 599. Several key informants indicated that there is a high potential to increase economic benefit from tourism in the Sundarbans. Tourism activities also create employment opportunities for local communities and

Table 4. Forest products and revenue collected over the course of years, 1999-2000 and 2015-2016 from the Bangladesh Sundarbans. (Source: FD, 2016).

CICES categories of ecosystem services	Service producers (Unit)	(1999-2000)		(2015–2016)	
		Amount	Revenue (USD)	Amount	Revenue (USD)
Provisioning	*Ceriops decandra* Numbers (No.) &/ or metric ton (MT)	21 078.2 (MT)	38 788.72	1 250 (No.) & 27 071 (MT)	394.23
	Thatching material *Nypa fruticans* (MT)	33 036.24	34 676.78	2 509.9408	37 153.88
	Phoenix paludosa (No.) &/or (MT)	1 040.8 (MT)	646.65	80 (No.) & 276.76 (MT)	397.13
	Thatching material (Grasses) e.g. Malia grass (*Cyperus javanicus*) (MT)	4 055.48[1]	788.95[1]	14.058	13.51
	Honey (MT)	222.08	7 118.59	76.96	19 048.77
	Wax (MT)	55.56	2 671.63	19.482	6 296.73
	Fuelwood (ft^3)	69 370[1]	47 523[1]	14 455[3]	10 190[3]
	Excoecaria agallocha (ft^3)	84630[1]	33186.59[1]	6026[3]	3893.96[3]
	Bivalves (Clams, mussels & oysters) and molluscs(MT)	2 435.92	781.91	9.44[2]	2 298.21[2]
	Dry fish (MT)	1 226[1]	18 997.60[1]	1 054.39	174 617.93
	Fishes/white fishes (MT)	4 205.28	84 001.13	1 045.41	124 209.73
	Crabs (MT)	145.68[1]	2 148.49[1]	495.16	57 898.51
	Shrimp fry (post larvae of Bagda, *P. monodon*) (No.)	3 436 940[1]	4 227.62[1]	52 400[3]	33.59[3]
Cultural	Tourists (No.)	59 169[1]	14 587.68[1]	128 175	171 226.41

[123] During year of [1](2001-2002); [2](2013-2014); [3](2014-2015). Collection of *Excoecaria agallocha* (cubic feet; ft^3), fuelwood (ft^3) and shrimp fry (post larvae of Bagda, *Peneaus monodon*) are legally prohibited and the revenues were generated from the auction of seized resources from illegal harvester. 1 USD is equivalent to 78 BDT.

there are still untapped opportunities for jobs through the stronger promotion of eco-tourism in the Sundarbans region.

Eco-tourism is a key neoliberal conservation intervention in many mangrove sites across the tropics, and can encourage conservation by encouraging responsible travel that conserves environmental features while promoting sustainable livelihoods (The International Ecotourism Society, 2015) and empowering local communities. However, due to poor focus on this topic by academics, we do not have a strong sense of the overall magnitude or financial value of mangrove eco-tourism at broad scales. What we do know from selected case studies is that strong tensions exist between environmental protection and economic development in mangrove eco-tourism activities. For example, Thompson *et al*. (2017) showed that rapidly increasing eco-tourism activities in mangroves in Langkawi, Malaysia was causing erosion and other negative environmental impacts. This was due to economic competition, governance issues and a mixed understanding of eco-tourism. Thus, decision-makers wishing to utilize cultural ecosystem services in the Bangladesh Sundarbans must do so in a sustainable manner that learns from the experiences of previous eco-tourism activities.

The ecological environment of the Sundarbans also provides important cultural services by shaping the religious belief of the forest-goers. Before entering the Sundarbans, forest-dependent Hindu communities follow various rituals and offer worship to the goddess, Bon Bibi (The Forest Lady). Idols of the forest goddess Bon Bibi are placed in different parts of the forest for worship. Forest-goers believe that Bon Bibi will protect all those who seek protection from her from all evils (Table 3). These are the least researched of all mangrove cultural services and are particularly hard to quantify and manage (Quieroz *et al*., 2017), though they are potentially some of the most important for local communities who interact with the mangrove ecosystem daily.

Recent changes in the Bangladesh Sundarbans and implications for ecosystem services

Changes in climatic variables in the Sundarbans

In this study**,** time series data on temperature, rainfall and humidity in three stations of the Sundarbans, Satkhira, Khulna and Mogla (Bagerhat), were analyzed over a period of 24 years (1991-2014). Temperatures increased by 0.07°C and 0.27°C per decade respectively in Satkhira and Khulna, which is higher than the average rate of global temperature increase of 0.06°C per decade (Mitra *et al*., 2009). Temperature at the Mongla station has decreased by 0.06°C per decade from 1991 to 2014.

Rainfall plays a significant role on mangroves due to its impact on salinity, which closely affects the distribution pattern of mangrove species. According to the data from Bangladesh Meteorological Department (2015), the highest rainfall in the Sundarbans was observed in June between 1991 to 2014. The amount of maximum rainfall was relatively low in Satkhira, when compared with Khulna and Bagerhat (Mongla). In this study, it was observed that rainfall patterns have been altering over the last 35 years, but this slightly varies from the finding of Rimi *et al*. (2009) which showed that, in Satkhira, rainfall had been decreasing in pre-monsoon and winter and increasing in monsoon and post-monsoon. In the present analysis, rainfall had an increasing trend from the mid pre-monsoon, monsoon and first part of the post-monsoon (April to October) while a decreasing trend was found for the last part of the post-monsoon, winter and first part of the pre-monsoon (November to March). These are statistically significant ($p < 0.001$).

Humidity is an important weather parameter that could influence the daily activities of people and other biota (Pitchaikani *et al.,* 2017). According to the data from Bangladesh Meteorological Department (2015), the humidity pattern of the Sundarbans is almost uniform in Khulna and Bagerhat (Mongla) regions and slightly reduced in Satkhira. Time series data of humidity from 1991 to 2014 suggested average humidity of the Sundarbans is 80 per cent. Humidity becomes low during summer (pre-monsoon) when high temperature and comparatively low rain was observed.

Ghosh *et al*. (2017) also found that over the period 1977–2015, average maximum and minimum temperature have been increasing in the Sundarbans, while annual total rainfall has been decreasing which has considerable impacts on mangrove canopy coverage. Increasing temperature trends could affect mangroves by changing phenological patterns and species composition (Gilman *et al*., 2008; Ghosh *et al*., 2017). Ghosh *et al*. (2017) found that the dominant mangrove tree species Sundri (*H. fomes*) has decreased considerably with the increase of average maximum temperature. Fish physiology, growth and reproduction are directly influenced by temperature (Chowdhury *et al*., 2010) and the breeding performance of many commercial mangrove fisheries species such as finfish (especially *Mugil* spp.), shrimp (Family: Penaeidae) and mud crab (*Scylla serrata*) are closely related to rainfall. For example, Staunton-Smith *et al*. (2004) found positive correlations among spawning seasons and rainfall for sea bass (*Lates calcarifer*). Thus, rainfall anomalies could affect the breeding performance of important commercial species of the Sundarbans. Lesser rainfall increases salinity, which is responsible for decreasing the growth, productivity and survival of mangrove seedlings (Gilman *et al*., 2008).

Community perceptions of other anthropogenic factor of changes

The communities that are dependent upon the Sundarbans reported negative trends of ecosystem services arising from the mangroves. They perceived a number of causes as responsible for this deterioration.

Unsustainable exploitation practices

Interviews with the respondents revealed that fishers use a number of harmful fishing practices such as the catching of buried and undersized crabs, harvest of white fish by draining out of mangrove creeks, and using chemicals that poison all species indiscriminately. In particular, the collection of shrimp and prawn using fine mesh gear is blamed for killing other non-target species. One key informant forest official elaborated

> More than 80 per cent of the households (mainly women and children) living on the forest edge are involved shrimp and prawn post larvae (PL) collection. The majority of them are poor, do not have any other occupation. Also, this fishing activity requires little capital, so they took it as an income earning option. However, it is widely recognized that this fishing activity kills hundreds of other species. This practice is illegal but usually not strictly applied as the participants are very poor.

Destructive fishing practices degrade overall habitat quality and catching high proportions of juvenile species could lead to 'recruitment overfishing' that would ultimately compromise the provisioning ecosystem service supply, as fish stocks are unable to reproduce sufficiently. This is particularly an issue when fishing close to mangroves, as mangroves are now well known to be important nursery areas for juvenile fish (Carrasquilla-Henao & Juanes, 2017; Whitfield, 2017) due to the dense above-

ground root network of mangrove vegetation providing shelter from larger predators. Thus, fishing close to the mangrove fringe or inside the forest is likely to target juvenile fish. Among commercially-important fish species in the Sundarbans, *Tenualosa ilisha* (Hamilton, 1822), *Lates calcarifer* (Bloch, 1790), *Pangasius pangasius* (Hamilton, 1822), *Plotosus canius* (Hamilton, 1822) and *Scylla serrata* (Forsskål, 1775), are considered over-exploited (Rouf & Jensen, 2001). One crab trader from Buri Goalini stated 'nowadays we are finding fewer and fewer full grown crabs from collectors. It seems there is over-fishing of crabs in the forest, thus crabs do not get the opportunity to reach sexual maturity age'.

Forest coverage with high canopy closures (≥60 per cent) has reduced significantly from 78 per cent (in 1959) to only 24 per cent (in 2010), mainly due to large-scale felling and death attributable to top dying diseases (IUCN, 2014). Illegal collection of other forest products like timber, fuel wood and thatching materials is also reported by the respondents. The respondents reported a number of factors that lead to unsustainable exploitation practices which include poverty, long term debt bondage and population growth. For example, the total number of fisherman in and around the Sundarbans has doubled between 2001 and 2010 (IUCN, 2014).

Shrimp farming and land use change

About 75 per cent of shrimp exported from Bangladesh are cultivated in Khulna, Bagerhat and Satkhira districts, where the Sundarbans are situated (Islam *et al*., 2015). The rapid expansion of shrimp farming to supply the increasing demand for shellfish has led to the destruction of around 9 500 ha of mangrove forest in the area (Azad *et al*., 2007). Some key informants and respondents indicated that shrimp farming had converted agricultural land, resulting in many people losing their agricultural jobs and ultimately becoming dependent on the forest ecosystem services. 'Before shrimp culture was introduced in the vicinity of the Sundarbans, many people were employed in agriculture, but shrimp culture in agricultural land made may people jobless. These people ultimately took forest-based occupations. Thus, exploitation of forest resources increased', said one NGO official. To supply shrimp and prawn fry to shrimp farming, many households have become involved in the destructive practices of shrimp and prawn fry collection. Another key informant revealed that salinity intrusion, caused by a number of factors including shrimp farming, is often responsible for reducing land fertility and agricultural production, e.g., crops, rice, poultry, livestock and terrestrial forest cover that ultimately exert more pressure on the resources of the Sundarbans.

The patterns observed in the study area are indicative of trends in the Sundarbans as a whole, with the Sundarbans losing 8.3 per cent of its land (about 50 000 ha) on its northern front due to deforestation for shrimp culture from 2000 to 2010 (Rahman & Rahman, 2013). Such direct mangrove losses due to land cover conversion to aquaculture mirror similar changes across the tropics (Hamilton, 2013; Thomas *et al*., 2017), particularly in Southeast Asia (Richards & Friess, 2016). While direct impacts of aquaculture due to conversion are relatively straightforward to quantify, aquaculture also has indirect impacts on neighbouring mangroves. These impacts include the deterioration of water quality (through hydrological and chemical effects) and increased loading of nutrients and suspended sediments into surrounding waters (Dierberg & Kiattisimkul, 1996). While mangroves are known to assimilate and filter shrimp pond effluent under certain conditions (Robertson & Phillips, 1995), high nutrient loads are likely to have adverse impacts on neighbouring mangrove macrobenthos and decrease the density of mangrove species in the forest (Swapan & Gavin, 2011; Hossain *et al*., 2013).

Coastal development activities

Respondents considered local coastal development activities a key threat to the Sundarbans mangroves, especially developments such as the Mongla seaport, the second largest sea port in Bangladesh. As part of the port activity, different cargo and water vessels use river channels inside the eastern part of the Sundarbans. Frequent movement of the vessels pollutes the water due to leaching of oil and accidental oil spills. For example, on 9 December 2014, the Cargo OT Southern Star, which was carrying 75 000 gallons (357 664 L) of heavy fuel oil (black furnace oil), collided with another vessel and partly sank in the Shela river (United Nations & Government of Bangladesh, 2014; Aziz & Paul, 2015). Respondents reported that they observed oil was deposited on the soil, leaves, roots, pneumatophores, stems and floating fruits. Many fishers had to stop their fishing operations for several weeks, with substantial impacts on livelihoods. Oil spills have a multitude of impacts on the mangrove ecosystem, as reviewed by Duke (2016). The most immediate and lethal issue is the oil that sticks to macro and microbenthic fauna and tree pneumatophores, reducing oxygen exchange and causing suffocation. However, oil also has longer-term, sub-lethal effects on components of the mangrove ecosystem due to toxicity and build-up in mangrove sediments. Clean-up operations may also impact mangroves, as oil dispersants may also be toxic. Duke (2016) describes recovery pathways for oil-impacted mangroves, depending on the magnitude of the spill and the time it takes for oil to break down into less toxic residual products under sunlight.

Reduction of freshwater flow

The Ganges River, through its tributaries, supplies freshwater to the Sundarbans, and thus plays a crucial role in maintaining the health of the mangrove ecosystem. Withdrawal of water from the Ganges River by the Farraka barrage in India has caused drastic reduction of freshwater flow to the Sundarbans, adversely affecting growth and vitality of mangrove species (IUCN, 2014). This is because mangroves are not obligate halophytes, so establishment and growth are reduced in hypersaline conditions (Lovelock & Feller, 2003; Krauss *et al.*, 2008). Findings of the focus group discussion indicated that three or four decades ago, freshwater remained in the river system of the Sundarbans (with very low salinities or even less than 0.5 ppt) for almost eight months (April to November) of the year due to excess volumes of freshwater from upstream. This freshwater pulse now remains for only 2.5-4 months during the rainy season (mid-August to October/November) due to the reduced freshwater flow from upstream.

Respondents also mentioned a number of negative consequences that have arisen from the construction of various dikes and polders, such as the enhanced deposition of silts in the river bed causing siltation that results in the shifting of fish habitats, migration routes, breeding areas and catch compositions, and creating problems for navigation in water ways. The respondents also identified siltation in rivers and rivulets as drastically decreasing the amount of fishable areas. Due to siltation, resources collectors can more easily travel over channels, as many are now dried up during dry season, allowing them to permeate the forest further and more easily. Fishers can now more easily drain channels to catch even the smaller fish. One key informant forest official from the Chandpai area said

> 'Due to high silt deposition in the forest, some channels around the Sundarbans become almost dried up during winter and low tide, which facilitates illegal and over-exploitation as

> people can easily pass over the channel on foot and collect wood, fuel wood and travel back safely without being apprehended by forest officials. This situation also increased the tendency to use poison for fishing in the mangrove creeks with shallower water'.

Due to high salinity, soil fertility has also decreased, requiring that farmers apply more agricultural fertilizers that in turn further degrade the mangrove environment through pollution, said one key informant. Reduction of freshwater flows disrupts the hydrological cycle and cause increased rainfall during the pre-monsoon, wet monsoon and post-monsoon in upper catchment areas, leading to more floods and waterlogging and causing more riverbank and coastal erosion (Rahman & Rahman, 2013). Increased salinity and sedimentation have also caused shifts in fish habitat by destroying or reducing the quality of the waterways. The dominant species of Sundri (*H. fomes*) and Goran (*C. decandra*) are affected by top-dying diseases (Islam & Gnauck, 2008). The reduction of water flows causes ecological changes in the forest and trailing active ecosystems function (Basar, 2009; Aziz & Paul, 2015). The prevailing air during dry seasons (summer and winter) carries more salt, feeling more humid and warm. The growth of fungus facilities in humid conditions, which may have some link with the top-dying disease, is highly related to the level of salinity, and will spread rapidly and affect *H. fomes* in the Sundarbans. Due to high salinities, the tree densities in the buffer territory or areas adjacent to the boundary are reduced, as many terrestrial plants are unable to survive (Ishtiaque *et al*., 2016).

Cyclones and other extreme events

The Sundarbans region has been struck by 174 natural disasters between 1965 and 2010 (Rahman *et al*., 2011). At least 70 major cyclones reached the coastal region of Bangladesh over the past two centuries and the Sundarbans mangroves have acted as a physical barrier, therefore reducing asset loss and damage. However, mangroves forests also suffer damage during coastal protection, with Cyclone Sidr in 2007 causing severe damage to 36 per cent of the mangrove area (CEGIS, 2007). When planting and rehabilitating mangroves for coastal protection, it is important to encourage the growth of species that can withstand damage or resprout after disturbance (Primavera *et al*., 2016; Villamayor *et al*., 2017).

Recurrent extreme events such as cyclone and tidal surges do a lot of harm to the communities of the Sundarbans by damaging houses, sanitation systems, fishing utensils and communication systems, pushing residents into debt cycle with money lenders (CEGIS, 2007). A study shows that in the aftermath of Cyclone Aila, almost 80 per cent of regional (local) workers lost their jobs, among which 40 per cent are bound to change their profession (Mallick *et al*., 2011). Almost all of the respondents in this study felt environmental shifts in the region after Cyclone Aila in 2009. One key informant from a local NGO in Burigualini stated

> 'Cyclone Aila caused complete changes in the livelihoods and environment in the region. The whole area became salty, nowadays with a drought-like situation created, forest resources were also destroyed but people became more dependent on the forest as the opportunity for livelihoods from agriculture were drastically reduced.'

The respondents perceived some other impacts, such as rising tidal water of cyclones removing mangrove propagules, thus hampering regeneration. A number of fishers perceived that saltwater driven in by cyclones negatively affected the fertility of fish eggs. Another study also indicated that saltwater intrusion from the cyclone caused fish

eggs and larvae to suffer osmotic stress, resulting in high mortalities (Islam & Chuenpagdee, 2018) This forced the people living in the impact zone to turn to shrimp fry collection or fishing as their primary survival strategy, thus increasing pressure on an already decreasing mangrove fishery.

Governance issues

The management regime of the Sundarbans is hierarchical and primarily focused on earning revenue. There are some regulation and conservation measures in place (such as temporal and spatial closures, gear restrictions, a moratorium on felling trees, etc.) to increase mangrove resources in the Sundarbans. However, a number of respondents reported that violations of these regulations are rampant, as many people are involved in illegal logging, poaching of wildlife, and using banned and destructive fishing practices such as poison and fine-meshed nets, and catching undersized species. These situations are common in mangroves in many countries across the tropics, where economic resource objectives at the provincial level clash with broader national obligations for habitat conservation (Primavera, 2000; Friess *et al.*, 2016).

Almost all of the respondents reported some cases of corruption where they had paid excess fees to obtain permission for entry into the mangrove forest to collect resources. Different studies indicated that fishers needed to pay up to ten to fifteen times extra than the actual fees for fishing permit. Such rampant corruption in the Sundarbans is another reason for overexploitation. Forest officials in the Sundarbans extract around 2.3 million BDT (about USD 28 400) per year from fishers operating in the forest (Khoda, 2008). Another concern raised by the communities is subjective insecurity, such as the incident of kidnapping by criminal gangs inside the forest. Some respondents indicated that, to pay ransoms or bribes, they often undertook destructive fishing practices or illegally overstayed in the forest to earn more money.

Markets and globalization

The majority of the forest-dependent people suffer high levels of income poverty and human development poverty (Table 5). The majority of the people interviewed in this study are poor and have limited access to formal credit markets. The patron-client relationship is mostly dominant in the region and wields the most social power. The majority of resource collectors don't have access to national or global markets for their products due to their financial inability and an established market structure regulated by existing intermediaries (money lenders, commission agents, etc.), so products are sold at the district level. The majority of respondents reported that they had to take loans from forest resources traders to undertake resource extraction. In order to repay these loans, respondents preferred to maximize income through over-exploitation. Some respondents mentioned that middlemen often pushed them to resort to destructive fishing practices (e.g., using fine-meshed illegal fishing gear, poison, harvest of protected species or illegal logging) to maximize their trade. These middlemen are powerful and backed by local politicians and officials of the Forest Department, one key informant complained. Globalization of mangrove products demand is another driver. The demand for live crabs in Southeast Asia appeared to be a driver governing the unsustainable exploitation practices in the Sundarbans. Many middlemen hired waged labour and employed them in crab harvests, which are mostly unsustainable. Respondents reported that these practices included the catch of undersized and buried crabs. Some respondents perceived these practices could put substantial pressure on the mangrove ecosystem.

Tourism

Eco-tourism in the Sundarbans has become a source of revenue for the Forest Department. Local people also benefited from tourism in different ways (e.g., by providing various modes of transportation, acting as boat men or tourist guides, through their grocery business, selling food, beverages and daily commodities, or via their hotel or resort). However, insufficient eco-tourism facilities, associated with irresponsible touristic activities, often result in noise pollution, water pollution, or disturbance to natural harmony of the biotics. According to a key informant from the Forest Department,

> 'a number of tourists often don't follow the guidelines of responsible tourism/good practice, often move inside the forest [frequent tourists walking through the forest may kill propagules, seedlings and saplings and cause breakdown of pneumatophores], climbing on trees, taking photographs, excessive sound and light on board at night time often disturb the homeostasis/tranquillity of wildlife, e.g., monkey, deer, bat, birds, snake, crocodile, etc.'

Cleaning certain areas of forest to create tourist facilities, such as corridors, boardwalks, watchtowers, cottages and other structures, also disturbs nature to some extent. A fisherman from Chila reported that, in addition to issues with the navigation of large tourist boats (cf. the death of mammals, dolphins, due to collision with commercial ships, cargo boats, and other mechanized boats), visitors also often enter small or narrow and shallow channels in small boats. These may disturb the migration or movement of the fishes, increasing turbidity and harming (often killing) fish by clogging their gills with sediment. Some harmful activities by tourists were noticed during the present study, included dumping of trash that could cause environmental degradation in the forest. Adverse environmental impacts are common in mangrove ecotourism activities. For example, the mangroves in the Kilim Geopark in Malaysia have suffered loss due to

Table 5. Socio-economic profile of the respondents in study areas.

Variable	Description	Mean (±SD)	Frequency (%)
Household composition	Number of family members	6 (1.8)	
	Number of earning members	1 (0.47)	
Education	Illiterate		51
	Primary School (class 1 to 5)		31
	Secondary School (class 6 to 10)		18
Dependency ratio	Dependent rate on earning members	4 (1.64)	
Income	Respondent's net yearly income (BDT)	69 400 (18 140)	-
Sanitation	1 → if the respondent belongs to a social organization/group 2 → otherwise	1.2 (0.36)	81
Credit from middleman (dadon)	1 → if the respondent has loans 2 → otherwise	1.55 (0.53)	56
Government scheme	1 → if the respondent receives government scheme 2 → otherwise	1.45 (0.48)	44
Food crisis	1 → if the respondent suffers from food crisis 2 → otherwise	1.27 (0.45)	74
Damage and loss from extreme events	1 → if the respondent lost their assets 2 → otherwise	1.12 (0.34)	86

infrastructure development and shoreline erosion due to increased boat speeds to ferry tourists between areas (Shahbudin *et al.*, 2012). Tourism operators may also cause environmental degradation due to negative practices to try and attract wildlife, or by not following boat speed limits (Thompson *et al.*, 2017).

Conclusions

Human overuse of the Sundarbans mangrove forest has created numerous threats and habitat deterioration could impact the provision of ecosystem services to local communities. Local resource users in coastal Bangladesh exploit a number of ecosystem services, particularly provisioning services (those linked to food and shelter, including employment and income opportunities) and cultural services such as spiritual strength and aesthetic values. Despite their importance, human-induced factors coupled with other environmental changes have created enormous pressure on the viability and sustainability of the Sundarbans mangrove system.

Coastal management and governance in the Sundarbans faces major challenges in dealing with multiple threats and stressors, which are both natural and anthropogenic in origin. Though the Sundarbans has been intensively managed since at least 1869, interestingly, the hierarchical governance system of the forest has persisted with little involvement of local people in management decisions. Due to a lack of well-defined resource ownership and rights and a top-down management approach, forest-dependent people have not been able to participate in activities undertaken for conservation and sustainable use of the Sundarbans mangrove resources. In the last few decades in particular, the Sundarbans has been under intense pressure from resource exploitation and the existing governance structure has, in some instances, proven ineffective in addressing the issue of sustainability. This calls for an immediate need for transformation in governance structure, one that will focus on restoring ecological diversity and fostering economic diversity, in line with the rapidly changing local socio-ecological context. For each commercially exploitable species, optimum harvest limits (e.g., maximum economic yield and maximum sustainable yield) need to be determined to control the level of harvesting effort. To this end, this study calls for the attention of policy makers to manage the Sundarbans ecosystem sustainably in a manner that is economically viable, socially equitable and ecologically sound.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Appendix S1. Supporting Information 1

Table 1. Check-list of available most commonly caught, commercially important bony fishes, crustaceans (sub-phylum: Crustacea; prawns/shrimps, crabs, lobsters), molluscs (Phylum: Mollusca; class: Bivalvia: bivalves; clams, mussels and oyster); gastropods (class: Gastropoda: Gastropods; snails) in the Bangladesh Sundarbans and adjacent waters