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Review

Global Mangrove Deforestation and Its Interacting Social-Ecological Drivers: A Systematic Review and Synthesis

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Abstract: Globally mangrove forests are substantially declining and a globally synthesized database of the drivers of deforestation and drivers' interaction is scarce. Here we synthesized the key social-ecological drivers of global mangrove deforestation by reviewing about two hundred published scientific studies over the last four decades (from 1980 to 2021). Our focus was on both natural and anthropogenic drivers with gradual and abrupt impacts and their geographic ranges of effects and how these drivers interact. We also summarized the patterns of global mangrove coverage decline between 1990 and 2020 and identified the threatened mangrove species and their geographic ranges. Our consolidated studies reported a 8,600 km^2 decline in the global mangrove coverage between 1990 and 2020 with the highest decline occurring in South and Southeast Asia (3870 km^2). We could identify 11 threatened mangrove species, two of which are critically endangered (*Sonneratia griffithii* and *Bruguiera hainseii*). Our reviewed studies pointed to aquaculture and agriculture as the predominant driver of global mangrove deforestation though the spatial distribution of their impacts varied. Gradual climate variations, i.e. seal-level rise, long-term precipitation and temperature changes and driven coastline erosion, constitute the second major group of drivers. Our findings underline a strong interaction across natural and anthropogenic drivers with the strongest interaction between the driver groups aquaculture and agriculture and industrialization and pollution. Our results suggest prioritizing globally coordinated empirical studies linking drivers and mangrove changes and a global development of policies for mangrove conservation.

Keywords: Mangroves; Driver;, Anthropogenic activities; Climate change; Extreme events; Wetlands; Interaction

1. Introduction

The tropical, subtropical and warm temperate climate regions of the world comprise intertidal mangrove forests forming an unique interface between terrestrial and marine ecosystems with enriched biodiversity composed of different species of flora and fauna, upon which millions of people depend on [1–3]. Mangroves provide unique and valuable ecosystem services, i.e. provisioning (e.g. aquaculture, fisheries, fuel, medicine, textiles), regulating (e.g. shoreline protection, erosion control, climate regulation), intermediate (nutrient cycling, nursery habitat), and cultural (recreation and tourism) [4–7]. Moreover, about 10-15% of coastal sediment retention and carbon storage are globally driven by the mangrove forests [8]. These values are five times greater per hectare (0.01 km^2) than those driven by tropical forests and other coastal wetlands together [9]. Mangrove forests also

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act as an important environmental barrier between shores and lands, protecting the inhabiting communities from the adverse impacts of extreme events, such as hurricanes and storms worldwide [5,10].

In spite of their critical contribution to human and ecosystem welfare, mangrove forests have been declining globally at an alarming rate during the past 40 years [11–13]. The severity of the mangrove deforestation has also been manifested in the substantial mangrove habitats, species and ecosystem services losses [14]. For example, during the last 75 years, Philippines has lost more than 75% of its mangrove forests, with more than 66% lost only since 1990 [15]. In Africa, which accounts for about 20% of global mangrove forests, 63 km^2 have been lost during 2005, dominantly in West Africa, e.g. in Gabon, Sierra Leone, Guinea-Bissau and Senegal [16]. Approximately 70 plant species that comprise global mangrove forests and are frequently used as indicators for coastal changes due to their specialized adaptation and minor variation across hydrological and tidal regimes, are on a noticeable decay [17]. Several mangrove species in Southeast Asia, e.g. *Aegiceras floridum* (with a native range from Malesia to New Guinea) [18], *Camptostemon philippinensis* (native range in Philippines) [19], *Heritiera globose* (native to Borneo) [20], and *Kandelia candel* (native to Asia-Tropical) [21] are now endemic.

The mangrove deforestation is subject to a multitude of social-ecological drivers, ranging from climate change and natural perturbations to pollution and anthropogenic exploitation of mangrove resources [22–24]. Two main groups of drivers emerged in recent studies:

- Environmental drivers such as climatic and associated geological changes [10], e.g. increased salinity driven by increasing temperatures [25], and natural disasters, e.g. tropical cyclones [26] and tsunamis [27]; and
- Anthropogenic activities, e.g. aquaculture and agriculture, in situ encroachment [28], exploitation of forest resources [29], water withdrawal [30], urbanization [31] and pollution in upstream [32].

Among these, tropical cyclones entailed disruptive temporary damages from which mangrove forests may or may not recover, whereas climatic changes and anthropogenic activities cause gradual and largely irreversible loss of mangrove forests [33]. Climate and related changes, e.g. changes in thermal regimes and sea-level rise, emerged as a dominant environmental driver of mangrove deforestation [34]. Sea-level has been indicated as the most important factor influencing the future distribution of mangroves while the mangrove ranges may shift further Northward and Southward as an effect of global warming and shift in thermal regimes [34]. As the frequency of the occurrences of tropical cyclones increased with the global warming and resulting climate change, mangrove responses to tropical cyclones and their regeneration patterns also altered [35–37]. Availability of sediments was identified as a crucial supporting factor for the regeneration of minerogenic mangroves from the cyclone aftermaths [6]. Among the anthropogenic drivers, land changes and encroachment were augmented in the Southeast Asia as a result of aquaculture and agriculture expansions, e.g. shrimp aquacultures and palm plantations [38,39]. Coastal development and urbanizations also drove a major decline in mangrove coverage, particularly in the Asian, Caribbean and Sub-Saharan regions [39–41].

The environmental and anthropogenic drivers may interact in a complex web and may exacerbate the rate of mangrove deforestation [42,43]. For example, salinity intrusion, which is an environmental driver of deforestation of the coastal mangrove belts in several regions, may be mediated and amplified by complex interaction among geographical location, flow modifications in upstream, costal embankments, sea level rise, cyclone and storm surge, brackish water effect, precipitation and shrimp aquaculture [17,44–47]. Global conservation and management efforts like "Global Mangrove Alliance" [11] require a global level synthesis and consolidation of these drivers of mangrove deforestation as well as an understanding of their complex interactions.

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Recently published articles studying global mangrove deforestation and drivers either focused on a subset of global mangrove areas [48] or a subset of drivers [1,31] and did not study the interaction among drivers [13,49]. In this review, we draw on scientific literature and synthesize the social-ecological drivers of mangrove deforestation at a global level. The deforestation of mangrove forests covers both total and permanent deforestation such as loss in mangrove coverage as well as partial and temporary deforestation such as defoliation and damages caused by cyclones. We start by analyzing the changes in the geographic distribution of mangrove forest coverage and subsequently assess the current status of the mangrove species. The drivers of mangrove forests deforestation are then identified along with their geographic ranges of effects. Our review ends with an analysis of the interactions among the drivers and a discussion on the challenges involved in mangrove forest conservation.

2. Methods

Two electronic scientific literature sources, i.e. Web of Science (webofknowledge.com) and Scopus (www.scopus.com), were accessed between 2017 and 2021 to search for original articles, commentaries, books, letters and reports related to mangrove deforestation. We searched across all literature that were published between 1st January 1980 and 28th February 2021 using the initial keywords: “mangrove distribution”, “mangrove biomass”, “mangrove species” and “mangrove ecosystems” to identify literature that studied mangrove forests in general (Table 1). We then excluded literature that either did not study changes and deforestation of mangroves or did not address the drivers of changes. A total of 250 scientific literature sources were found, which were further filtered using three sets of keywords based on *a priori* knowledge of drivers of global mangrove deforestation (Table 1). The first keyword set “Climate” included drivers related to the long-term gradual changes in temperature, precipitation and sea level rise. The keyword set “Extreme events” involved extreme events like cyclones and Tsunamis. “Land changes” indicated a set of anthropogenic drivers and included search terms related to agriculture and aquaculture expansion and urbanizations, while pollution aspects such as heavy metal contamination were included in the “Pollution” set. Finally, the “Flow modification” set included drivers related to the diversion of surface water flow and their impacts on the mangrove forests. The returned search records included at least one entry from each of the four keyword sets. We obtained further inputs from subject experts to revise the search strategy and also to locate additional literature. Thus, we arrived at a final set of 201 scientific literature for the analyses and synthesis of this review.

Table 1. List of the combination of keywords and keyword sets, and the number of literature obtained.

Initial keywords	**Driver related keyword sets**	**Number of literature**		
		WOS	**Scopus**	**Total**
{mangrove distribution, mangrove biomass, mangrove species, mangrove ecosystems}	Climate	15	14	29
	Extreme events	20	25	45
	Land changes	29	25	54
	Pollution	12	15	27
	Flow modification	16	30	46
	Total	**92**	**109**	**201**

To assess the change in mangrove forest coverage and the current status of the mangrove species, we linked the consolidated literature with four online databases on mangrove forests distribution and species: a) Global Mangrove Watch (GMA: https://www.globalmangrovewatch.org/), b) the mangrove species occurrence dataset of

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Global Biodiversity Information Facility (GBIF: https://www.gbif.org), c) the native distribution dataset of Plants of the World Online (POWO: www.plantsoftheworldonline.org), and d) International Union for Conservation of Nature (IUCN) Red List of Threatened Species (www.iucnredlist.org).

We first examined the change in the global mangrove forests coverage during the period represented by the consolidated literature. We found 36 studies that consistently reported mangrove forests coverage across five global mangrove regions and three decades between 1990 and 2020 (see Table 2 for details). The reported area coverage values for mangrove forests were checked against the GMA datasets and compared to calculate the change in the coverage of global mangrove forests. Subsequently, we identified the vulnerable and endangered mangrove species from the IUCN database and their occurrence and native distribution from the GBIF and POWO databases. This information was cross-checked using the consolidated literature. We mapped the status of the mangrove species across the United Nations Food and Agriculture Organization (FAO) delineated marine fishing areas [50] using QGIS v.3.4.4 (see Figure 1), as these provide the most detailed account of the coastal wetland and mangrove species. In the third step, we identified and grouped the drivers of mangrove forest deforestation and identified their impacts on mangrove habitats, species, ecosystems and societies in general, and also examined their geographic ranges of effects (Figure 2, Table 3). For each driver and driver group, interacting drivers and driver groups were also identified when reported by the consolidated literature. Finally, the interactions among the drivers were mapped using a Chord-Dependency Diagram (Figure 3).

Table 2. Mangrove coverage in global regions and the decline in coverage between 1990 and 2020.

Global regions	**Mangrove coverage km²**				**Rate of decline %/year**		
	1990	**2000**	**2010**	**2020**	**1990-2000**	**2000-2010**	**2010-2020**
Western & Central Africa	24,360	24,200	23,890	23,840	0.07	0.13	0.02
Eastern & Southern Africa	9,290	9,050	9,020	8,830	0.26	0.03	0.21
Total Africa	*33,650*	*33,250*	*32,910*	*32,670*	*0.12*	*0.10*	*0.07*
East Asia	320	250	240	220	2.19	0.40	0.83
South & Southeast Asia	57,170	57,080	55,130	53,300	0.02	0.34	0.33
Western & Central Asia	1,900	1,900	1,900	1,840	0.00	0.00	0.32
Total Asia	*59,390*	*59,230*	*57,270*	*55,360*	*0.03*	*0.33*	*0.33*
Caribbean	7,910	7,890	7,870	7,740	0.03	0.03	0.17
Central America	4,920	4,830	4,820	4,660	0.18	0.02	0.33
North America	11,950	11,900	11,670	11,520	0.04	0.19	0.13
Total Caribbean, Central and North America	*24,780*	*24,620*	*24,360*	*23,920*	*0.06*	*0.11*	*0.18*
Total Oceania	*12,470*	*12,140*	*11,550*	*11,500*	*0.26*	*0.49*	*0.04*
Total South America	*21,520*	*21,240*	*20,500*	*19,760*	*0.13*	*0.35*	*0.36*
World	***151,810***	***150,480***	***146,590***	***143,210***	***0.09***	***0.26***	***0.23***

3. Changes in mangrove forests coverage

Our consolidated literature (36) that reported changes in the mangrove forests coverage covered three decades, i.e. between 1990 and 2020 and about all of the global mangrove forests [49,51] (see Table 2 for details). The mangrove belts are largely found in the

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equatorial coastal regions with the tropical, sub-tropical and warm temperate climate between 30° N and 30° S [11,52]. Mangroves typically grow in harsh environment with moderate to high temperatures, tidal fluctuations and high salinity in groundwater [53,54]. These conditions nourish canopies of mangrove growth up to 30-40m in height [55]. The majority of mangrove forests (about 40%) covers only 4 countries, i.e. Indonesia, Australia, Brazil and Mexico with the Asian region holding the largest (around 42%) and most diverse mangrove areas [12,39]. About 15% of the mangrove forests is situated in Africa, while Oceania and South America cover 12% and 11% of the global mangrove forests, respectively [56,57]. Ramsar wetlands (the Sundarbans in Bangladesh and India, Garig Gunak Barlu in Australia, Cayapas-Mataje in Ecuador, Everglades in the United States and Douala Edea in Cameroon) had a mangrove coverage of about 378,960 km^2 in 2020 [11,58,59].

The studied mangrove forests by our consolidated literature exhibited an overall decline of more than 5% in global coverage between 1990 and 2020 [11,39,49,60] (Table 2). Globally, the mangrove cover declined by 8600 km^2 between 1900 and 2020 (Table 2) at a rate of 287 km^2 per year (Mangrove Alliance 2020). 60% of the literature that reported changes in the mangrove forests distribution studied countries in the South and Southeast Asian region, which experienced the highest mangrove loss (3870 km^2 and more than 6% decline in the coverage) between 1990 and 2020 [11,59,62,63]. The mangrove habitat loss in South and Southeast Asia was recorded at an average rate of 0.34% and 0.33% per year between 2000 and 2010 and between 2010 and 2020, respectively, which are also the highest among the mangrove regions globally [12,31,64]. The mangrove habitat loss in South America followed a similar average rate of 0.30% and 0.31% per year between 2000 and 2010 and between 2010 and 2020, respectively [11,12,65]. The total areal loss of mangrove forests in South America is 1360 km^2 between 1990 and 2020 while 3937 km^2 was lost in Asia (Table 2). Among the Asian countries, Indonesia encountered the highest areal loss (more than 700 km^2) [38], while Malaysia experienced highest loss in percentage (more than 3%) [66] between 2000 and 2010. Mangrove forests in Ramsar sites also encountered substantial losses (5% of the global coverage) between 2000 and 2010 [58].

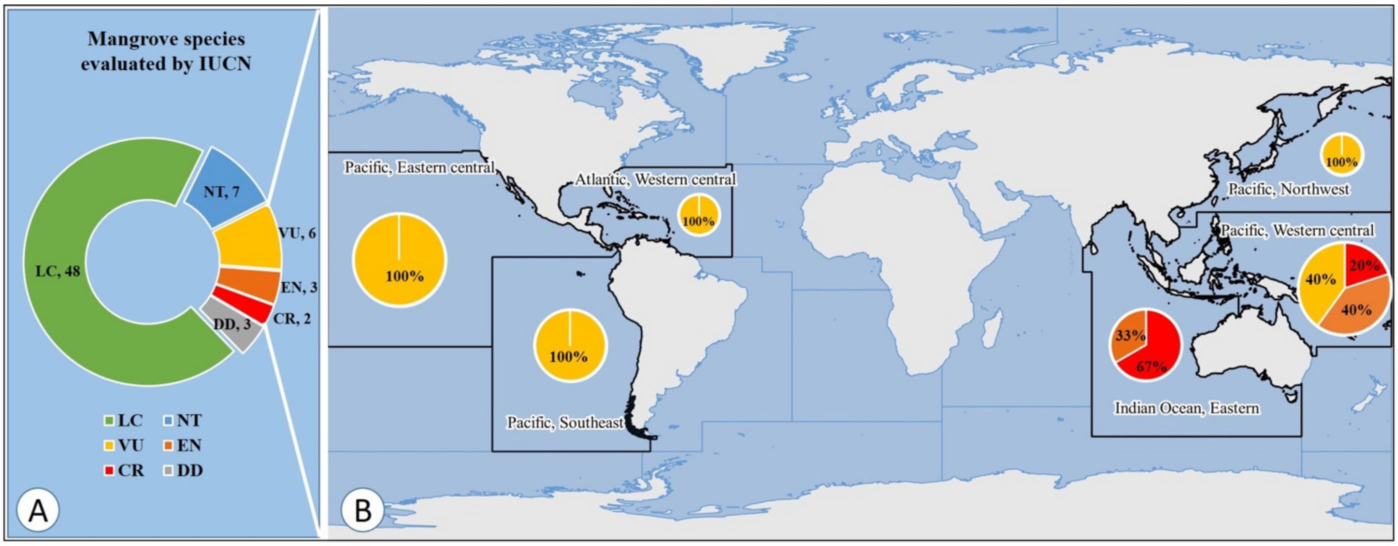

Figure 1. Geographic ranges of the threatened mangrove species (LC: Least Concern; VU: Vulnerable; CR: Critically Endangered; NT: Not Threatened; EN: Endangered; DD: Data Deficient).

4. Status of the mangrove species

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Our consolidated literature reported the status of 69 mangrove plant species [67,68], 35 of which have their native ranges in the Philippines [69,70]. Among the reported mangrove plant species, 11 are listed as threatened (2 as Critically Endangered "CR", 3 as Endangered "EN" and 6 as Vulnerable "VU") (Figure 1). The geographic ranges of the 5 CR and EN mangrove species are dominantly Southeast Asia (Figure 1). Among the CR species, *Sonneratia griffithii* (Lythraceae) has a restricted distribution in South Asia, and is considered very rare or is locally extinct in many parts of its range [71]. *Bruguiera hainesii* (Rhizophoraceae), the other CR species, is very rare and has a limited and patchy distribution in Singapore, Malaysia and Papua New Guinea [71]. The three EN species (i.e. *Camptostemon philippinense, Heritiera fomes* and *Heritiera globose*, all from Malvaceae family) are very rare showing a patchy distribution in South Asia, particularly in areas impacted by ongoing coastal developments [70–72].

The VU mangrove plant group includes genera *Avicennia* and *Rhizophora,* which protect coastal areas from erosion, salt water intrusion, storms, high tides and floods [53,73,74]. The three VU *Avicennia* species (i.e. *Avicennia bicolor; Avicennia rumphiana* and *Avicennia integra*) have experienced severe decline during 1980 - 2005 in central America [68]. *Avicennia bicolor*, and three other VU mangrove species, i.e. *Mora oleifera, Tabebuia palustris* and *Pelliciera rhizophorae,* have their native distribution is in the Eastern Tropical Pacific ranging from Mexico to Colombia [68,71,75] (Figure 1).

The threatened mangroves species use to provide last refuge for several terrestrial animal species, like the yellow-shouldered blackbird (Agelaius xanthomus) and the Philippine cockatoo (Cacatua haematuropygia), which have now gone extinct [62,76,77].

5. Environmental drivers of mangrove deforestation

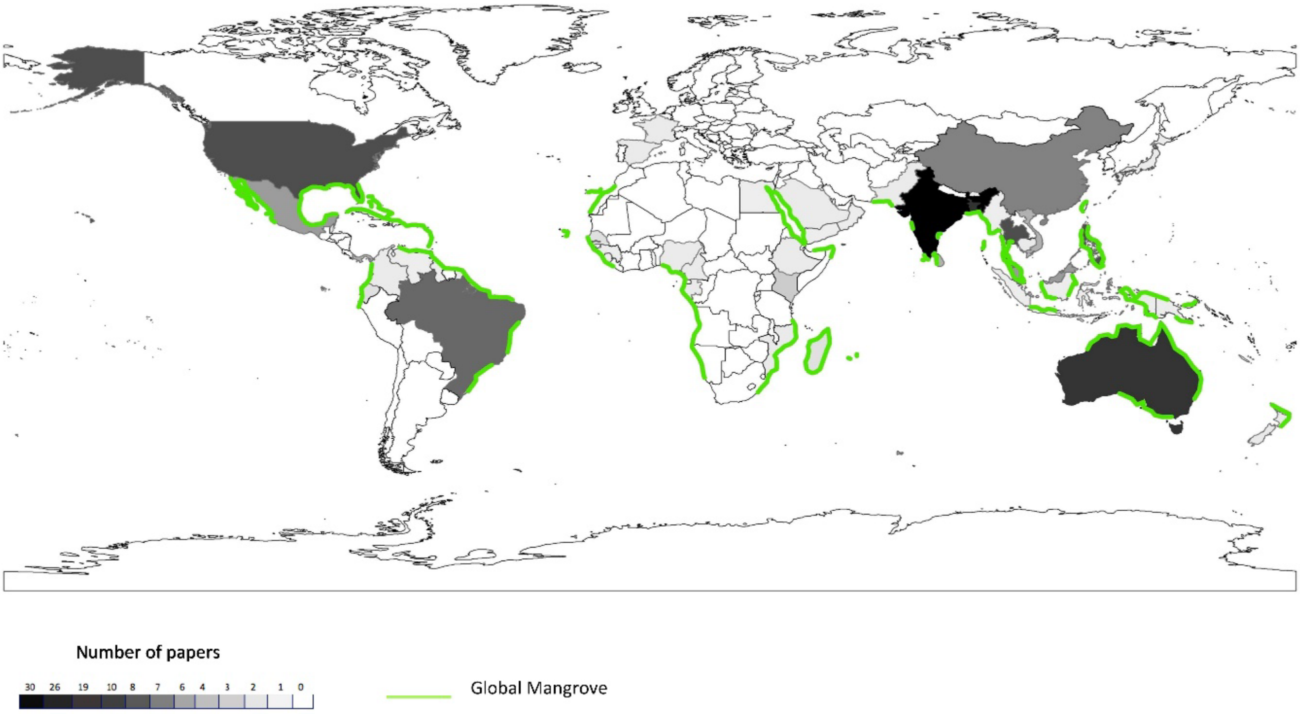
Figure 2 provides a representation of the drivers of mangrove forest deforestation and its consequences which are explained in the following subsections. In Table 3, the environmental and anthropogenic drivers of mangrove deforestation and their geographic ranges of effects are presented.

5.1. Climate change

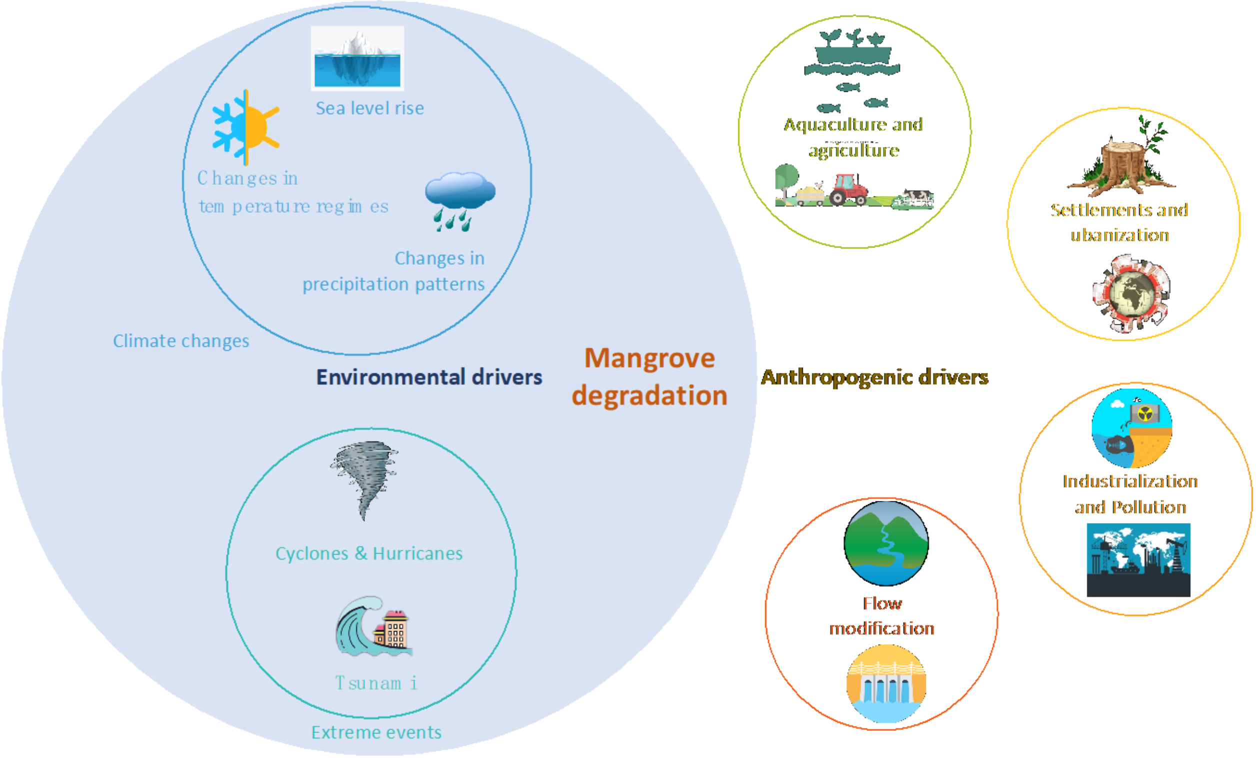
79 (39%) of our consolidated literature indicated climate change driven coastline erosion as a dominant environmental driver of mangrove deforestation (Table 3). Climate changes and impacts studied included alternations and variations in sea-levels, temperature regimes and precipitation patterns. These alternations were shown to impact the growth, recovery and spatial distribution patterns of the mangrove forests as well as to alter the composition of mangrove species [78]. The geographic ranges of climate change impacts covered almost all mangrove containing countries (Table 3). This section of the review provides a synthesis of the impacts of climate change on mangrove species and the past and future distribution of mangrove forests globally.

5.1.1. Sea-level rise

Sea-level rise was identified as an important driver of global mangrove deforestation by the literature studying the impacts of climate change [44,79,80]. Global warming driven melting of polar ice caps are projected to increase global sea level by 0.18–0.59 m between 2090-2099 [81]. This may lead to a retreat of the mangrove forest belts in low-lying coastal regions and small islands, e.g. Palembang (Indonesia), Sagar Island (India), Sundarbans (Bangladesh), Shenzhen (China) and Small Island States such as Solomon and Nuatambu [82–86]. For example, sea-level is rising at a rate of 3.14 mm per year (which may increase up to 3.5 mm per year) at the coast of Sagar Island, India, which has led to an approximate 0.4 km^2 areal loss of mangrove forests between 2000 and 2015 [87].



(a)



(b)

Figure 2. (a) Current global mangrove distribution (green stripe) and associated consolidated studies at the country level and (b) identified drivers and driver groups of mangrove deforestation.

The effects of rising sea-level is mediated by the availability of the coastal wetland sediment surfaces for the minerogenic mangroves [88,89]. The availability of sediments often depend on the local tectonic progressions, erosion and other geological processes [90]. When the coastal sediment level and the rate of accretion are exceeded by the mean tide level as a result of sea-level rise, the minerogenic mangrove forest may encounter areal loss or even collapse [91].

The increase in sea-level can be coupled with extreme high water occurrences as a consequence of fluctuations in oceanic circulations, such as El Nino Southern Oscillation (ENSO)'[92] and 'Northern Atlantic Oscillation (NAO)'[93] and temperature regimes [94]. Such increase in the high water occurrences may further increase the mean tide level and impose coastal sediments to sulfide toxicity [5,35].

5.1.2. Changes in temperature regimes

There has been an increase in global temperature by 0.74 °C between 1906 and 2005 with a doubled warming rate (0.13 °C per decade) during the past five decades compared to the last 100 years average [95]. The warming could further accelerate ranging from about 0.2°C per decade to 0.4°C – 0.8°C per decade if emissions reduction strategies fail and aerosols were to be rapidly removed [96].

Increased temperature affects mangroves by changing the ecosystems configuration and the species distribution as well as by reducing mangrove productivity rate and changing their phenological patterns [52]. For example, the mangrove canopy heights and biomasses depend on the regional temperature regime. An exceedance of this regional temperature regime threshold may decrease canopy growth by 1-2 m [97]. Summer heat waves, which are results of the global warming, drive habitat losses in the mangroves through defoliation and intense herbivory. For example, Hong Kong lost 22% of the mangrove coverage during due to summer heat wave driven defoliation in the flowering seasons leading to low reproductivity and fewer seedlings [98]. Exceedance of the temperature tolerance regime may also drive extinction of mangrove species, as dominantly for the cases of *Sonneratia griffithii* and *Bruguiera hainesii* in the Southeast Asia [71].

"Hard freeze" (temperature region below -3°C) is a natural phenomenon in winter in the Southwest Florida, which managed the growth and expansion of the coastal mangrove forest [65]. With the decreasing hard freezes due to global warming, invasive plant species are advantaged and replacing mangrove species in this region [99]. Moreover, the sudden high temperature variations before and after the hard freezes slowed down the mangrove recovery process after the hard freezes [100]. However, the decreasing hard freezes and global warming, coupled with the sea-level rise, may also expand the mangrove belts towards the higher altitudes and thus entail a northward shift in the global mangrove belt [101].

5.1.3. Changes in precipitation patterns

Global warming will cause an increase of about 25% in average global precipitation by 2050 [102], although the regional patterns will vary, i.e. precipitation will increase in high latitudes whereas decrease in most subtropical countries that contains mangrove forests [103,104]. The decreased precipitation with amplified evaporation can lead to high salinity in the coastal wetland zones, which in turn may adversely affect mangrove productivity, development, sapling and seedling and thus shrink the coverage of mangrove forests, particularly where mangroves are already at their precipitation limits, e.g. arid zones of Africa and Central and South America [53,104,105]. The decreased precipitation may also drive a decline in groundwater table and reduce freshwater supply to mangroves, which exacerbate salinity intrusion in coastal wetlands and mangrove forests [104,106,107].

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Table 2. Environmental and anthropogenic drivers of mangrove deforestation and their geographic ranges of effects. N/A – Not available.

Countries	Environmental drivers		Anthropogenic drivers			
	Climate changes (Sea-level rise, temperature and precipitation changes)	**Extreme events**	**Aquaculture and agriculture**	**Settlements and Urbanization**	**Industrialization and Pollution**	**Flow modification**
Mexico	5	N/A	3	5	1	N/A
Cuba	N/A	N/A	1	2	1	N/A
Brazil	3	N/A	3	6	3	3
Guinea Bissau	1	1	N/A	2	N/A	N/A
Guyana	N/A	N/A	2	2	1	N/A
Saudi Arabia	1	1	1	4	N/A	N/A
Ethiopia	2	1	4	3	N/A	N/A
Mozambique	1	N/A	2	2	1	N/A
Madagascar	4	2	N/A	2	N/A	N/A
India	9	4	6	11	7	4
Bangladesh	6	4	6	8	2	3
Myanmar	1	2	N/A	N/A	N/A	N/A
Malaysia	3	N/A	3	2	N/A	N/A
Philippines	6	2	6	1	1	1
Indonesia	7	2	8	2	1	1
Australia	3	4	1	6	2	N/A
Papua New Guinea	1	1	1	1	N/A	N/A
New Zealand	2	2	1	1	N/A	N/A
Thailand	4	2	6	N/A	1	N/A
Colombia	3	2	1	1	N/A	N/A
Nigeria	2	2	1	2	N/A	1
Vietnam	1	2	3	1	N/A	N/A
China	2	N/A	1	9	2	1
South Africa	1	N/A	N/A	4	2	1
Ecuador	N/A	N/A	2	N/A	1	N/A
Pakistan	1	2	2	4	1	3
Venezuela	2	N/A	N/A	1	1	1
United States	2	4	N/A	3	N/A	N/A
Mauritius	1	1	N/A	1	2	1
Sri Lanka	2	2	1	6	N/A	N/A
Kenya	1	1	N/A	2	1	N/A
Japan	2	3	N/A	4	N/A	N/A
Total	79	47	65	98	31	20

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The increased precipitation in high latitudes coupled with the increasing sea-level may increase productivity and expand mangrove coverage towards the landward fringe of the tidal wetland zones [52]. The diversity of mangrove species may also increase as a result of an increased fluvial sand deposits and nutrients as well as abridged sulfate level and decreased salinity in the high latitudinal regions, e.g. South Florida [33]. However, heavy and flash precipitation can cause overflow of coastal waterbodies and introduce freshwater channels through the coastal uplands, which can transport sediments accumulated in downstream back upstream coastal areas. Such sediments overflow occurred in the Choluteca River of the Pacific coast of Honduras during Hurricane Mitch in 1998 [108] and in the Tijuana River in Southern California during the El Niño storm of 1993 [91], causing severe damage to the mangrove forests in these area [91].

5.2. Extreme events

The geographic location of the mangrove forests makes them particularly vulnerable to two groups of extreme events: (i) cyclones and hurricanes and (ii) Tsunamis [37]. According to the Intergovernmental Panel on Climate Change (IPCC), global warming resulted in the intensification of peak wind strength, tidal surge and precipitation resulted by the tropical cyclones and hurricanes along with an increase in their frequency of occurrences [109]. These impact mangrove forests temporarily through three primary means: sediment deposition, wind damage and submersion [35]. The intense winds lead to sudden and topple stems, defoliation of the canopies and damage of the mangrove tree branches [110]. Cyclones and hurricanes may also uproot mangrove trees through strong wind flow [111]. This may also affect soil stability and lead to soil erosion [91]. The long term impacts of cyclones on the mangroves are the decreased fertility rate, delayed seedling seasons and changes in coastal hydrology causing permanent ecosystem conversion [112]. Moreover, with the increased cyclone and hurricane frequencies, mangroves may lack the time required for recovery from the temporary damages and hence, may encounter permanent loss [63].

Damages of several mangrove regions by extreme events were noted by 47 (23%) of our consolidated literature (Table 3). For example, Caribbean hurricane ‘Joan’ in 1988 caused 11% areal damage to the mangrove forests in Caribbean and Central America with reduced soil stability, permanent loss of several mangrove species and loss of forest density [113]. Sundarbans in Bangladesh and India – the world’s largest mangrove forest region – has encountered a high frequency of tropical cyclones and tidal surge since the 1960s [114]. The Sundarbans encountered an areal damage of 2500 km^2 by the tropical cyclone Sidr in 2007 [26]. Mangrove regions in Orissa and Tamilnadu in India experienced severe damages by several cyclones, e.g. the Super cyclone in 1999 [115], Vardah cyclone in 2016 [116], Ockhi cyclone in 2017 [117], and Gaja cyclone in 2018 [118].

Tsunamis have emerged as an environmental driver of mangrove deforestation leaving permanent damages to coastal mangrove ecosystems [119]. Particularly, the Great Tsunami of 2004, which originated in the Indian Ocean by an earthquake with the epicenter in Sumatra, Indonesia, on the Richter magnitude scale of 9.1 – 9.3, led to a major 300 km^2 areal loss of mangrove forests in 14 countries [120,121]. Indonesia encountered the largest loss (35%) followed by India, Sri Lanka and Thailand. Andaman Island, India, Aceh Province, Sumatra and Andaman coast, Thailand lost approximately 38 km^2, 7.5 km^2 and 3 km^2 of mangrove forest coverage as a result of this Tsunami, respectively [122–124]. Tsunami driven mangrove cover and habitat losses were also observed later in Japan in 2011 and Papua New Guinea in 1999 [119,125,126].

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6. Anthropogenic drivers of mangrove deforestation

6.1. Aquaculture and agriculture

Aquaculture and agriculture were identified as the most dominant driver of global mangrove deforestation in our consolidated literature accounting for approximately 47% of the global mangrove coverage loss [3,31,66]. Besides conversion of mangrove forests for fisheries, aquaculture and agriculture was related to reduced ground water levels, and soil and water pollution from the effluents, which further intensified mangrove deforestation [127]. For example, the mangrove habitat losses in Kenya during 2000-2010 are associated with soil and water pollution [128], caused by the potential agricultural and aquacultural intensification [66,129]. Aquaculture and agriculture were also shown to be the main driver of losses for the CR and EN mangrove species [71,72].

Globally, shrimp and other forms of aquaculture drove conversion of 38% and 14% of the mangrove forest areas, respectively, between 1990 and 2020 [42]. Several Southeast Asian countries (Myanmar, Borneo, Malaysia, and Sumatra Island) have undergone a total 10% areal loss of mangroves between 2000 and 2012 due to aquaculture [64]. Thailand and Vietnam are the hotspots of mangrove deforestation by aquaculture that encountered mangrove forests loss at an average rate of 0.09 km^2 per year between 1990 and 2020 [39]. In Thailand, 694 km^2 of mangrove areas was converted into aquaculture between 1990 and 2019, followed by 1020 km^2 in Vietnam and 65 km^2 in Bangladesh. In India about 40% of mangrove habitats on the western coastline has been transformed for aquaculture [130]. About 2055 km^2 and 2110 km^2 of mangrove marshlands have been transformed into shrimp and other fish farms in the Philippines and Indonesia, respectively [131]. The major decline of mangrove forest in Latin America is also associated with large scale shrimp farms and agricultural development [132], such as mangrove losses of 216 km^2 in Ecuador, and 115 km^2 in Honduras [112].

Intensification of agriculture is another dominant driver of defoestation in all mangrove forests containing countries, particularly in South Asia and Latin America. For example, the Philippines and Indonesia lost major mangrove areas to agriculture [127]. The recent growth of oil palm plantations in Thailand, Malaysia, Sumatra, Colombia and Indonesia is the main driver of mangrove forests loss [38,133]. The increasing demand for palm oil Indonesia drove an areal expansion of palm plantation by 30% in 2019 compared to the coverage in 2012 by replacing mangrove forests [134]. Mangroves in Central America have been mostly cleared for cattle grazing and industrial farming [135].

6.2. Settlements and Urbanization

The majority of our consolidated literature (98 studies) suggests human settlements and urbanization as an important anthropogenic driver of global mangrove deforestation [31,39] (see Table 3). Urbanization related activities such as clearing for urban infrastructures and timber production have led to the destruction of significant mangrove areas in Asia and Africa during the past 20 years [38,136]. Human settlements occupy 150 km along the global coastal belt land that previously contained mangroves among other coastal wetland elements [32,137]. The human population density in coastal regions is around 80 person per sq km [138] and the urbanization in coastal areas is expanding, particularly in low-lying developing countries [139]. For example, nearly 50% of the population in African countries and Bangladesh lives at the coastline, which affect the adjacent mangrove ecosystems [140].

The geographic ranges of effect for settlements and urbanization is predominantly Asia and Africa [141]. Particularly, the Indian Ocean coastline, which contains the mangrove with rich biodiversity and expands over several countries such as Sri Lanka, Myanmar, Bangladesh, Singapore, Indonesia and Australia, has been losing mangrove coverage during the last three decades due to urban encroachment [142]. Sub-Saharan countries

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such as Mauritania, Comoros, Djibouti and Somalia encountered rapid urban development and associated mangrove loss [143]. In Indonesia, Guinea, and Guinea-Bissau, mangrove forests are exploited for wood harvesting and timber extraction [63] [144]. The VU species *Avicennia rumphiana* that dominantly occurs in Southeast Asia is threatened by the expansion of human settlements [19].

6.3. Industrialization and Pollution

Industrialization and pollution represent an emerging group of driver for mangrove deforestation as reported by 15% of our consolidated literature (Table 3) [145]. The Caribbean mangrove zone, which encountered the second highest areal loss after Asia over the past three decades, was impacted by sewage, oil pollution, solid waste and conversion to landfills, mainly driven by rapid industrialization [7,146,147]. In India, a considerable amount of stress on mangroves is caused by domestic and industrial waste, heavy metals and other toxic discharge from thermal power stations in Ennore and Tuticorin [148], Vedanta Sterlite Copper industry in Tuticorin, nuclear power plants (Kudankulam and Kalpakkam) [149] and dye factories. Recent proposal by the Indian Government for drilling in the Cauvery delta region for hydrocarbon and methane exploration threatened Pichavaram mangrove forest, Tamilnadu, which is only 490 meters away from the exploration zone sheltering the stretch of the Tamilnadu coast from natural calamities such as the 2004 tsunami [150].

Petroleum explorations, such as in the Persian Gulf zone and resulted oil wells, oil refiners and oil transport led to pollutions from oil spills driving substantial mangrove habitat losses [151]. They can also lead to accidents, for example, the Gulf of Mexico oil spill in 2010 affected 10% areas of mangrove forests in with a residue impact lasting for 10 years [152]. On January 2017, the toxic bunker oil spill along the coast of Chennai, India spread 34 km across the Ennore coast and reached Pichavaram and Pulicat mangrove forests affecting several native mangrove species [153].

Immobilization of heavy metals, such as Copper, Iron, Magnesium, Manganese, Zinc, Mercury, Lead and Tin, has emerged as a driver of mangrove deforestation globally [154,155]. At a low level of heavy metal contamination, mangrove forests may act as biological pollution sinks [156]. Depending on the nutrients cycles and sediment characteristics, mangroves can dissolve metals in the deposits by exuding oxygen into the anoxic soil sediment through aerial roots [32,145,157,158]. However, the increasing contamination and discharge of heavy metals are exceeding the mangrove sink capacity and causing direct damages by pollution [155].

6.4. Flow modification

Flow modification by diverting upland water flows from mangroves diminishes mangrove productivity, as identified by 20 (8%) of our consolidated literature [136]. In Asia, the construction of upstream reservoirs and dams reduced the supply of sediments to several deltaic mangrove regions, including Ganges and Cauvery in India, the Sundarbans deltas of India and Bangladesh and Indus river delta of Pakistan, leading to an increase in wetland erosions in these regions [159]. Likewise, the annual sediment flow to the deltaic regions of China has reduced to 0.4 billion metric tons in 1994 to 1.1 billion metric tons in 2009 [87,143].

Coastal erosion prevention structures and seawalls lead to the modification of surface run-off by increasing downwards currents and inundation in the mangrove forests during flash flood events [63,153,160]. In the Mississippi Delta, construction of flood control walls led to hydrological disturbances in the deltaic plain and an isolation of the river from the Delta affecting the mangrove zone [161,162]. Conversion of mangrove areas into salt pans and construction of river dams are the major causes of mangrove deforestation in Brazil [163].

7. Interactions among drivers

Mangrove deforestation is the outcome of the complex interactions among the interconnected environmental and anthropogenic drivers [164]. Our consolidated literature suggest that the drivers may interact within and across their groups and may thus amplify their impacts on mangroves [120,143,165] (Figure 3). For example, climate change induced decreased precipitation and drought events lead to an increase in the groundwater extraction [30]. The increase in the upstream groundwater extraction in turn leads to an increased level of salinity intrusion in the downstream coastal mangrove zones [166]. Moreover, expansion of aquaculture also leads to an increase in groundwater extraction in the coastal zones, which also in turn leads to an increased salinity intrusion [40].

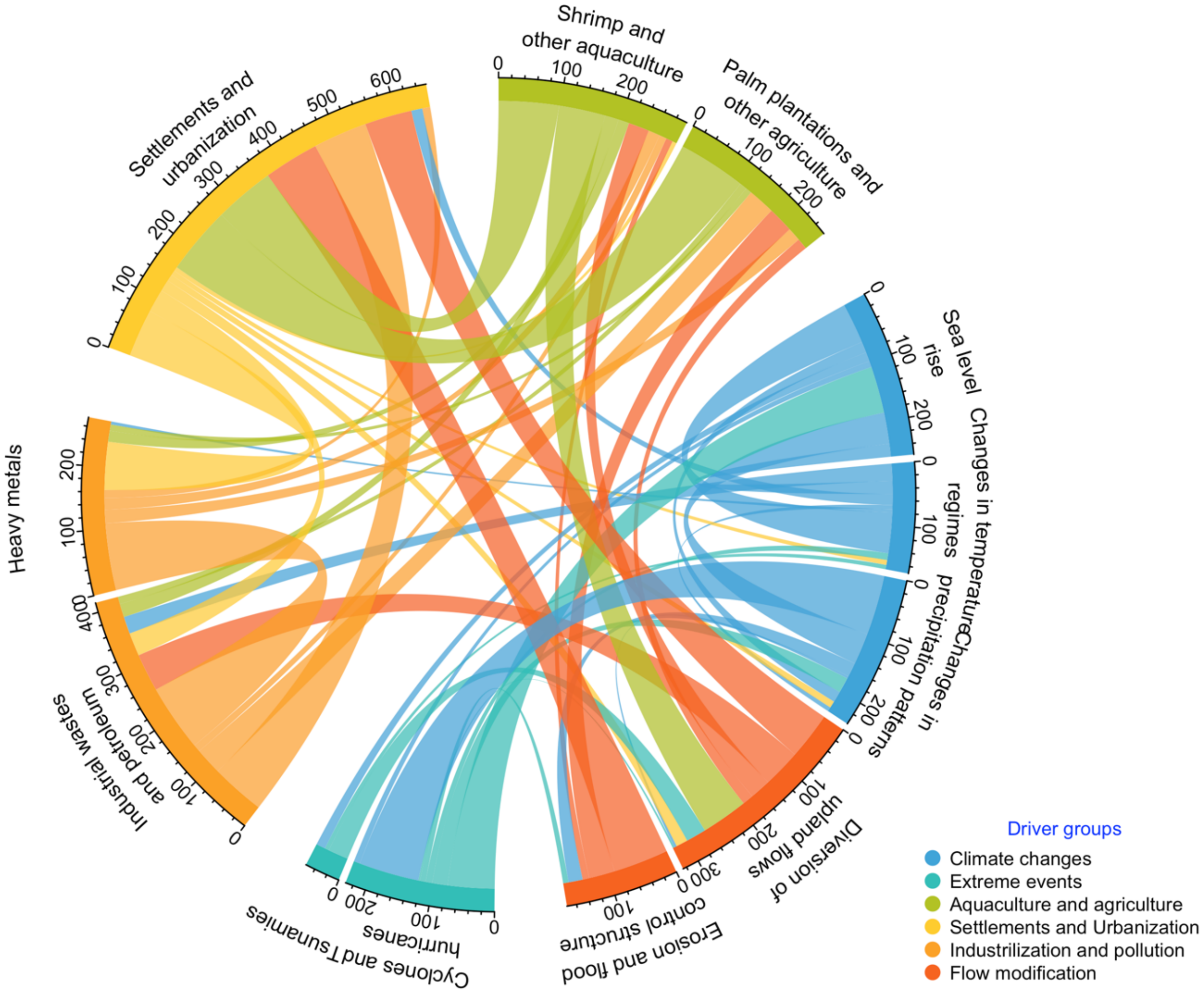

Figure 3. Interactions among the identified drivers and drivers groups of mangrove deforestation. The scale indicates the number of consolidated studies indicating such interactions.

Settlements and urbanization in the costal wetland zones directly lead to interruptions and alternations in the hydrological and sedimentation processes [167]. Settlements and urbanization are also major sources of pollution and nutrients overload [12]. The urbanization processes also lead to an expansion of aquaculture and agriculture in the vicinity, which may also be sources for pollution in the mangroves [168]. In fact, the driver groups aquaculture and agriculture and industrialization and pollution exhibited the strongest interaction in our consolidated literature (Figure 3).

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A considerable dieback of mangrove forests occurred between 2015 and 2016 in the Northwest Australian coastline is a strong manifestation of the interaction of drivers [169,170]. Mangrove forests on the coastline bounding low-lying plains of Australia's Gulf of Carpentaria progressively extended inland and to a lesser extent in a seaward direction between 1987 and 2015. However, between 2015 and 2016, a significant dieback occurred in several mangrove regions of the North and Northwest Australia [169,170]. The dieback is driven by a complex interaction among long term temperature and precipitation anomalies, El Niño Southern Oscillation (ENSO) related variation in sea level, particularly a 20–30 cm decline in sea level during the immediate pre-dieback period and a 20–30% increase in soil salinization above the pre-dieback level [170]. The interaction among these drivers led to mangrove canopy loss, reduced Normalized Difference Vegetation Index (NDVI) and reduced recruitment, which in combination led to an irreversible dieback event.

Global warming can amplify and widen the ranges of plant diseases and insect pests, such as fungal fruit and leaf diseases and wood-boring and leaf-feeding beetles, by spreading their habitats and creating favorable condition for reproduction [18,171]. These diseases and pests can lead to mangrove deforestation through branch and stem cankers, die-back and leaf galls [18]. Several mangrove species were shown to be vulnerable to these global warming led diseases and pests, such as *Barringtonia racemosa* is vulnerable to fruit and leaf diseases and *Hibiscus tiliaceus* is vulnerable to herbivory beetles [171]. The die-back and canker levels observed in *A. marina* are also associated with these diseases and pests.

The impacts of sea-level rise have been exacerbated by coastal subsidence in several regions [172]. Coastal subsidence results from excessive extraction of subsurface ground water and variations in the thermal expansion across geographies, which lead to the vertical motion of the landform during the tectonic movement [173]. Coastal erosion and sediment deposition from the banks of large rivers have further increased subsidence levels through silt depositions [107]. The subsidence is particularly evident along the shorelines where mangrove forests area are located [10,173]. Several deltaic regions, including Changjiang river delta (China), Chao phraya delta (Thailand) and Mississippi river delta (Gulf of Mexico), were identified as extremely sensitive to sea-level fluctuations due to subsidence [162,174,175]. Most of the mangrove forests in Ganges–Brahmaputra–Meghna delta in India and Bangladesh are affected simultaneously by subsidence due to ground water extraction and erosion from the monsoons rains, and accelerated sea-level-rise, which has led to substantial habitat loss of the Sundarbans mangroves [176].

The aftermaths of extreme events may create opportunities for several anthropogenic drivers, such as aquaculture and agriculture [79,177,178]. For example, the South and North provinces in Thailand have converted the tsunami damaged mangrove areas into aquaculture and agricultural lands [79]. Around 1000 km^2 of the degraded mangrove forests in Asia were converted to other land forms (e.g. for agriculture and aquaculture) between 1990 and 2020, largely triggered by the development policies for hurricane damaged lands [29,35,178,179].

The drivers and their interactions may go beyond the specific drivers of mangrove deforestation. Several coastal ecosystems, such as ocean algae, coral reefs and seagrasses, are closely associated with adjacent mangrove forests [53,180]. For example, coral reefs supply nutrition to the downstream mangrove forests shaping overall mangrove health and seedling rates [181]. Drivers affecting these adjacent coastal ecosystems also passively affect mangrove forests, e.g. bleaching of coral reefs will decrease nutrition flows and in turn lower productivity of mangrove forests [53,182].

8. Conclusions and outlook

This review contributes with a global synthesis of the mangrove deforestation scenario over three decades, i.e. between 1990 and 2020. Our global level synthesis indicates the Southeast Asian region as particularly vulnerable to mangrove deforestation with the

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highest loss of mangrove coverage between 1990 and 2020 (Table 2). Consequently, we urge for strong mangrove monitoring and conservation measures in the Asian region, particularly in countries like Indonesia, Malaysia and Bangladesh.

Several technical difficulties have been reported by our consolidated studies regarding monitoring of mangrove regions. For example, most of the deforested mangrove areas replaced with agriculture or other plantations has been misclassified as mangrove forests, particularly in Indonesia [64]. This is due to oil palm plantations and palm orchards that replace mangrove forests may reflect the same color bands in satellite images [134]. Also, even though the mangrove forests in Brazil have been substantially affected by human settlements, aquaculture and water pollution, little mangrove area loss has been documented since 1980 [68].

Technical difficulties also remain in quantifying anthropogenic drivers' impacts, for example, quantification of the impacts of population increase and urbanization on mangrove forests coverage in Asia (Gandhi and Jones 2019a, Giri *et al* 2015, Latiff and Faridah-Hanum 2014). The advent of satellite imageries and sophisticated image classification and detection techniques have advanced quantification and trend analyses for anthropogenic activities [31]. Future research should focus on advancing the quantification of the association between anthropogenic drivers and mangrove coverage changes in under studied regions.

We also drew on 11 threatened mangrove species and their native geographic ranges. Many of these species may soon be locally extinct, e.g. *Sonneratia griffithii* and *Bruguiera hainseii* [71] in Asia. Local extinction of these species may infer global loss. According to IUCN, there are no conservation measures specific to most of these threatened species. We therefore recommend a continued monitoring and research on these species, as well as the inclusion of these species in the marine and coastal areas protection programs [68]. Although mangroves are protected and marginally restored during the last decades in several regions (for example, *Avicennia integra* [73] has been conserved in a remote area of northern Australia [184,185]), little is known about the achievements of these local conservation efforts while mangrove areas globally continued to decline. Hence, a global coordination of these *in-situ* conservation actions is required with a correct management of Protected Areas Network, to fully protect species and the entire mangrove ecosystems [186,187].

We identified two major groups of environmental drivers: climate changes and extreme events, and four groups of anthropogenic drivers: aquaculture and agriculture, settlements and urbanization, industrialization and pollution and flow modification, which led to the mangrove deforestation globally observed in our consolidated literature. Our reviewed studies pointed to aquaculture and agriculture and related anthropogenic activities as the predominant driver of global mangrove deforestation although the geographic ranges of their effects varied (Table 3). Gradual climate variations, i.e. seal-level rise, precipitation and temperature changes, constitute the second major group of drivers of deforestation of the global mangrove forest with visible direct impacts on the equatorial regions, e.g. Central America and Asia. Settlements and urbanization constitute the third major group of drivers and were indicated as the main drivers of mangrove deforestation in Asia and Africa including India, Bangladesh, Thailand, Vietnam, Mauritania, Comoros, Djibouti and Somalia by the majority of our consolidated literature (Table 3). However, the data for drivers available from certain areas needed to be consolidated to arrive at our global drivers database and therefore, a robust global drivers database for mangrove deforestation requires a precise global assessment, e.g. regular updates of Global Mangrove Watch [11]. Our review results can contribute to update the datasets for assisting the development of policies for mangrove conservation. Such global level assessments will also be helpful for disentangling and quantifying the associations of climatic changes and anthropogenic activities with mangrove cover changes globally and also for predicting future mangrove patterns and provision of ecosystem services.

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The complex interactions among the drivers identified in this review indicates that mitigating drivers of mangrove deforestation may have co-benefits for other ecosystems. For example, bad shrimp farming practices and produced pollution degrade mangroves but also adjacent freshwater and coastal ecosystems [188]. Investments in proper shrimp farming infrastructure and development of sewage treatment plants will thus benefit both mangrove forests and those adjacent ecosystems [42]. The consequent increase in the availability of usable freshwater may in turn decrease the pressure on groundwater extraction and thus reduce salinity intrusion to mangroves.

Overall, mangrove conservation should be prioritized over restoration. Measures have been taken to restore the wetlands by diverting the river water into the wetlands and by creating marshes by pumping the dredged sediments [32]. However, these measures are expensive and unaffordable in many places and may have adverse consequences for other ecosystems [32].

Author Contributions: A.K.B. and P.C. conceived the study. R.P. conducted the review under the supervision of A.K.B, P.C. and M.M.R. A.K.B. and R.P. wrote the article and all reviewed and revised the article. M.M.R. provided information and input regarding mangrove species.

Funding: This study was supported through the FCT (Fundação para a Ciência e a Tecnologia) under the projects PTDC/CTA-AMB/28438/2017—ASEBIO and UIDB/04152/2020—Centro de Investigação em Gestão de Informação (MagIC).

Conflicts of Interest: The authors declare no conflict of interest.

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