

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 containing the drivers of deforestation and drivers' interactions 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 their gradual and abrupt impacts and on their geographic coverage 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. Our consolidated studies reported an 8600 km² decline in the global mangrove coverage between 1990 and 2020, with the highest decline occurring in South and Southeast Asia (3870 km²). 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 their impacts varied across global regions. Gradual climate variations, i.e., sea-level rise, long-term precipitation, and temperature changes and driven coastline erosion, salinity intrusion and acidity at coasts, 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 deforestation and global development of policies for mangrove conservation.

Keywords: mangroves; drivers; aquaculture; agriculture; climate change; extreme events; coastal wetlands; interaction



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1. Introduction

The tropical, subtropical, and warm temperate climate regions of the world contain intertidal mangrove forests forming a 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 the global coastal sediment retention and carbon storage are managed by mangrove forests [8]. These values are five times greater per hectare (0.01 km²) than

those driven by tropical forests and other coastal wetlands together [9]. Mangrove forests also act as an important environmental barrier between shores and lands, protecting the inhabiting ecological and social 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 loss of mangrove habitats, species, and ecosystem services [14]. For example, during the last 75 years, the Philippines 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 the global mangrove forests, 63 km² were 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 threatened with extinction.

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:

1. 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
2. Anthropogenic activities, e.g., aquaculture and agriculture, in situ encroachment [28], exploitation of forest resources [29], water withdrawal [30], urbanization [31], and upstream pollution [32].

Among these, tropical cyclones entail 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 the thermal regimes [34]. As the frequency of the occurrences of tropical cyclones increased with global warming and resulting climate change, mangrove responses to tropical cyclones and their regeneration patterns also altered [35–37]. The 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 encroachments were augmented in Southeast Asia as a result of aquaculture and agriculture expansions, e.g., shrimp aquaculture and palm plantation [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 has been identified as an environmental driver of mangrove deforestation in several regions, may be mediated and amplified by the complex interaction among geographical location, flow modifications in upstream, coastal 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 in-depth understanding of their complex interactions.

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. Mangrove deforestation covers both total and permanent deforestation, such as loss in the 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 global coverage of mangrove forests and subsequently assess the current status of the mangrove species. The drivers of mangrove deforestation are then identified along with their geographic coverage of effects. Our review ends with an analysis of the interaction among the drivers and a discussion on the challenges involved in mangrove forest conservation.

2. Methods

We conducted a systematic literature review following the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) framework [50] (see Figure A1 in Appendix A for details). Two electronic scientific literature sources, i.e., Web of Science (webofknowledge.com) and Scopus (www.scopus.com), were accessed between 2 September 2017 and 31 December 2021 to search for original articles, commentaries, books, letters, and reports related to mangrove deforestation. We searched across all studies that were published between 1 January 1980 and 28 February 2021 using the initial keywords: “mangrove distribution”, “mangrove biomass”, “mangrove species”, and “mangrove ecosystems” to identify the literature that studied mangrove forests in general (Table 1). We then excluded the 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 the 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 urbanization, 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 studies for the analyses and synthesis of this review.

Table 1. List of the combination of keywords and keyword sets, and the number of the 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 (GMW: <https://www.globalmangrovetwatch.org/>), (b) the mangrove species occurrence dataset of 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) (all accessed between 2 September 2017 and 31 December 2021).

We first examined the changes in the global mangrove forests coverage during the period represented by the consolidated literature. We found 36 studies that consistently reported mangrove forest 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 GMW datasets and compared to calculate the changes in the coverage of global mangrove forests. Note that these studies and databases reported both gains and losses of mangrove forests, from which we calculated the net change. 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 again 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 [51] using QGIS v.3.4.4 (see Figure 1), as these provide the most detailed account of the coastal wetlands and mangrove species. In the third step, we identified and grouped the drivers of mangrove deforestation and identified their impacts on mangrove habitats, species, ecosystems, and societies in general, and also examined their geographic coverage of effects (Figure 2, Table 3). The number of studies reporting each identified driver and driver group for 32 countries across five global mangrove regions were documented (Table 3), and their driven mangrove coverage losses were identified at the country, region, and global levels. 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 at a global level using a Chord-Dependency Diagram (Figure 3).

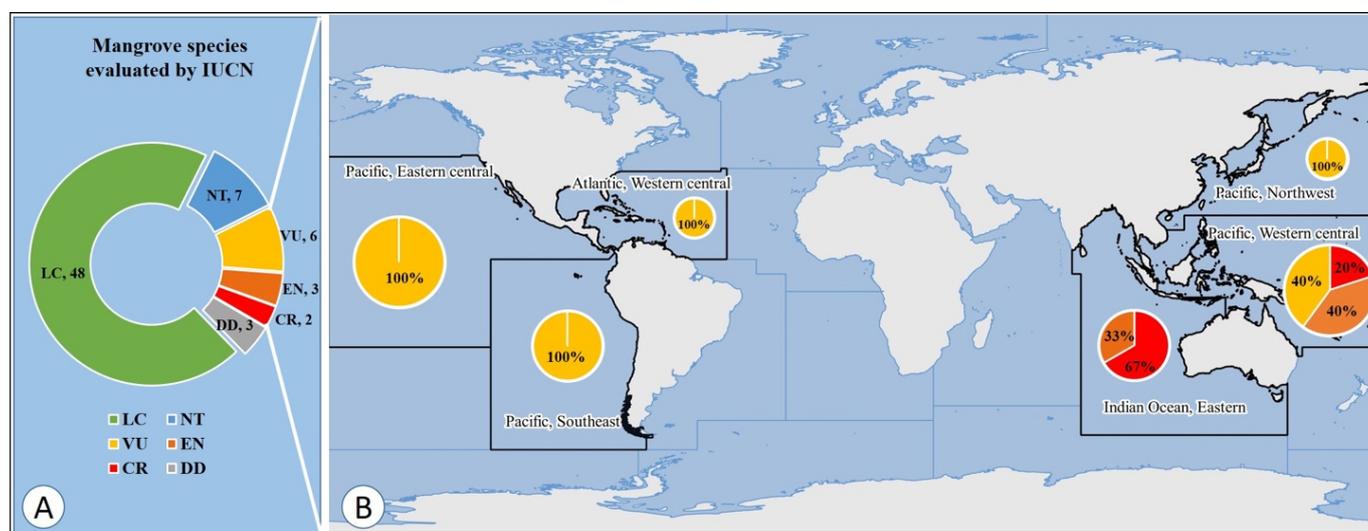
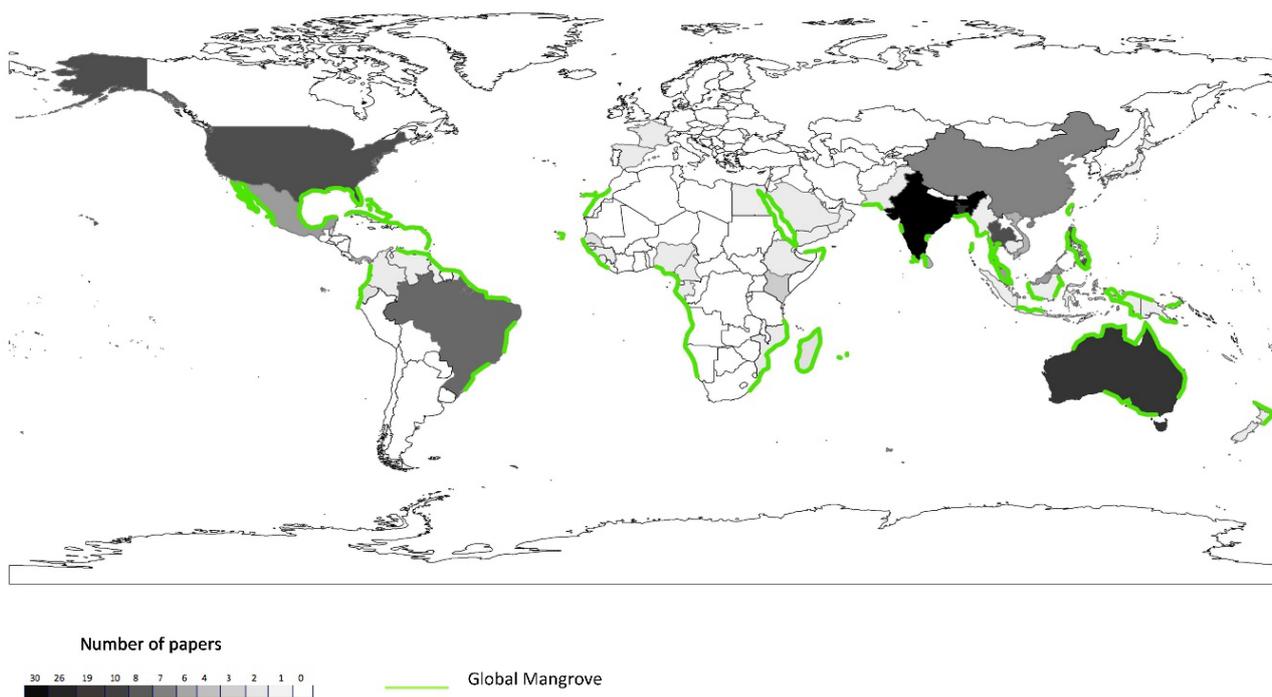
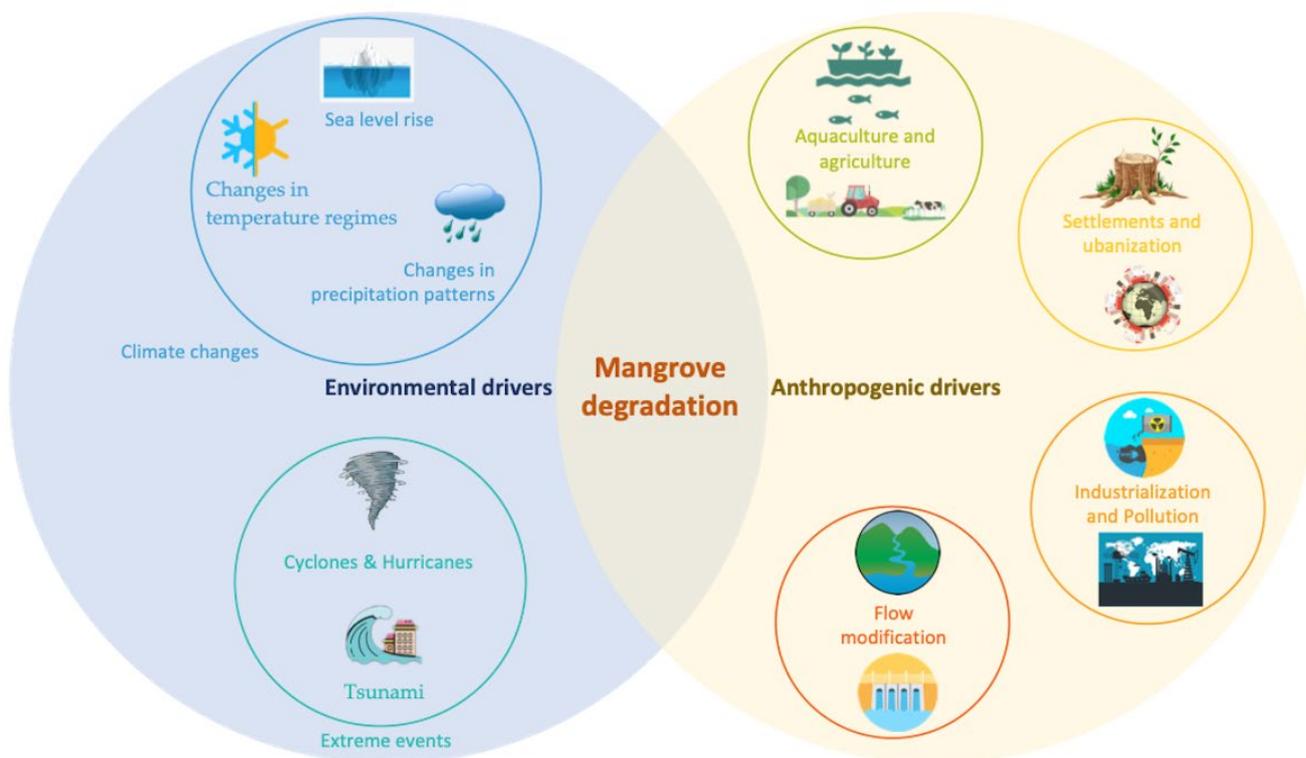


Figure 1. (A) Status of the global mangrove species and (B) geographic coverage of the threatened mangrove species (LC: Least Concern; VU: Vulnerable; CR: Critically Endangered; NT: Not Threatened; EN: Endangered; DD: Data Deficient).



(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.

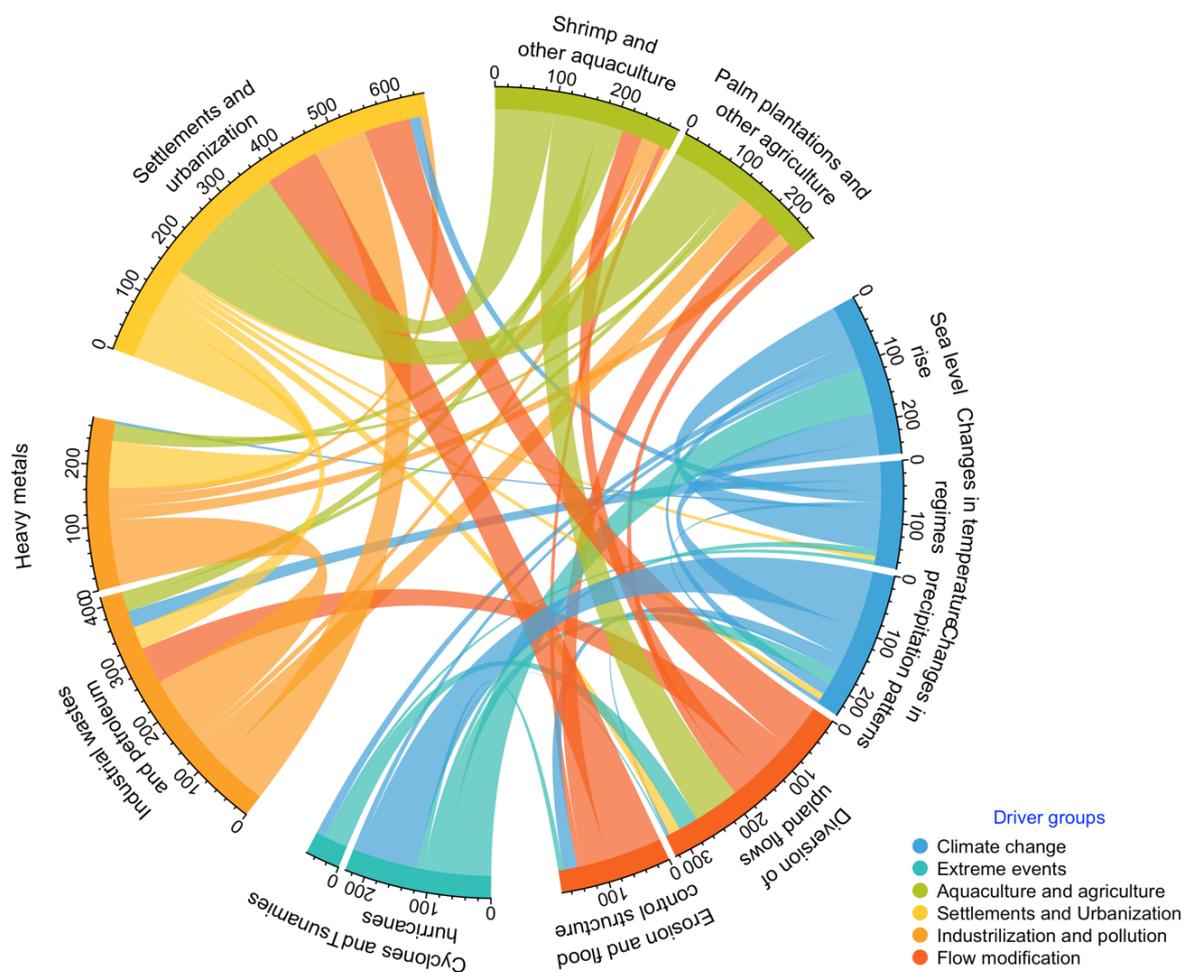


Figure 3. Interactions among the identified drivers and driver groups of mangrove deforestation. The scale indicates the number of consolidated studies indicating such interactions.

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

Global Regions	Mangrove Coverage km ²				Rate of Decline %/year		
	1990	2000	2010	2020	1990–2000	2000–2010	2010–2020
Western and Central Africa	24,360	24,200	23,890	23,840	0.07	0.13	0.02
Eastern and Southern Africa	9290	9050	9020	8830	0.26	0.03	0.21
<i>Total Africa</i>	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 and Southeast Asia	57,170	57,080	55,130	53,300	0.02	0.34	0.33
Western and Central Asia	1900	1900	1900	1840	0.00	0.00	0.32
<i>Total Asia</i>	59,390	59,230	57,270	55,360	0.03	0.33	0.33
Caribbean	7910	7890	7870	7740	0.03	0.03	0.17
Central America	4920	4830	4820	4660	0.18	0.02	0.33
North America	11,950	11,900	11,670	11,520	0.04	0.19	0.13
<i>Total Caribbean, Central, and North America</i>	24,780	24,620	24,360	23,920	0.06	0.11	0.18
<i>Total Oceania</i>	12,470	12,140	11,550	11,500	0.26	0.49	0.04
<i>Total South America</i>	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

Table 3. Environmental and anthropogenic drivers of mangrove deforestation and their geographic coverage of effects. The values refer to the number of corresponding literature reviewed. N/A—Not available. Note that the numbers of literature are absolute and are not weighted by the mangrove coverages of the corresponding countries.

Countries	Environmental Drivers			Anthropogenic Drivers		
	Climate Change (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

3. Decline in the Mangrove Forests Coverage

Our consolidated literature (total 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 [49,52] (see Table 2 for details). The mangrove belts are largely found in the equatorial coastal regions with the tropical, sub-tropical, and warm temperate climates between 30° N and 30° S [11,53]. Mangroves typically grow in harsh environments with moderate to high temperatures, tidal fluctuations, and high salinity in groundwater [54,55]. These conditions nourish canopies of mangrove growth up to 30–40 m in height [56]. The majority of mangrove forests (about 40%) covers only four 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 are situated in Africa, while Oceania and South America cover 12% and 11% of the global mangrove forests, respectively [57,58]. 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 km² in 2020 [11,13,59].

The studied mangrove forests by our consolidated literature exhibited an overall decline (net loss) of more than 5% in global coverage between 1990 and 2020 [11,39,49,60] (Table 2). Globally, the mangrove cover declined by 8600 km² between 1990 and 2020 (Table 2) at a rate of 287 km² per year [61,62]. Sixty percent 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 km² and more than 6% decline in the global coverage) between 1990 and 2020 [11,62–64]. 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 is also the highest among the mangrove regions globally [12,31,38]. 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 km² between 1990 and 2020 (Table 2). Among the Asian countries, Indonesia encountered the highest areal loss (more than 700 km²) [38], while Malaysia experienced the highest loss in percentage (more than 3%) [66] between 2000 and 2010. Mangrove forests in Ramsar sites also encountered a substantial loss (5% of the global coverage) between 2000 and 2010 [59].

4. Status of the Mangrove Species

Our consolidated literature reported the status of 69 mangrove plant species [67,68], 35 of which have their native coverage in the Philippines [69,70]. Among the reported mangrove plant species, 11 are listed as threatened (two as Critically Endangered “CR”, three as Endangered “EN” and six as Vulnerable “VU”) (Figure 1). The geographic coverage of the five 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 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 globosa*, 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 species group includes genera *Avicennia* and *Rhizophora*, which protect coastal areas from erosion, salt water intrusion, storms, high tides, and floods [54,73,74]. 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 in the Eastern Tropical Pacific region ranging from Mexico to Colombia [68,71,75] (Figure 1).

Several terrestrial animal species, like the yellow-shouldered blackbird (*Agelaius xanthomus*) and the Philippine cockatoo (*Cacatua haematuropygia*), which used many of the threatened mangroves species as the last refuge, have now gone extinct [63,76,77].

5. Drivers of Mangrove Deforestation

Figure 2 provides a representation of the drivers and driver groups of global mangrove deforestation identified by our consolidated literature. We identified two major groups of environmental drivers: Climate change and extreme events, and four groups of anthropogenic drivers: Aquaculture and agriculture, settlements and urbanization, industrialization and pollution, and flow modification. The driver groups and drivers' distribution among the groups are drawn from the keyword sets used for the literature search and the returned literature results (Table 1). The environmental driver group referred to the drivers that originate from the environment, although they can be influenced by anthropogenic activities. By contrast, anthropogenic drivers originate from human and socio-economic activities, which might be triggered by available environmental (and mangrove) resources. The driver sub-group of climate change included gradual changes related to the global sea level, global and regional temperature and precipitation patterns, and associated geological changes, e.g., salinity intrusions. The subgroup of extreme events involved abrupt natural perturbations like cyclones and Tsunamis. Two driver subgroups emerged from the keyword "Land changes": (1) Aquaculture and agriculture and (2) settlements and urbanization. The aquaculture and agriculture group referred to aquaculture- and agriculture-related activities that directly replaced mangrove forests, while settlements and urbanization included settlement expansions and urbanization processes that directly replaced or indirectly degraded mangrove forests, e.g., timber extraction for furniture and charcoal production and encroachments. The industrialization and pollution subgroup included drivers related to industrial and commercial activities and associated discharges and pollution. The final subgroup flow modification included drivers related to the diversion and withdrawal of upstream surface water and associated geological changes, e.g., subsidence and sedimentation. In Table 3, the environmental and anthropogenic drivers of mangrove deforestation and their geographic coverage of effects are presented. We explain the drivers and their impacts in Sections 6 and 7.

Our reviewed studies pointed to aquaculture and agriculture, and related anthropogenic activities as the predominant driver of global mangrove deforestation, although the geographic coverage of their effects varied (Table 3). Gradual climate variations, i.e., sea-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).

6. Environmental Drivers

6.1. Climate Change

Seventy-nine (39%) of our consolidated studies indicated climate-change-driven coastline erosion, salinity intrusion, and acidity as a dominant environmental driver of mangrove deforestation (Table 3). Climate change 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 change the composition of mangrove species [78]. The geographic coverage of climate change impacts covered almost all mangrove-containing countries (Table 3).

6.1.1. Sea-Level Rise

A review of published literature on the impacts of global climate change revealed sea-level rise as a major driver for mangrove loss [44,79,80]. Global-warming-driven melting of polar ice caps is projected to increase the global sea level by 0.18–0.59 m between 2090 and 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 km² areal loss of mangrove forests between 2000 and 2015 [87].

The increase in sea level can be coupled with extreme high water occurrences as a consequence of the fluctuations in oceanic circulations, such as El Nino Southern Oscillation (ENSO) [88] and ‘Northern Atlantic Oscillation (NAO)’ [89] and temperature regimes [90]. Such an increase in the high water occurrences may further increase the mean tidal level and impose coastal sediments to sulfide toxicity [5,35].

6.1.2. 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 [91]. The warming could further accelerate, ranging from about 0.2 °C per decade to 0.4–0.8 °C per decade if emissions reduction strategies fail and aerosols were to be rapidly removed [92].

Increased temperature affects mangrove forests by changing the ecosystem configuration and the species distribution as well as by reducing mangrove productivity rate and changing their phenological patterns [53]. For example, the mangrove canopy heights and biomass depend on the temperature regimes. An exceedance of the temperature regime threshold may decrease canopy growth by 1–2 m [93]. Global warming caused an increase in the frequency and intensity of heat waves drive habitat losses in the mangrove forests through defoliation and intense herbivory. For example, Hong Kong lost 22% of the mangrove coverage due to summer heat-wave-driven defoliation in the flowering seasons leading to low reproductivity and fewer seedlings [94]. Exceedance of the temperature regimes may also drive the extinction of mangrove species, as dominantly for the cases of *Sonneratia griffithii* and *Bruguiera hainesii* in Southeast Asia [71].

“Hard freeze” (sudden temperature drop below −3 °C) is a natural phenomenon in winter in Southwest Florida, to which the local mangrove forests have adapted [65]. With the decreasing hard freeze events due to global warming, invasive plant species are advantaged and replacing local mangrove species in this region [95]. Moreover, the sudden high temperature occurrences before and after the hard freeze events slowed down the mangrove recovery preparations and follow-up processes [96]. However, the decreasing hard freeze events due to global warming coupled with sea-level rise may also expand the mangrove belts towards the higher altitudes and thus entail a northward shift in the global mangrove belt [97].

6.1.3. Changes in Precipitation Patterns

Global warming may cause a 25% increase in the global average precipitation by 2050 [98], although the regional patterns will vary, i.e., precipitation will increase in high latitudes, whereas it will decrease in most subtropical countries that contains mangrove forests [99,100]. 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. Consequently, the coverage of mangrove forests may shrink, particularly where mangroves are already at their precipitation limits, e.g., in the arid zones of Africa and Central and South America [54,100,101]. The decreased precipitation may also drive groundwater depletion and reduce freshwater supply to

mangrove forests, which further exacerbate salinity intrusion in coastal wetlands and mangrove forests [100,102,103].

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 [53]. The diversity of mangrove species may also increase as a result of increased fluvial sand deposits and nutrients, as well as abridged sulfate levels and decreased salinity in the high latitudinal regions, e.g., South Florida [33]. However, heavy and flash precipitation events can cause an overflow of coastal water bodies and introduce freshwater channels through the coastal uplands, which can transport sediments accumulated downstream back to upstream coastal areas. Such sediments overflow occurred in the Choluteca River on the Pacific coast of Honduras during Hurricane Mitch in 1998 [104] and in the Tijuana River in Southern California during the El Niño storm of 1993 [105], causing severe damage to the mangrove forests in these areas [105].

6.2. 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 from tropical cyclones and hurricanes, along with an increase in their frequency of occurrences [92]. These impact mangrove forests temporarily through three primary means: Sediment deposition, wind damage, and submersion [35]. The intense winds lead to sudden gusts and consequently topple stems, causing defoliation of the canopies and damage of the mangrove tree branches [106]. Cyclones and hurricanes may also uproot mangrove trees through strong wind flow [107]. This may also affect soil stability and lead to soil erosion in mangrove forests [105]. The long-term impacts of cyclones on the mangrove forests are the decreased fertility rate, delayed seedling seasons, and changes in the coastal hydrology, causing permanent ecosystem conversion [108]. Moreover, with the increased cyclone and hurricane occurrences, mangrove forests may lack the time required for recovery from the temporary damages and hence, may encounter permanent loss [64].

Damage to several mangrove regions by cyclones and hurricanes was noted in 47 (23%) of our consolidated studies (Table 3). For example, the Caribbean hurricane 'Joan' in 1988 caused 11% areal damage to the mangrove forests in the Caribbean and Central America with reduced soil stability, permanent loss of several mangrove species, and loss of forest density [109]. 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 [110]. The Sundarbans encountered areal damage of 2500 km² by the tropical cyclone Sidr in 2007 [26]. Mangrove regions in Orissa and Tamilnadu in India experienced severe damage by several cyclones, e.g., the Super cyclone in 1999 [111], Vardah cyclone in 2016 [112], Ockhi cyclone in 2017 [113], and Gaja cyclone in 2018 [114].

Tsunamis have emerged as an environmental driver of mangrove deforestation, leaving permanent damage to coastal mangrove ecosystems [115]. Particularly, the Great Tsunami of 2004, which was 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 km² areal loss of mangrove forests in 14 countries [116,117]. 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 km², 7.5 km² and 3 km² of mangrove forest coverage as a result of this tsunami, respectively [118–120]. Tsunami-driven mangrove cover and habitat losses were also observed later in Japan in 2011 and Papua New Guinea in 1999 [115,121,122].

7. Anthropogenic Drivers

7.1. 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% loss of the global mangrove coverage [3,31,66]. Besides conversion of mangrove forests for fisheries and plantations, aquaculture and agriculture were associated with reduced ground water levels, and soil and water pollution from the effluents, which further intensified mangrove deforestation [123]. For example, the mangrove habitat loss in Kenya during 2000–2010 was associated with soil and water pollution [124], caused by agricultural and aquacultural intensification [66,125]. Aquaculture and agriculture were also shown to be the main driver of loss for the CR and EN mangrove species [71,72].

Globally, shrimp and other forms of aquaculture drove the 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 [38,126]. Thailand and Vietnam are the hotspots of mangrove deforestation by aquaculture that encountered mangrove forests loss at an average rate of 0.09 km² per year between 1990 and 2020 [39]. In Vietnam, 1020 km² of mangrove areas were converted into aquaculture between 1990 and 2019, followed by 694 km² in Thailand and 65 km² in Bangladesh. In India, about 40% of mangrove habitats on the western coastline have been transformed for aquaculture [127]. About 2055 km² and 2110 km² of mangrove marshlands have been transformed into shrimp and other fish farms in the Philippines and Indonesia, respectively [128]. A major decline of mangrove forests in Latin America, such as mangrove losses of 216 km² in Ecuador, and 115 km² in Honduras [108], is also associated with large scale shrimp farms and agricultural development [129].

Intensification of agriculture is another dominant driver of deforestation in all mangrove regions, particularly in South Asia and Latin America. For example, the majority of mangrove areas in the Philippines and Indonesia were replaced by agriculture [123]. The recent growth of oil palm plantations in Thailand, Malaysia, Sumatra, Colombia, and Indonesia is the main driver of mangrove forests loss in these areas [38,130]. The increasing demand for palm oil in Indonesia drove an areal expansion of palm plantations by 30% between 2012 and 2019 by replacing mangrove forests [131]. Mangroves in Central America have been mostly cleared for cattle grazing and industrial farming [132].

7.2. 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 extraction, have led to the destruction of significant mangrove areas in Asia and Africa during the past 20 years [38,133]. Human settlements occupy 150 km along the global coastal belt that previously contained mangrove forests, among other coastal wetlands [32,134]. The human population density in coastal regions is around 80 people per sq km [135], and urbanization in coastal areas is expanding, particularly in low-lying areas in developing countries [136]. For example, nearly 50% of the population in African countries and Bangladesh lives at the coastline, which affects the adjacent mangrove ecosystems [137].

The geographic coverage of the effect of settlements and urbanization is predominantly Asia and Africa [138]. Particularly, the Indian Ocean coastline, which contains mangrove forests with rich biodiversity expanding over several countries, such as Sri Lanka, Myanmar, Bangladesh, Singapore, Indonesia, and Australia, has been encountering mangrove coverage loss during the last three decades due to urban encroachment [139]. Sub-Saharan countries, such as Mauritania, Comoros, Djibouti, and Somalia, encountered rapid urban development and associated mangrove loss [140]. In Indonesia, the Philippines, Guinea, and Guinea-Bissau, mangrove forests have been heavily exploited for wood harvesting and

timber extraction [64,141,142]. The VU species *Avicennia rumphiana* that dominantly occurs in Southeast Asia is threatened by the expansion of human settlements [19].

7.3. Industrialization and Pollution

Industrialization and pollution represent an emerging group of drivers of mangrove deforestation, as reported by 15% of our consolidated literature (Table 3) [142]. The Caribbean mangrove zone, which encountered the second-highest areal loss after Asia over the past three decades, was impacted by sewage, oil spill, solid wastes, and conversion to landfills, mainly driven by rapid industrialization [7,143,144]. In India, a considerable amount of stress on mangroves has been caused by domestic and industrial wastes, heavy metals, and other toxic discharges, for example, discharges from thermal power stations in Ennore and Tuticorin [145], Vedanta Sterlite Copper industry in Tuticorin, nuclear power plants in Kudankulam, and dye factories in Kalpakkam [146]. A recent project of the Indian Government for drilling in the Cauvery delta region for hydrocarbon and methane exploration threatened Pichavaram mangrove forest, Tamilnadu, which lies only 490 meters away from the exploration zone sheltering the inhabitants of Tamilnadu coast from natural calamities such as the 2004 tsunami [147].

Petroleum explorations, for example, in the Persian Gulf zone, resulted in oil spills from oil wells, oil refiners, and oil transports, which, in turn, led to pollution, driving substantial mangrove habitat loss [148]. These activities can also lead to accidents, for example, the Gulf of Mexico oil spill in 2010 affected 10% of the mangrove forests in the region, with a residue impact lasting for 10 years [149]. In 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 [150].

Immobilization of heavy metals, such as copper, iron, magnesium, manganese, zinc, mercury, lead, and tin, has emerged as a driver of mangrove deforestation globally [151,152]. At a low level of heavy metal contamination, mangrove forests may act as biological pollution sinks [153]. 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 [32,142,154,155]. However, the increasing contamination and discharges of heavy metals can exceed mangrove sink capacity and cause damage [152].

7.4. Flow Modification

Flow modification by diverting upland water flows diminishes mangrove productivity, as identified by 20 (8%) of our consolidated literature [133]. In Asia, the construction of upstream reservoirs and dams reduced the supply of sediments to several deltaic mangrove regions, including the Ganges and Cauvery in India, the Sundarbans deltas of India and Bangladesh, and the Indus river delta of Pakistan, leading to a decrease in sediment deficit in coastal wetlands of these regions [156]. Likewise, the annual sediment flow to the deltaic regions of China decreased from 1.1 billion metric tons in 1994 to 0.4 billion metric tons in 2009 [87,140].

Coastal erosion prevention structures and seawalls lead to the modification of surface run-off by obstructing downwards currents and inundation in the mangrove forests during flash flood events [64,150,157]. In the Mississippi Delta, the construction of flood control walls led to hydrological disturbances in the deltaic plain and isolation of the river from the Delta, affecting the mangrove zone [158,159]. The conversion of mangrove areas into salt pans and the construction of river dams are the major causes of mangrove deforestation in Brazil [160].

8. Interactions among Drivers

Mangrove deforestation is the outcome of complex interactions among the interconnected environmental and anthropogenic drivers [161]. Our consolidated literature suggests that the drivers may interact within and across their groups and may thus amplify their impacts on mangroves [116,140,162] (Figure 3). For example, climate-change-induced

decreased precipitation and drought events lead to an increase in groundwater extraction and thus, flow modification [30]. The increase in the upstream groundwater extraction in turn exacerbate the salinity intrusion induced by climate change in the downstream coastal mangrove zones [163]. Moreover, expansion of aquaculture and agriculture also leads to an increase in groundwater extraction and flow modification in the coastal zones, which also, in turn, leads to an increased salinity intrusion [40].

Settlements and urbanization in the coastal wetland zones directly lead to interruptions and alternations in the hydrological and sedimentation processes [164]. Settlements and urbanization are also major sources of pollution and nutrient overload [12]. The urbanization processes also lead to an expansion of aquaculture and agriculture in the vicinity, which may also be sources of pollution in the mangroves [165]. In fact, the driver groups aquaculture and agriculture and industrialization and pollution exhibited the strongest interaction in our consolidated literature (Figure 3).

A considerable dieback of mangrove forests that occurred between 2015 and 2016 in the Northwest Australian coastline is an example of the interaction among driver groups regarding climate changes, extreme events, and flow modification [166,167]. 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 [167]. The interaction among these drivers led to mangrove canopy loss, degraded vegetation health, and reduced recruitment, which in combination, led to an irreversible dieback event.

Climate change can amplify and widen the coverage 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 conditions for reproduction [18,168]. These diseases and pests can lead to mangrove deforestation through branch and stem cankers, dieback, and leaf galls [18]. Several mangrove species were shown to be vulnerable to these climate-change-led diseases and pests, such as *Barringtonia racemosa* is vulnerable to fruit and leaf diseases, and *Hibiscus tiliaceus* is vulnerable to herbivory beetles [168]. The dieback and canker levels observed in *A. marina* are also associated with these diseases and pests.

The effects of sea-level rise on the minerogenic mangroves are often mediated by the availability of coastal sediments [169,170]. The availability of sediments often depends on the local tectonic progressions, erosion, and other geological processes [171]. When the coastal sediment level and the accretion rates are exceeded by the mean tidal levels as a result of sea-level rise, the minerogenic mangrove forests may encounter areal loss or even collapse [105].

The impacts of sea-level rise (climate changes) have been exacerbated by coastal subsidence in several regions [172]. Coastal subsidence results from excessive extraction of subsurface ground water (flow modification) 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 [103]. 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 [159,174,175]. Most of the mangrove forests in the Ganges–Brahmaputra–Meghna delta in India and Bangladesh are affected simultaneously by subsidence due to ground water extraction (flow modification) and erosion from the monsoons rains, and accelerated sea-level-rise (climate changes), 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]. Some mangrove species can withstand or recover

and regenerate from the impacts of strong cyclones and typhoons [26,179,180]. However, a net decline in the overall mangrove forests coverage has been reported for many global regions as a result of the interactions with anthropogenic drivers. For example, around 1000 km² 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 cyclone-damaged lands [29,35,178,181].

The drivers and their interactions may go beyond the specific driver groups of mangrove deforestation. Several coastal ecosystems, such as ocean algae, coral reefs, and seagrasses, are closely associated with adjacent mangrove forests [54,182]. For example, coral reefs supply nutrition to the downstream mangrove forests, shaping overall mangrove health and seedling rates [183]. 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 the productivity of mangrove forests [54,184].

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 [185]. 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.

9. Conclusions and Outlook

This review contributes to the global synthesis of mangrove deforestation scenarios over three decades, i.e., between 1990 and 2020. Our global level synthesis indicates the Southeast Asian region is particularly vulnerable to mangrove deforestation, with the 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 the monitoring of mangrove regions. For example, most of the deforested mangrove areas replaced with agriculture or other plantations have been misclassified as mangrove forests, particularly in Indonesia [126]. This is because oil palm plantations and palm orchards that replace mangrove forests may reflect the same color bands in satellite images [131]. Moreover, 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 [39,64,66]. 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.

Local extinction of threatened mangrove species may infer global loss. According to IUCN, there are no conservation measures specific to most of the threatened mangrove species. We, therefore, recommend continued monitoring and research on these species, as well as the inclusion of these species in the marine and coastal area protection programs [68]. Although mangroves are protected and marginally restored during the last decades in several regions (for example, *Avicennia integrata* [73] has been conserved in a remote area of northern Australia [186,187] and mangrove deforestation has been reversed in Costa Rica [188]), little is known about the achievements of these local conservation efforts while mangrove areas globally continue to decline. Hence, global coordination of these in-situ conservation actions is required with correct management of the Protected Areas Network to fully protect species and the entire mangrove ecosystems [189,190].

The data for drivers available from certain areas needed to be consolidated to arrive at our global driver 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 updating 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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Appendix A

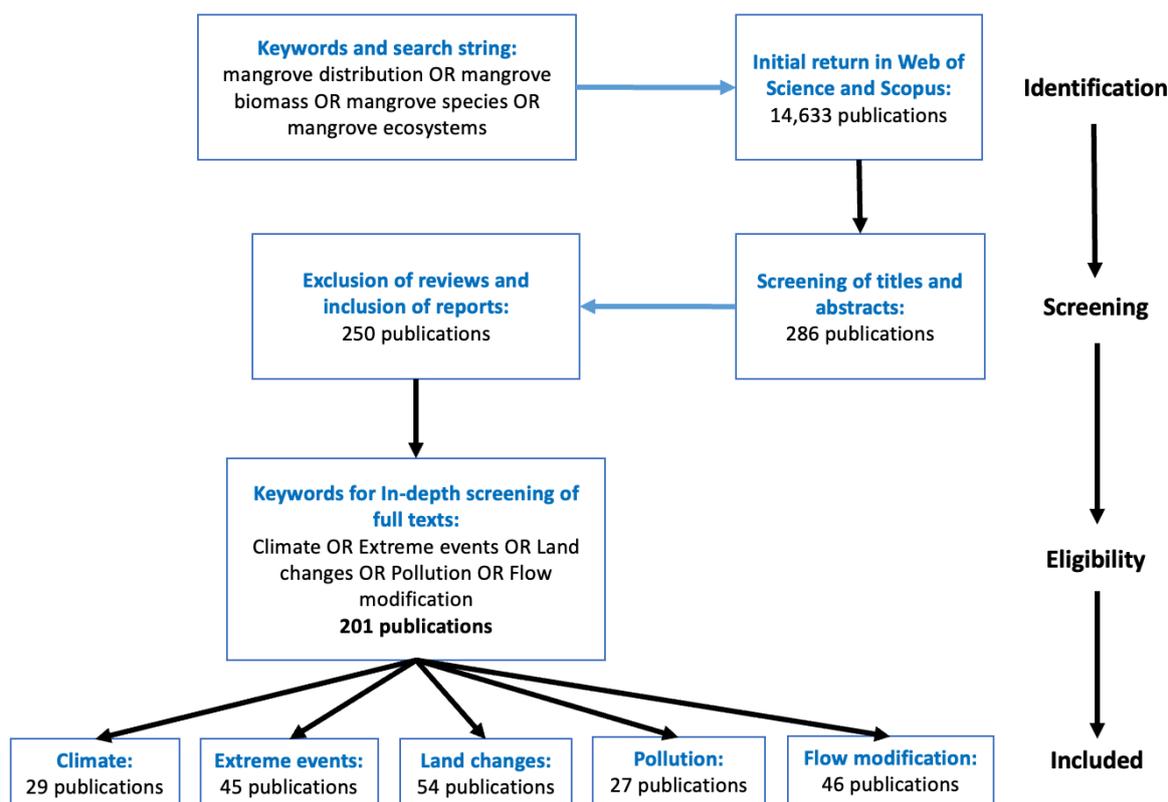


Figure A1. The schema for this review following the PRISMA framework [50].

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