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REVIEW

Mangroves of the Maldives: a review of their distribution, diversity, ecological importance and biodiversity of associated flora and fauna

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Abstract
Mangrove forests are one of the most important biological, ecological and economic ecosystems in the world. In the Maldives, they play a crucial role in maintaining coastal biodiversity, providing ecosystem services, such as coastal protection, and supporting livelihoods by providing income and food. Overall, 23 Maldivian islands have at least 1 protected mangrove area. However, knowledge of the mangroves of the Maldives is scarce, scattered and sometimes conflicting. There is a lack of information on a national scale regarding their distribution, diversity, ecological importance and associated biodiversity. The aim of this review is to analyse scientific publications, reports, and online documents on mangroves for the entire Maldivian archipelago to provide the first comprehensive summary of the current state of knowledge of mangroves from a national perspective. This includes the geographical location of mangrove forests, the identity and distribution of mangrove species, ecosystem services, ecological importance and diversity of mangrove-associated flora and fauna. We analysed available information from both the grey literature and scientific publications and found that 14 mangrove species have been documented on 108 islands (9% of all Maldivian islands). Mangroves are mainly concentrated in northern atolls and are associated with diverse flora and fauna. Furthermore, we identified inconsistencies and gaps in the literature and proposed future directions for research. This is crucial for informed decision-making, developing effective conservation strategies and long-term sustainability of mangrove ecosystems.

Keywords Mangrove ecology · Geographical distribution · Mangrove species · Literature review · Maldives biodiversity · Ecosystem services

Introduction

Mangroves are a group of salt-tolerant woody plants that grow in the intertidal region where seawater and freshwater mix. Mangroves are mostly confined to tropical and subtropical latitudes, between 30° north and 30° south (Kandasamy and Bingham 2001; Selvam 2007). They are able to cope with dynamic and extreme conditions, such as high and variable salt concentrations (as a consequence of tides and precipitation), high temperatures, strong winds and anaerobic soils, owing to morphological, biological, ecological, and physiological adaptations (Kandasamy and Bingham 2001; Srikanth et al. 2016). Such adaptations include specialised above-ground roots called breathing roots or pneumatophores, stilt roots, vivipary and salt exclusion and secretion (Scholander 1968; Shi et al. 2005; Selvam 2007; Srikanth et al. 2016).

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Mangrove ecosystems are one of the most productive ecosystems in the world. They are important both biologically and ecologically; supporting several terrestrial, estuarine and marine species through habitat and food provision, and playing a crucial role for other coastal marine environments, such as coral reefs and seagrass beds, by acting both as a source and a reservoir of nutrients and sediments (Polidoro et al. 2010; Agardy et al. 2017). Furthermore, mangrove forests make a significant contribution to ecosystem services (Zhang et al. 2018) which have been estimated to have an economic value of at least US$1.6 billion annually (Costanza et al. 1997). For example, they are able to stabilise shorelines, thereby preventing coastal erosion, reduce the devastating impacts of natural disasters, such as tsunamis, provide food (e.g. 80% of global fish catch depend on mangroves), sequester up to 25.5 million tonnes of carbon per year, control fluxes of energy and nutrients in the water column, neutralise toxins and heavy metals, regulate salt balances, contribute to recreation and touristic activities and provide a source of novel compounds for drug discovery, as well as medicines, edible by-products, firewood fuel and building materials (Eong 1993; Dahdouh-Guebas et al. 2015; Das and Vincent 2009; Polidoro et al. 2010; Duke et al. 2014; Agardy et al. 2017; Spalding and Parrett 2019; Cerri et al. 2022).

However, mangrove forests are among the most threatened ecosystems on the planet, with the overall rate of mangrove loss being three-to-five times that of global forests (Duke et al. 2014). Up to 35% of mangrove areas have been lost since the 1980s (Curnick et al. 2019), mainly owing to overexploitation of their resources and land conversion for aquaculture, agriculture and urban coastal developments (Valiela et al. 2001; Upadhyay et al. 2002; Ellison 2008). Furthermore, the rate of loss is accelerating and the functional disappearance of mangrove forests is predicted to occur within the next 100 years (Duke et al. 2007; Polidoro et al. 2010). Owing to this rapid decline and to better manage their protection and restoration, it is imperative to further the knowledge about these ecosystems.

Mangrove forests have been studied for many years, yet in many countries they remain poorly understood. For example, in the Maldives, mangrove ecosystems are facing increasing anthropogenic threats, such as infrastructure development, improper waste disposal, plastic pollution and land reclamation actions (Dryden et al. 2020a, b). However, information on mangroves in the Maldives is limited and scattered. The lack or absence of information about an ecosystem can hinder our understanding, impede management and conservation efforts, compromise decision making, limit assessments, hamper stakeholder engagement and lead to missed opportunities for sustainable development and conservation. The aim of this review is therefore to analyse and synthesise the existing data and information available on the mangroves of the Maldives. The objective is to present, for the first time, a comprehensive summary of the current state of knowledge regarding Maldivian mangrove forests.

Methods

A comprehensive review of scientific publications along with an examination of grey literature, unpublished materials and relevant information from Maldivian non-governmental organisations (NGOs) websites was conducted. Scientific articles and books were retrieved from online databases, such as Google Scholar, Scopus and Web of Science during the literature review process. The search incorporated a combination of the following terms: ‘mangrove’, ‘Maldives’, ‘species’, ‘geographic distribution’, ‘flora’, ‘fauna’ and ‘algae’. The grey literature sources reviewed for this study were diverse. The search incorporated commonly used online platforms, such as Google, as well as conventional repositories of information, such as government documents, NGOs’ websites, policy literature and white papers. Additionally, the review considered and ensured a thorough examination of published and unpublished material. Grey literature was not easily searchable through conventional databases, posing a barrier to obtaining up-to-date and comprehensive information about the studied ecosystem. To address this problem, we contacted local government officials and university representatives for guidance toward relevant documents.

Geomorphology and classification of mangroves in the Maldives

The mangrove forests in the Maldives are unique owing to the geomorphological nature of the country itself, which is an archipelago of 1192 islands, divided into 26 geographical atolls, stretching 870 km from 7° north to 0.5° south of the equator in the Indian Ocean (Fig. 1) (Stevens and Froman 2019). Mangroves are commonly found in estuaries, but there are no rivers in the Maldives. Therefore, in the Maldivian islands, the morphology of mangrove forests generally consists of small patches of mangrove plants present in closed or semi-enclosed brackish water bodies, ‘kulhi’ in the local language, or muddy regions locally known as ‘chasbin’. In general, the classification of mangrove forests in the Maldives consists of closed and open mangrove systems. Closed systems are further subdivided into lake-based inland mangroves, in which mangroves surround a brackish pond formed in a depression in the land, and marsh-based inland mangroves, in which mangroves are located in a muddy area. Open systems, on the other hand, can be further subdivided into coastal

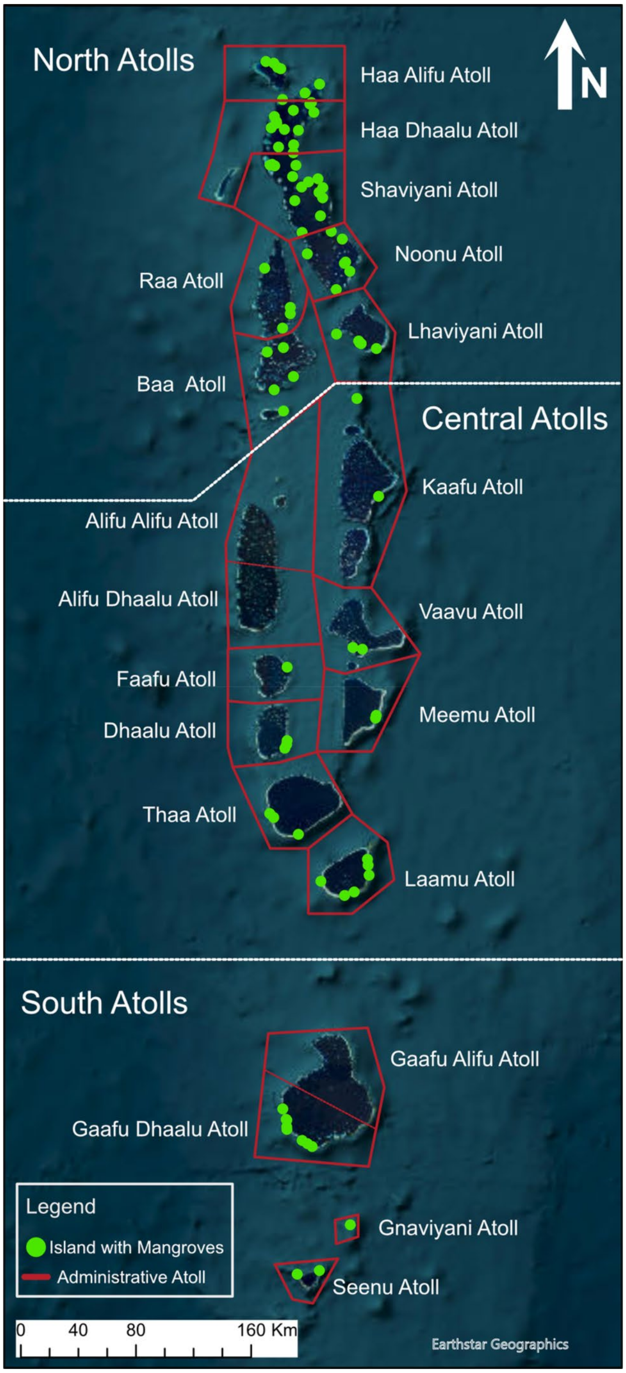

Fig. 1 Distribution of islands with a reported presence of mangroves (green points) in the Maldives according to our review of the literature. The different atolls are indicated in red boxes (Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

fringe mangroves, in which the mangroves lie on the shore directly exposed to the sea, and bay mangroves, which are subject to daily tidal flushing (Saleem and Nileysha 2003; Shadiya et al. 2016).

Species diversity of mangroves in the Maldives

Mangrove species are classified as 'true mangrove' species and 'mangrove associates'. True mangrove species are exclusively found in tropical intertidal habitats, whereas mangrove associates are not exclusive to these habitats but are also distributed in terrestrial or aquatic habitats (Lugo and Snedaker 1974; Parani et al. 1998; Polidoro et al. 2010). Tomlinson (1996) introduced strict criteria to classify a true mangrove, namely that it must be found exclusively in the mangrove environment, have morphological specialisations (aerial roots, gas exchange mechanisms and viviparity), have a physiological mechanism for salt exclusion and/or excretion and be taxonomically isolated from terrestrial relatives (Wang et al. 2010; Kandasamy and Bingham 2001). Moreover, Duke (1992) defined a true mangrove species as a tree, shrub, palm or ground fern exceeding 0.5 m in height, and which normally grows above mean sea level in the intertidal zone of coastal or estuarine environments (Polidoro et al. 2010). Kandasamy and Bingham (2001) considered the historical classifications and recognised 65 true mangrove species in 22 genera and 16 families globally. However, for some species, a consensus among scientists was not found, and the classification remains debatable. Wang et al. (2010) defined these as 'controversial' species and differentiated them on the basis of leaf traits and osmotic properties. They categorised as 'controversial' those species for which there is, as yet, no acceptable classification consensus whether to include them in the group of true mangroves or in the group of mangrove associate species.

In the Maldives, the exact number of mangrove species present in the archipelago varies in literature; limited information is available on the methodology used for species identification. In 2007, the Ministry of Fisheries, Agriculture and Marine Resources of the Maldives reported the occurrence of 13 mangrove species with their respective characteristics, such as status, description, uses, ecology, propagation and management (Selvam 2007). The species reported were: *Avicennia marina*, *Bruguiera cylindrica*, *Bruguiera gymnorrizha*, *Bruguiera sexangula*, *Ceriops tagal*, *Excoecaria agallocha*, *Heritiera littoralis*, *Lumnitzera racemosa*, *Pemphis acidula*, *Rhizophora apiculata*, *Rhizophora mucronata*, *Sonneratia caseolaris* and *Xylocarpus rumphii*. In addition to these 13 species, Dryden et al. (2020a, b) reported the presence of *Bruguiera hainesii* in the Maldives, a hybrid species between *B. cylindrica* and *B. gymnorrhiza* (Ono et al. 2016). However, there are other sources in literature that report different species. For example, in a study conducted by Saleem and Nileysha (2003), it was reported that the number of mangrove species was 14. In comparison with Selvam (2007), Saleem and Nileysha (2003) specifically reported three species of *Rhizophora* instead of two, indicated the occurrence of *Xylocarpus moluccensis* instead of *Xylocarpus rumphii* and noted the presence of *Derris heterophylla*. Furthermore, they classified *Pemphis acidula* as a mangrove associate rather than a true mangrove. The non-governmental organisation (NGO), Bluepeace (2007) reported 13 mangrove species, including the presence of the mangrove fern *Acrostichium aureum*, while *Xylocarpus* spp. and *P. acidula* were not indicated. Furthermore, Dhunya et al. (2017) and Sivakumar et al. (2018) reported 14 and 15 mangrove species, respectively, but the species names were not specified in both studies.

Acrostichum auerum, *Derris heterophylla* and *Xylocarpus rumphii* are not considered mangrove species according to Kandasamy and Bingham (2001); *Xylocarpus rumphii* is a rare non-mangrove plant (Guo et al. 2018) and *Acrostichum aureum* and *Derris heterophylla* are mangrove associate species (Das et al. 2002; Mukherjee et al. 2006; Wang et al. 2010). On the basis of the above articles, we suggest that in the Maldives there are 14 mangrove species: *A. marina*, *B. cylindrica*, *B. gymnorrhiza*, *B. hainesii*, *B. sexangula*, *C. tagal*, *E. agallocha*, *H. littoralis*, *L. racemosa*, *P. acidula*, *R. apiculata*, *R. mucronata*, *S. caseolaris* and *X. moluccensis*, of which 3 are considered as controversial species, (*E. agallocha*, *H. littoralis* and *P. acidula*) (Wang et al. 2010). The mangrove species of the Maldives are reported in Table 1. Their vulnerability status is also given according to the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (Polidoro et al. 2010). Family name (Polidoro et al. 2010), common name and local name (Dhivehi) (Selvam 2007; Save Maldives 2020; Ali 2020) are also given.

The possible reasons for the inconsistencies in the number and identity of species reported in the different studies conducted in the Maldives, include:

(i) unclear classification between true or associate mangrove species for so-called 'controversial' species. The same species can be considered true mangrove or mangrove associate according to different sources.

(ii) Differences in taxonomic expertise among researchers can influence the precision of species identification and lead to variations in reported species numbers.

(iii) Different studies may employ different taxonomic approaches or classifications, leading to variations in species identification and categorisation. Taxonomic revisions or advances in species identification techniques can also result in discrepancies between studies.

(iv) Studies might have focused on specific regions or sampling sites, resulting in variations in the observed species composition. Differences in sampling methodologies, such as sampling effort, spatial coverage or seasonal variations, can also contribute to discrepancies.

(v) Mangrove ecosystems are dynamic and can undergo natural variations and ecological succession over time. Different studies carried out at different periods may capture different stages of ecosystem development, leading to variations in observed species diversity.

Table 1 Mangrove species of the Maldives

Scientific name	Family	Common name	Local name (Dhivehi)	IUCN Red List Category	Classification
Avicennia marina	Acanthaceae	Grey mangrove	Baru	LC	TS
Bruguiera cylindrica	Rhizophoraceae	Small-leafed orange mangrove	Kan'doo	LC	TS
Bruguiera gymnorrhiza	Rhizophoraceae	Oriental mangrove or large-leafed mangrove	Bodukandoo or Bodavaki	LC	TS
Bruguiera hainesii	Rhizophoraceae	Eye of the crocodile	Kelavaki, or bodukandoo or makandoo	CR	TS
Bruguiera sexangula	Rhizophoraceae	Upriver orange mangrove	Bodavaki	LC	TS
Ceriops tagal	Rhizophoraceae	Yellow mangrove	Karamana	LC	TS
Excoecaria agallocha	Euphorbiaceae	Blind-your eye mangrove or milky mangrove	Thela	LC	CS
Heritiera littoralis	Malvaceae	Looking-glass mangrove	Kaharuvah	LC	CS
Lumnitzera racemosa	Combretaceae	Black mangrove	Burevi	LC	TS
Rhizophora apiculata	Rhizophoraceae	Tall-stilt mangrove	Thakafathi	LC	TS
Rhizophora mucronata	Rhizophoraceae	Red mangrove	Ran'doo	LC	TS
Sonneratia caseolaris	Lythraceae	Mangrove apple	Kuhlhavah	LC	TS
Pemphis acidula	Lythraceae	Ironwood	Kuredhi	LC	CS
Xylocarpus moluccensis	Meliaceae	Cannonball tree or puzzlenut tree	Marugas	LC	TS

LC least concern, *CR* critically endangered, *CS* controversial species, *TS* true mangrove species

Distribution of mangroves in the Maldives

Considering information from various sources, mangroves have been reported on different islands of the Maldivian archipelago (Fig. 1). The total area of wetlands and mangroves is estimated to be approximately 7.39 km^2 (Ministry of Environment and Energy [MEE] 2015). Reports show that not all mangrove species can be found on a single island. This could be due to the relatively small size of both the mangrove forests and the Maldivian islands; they may not be able to sustain a high diversity of species. The distribution of the different species can also be affected by environmental variations. From north to south of the archipelago, the environmental conditions are different, restricting the distribution of some species to specific geographical locations (Shazra et al. 2008). The dominant mangrove species are *B. cylindrica*, *B. gymnorhiza*, *L. racemosa* and *P. acidula*, while other species are occasional and rare, such as *H. littoralis* and *B. hainesii* (Selvam 2007). Saleem and Nileysha (2003) reported the occurrence of mangroves on at least 150 islands. On the basis of the literature and the website of the Maldivian Environmental Protection Agency (EPA) (https://en.epa.gov.mv/), where protected and sensitive areas are reported, below we summarise the mangrove species present for each of the 20 administrative atolls, their health and conservation status. The names of atolls and islands and the subdivision of the archipelago into northern, central and southern atolls follow that of Fallati et al. (2017).

Haa Alifu Atoll

Haa Alifu Atoll, officially known as Thiladhunmathi Uthuruburi (or Northern Thiladhunmathi Atoll), is the third largest atoll in terms of land area in the northest administrative division of the Maldives. Mangrove forests on the islands of Baarah, Kelaa and Gallandhoo were declared protected areas by the Ministry of Environment of the Maldives (Protected Area Announcement (IUL) 438-ENV- 438–2018-322 and (IUL)438-ENV-438-2019-150). On Baarah Island there are several wetland areas but only some are protected. Bluepeace conducted a comprehensive baseline study on the ten different wetlands identified on the island and for each water body, the presence of mangroves and their distribution was evaluated. The wetlands within the protected area are those that present the highest mangrove diversity on the island, while the two non-protected wetlands do not host any mangroves. The most common species was *B. cylindrica*. The other species reported were *C. tagal*, *E. agallocha*, *L. racemosa*, *R. apiculata* and *R. mucronata* (Bluepeace 2007). Shazra et al. (2008) further identified *P. acidula* in the atoll. The Kelaa mangrove forest plays an important ecological role owing to the diversity and abundance of mangrove trees that host various species of birds and invertebrates (Dryden et al. 2020a, b). Kelaa's mangrove ecosystem comprises one of the most extensive areas of *B. cylindrica* (locally known as 'kandoofaa') in the Maldives (Island Development and Environmental Awareness Society [IDEAS] 2017). The other mangrove species on the island are *B. gymnorrhiza*, *L. racemosa*, *S. caseolaris*, *Acrostichium aureum* (Dryden et al. 2020a, b) and *R. mucronata* (IDEAS 2017). Dryden et al. (2020a, b) also reported the presence of four *Bruguiera hainesii* trees for the first time in the Maldives. *B. hainesii* is a 'critically endangered' mangrove plant according to the IUCN Red list of threatened species, with fewer than 250 mature trees remaining globally (Polidoro et al. 2010).

Mangroves are also reported in Berinmadhoo, Maafahi, Madulu, Maarandhoo, Muraidhoo, Naridhoo, Uligan and Vangaaru (EPA Sensitive Areas 2015), and on Thakandhoo Island a strip of mangroves is reported on the south-eastern side of the island (Naeem 2008).

Additionally, Bluepeace (2015) reported five small wetland areas on Filladhoo Island. The mangroves are at the perimeter of three of these water bodies. The observed species were *B. cylindrica*, *L. racemosa* and *R. apiculata* (Bluepeace 2015). MEE (2015) also reported the presence of *B. gymnorrhiza* on that island. Furthermore, Dhapparu Island, an island physically connected to Filladhoo by a strip of land and recently re-placed under its jurisdiction, has a water body surrounded by *R. mucronata* and *R. apiculata* (Bluepeace 2015).

In summary, based on the information from the different sources, mangroves have been reported on 13 islands of Haa Alifu Atoll (Fig. 2). In total, ten species have been reported, including *A. aureum*, *B. cylindrica*, *B. gymnorrhiza*, *B. hainesii*, *C. tagal*, *E. agallocha*, *L. racemosa*, *R. apiculata*, *R. mucronata* and *S. caseolaris* (Table S1, Supplementary Information).

Haa Dhaalu Atoll

Haa Dhaalu Atoll, officially known as Thiladhunmathi Dhekunuburi (or Southern Thiladhunmathi Atoll), comprises several islands with a reported presence of mangroves. Among them, the mangrove forests of Keylakunu and Neykurendhoo have been declared protected areas (Protected Area Announcement (IUL)438-ENV- 438-2018-322). The entire Island of Keylakunu is a protected area. The mangrove forest is located within a wetland area in the southeastern part of the island, which includes two separate water bodies. The available reports exhibit discrepancies with respect to the diversity of species present on the island. Bluepeace (2015) reported that the mangrove forest is dominated by *B. cylindrica*. The other reported species were *R. apiculata*, *E. agallocha*

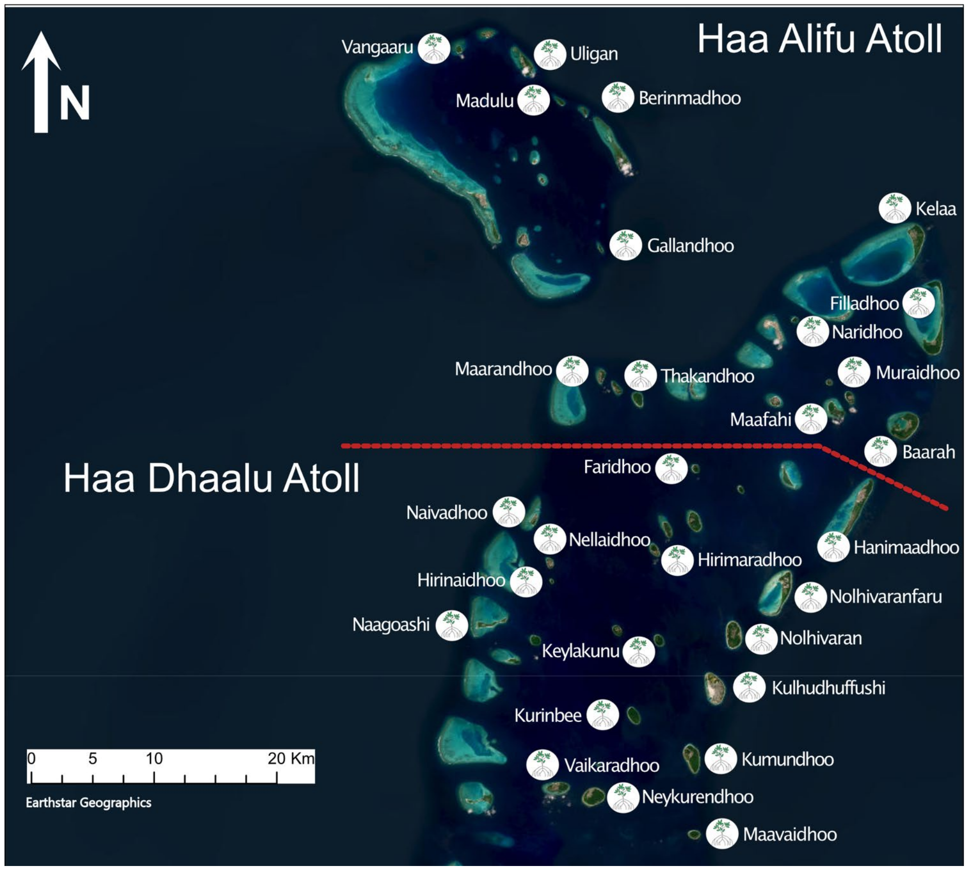

Fig. 2 Geographic location of islands with a reported presence of mangroves in Haa Alifu Atoll and Haa Dhaalu Atoll (Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

and *A. marina* (Bluepeace 2015). On the other hand, the IUCN (2020) reported that the species present were *B. cylindrica*, *R. mucronata* (found in the area of mangroves with highest water depth), *A. marina*, *P. acidula* and a single *S. caseolaris* tree (found at the northern end of the mangrove forest). The second protected mangrove area is the wetland with the two water bodies on the eastern side of the Island of Neykurendhoo. Bluepeace (2015) reported that *B. cylindrica* was abundant in that area. The presence of *E. agallocha*, *L. racemosa* and *X. moluccensis* was also observed.

The EPA reported the presence of mangroves in Faridhoo, Hanimaadhoo, Hirinaidhoo, Kulhudhuffushi, Kumundhoo, Kurinbee, Maavaidhoo, Naagoashi, Naivaadhoo, Nellaidhoo, Nolhivaran and Vaikaradhoo (EPA Sensitive Areas 2015). However, for most of these islands, no further details on mangrove forests have been found in literature. Kulhudhuffushi, the capital island of Haa Dhaalu, is the most well documented. The island gets its name from the mangrove forest (Jaufar 2021) and the dominant species reported are *L. racemosa*, *B. cylindrica* and *R. mucronata* (IUCN 2019). The presence of *S. caseolaris* was also observed on the island (MEE 2015). Curnick et al. (2019) estimated that the construction of an airport may have destroyed 70% of the mangrove forests.

Additionally, the presence of a mangrove forest has been reported in a wetland in Nolhivaranfaru (IDEAS 2018a). The wetland is reported to consist of *B. cylindrica* trees around the perimeter of a water body, together with patches of *P. acidula*. These mangroves create a belt between the lake and the sea and are subject to tidal flooding. Near the beach, two *X. moluccensis* trees have been documented. *R. mucronata* has been reported in high abundance around another smaller water body (IDEAS 2018a). In Hirimaradhoo, the presence of a wetland area has been documented and listed as a sensitive area by the EPA (EPA Sensitive Areas 2015). Saleem and Nileysha (2003) reported the presence of mangroves in the area. This mangrove forest is classified as embayment mangrove.

Taking into account the data gathered from various sources, mangroves have been reported on 16 islands of Haa Dhaalu Atoll (Fig. 2). In total, nine species have been documented, including *A. marina*, *B. cylindrica*, *E. agallocha*, *L. racemosa*, *P. acidula*, *R. apiculata*, *R. mucronata*, *S. caseolaris,* and *X. moluccensis* (Table S1, Supplementary Information).

Shaviyani Atoll

Shaviyani Atoll is officially known as Miladhunmadulu Uthuruburi Atoll (or Northern Miladhunmadulu Atoll). The entire Island of Farukolhu is a protected area [Protected Area Announcement (IUL)438-ENV- 438–2018-262]. In the south of the island there is a long mangrove bay dominated by *C. tagal*. Other species present include *P. acidula* and *R. mucronata* (IUCN 2020). *C. tagal* is a rare species, found only along the borders of this large lagoon and on the island just south of it (Selvam 2007). In the north of Farukolhu Island, there are several brackish-water ponds with patches of *R. mucronata*. Based on the information provided by the IUCN (2020), there is evidence that mangroves in this area are experiencing a decline in health.

Other islands with a documented presence of mangroves include Eriyadhoo, Feevah, Feydhoo, Firunbaidhoo, Foakaidhoo, Funadhoo, Gooidhoo, Kandeetheemu, Kudadhoo, Kudalhaimendhoo, Keekimini, Maakandoodhoo, Madidhoo, Maroshi, Migoodhoo, Milandhoo, Narudhoo, and Noomaraa (EPA Sensitive Areas 2015). More information from literature has been found only for Milandhoo and Maakandoodhoo. In Milandhoo, a water body is present, with *R. mucronata*, *L. racemosa* and *P. acidula* trees reported along its perimeter (IDEAS 2018b). Maakandoohoo has a large pond in the centre of the island and wetland areas in the north. There are no channels that connect the sea and the water bodies, but the marshy terrain is an indicator of a high water table on the island. The mangrove species *L. racemosa* and *B. cylindrica* are dominant at both sites, but the mangrove forest around the central water body is healthier than that found in the north. Other identified mangrove species include *A. aureum*, *E. agallocha* and *R. apiculata* (IUCN 2020).

Based on information compiled from different sources, mangroves have been reported on 19 islands of Shaviyani Atoll (Fig. 3). In total, seven species have been documented, including *A. aureum*, *B. cylindrica*, *C. tagal*, *E. agallocha*, *L. racemosa*, *P. acidula* and *R. mucronata* (Table S1, Supplementary Information).

Noonu Atoll

Noonu Atoll, officially known as the Southern Miladhunmadulu Atoll (or Miladhunmadulu Dhekunuburi), consists of two protected mangrove ecosystems: Bodulhaimendhoo and Kendhikulhudhoo (Protected Area Announcement (IUL)438-ENV-438–2019-150). Bodulhaimendhoo, is a small circular island with vegetation situated around the perimeter of a large brackish water body. The mangrove species *R. apiculata* and *P. acidula* have been reported there (IUCN 2020). Kendhikulhudhoo has a long mangrove forest on the eastern edge of the island. The forest consists of water bodies artificially connected to the sea to create a water flow for aquaculture activities. *Bruguiera* spp., *Rhizophora* spp. and *P. acidula* have been reported on the island (IUCN 2020).

In addition, mangroves have been documented on the islands of Burehifasdhoo, Goanbilivaadhoo, Kandoodhoo, Kuramaadhoo, Landhoo, Lhohi, and Manadhoo (EPA Sensitive Areas 2015). In literature, another report of mangroves on Landhoo was documented by Kathiresan and Rajendran (2005). Additionally, Nishan (2010) reported the presence of *C. tagal*, *E. agallocha* and *R. apiculata* on the Island of Maalhendhoo.

Based on the information collected for Noonu Atoll, mangroves have been reported on ten islands (Fig. 3). In total, seven species have been reported, including *Bruguiera* spp., *C. tagal*, *E. agallocha*, *P. acidula*, *R. apiculata* and *Rhizophora* sp. (Table S1, Supplementary Information).

Lhaviyani Atoll

Lhaviyani Atoll, officially known as Faadhippolhu Atoll, comprises two protected areas, in Dhiffushimaadhoo and in Maakoa, respectively (Protected Area Announcement (IUL)438-ENV-438–2020-179). Dhiffushimaadhoo is an uninhabited island that represents one of the richest natural heritage sites in the Maldives. It originally consisted of four separate islands (Dhiffushi, Maidhoo, Sehlhifushi and Hiriyadhoo) and is still evolving (Bluepeace 2008). This island has a huge bay area in the Lhohifushi-Hithaadhoo region where *P. acidula* is the dominant vegetation, and *H. littoralis* is also reported (IUCN 2020). Maakoa is also an uninhabited island under the jurisdiction of the Maldives National Defence Force (MNDF) owing to its proximity to Maafilaafushi Island, which hosts the northern military base of the MNDF. *P. acidula* is reported to be the dominant species. *B. cylindrica* has also been documented around the large pond found on the island (IUCN 2020).

The islands of Faadhoo, Kanifushi, Lhohi, Lhossalafushi, Thilamaafushi and Varihuraa are listed as sensitive areas owing to the presence of mangroves (EPA Sensitive Areas 2015). In Lholi, a small patch of mangroves is reported on the southwest side of the island which hosts *B. cylindrica* (Jameel and Faiz 2016).

In summary, based on information from the different sources, mangroves have been reported on eight islands of Lhaviyani Atoll (Fig. 4). In total, three species have been reported, including *B. cylindrica*, *H. littoralis* and *P. acidula* (Table S1, Supplementary Information).

Raa Atoll

Raa Atoll, officially known as Northern Maalhosmadulu Atoll (or Maalhosmadulu Uthuruburi), consists of

Fig. 3 Geographic location of islands with a reported presence of mangroves in Shaviyani Atoll and Noonu Atoll (Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

four islands in which mangroves have been reported: Dheburidheythereyvaadhoo, Kan'doogan'du, Neyo and Vaadhoo (EPA Sensitive Areas 2015) (Fig. 5). No information has been found in literature regarding the identity of the species present in this atoll.

Baa Atoll

Baa Atoll, officially known as Southern Maalhosmadulu Atoll (or Maalhosmadulu Dhekunuburi), has been a UNESCO World Biosphere Reserve since 2011 (https://en.unesco.org/biosphere/aspac/baa-atoll). The presence of mangroves has only been documented in Goidhoo, Olhugiri, Maamaduvvari and Keyodhoo (Bers 2005). The mangrove forests of Goidhoo and Olhugiri are classified as protected areas (Protected Area Announcement (IUL)138-FS2-1–2011-35 and Environment Law 174-AB1/2006/13, resp.). The most common mangrove species in Baa Atoll are *B. cylindrica*, *R. mucronata* and *P. acidula*, but *A. marina*, *E. agallocha*, *P. acidula* and *S. caseolaris* have been also reported (Bers 2005). Additionally, the presence of mangroves has also been reported in Dhakandoo, Keyodhoo, Maamaduvvari and Maddoo (EPA Sensitive Areas 2015).

In summary, based on the information from the different sources, mangroves have been reported on six islands of Baa Atoll (Fig. 5). In total, six species have been reported, including *A. marina*, *B. cylindrica*, *R. mucronata*, *P. acidula*, *E. agallocha* and *S. caseolaris*.

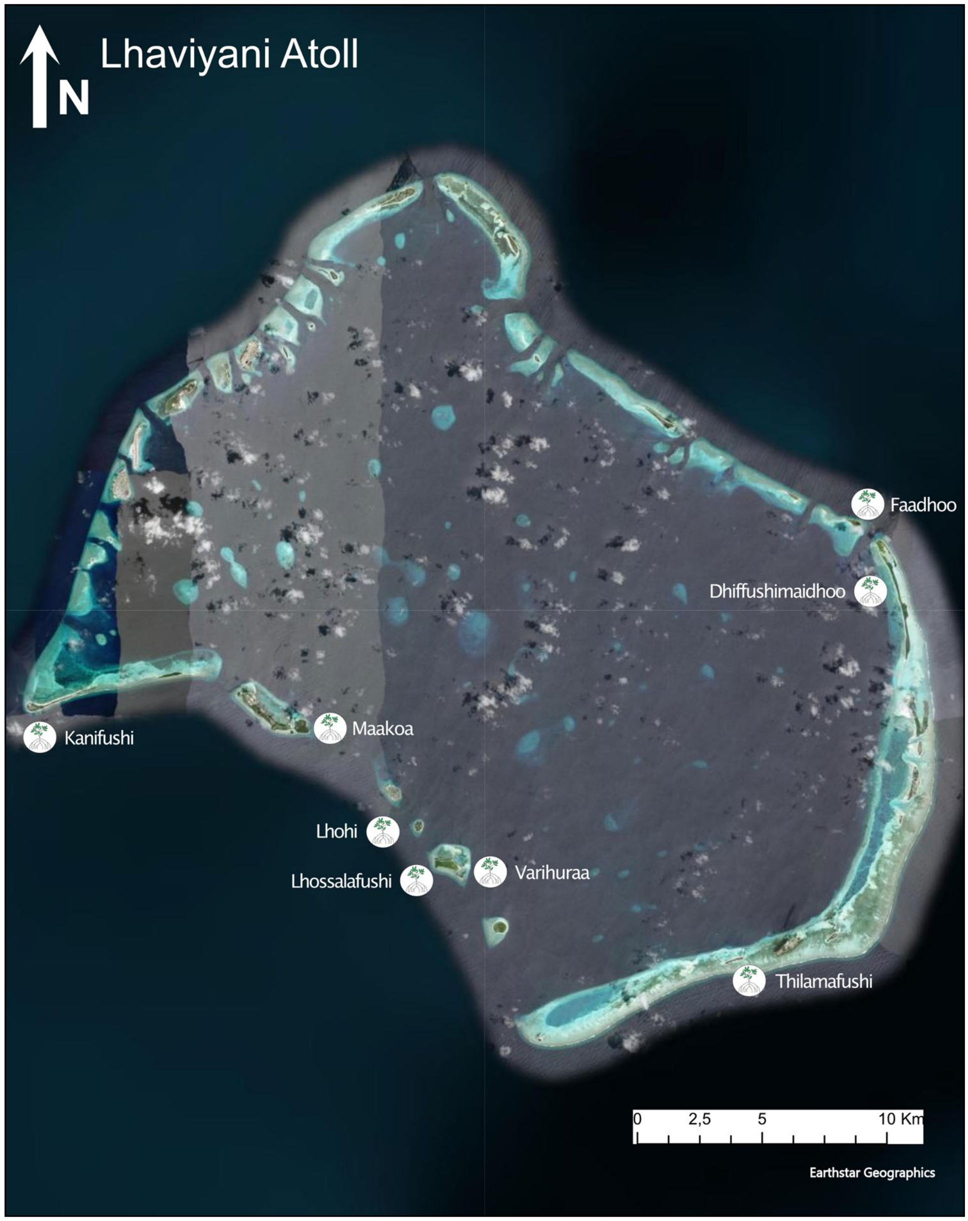

Fig. 4 Geographic location of islands with a reported presence of mangroves in Lhaviyani Atoll (Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

Kaafu Atoll

Kaafu Atoll, officially known as Malé Atoll or Malé Atolhu, consists of four geographical atolls, Kaashidhoo, Gaafaru, North Malé Atoll and South Malé Atoll. There are only two mangrove forests in Kaafu Atoll. They are found on the Kaashidhoo and Huraa islands (Protected Area Announcement (IUL)438-ENV-438–2021-24 and Environment Law 174-AB1/2006/13, respectively). Both forests are protected areas. The presence of mangroves on Kaashidhoo Island was reported by Kathiresan and Rajendran (2005). The Huraa Mangrove Nature Reserve is about 9 ha in size and is located on the western side of the island; 4000 mature mangrove trees belonging to four different species have been documented: *B. cylindrica*, which is the most common, *B. gymnorrhiza*, *R. apiculata* and the less common *R. mucronata* (MEE 2015; Shadiya et al. 2016).

In summary, based on information from the different sources, mangroves have been reported on two islands of Kaafu Atoll (Fig. 6). In total, four species have been reported, including *B. cylindrica*, *B. gymnorrhiza*, *R. apiculata* and *R. mucronata* (Table S1, Supplementary Information).

Northern Ari Atoll

In the Northern Ari Atoll, officially known as Alif Alif Atoll (or Ari Atholhu Uthuruburi), no mangroves have been reported.

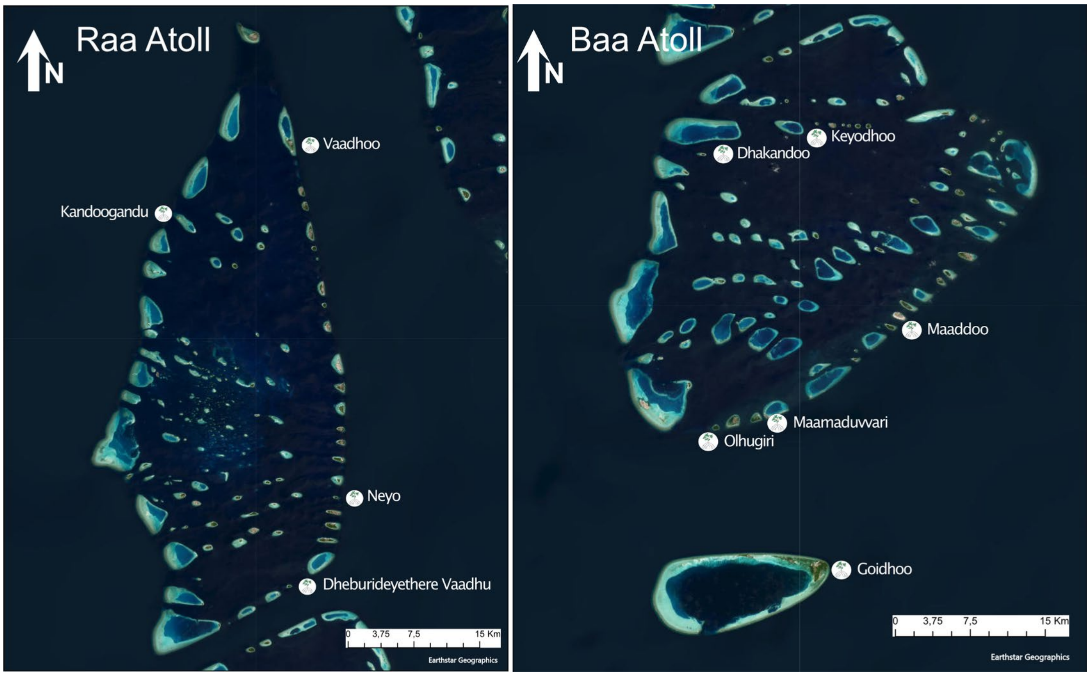

Fig. 5 Geographic location of islands with a reported presence of mangroves in Raa Atoll and Baa Atoll (Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

Southern Ari Atoll

In the Southern Ari Atoll, officially known as Alifu Dhaalu Atoll (or Atholhu Dhekunuburi), no mangroves have been reported.

Vaavu Atoll

Vaavu Atoll, officially known as Felidhu Atoll, includes only two islands with mangroves: Run Hurihuraa and Anbaraa (EPA Sensitive Areas 2015) (Fig. 7). However, no study has reported the identification of the species present.

Meemu Atoll

In Meemu Atoll, officially known as Mulaku Atoll, only two islands have been documented for the presence of mangroves: Mulah and Muli (EPA Sensitive Areas 2015) (Fig. 7). No study has reported the identity of the species present.

Faafu Atoll

In Faafu Atoll, officially known as Nilandhe Atholhu Uthuruburi (or Northern Nilandhe Atoll), the presence of mangroves has been reported only on the Island of Dhiguvarufinolhu (EPA Sensitive Areas 2015) (Fig. 8). *Brugueira cylindrica* and *Pemphis acidula* are the mangrove species reported on the island (Dryden et al. 2021).

Dhaalu Atoll

Dhaalu Atoll, officially known as Nilandhe Atholhu Dhekunuburi (or Southern Nilandhe Atoll), has only three islands with the reported presence of mangroves: Kan'dinma, Thilabolhufushi and Thinhuraa (EPA Sensitive Areas 2015) (Fig. 8). No study has reported the identity of the species present.

Thaa Atoll

Thaa Atoll, officially known as Kolhumadulu Atoll, consists of three islands with reported presence of mangroves: Kan'doodhoo, Vandhoo, and Veymandoo (EPA Sensitive Areas 2015) (Fig. 9). No study has reported the identity of the species present.

Laamu Atoll

In Laamu Atoll, officially known as Haddhunmathi Atoll, the islands of Gaadhoo, Gan, Hithadhoo and Maabaidhoo have protected areas in which mangroves have been documented. *C. tagal* and *R. mucronata* have been reported in the mangrove forest of Maabaidhoo and Hithadhoo. Furthermore, *L. racemosa* has been reported on Hithadhoo.

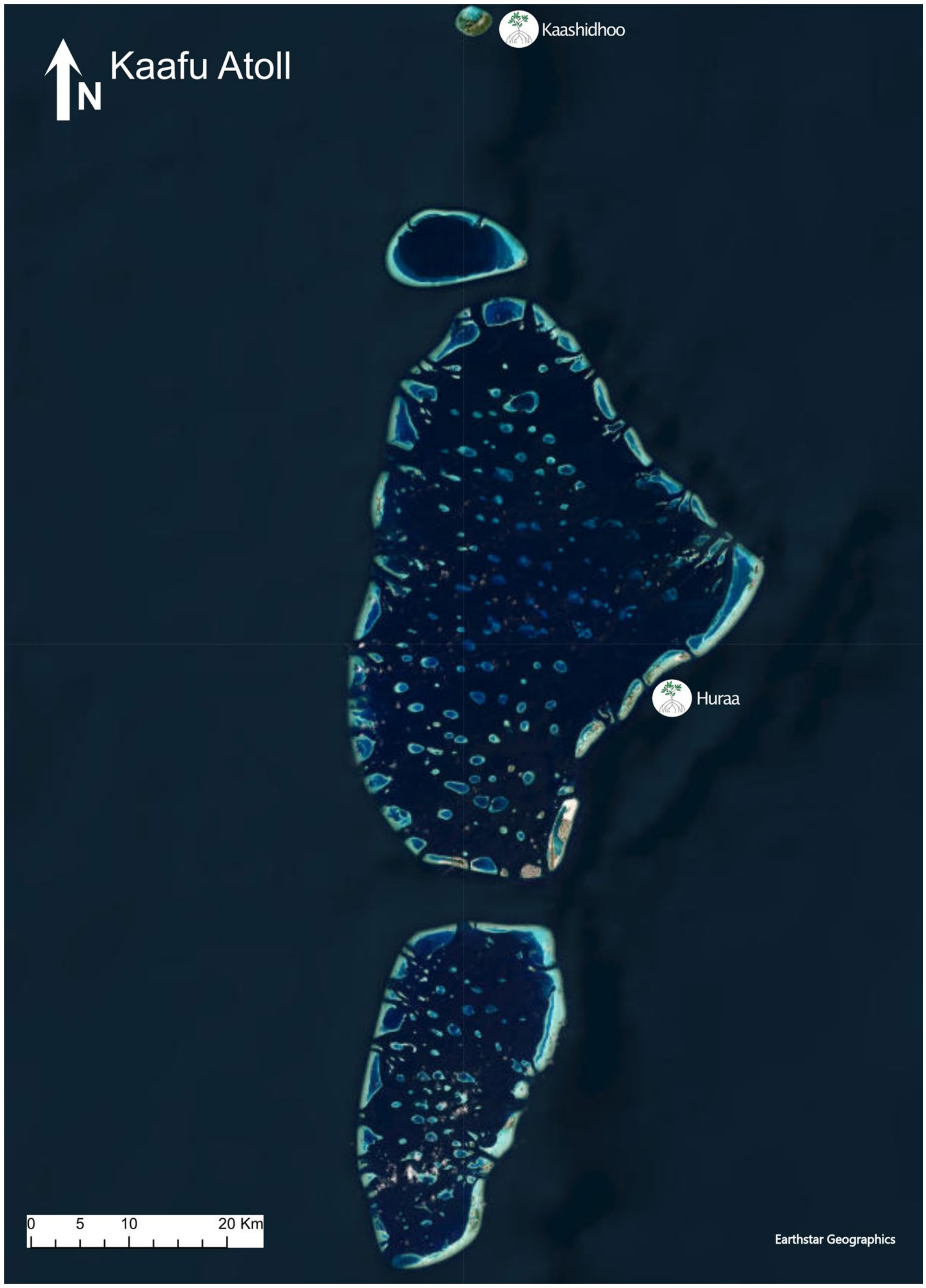

Fig. 6 Geographic location of islands with a reported presence of mangroves in Kaafu Atoll (Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

In Gan, *B. gymnorrhiza* has been reported (Protected Area Announcement (IUL)438-ENV-438–2021-371). Additionally, mangroves have been reported on Kalhaidhoo and Maavah islands (EPA Sensitive Areas 2015). In Maavah, some plants of *B. cylindrica* and *S. caseolaris* have been reported (Rifqa 2022).

To summarise, mangroves have been reported on six islands of Laamu Atoll (Fig. 10). In total, five species have been reported, including *B. cylindica*, *C. tagal*, *L. racemosa*, *R. mucronata* and *S. caseolaris* (Table S1, Supplementary Information).

Gaafu Alifu Atoll

In Gaafu Atoll, officially known as Huvadhu Atholhu Uthuruburi (or Northern Huvadhu Atoll), no mangroves have been reported.

Gaafu Dhaalu Atoll

Gaafu Dhaalu Atoll is officially known as Huvadhu Atholhu Dhekunuburi (or Southern Huvadhu Atoll). The atoll consists of 153 islands. Among these, Dhigulaabadhoo

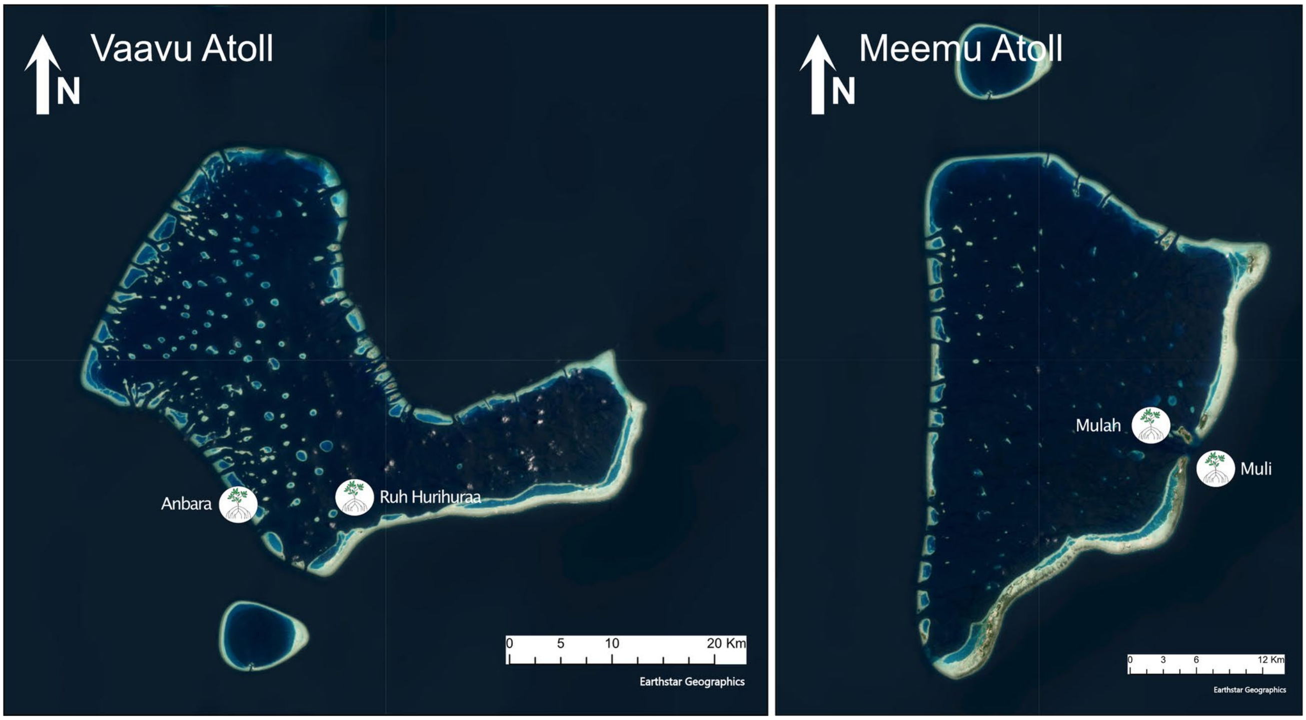

Fig. 7 Geographic location of islands with a reported presence of mangroves in Vaavu Atoll and Meemu Atoll (Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

has been declared a protected area since 7 October 2018 (Protected Area Announcement (IUL)438-ENV- 438–2018-262). An embayment of mangrove forest has been reported on that island. The forest is reported to be dominated by *P. acidula* and *C. tagal*, with a few patches of *R. mucronata* (IUCN 2020).

The EPA reported the presence of mangroves in sensitive areas of Dekaanba, Femunaidhoo, Fiyoari, Hoan'dehdhoo, Kalhuhutta, Kodurataa, Maathoda and Mathaidhoo (EPA Sensitive Areas 2015). Additionally, in Hoan'dehdhoo, the presence of *B. cylindrica*, *B. gymnorrhiza* and *L. racemosa* has been reported (MEE 2015).

Mangroves have been reported on nine islands of Gaafu Dhaalu Atoll (Fig. 11). In total, five species have been reported, namely *B. cylindrica*, *B. gymnorrhiza*, *C. tagal*, *P. acidula* and *R. mucronata* (Table S1, Supplementary Information).

Gnaviyani Atoll

Gnaviyani Atoll consists only of the inhabited Island of Fuvahmulah (Fig. 12) which is located below the equator. Fuvamulah, a UNESCO Biosphere Reserve, consists of two protected areas known as Dhandimagu Kilhi and Bandaara Kilhi (Protected Area Announcement (IUL)438-PPIRS-438–2012-2). The presence of mangroves has been documented in both protected areas (https://www.unesco.org/en/biosphere/fuvahmulah-biosphere-reserve-maldives). However, no studies have reported the identity of the species present.

Seenu Atoll

Geographically, the southernmost atoll in the Maldives is Seenu Atoll (also called Addu Atoll). Seenu Atoll is located south of the equator and is a UNESCO Biosphere Reserve (https://en.unesco.org/biosphere/aspac/addu-atoll). The atoll has two islands with mangroves: Hithadhoo Island and Hulhumeedhoo Island (Hulhudhoo and Meedhoo islands; Fig. 12). On the Island of Hithadhoo, there are two different protected areas: one is located on the northern edge of the island and has been protected since 13 September 2018 [Protected Area Announcement (2018-R-105)] and the other is in the middle of the urbanised area and has been protected since 22 September 2020 (Protected Area Annoucement (IUL)438-ENV-438–2020-162). The mangrove forest consists of *C. tagal*, *L. racemosa*, *P. acidula* and *R. mucronata* (Latheefa et al. 2009). Mangroves can also be found in Hulhumeedhoo islands, which geographically is a single island consisting of the two administratively separated islands Hulhudhoo and Meedhoo, and in which there are two mangrove/wetland ecosystems that have been protected since 22 September 2020 (Protected Area Announcement (IUL)438-ENV-438–2020-162).

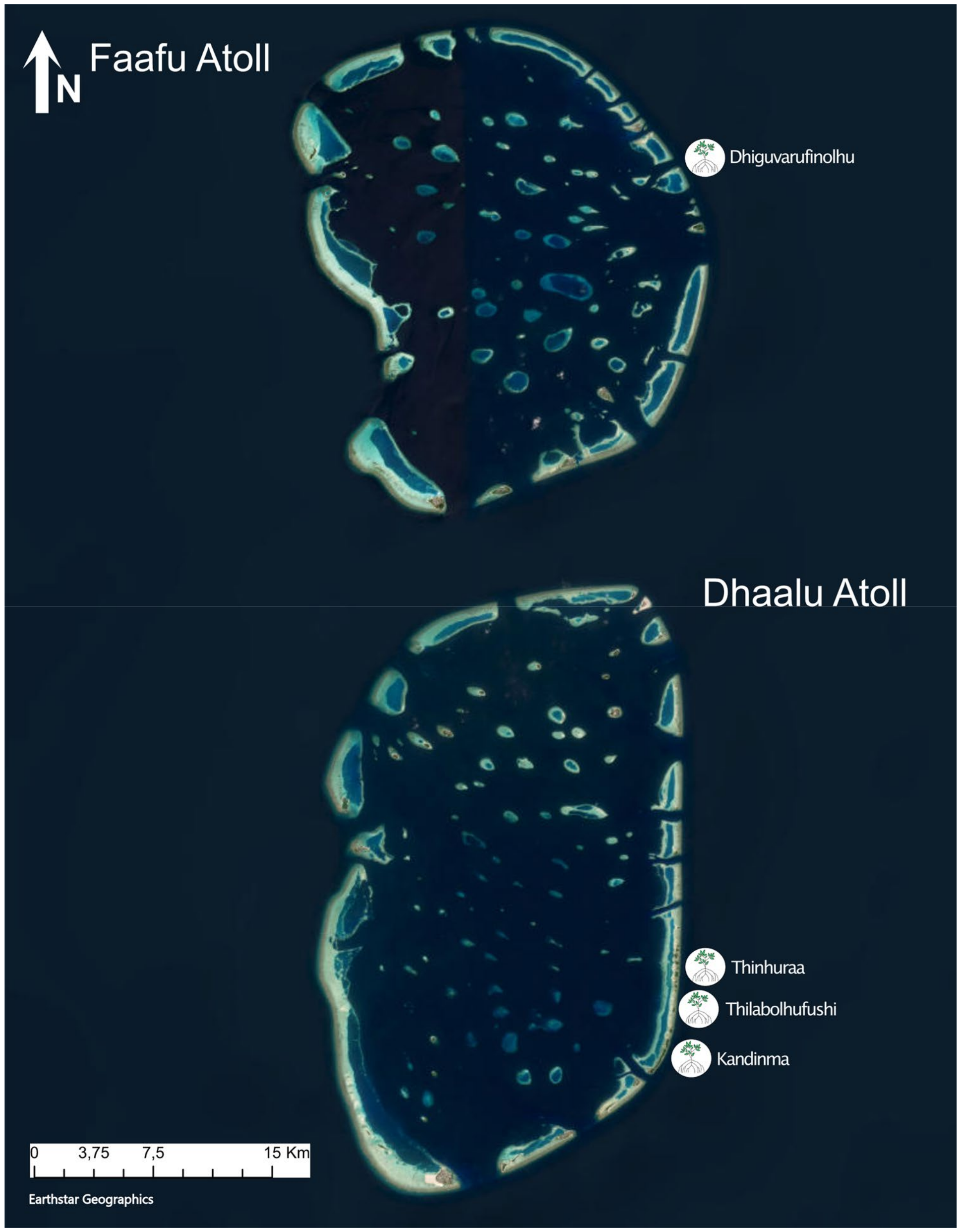

Fig. 8 Geographic location of islands with a reported presence of mangroves in Faafu Atoll and Dhaalu Atoll (Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

Following our extensive review of the literature, we found documented evidence of only 108 islands, representing ~9% of all islands in the entire Maldivian archipelago, with mangroves (Table S1, Supplementary Information). Our estimate contrasts with Saleem and Nileysha (2003), who estimated the number of islands with mangroves to be 150; however, the methodology of how this number was obtained was unclear in their study. Of the 108 islands with mangroves, only 23 of them (21.3%) have at least one protected mangrove area. From north to south of the archipelago, mangroves are unevenly distributed. The highest occurrence of mangroves is in the northern atolls. On a national scale, 70.4% of islands with mangroves are reported to be in the northern atolls (Fig. 1). There are 76 islands with mangroves in the northern atolls, 19 in the central atolls, and 13 in the southern atolls. Among the northern atolls, Shaviyani Atoll has 19 islands with mangroves. Shaviyani Atoll is closely followed by Haa Dhaalu Atoll, which comprises 16 islands with a reported presence of mangroves. The Haa Alif Atoll consists of 13 islands with mangroves. These three atolls stand out as the regions with the most significant occurrence of mangrove ecosystems in the Maldives. Northern Ari Atoll, Southern Ari Atoll and Gaafu Alifu Atoll are the only atolls with no reported presence of mangroves.

However, to better understand the distribution pattern of mangroves, it is imperative to determine the relative proportion of islands with mangroves in each atoll relative to

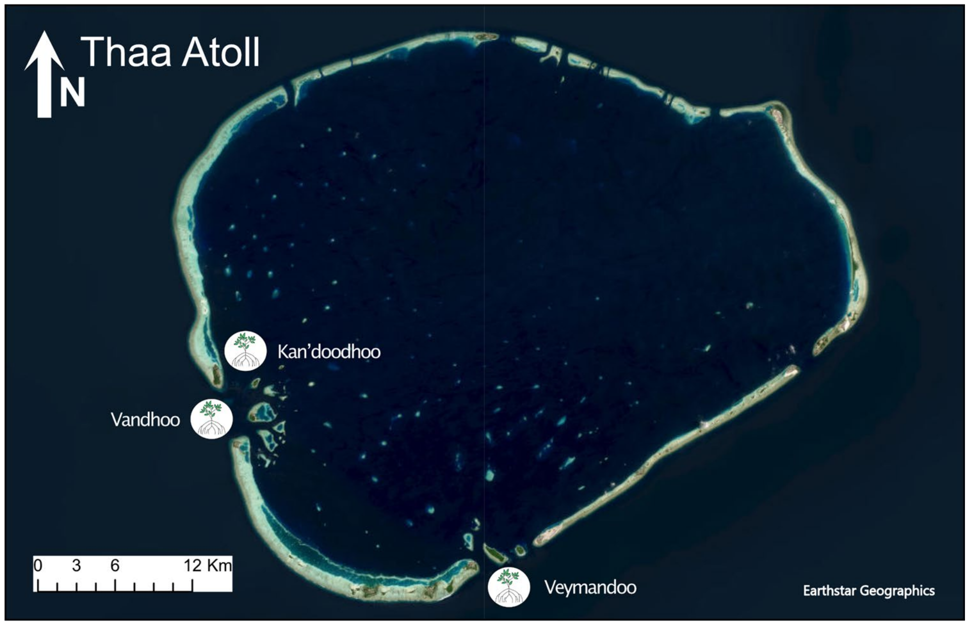

Fig. 9 Geographic location of islands with a reported presence of mangroves in Thaa Atoll (Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

Fig. 10 Geographic location of islands with a reported presence of mangroves in Laamu Atoll (Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

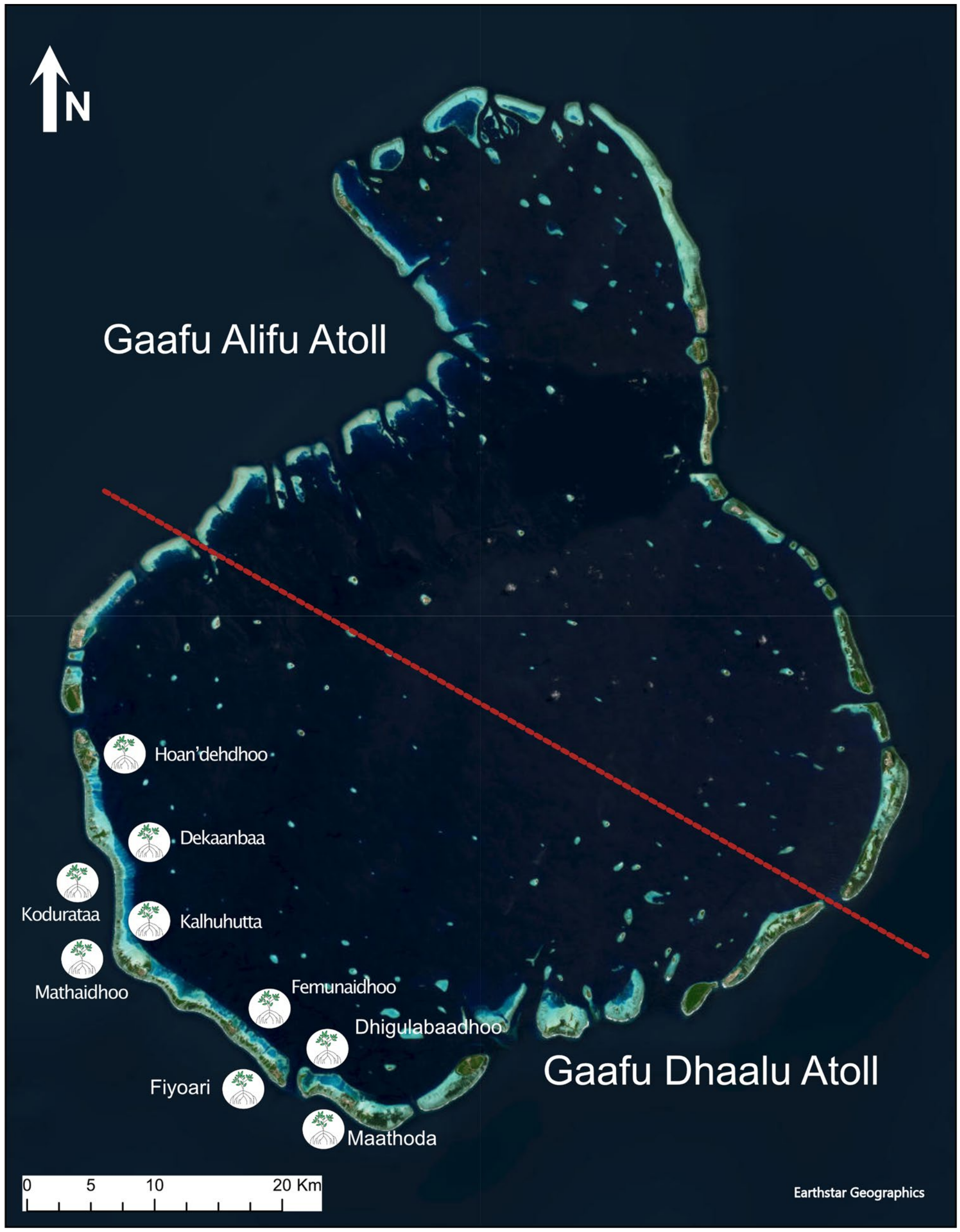

Fig. 11 Geographic location of islands with reported presence of mangroves in Gaafu Atoll (Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

the total number of islands. This is crucial because a higher number of islands in an atoll increases the likelihood of having mangroves. To address this requirement, we generated Fig. 13 (on the basis of our review of the relevant literature). This figure provides a visual representation of the percentage of islands with reported presence of mangroves out of the total number of islands in the northern, central and southern regions, respectively. The northern atolls have the highest percentage of islands with mangroves, with more than 17.4% of islands with mangroves, compared with 3.9% in the central atolls and 4.7% in the southern atolls. This nonuniform distribution could be related to the proximity of sources of mangrove seeds and propagules, particularly India and Sri Lanka to the northeast, and also the climatic conditions that strongly influence the structure of the archipelago. Monsoons have significantly impacted the shape of atolls and islands, resulting in a noticeable difference in morphology along a north–south gradient. Differences in climate and oceanographic conditions cause this variation. The archipelago experiences monsoon conditions that shift from west to northeast in a predictable manner, affecting wave and current patterns. The intensity of the monsoon increases toward the north, while the wave energy decreases in magnitude towards the north, and annual rainfall reduces from the south to the north along the archipelago (Kench 2012).

The northern atolls not only have the largest number of islands with a documented presence of mangroves, but also have the largest diversity of mangrove species and this too

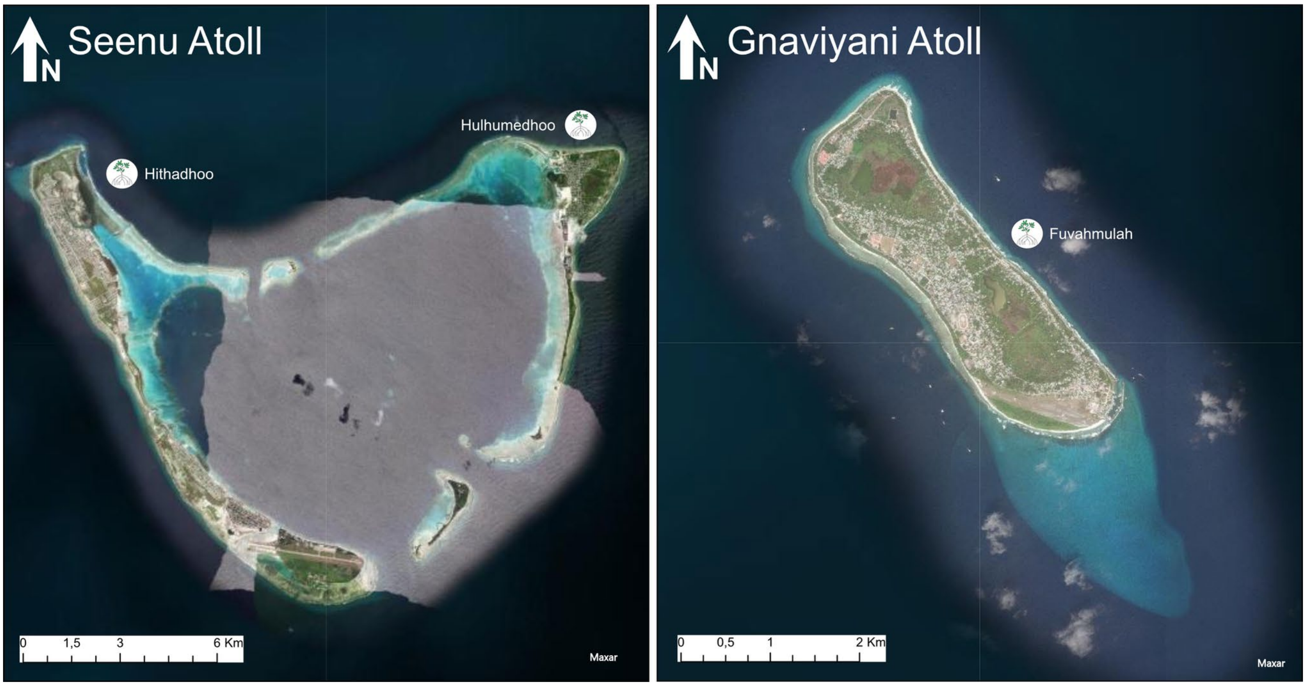

Fig. 12 Geographical location of islands with a reported presence of mangroves of Gnaviyani Atoll and Seenu Atoll (Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

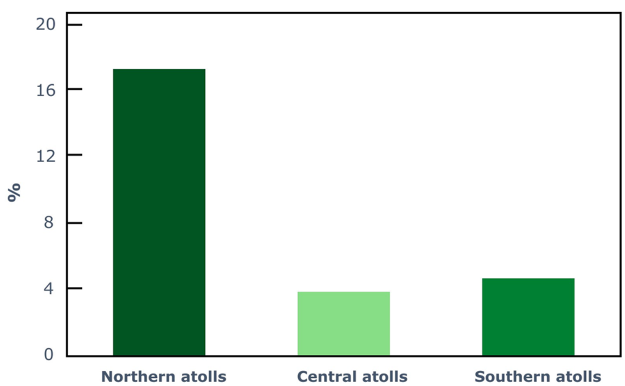

Fig. 13 Percentage of islands with documented presence of mangroves out of the total number of islands in the northern, central and southern atolls

is likely related to the closer proximity of regional sources of mangrove seeds and propagules. In fact, 14 species have been reported in the northern atolls, 7 in the central atolls and 6 in the southern atolls. Of the 14 mangrove species in the northern atolls, *A. marina*, *A. aureum*, *B. hainesii*, *E. agallocha*, *H. littoralis* and *X. moluccensis* are reported exclusively in the northern atolls. On the other hand, *B. cylindrica*, *B. gymnorrhiza*, *C. tagal*, *L. racemosa* and *R. mucronata* are documented in all regions of the Maldives without geographical restriction (Table S1**,** Supplementary material).

It is important to note that half of the islands with mangroves, specifically 55 out of 108, are inhabited. With a total of 188 inhabited islands in all of the Maldives (National Bureau of Statistics 2021), this indicates that almost one third of the inhabited islands in the Maldives have mangroves. On the one hand, this presents concern regarding the potential impacts on this crucial ecosystem arising from human activities. On the other hand, a sustainable co-management of these ecosystems through protection and preservation offers an invaluable opportunity for the local communities.

Ecosystem services of mangroves in the Maldives

Mangroves provide several ecosystem services, some of which are very important for the Maldives. Historically, fruits of *B. cylindrica* ("Kandhoo") represented a vital source of subsistence during the national famine, locally known as 'bodu thadhu', that occurred during World War II (IDEAS 2017; Dryden et al. 2020a, b). During the war, islands with Kandhoo plants were among the most food secure. Strict rules were imposed on the population, such as regulated harvest periods. Today, owing to the easy availability of rice, the Kandoo fruit is not a staple food, but it is eaten as a rare delicacy (IDEAS 2017).

Mangroves provide another crucial ecosystem service, which involves coastal protection by mitigating the impact of tidal events and reducing the risk of catastrophic flooding, particularly during monsoons (Guannel et al. 2016; Agardy et al. 2017). For example, on Kendhikulhudhoo Island, during the 2004 tsunami, mangroves, together with coral reefs and coastal vegetation, mitigated and absorbed the force of deadly waves, reducing the loss of human lives and the destruction of buildings (Bluepeace 2010; CHEC 2020). Furthermore, during the rainy season, the roots of the mangrove absorb part of the water and transfer it to the water lens of the island. In addition, mangroves help to remove toxic substances and contaminants from water bodies and water lenses (CHEC 2020).

Mangrove forests are carbon-fixing habitats and play a role in reducing the level of anthropogenic carbon dioxide released into the atmosphere. However, no research has been published on the rate of carbon sequestration in the Maldives (Agardy et al. 2017).

Mangrove plants are a source of timber, firewood and thatching materials, particularly *B. cylindrica*, *B. gymnorrhiza* and *R. mucronata* (Shadiya et al. 2016; Dryden et al. 2020a, b). Furthermore, especially in the past, but also now, fish in the mangrove ecosystem were an important source of protein for the local community (Shadiya et al. 2016).

Fauna associated with mangroves in the Maldives

Mangroves in the Maldives play a crucial role in sustaining the biodiversity of coastal ecosystems, providing protection, food and habitat for various animals (Shadiya et al. 2016; Agardy et al. 2017). Numerous species of birds use mangrove areas for feeding, breeding and shelter. Mangrove trees are often a roosting site for migratory birds, and nests of resident birds are common within mangrove trees (IDEAS 2018a, 2018b; IUCN 2020).

Fish take refuge and hunt within the mangrove forests. The complex root systems of many species, including *Rhizophora* spp., provide an important nursery site for many fish, including *Carcharhinus melanopterus* (or black-tip reef shark), but also herbivorous species that feed on algae that grow in the wetland. Numerous other fish species, such as those shown in Table S2 (Supplementary Information), have been sighted within mangrove bays together with fish belonging to the families Mullidae, Ostraciidae and Gerreidae (Shadiya et al. 2016; IUCN 2020). Common fish species found in lake-based mangrove systems include *Chanos chanos* (milkfish), and various species of the Chanidae, Cichlidae, Congridae, Gobiidae, Poeciliidae and Sphyraenidae families (IUCN 2020). Additionally, a large number of upside-down jellyfish (*Cassiopea xamachana*) have been found in the shallow mangrove bay of Goidhoo (Bers 2005). Furthermore, in some mangrove areas, turtle nests are found on the beach (IUCN 2020).

There is a diverse population of crabs in mangrove sediments, particularly noticeable during low tides. These crabs play a crucial role in the sustainability of the mangrove ecosystem by influencing the structure of the forest, zonation patterns, nutrient cycling, sediment dynamics, and overall productivity. Crabs in the family Sesarmidae collect fallen leaves, seeds and propagules and drag them down into their burrows to feed on them. This feeding behaviour contributes to soil enrichment and accelerates the integration of mangrove biomass into the food chain. Their burrowing activities aerate the substrate and promote water flow into sediments, facilitating sediment mixing and creating microenvironments for bacteria and fungi that supply essential nutrients for primary production. These crabs serve as a vital food source for various species of fish and birds (Ewel et al. 1998; Bluepeace 2015; Shadiya et al. 2016; Dryden et al. 2020a, b). Other typical crab species found in mangrove ecosystems include fiddler crabs (Family Ocypodidae e.g. *Uca rapax*), which sieve the sediment to consume plant detritus, microbes and algae, and whose presence has been associated with enhanced mangrove health (Smith et al. 2009), land crabs (Family Geocarcinidae -*Cardisoma carnifex*) and hermit crabs (Bluepeace 2015; Shadiya et al. 2016).

Limited research exists on the meiofauna and macrofauna that reside within mangrove sediments (infauna) in the Maldives. However, they play crucial ecological roles in maintaining ecosystem function, nutrient cycling and biodiversity (Aller 1988; Snelgrove 1997). Macrofauna, larger visible organisms (250 µm–1 cm; Snelgrove 1998), participate in burrowing and bioturbation activities, improving oxygenation, nutrient cycling, and ecosystem health. They decompose organic matter, release nutrients and act as prey and predators, regulating populations. The macrofauna also creates complex burrow systems that provide habitat and shelter. The macrofauna includes a diverse range of species, including isopods (sea slaters), amphipods (crustaceans), small gastropods (snails), polychaete worms and bivalves (clams, oysters, cockles, mussels and scallops). The meiofauna, smaller organisms (32 µm and 1 mm in size; Giere 2009), accelerate decomposition, promote nutrient recycling and serve as a food source. They include tiny animals, such as nematodes, copepods, ostracods and small worms (Lalli and Parsons 1997). Their movements and feeding activities influence the structure, oxygenation, and stability of the sediment. Both groups act as indicators of environmental health and water quality, responding to changes in their habitat, and providing information on overall ecosystem conditions. Monitoring their composition and diversity helps assess and manage the environmental impact on mangrove habitats.

In the Maldives, most studies on mangrove infauna have focused mainly on nematodes. In particular, in the Noonu Atoll, a study by Gerlach (1962) reported the presence of the free-living nematode *Halalaimus filum*. Furthermore, Schulz (1935) documented the occurrence of *Nudora thorakist*a in the atolls of Addu and Noonu. The meiofauna and macrofauna in the Maldives have been studied primarily in habitats such as coral reef and lagoon sediments (Semprucci et al. 2018; Grassi et al. 2022).

The study of macrofauna and meiofauna in the mangroves of the Maldives is essential and therefore deserves further investigation. Such studies would provide valuable information on biodiversity, community dynamics and functional contributions of macrofauna and meiofauna in mangrove sediments. Furthermore, investigating the interactions between these organisms and the surrounding mangrove environment can shed light on the general health and resilience of these fragile ecosystems. In the Maldives, and in the Indian ocean region in general (Hollander et al. 2020), very few studies have focused on the capacity of marine organisms and ecosystems to adapt to climate change. Therefore, conducting research on macrofauna and meiofauna in the mangroves of the Maldives is both necessary and important for comprehensive ecosystem management and conservation efforts.

Flora associated with mangroves in the Maldives

Mangrove forests are globally known to support a wide range of floral diversity (Kathiresan and Rajendran 2005). In the Maldives, Saleem and Nileysha (2003) reported the occurrence of *Tournafortia argentea* (or tree heliotrope, locally known as 'Boashi'), *Thespesia populnea* (or milo, 'Hirundhu'), *Scaevola taccada* ('Magoo'), *Pandanus* sp. ('Kashikeyo'), *Hibiscus tiliaceous* (or beach hibiscus, 'Dhiggaa') and *Baringtonia asiatica* (or fish poison tree, 'Kinbi') in association with mangroves. Seagrasses (marine plants, or 'Moodhu vina') have also been reported to grow within Maldivian mangrove ecosystems (Glen et al. 2008). Five species of seagrass are known to occur in the Maldives (*Syringodium isoetifolium*, *Thalassia hemprichii*, *Thalassodendron ciliatum*, *Cymnodoea rotundata* and *Cymnodocea* sp.), of which *Thalassia hemprichii* is the most common (Hameed 2022). However, little information is available on which of these species are commonly found in mangrove habitats or which mangrove species they are associated with.

Mangrove forests provide habitats for macroalgal species that grow epiphytically in mangrove pneumatophores, prop roots, basal trunks and surrounding sediments (Zuccarello et al. 2001; Mendonça and Lana 2021). Macroalgae (seaweeds) are a primary source of energy and provide a habitat for diverse communities of small benthic animals, such as nematode worms, bivalves, copepods, polychaetes and crabs, thus enhancing the faunal diversity of mangrove systems (Mendonça and Lana 2021; Neba et al. 2021). Despite their important ecological functions, macroalgae are often excluded from ecological surveys around mangrove flora (West et al. 2013), mainly as a consequence of their inconspicuous size and difficult identification. Studies reporting on algal diversity in the Maldives are extremely scarce and tend to be based on taxonomy inventories and species richness analysis, either with no molecular validation of the identified species or with molecular validation carried out only for a few selected specimens (e.g. *Dictyota* J.V. Lamouroux, *Padina* Adanson and *Halimeda* J.V. Lamouroux, from Payri et al. 2012). In reports by the Maldivian government, algae are often broadly described as 'algal turf' (e.g. MEE 2015; Dryden et al. 2020a, b). Dhunya et al. (2017) reviewed ecosystem function services and threats to coral, mangrove and seagrass habitats, but only briefly mentioned the presence of algae in these habitats, without discussing a mangrove-algal association. The survey conducted by Hackett (1977) is often used as a reference for the diversity of algae in the Maldives. However, in this survey, the author only briefly reported on a few species of algae associated with the mangrove *Rhizophora mucronata*. Although Payri et al. (2012) provided the most comprehensive census of algal diversity in the Maldives to date (321 species), these observations are limited to the Baa Atoll, and there is no mention of the types of habitats these species were associated with. Although very little is known about mangrove-associated macroalgae in the Maldives, mangrove habitats are globally known to support diverse macroalgal communities (Post 1936). The representative assemblage of mangrove-associated macroalgae is often referred to as the 'bostrychietum complex' (Post 1936) and includes red algal genera, such as *Bostrychia*, *Caloglossa* and *Catenella*. Although the bostrychietum complex has been reported from various locations in the Indian Ocean (Lambert et al. 1987; Steinke and Naidoo 1990; Phillips et al. 1996; Ganesan et al. 2018), it has not been described in the Maldives. Furthermore, currently there are no studies that have thoroughly characterised Maldivian algae at the molecular level. However, understanding the genetic variability of species is crucial to the adequate management and conservation of these ecosystems. Furthermore, a thorough understanding of the ecology and genetic diversity of macroalgae associated with Maldivian mangrove habitats will allow a comprehensive analysis of the contribution of these species to the functions of the mangrove ecosystem and will lead to a greater understanding of how changes in the environment affect these important organisms.

Knowledge gaps

This extensive review highlights several critical knowledge gaps in the literature regarding various aspects of the mangrove ecosystems of the Maldives, notably:

(i) lack of information on the specific location and boundaries of mangrove forests and absence of satellite/aerial mapping of these areas, which limits comprehensive assessments of mangrove health, ecosystem services and biodiversity.

(ii) Lack of accurate data on the identity and abundance of mangrove species in each mangrove area. This gap also extends to the associated fauna and flora within these ecosystems. Species identification concerns only a few mangrove areas (Table S1, Supplementary Information) and the method of identification is unclear. The identification of the different taxa must be carried out using standard taxonomic references in combination with DNA barcoding to confirm the identity of cryptic species. The information on the identity and abundance plays a crucial role in both conservation efforts and in assessing the general health of mangroves in an ever-changing world. Therefore, there is an urgent need to fill these knowledge gaps to better protect and manage this valuable natural resource.

(iii) Lack of long-term monitoring of environmental parameters within mangrove areas, particularly air and water temperature, pH and salinity of water and light intensity, which are of utmost importance as they are undergoing significant changes owing to climate change, altered precipitation patterns and rising sea levels. Integrating environmental parameter monitoring with other ecological studies, such as biodiversity assessments and species distribution surveys, can provide a more holistic understanding of how our changing environment is affecting mangrove flora and fauna.

(iv) Lack of studies on soil and sediment analysis in mangrove forests. Soil composition, grain size distribution, clay content, organic content, cation exchange capacity and physicochemical parameters, including pH, salinity and temperature of mangrove sediment, are crucial for a comprehensive ecological study of a mangrove ecosystem. Furthermore, these data are essential for understanding the potential relationship between species distribution and soil characteristics.

Conclusions and future research

The existing literature on mangrove forests in the Maldives reveals their unique nature, consisting of patches of trees in closed or semi-closed brackish water bodies or muddy regions. These mangroves are found on 108 islands, representing 9% of all islands in the country. Within the Maldives, there are 11 true mangrove species (*A. marina*, *B. cylindrica*, *B. gymnorrhiza*, *B. hainesii*, *B. sexangula*, *C. tagal*, *L. racemosa*, *R. apiculata*, *R. mucronata*, *S. caseolaris* and *X. moluccensis*) and 4 controversial species (*A. aureum*, *E. agallocha*, *H. littoralis* and *P. acidula*). Most mangrove forests are concentrated in the northern atolls, particularly in the Haa Alif, Haa Dhaalu and Shaviyani atolls, which total 76 islands. In particular, 23 islands have at least one protected area with mangroves, highlighting their conservation significance. These mangrove ecosystems play a vital role in the Maldives, providing various ecosystem services that sustain livelihoods, such as acting as a source of food, coastal protection and purifying water bodies. In addition, they serve as a valuable resource for wood, firewood and straw materials. In addition, mangroves are instrumental in supporting coastal biodiversity, providing essential protection, food and habitat for a wide variety of organisms, including numerous bird species, fish and crabs. Mangroves in the Maldives also host multiple marine fauna, such as resident and migratory birds, various species of carnivorous and herbivorous fish, upside-down jellyfish (*Cassiopea xamachana*), free-living nematodes (*Halalaimus filum* and *Nudora thorakista*), fiddler crabs (*Uca rapax*), land crabs (*Cardisoma carnifex*) and hermit crabs. Furthermore, several species of plants, including *T. argentea*, *T. populnea*, *S. taccada*, *Pandanus* sp., *H. tiliaceous* and *B. asiatica*, are associated with the mangroves of the Maldives, contributing to the overall diversity and health of the ecosystem.

However, we found that there were inconsistencies and gaps in the literature, concerning various aspects of mangrove ecosystems of the archipelago, especially in uninhabited islands, including the lack of precise information on mangrove species locations and boundaries, the absence of satellite/aerial mapping, the lack of long-term monitoring of environmental parameters, such as temperature, pH and salinity, and the analysis of soil and sediments. These knowledge gaps hinder the comprehensive understanding of mangroves, their distribution patterns, and the impacts of environmental changes on their health and resilience.

We suggest that to fill the gap in current knowledge of mangroves in the Maldives, a nationwide biodiversity survey of all mangrove forests in the Maldives is essential. Such a survey would provide invaluable information on the precise locations and boundaries of mangrove areas throughout the archipelago. By systematically documenting and mapping the distribution of mangroves and their associated fauna and flora, researchers and conservationists can establish a comprehensive baseline to monitor changes and assess the health of these ecosystems. Furthermore, conducting field surveys would allow the collection of vital data on environmental parameters, such as temperature and salinity and changing sea levels, filling the gap in our understanding of the impacts of climate change on mangrove ecosystems, as well as soil and sediment sampling to study their physicochemical parameters and characteristics. An inclusive and thorough survey effort would contribute significantly to make well-informed decisions, implement policies, improve our knowledge and inform evidence-based management and conservation strategies to protect the invaluable mangrove ecosystems of the Maldives and ensure their long-term sustainability.

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Data availability Datasets are provided in the text (Table 1, Table S1 and S2).

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

References

Agardy T, Hick F, Nistharan F, Fisam A, Abdulla A, Schmidt A, Grimsditch G (2017) Ecosystem services assessment of North Ari Atoll. IUCN, Gland

Ali FF (2020) Local name finalized for new mangrove species found in Maldives. The Times of Addu. https://timesofaddu.com/2020/10/24/name-given-for-the-newly-found-mangrove-species/. Accessed on 26 July 2023

Aller R (1988) Benthic fauna and biogeochemical processes in marine sediments: the role of burrow structures. In: Blackburn TH, Sørensen J (eds) Nitrogen cycling in coastal marine environments. Wiley Press Inc, Chichester, pp 301–338

Bers AV (2005) Biodiversity assessment for Maldives Baa Atoll. Baseline information for UNDP's atoll ecosystem-based conservation programme. UNDP and Ministry of Environment, Energy and Water, Malé

Bluepeace (2007) Atoll mangroves absorbed lethal power of Asian tsunami. Bluepeace blog, Environment News, Articles and Reports. http://www.bluepeacemaldives.org/news2007/atoll_mangroves.htm. Accessed 23 July 2023

Bluepeace (2008) Hudhufushi – Dhiffushimaadhoo area should be declared as nature reserve. Bluepeace blog, Biodiversity. http://www.bluepeacemaldives.org/blog/biodiversity/hudhufushi-dhiffushimaadhoo-must-be-made-nature-reserve. Accessed 23 July 2023

Bluepeace (2010) Mangroves that saved Kendhikulhudhoo from tsunami under threat now. Bluepeace blog, Biodiversity. http://www.bluepeacemaldives.org/blog/biodiversity/kendhikulhudhoo-mangroves-under-threat. Accessed 23 July 2023

Bluepeace (2015). Conserving mangroves through the development of an informative website and community advocacy. http://www.bluepeacemaldives.org/mangroves/about/. Accessed 23 July 2023

Cerri F, Giustra M, Anadol Y, Tomaino G, Galli P, Labra M, Campone L, Colombo M (2022) Natural products from mangroves: an overview of the anticancer potential of *Avicennia marina*. Pharmaceutics 14(12):2793. https://doi.org/10.3390/pharmaceutics14122793

CHEC (2020) Report for #SaveNeykurendhooKandoofaa for activities funded by the Commonwealth Human Ecology Council (CHEC). Commonwealth Human Ecology Council 1–23. http://saruna.mnu.edu.mv/jspui/handle/123456789/13973. Accessed 23 July 2023

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387(6630):253–260. https://doi.org/10.1038/387253a0

Curnick DJ, Pettorelli N, Amir AA, Balke T, Barbier EB, Crooks S, Dahdouh-Guebas F, Duncan C, Endsor C, Friess DA, Quarto A, Zimmer M, Lee SY (2019) The value of small mangrove patches. Science 363(6424):239–239. https://doi.org/10.1126/science.aaw0809

Dahdouh-Guebas F, Jayatissa LP, Di Nitto D, Bosire JO, Seen DL, Koedam N (2015) How effective were mangroves as a defence against the recent tsunami? Curr Biol 15(12):R443–R447. https://doi.org/10.1016/j.cub.2005.07.025

Das S, Vincent JR (2009) Mangroves protected villages and reduced death toll during Indian super cyclone. Proc Natl Acad Sci 106(18):7357–7360. https://doi.org/10.1073/pnas.0810440106

Das A, Parida A, Basak U, Das P (2002) Studies on pigments, proteins and photosynthetic rates in some mangroves and mangrove associates from Bhitarkanika. Orissa Mar Biol 141(3):415–422. https://doi.org/10.1007/s00227-002-0847-0

Dhunya A, Huang Q, Aslam A (2017) Coastal habitats of Maldives: status, trends, threats, and potential conservation strategies. Int J Sci Eng Res 8:47–62

Dryden C, Basheer A, Didi AA, Riyaz EM, Sufran H (2020a) HA Kelaa - An ecological assessment on biodiversity and management. IUCN and Government of Maldives, Malé

Dryden C, Basheer A, Grimsditch G, Musthaq A, Newman S, Shan A (2020b) A rapid assessment of natural environments in the Maldives. IUCN and Government of Maldives, Gland

Dryden C, Musthag A, Basheer A (2021) Faafu dhiguvaru: an ecological assessment on biodiversity and management

Duke NC (1992) Mangrove floristics and biogeography. In: Robertson AI, Alongi DM (eds) Tropical mangrove ecosystems. American Geophysical Union, Washington, pp 63–100

Duke NC, Meynecke J-O, Dittmann S, Ellison AM, Anger K, Berger U, Cannicci S, Diele K, Ewel KC, Field CD, Koedam N, Lee SY, Marchand C, Nordhaus I, Dahdouh-Guebas F (2007) A world without mangroves? Science 317(5834):41–42. https://doi.org/10.1126/science.317.5834.41b

Duke N, Nagelkerken I, Agardy T, Wells S, Van Lavieren H, Huxham M (2014) The importance of mangroves to people: a call to action. United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), Cambridge

Ellison AM (2008) Managing mangroves with benthic biodiversity in mind: moving beyond roving banditry. J Sea Res 59(1–2):2–15. https://doi.org/10.1016/j.seares.2007.05.003

Eong OJ (1993) Mangroves—a carbon source and sink. Chemosphere 27(6):1097–1107. https://doi.org/10.1016/0045-6535(93)90070-L

EPA Sensitive Areas (2015) Sensitive areas V02 (KMZ File). Environmental Protection Agency, Malé, Republic of Maldives. https://en.epa.gov.mv/publications. Accessed 23 July 2023

Ewel K, Twilley R, Ong J (1998) Different kinds of mangrove forests provide different goods and services. Glob Ecol Biogeogr Lett 7(1):83–94. https://doi.org/10.1111/j.1466-8238.1998.00275.x

Fallati L, Savini A, Sterlacchini S, Galli P (2017) Land use and land cover (LULC) of the Republic of the Maldives: first national map and LULC change analysis using remote-sensing data. Environ Monit Assess 189(8):417. https://doi.org/10.1007/s10661-017-6120-2

Ganesan EK, West JA, Necchi O Jr (2018) A catalogue and bibliography of non-marine (freshwater and estuarine) Rhodophyta (red algae) of India. Phytotaxa 364(1):1–48

Gerlach SA (1962) Freilebende Meeresnematoden von den Malediven. Kieler Meeresforsch 18:81–108

Giere O (2009) Meiofauna taxa: a systematic account. In: de Leon OA (ed) Meiobenthology: the microscopic motile fauna of aquatic sediments. Springer, Berlin, pp 137–155

Glen E, Smith J, Ahmed Z, Shazna M, Shafeeqa F (2008) Field guide to Maldivian mangroves with Minna Mas. UNICEF and Educational Development Centre

Grassi E, Montefalcone M, Cesaroni L, Guidi L, Balsamo M, Semprucci F (2022) Taxonomic and functional nematode diversity in Maldivian coral degradation zones: patterns across reef typologies and depths. PeerJ 10:e13644. https://doi.org/10.7717/peerj.13644

Guannel G, Arkema K, Ruggiero P, Verutes G (2016) The power of three: coral reefs, seagrasses and mangroves protect coastal regions and increase their resilience. PLoS ONE 11(7):e0158094. https://doi.org/10.1371/journal.pone.0158094

Guo Z, Guo W, Wu H, Fang X, Ng WL, Shi X, Liu Y, Huang Z, Li W, Gan L, He S, Zhong C, Jian S, Gong X, Shi S, Huang Y (2018) Differing phylogeographic patterns within the Indo-West Pacific mangrove genus *Xylocarpus* (Meliaceae). J Biogeogr 45(3):676–689. https://doi.org/10.1111/jbi.13151

Hackett H (1977) Marine algae known from the Maldive Islands. Atoll Res Bull 210:2–37

Hameed F (2022) First national report to the conference of the parties to the convention on biological diversity. Ministry of Home Affairs, Housing and Environment, Malé, Republic of Maldives. http://saruna.mnu.edu.mv/jspui/handle/123456789/14610. Accessed 23 July 2023

Hollander J, Linden O, Gudka M, Duncan M, Obura D, James NC, Bhagooli R, Nyanapah J, Onyango C, Duvane J, Louis YD, Ngotho D, Mvungi E, Mamboya F, George R, Hama H, Hamisi MI, Adeleke B, Ngoa E, Harlay J, Oduor N, Fondo E, Nina W, Raharinaivo LR, Winkler A, Okemwa GM, Karisa J, Bamdou M, Mtaki K, Randrianandrasana J (2020) Marine organisms response to climate change effects in the Western Indian Ocean. JIORS 3(1):33–59

International Union for Conservation of Nature (IUCN) (2019) Preliminary site survey of Kulhudhuffushi mangroves. IUCN, Mangrove Action Project, and Government of Maldives, Malé

International Union for Conservation of Nature (IUCN) (2020) A rapid assessment of natural environments in the Maldives: supplementary site assessments. IUCN and Government of Maldives, Malé

Island Development and Environmental Awareness Society (2017) Of famine and food security: a story from Kelaa's kandoofaa (mangrove). Ideaskelaa in mangroves, Mangroves of Maldives. https://ideaskelaa.wordpress.com/2017/08/24/of-famine-and-food-security/. Accessed 23 July 2023

Island Development and Environmental Awareness Society (2018a) Hdh Nolhivaranfaru bodukulhi: state of mangrove series. Ideaskelaa in mangroves. https://ideaskelaa.wordpress.com/2018/05/07/hdh-nolhivaranfaru-bodukulhi-state-of-mangrove-series/. Accessed 23 July 2023

Island Development and Environmental Awareness Society (2018b) Sh Milandhoo's sikundi kulhi – state of mangroves series. Ideaskelaa. In mangroves, Mangroves of Maldive. https://ideaskelaa.wordpress.com/2018/04/21/sh-milandhoos-sikundi-kulhi-state-of-mangroves-series/. Accessed 23 July 2023

Jameel A, Faiz I (2016) Environmental impact assessment for the proposed agriculture development project at Lh. Lhohi. Water Solutions Pvt. Ltd., Malé, Republic of Maldives. http://saruna.mnu.edu.mv/jspui/handle/123456789/4506. Accessed 23 July 2023

Jaufar S (2021) Shaping of sustainable citizenship among young people of Kulhudhuffushi, Maldives and Hamilton, New Zealand: context, conditions and experiences. Sustain Earth 4(1):1. https://doi.org/10.1186/s42055-020-00040-3

Kandasamy K, Bingham B (2001) Biology of mangroves and mangrove ecosystems. Adv Mar Biol 40:81–251. https://doi.org/10.1016/S0065-2881(01)40003-4

Kandasamy G, West J, Necchi O Jr (2018) A catalogue and bibliography of non-marine (freshwater and estuarine) Rhodophyta (red algae) of India. Phytotaxa 364:1–48. https://doi.org/10.11646/phytotaxa.364.1.1

Kathiresan K, Rajendran N (2005) Mangrove ecosystems of the Indian Ocean region. J Mar Sci 34:104–113

Kench PS (2012) The geomorphology of Baa (South Maalhosmadulu) Atoll and its reef islands. Biodiversity, resources, and conservation of Baa Atoll (Republic of Maldives): a Unesco man and biosphere reserve. Atoll Research Bulletin. Smithsonian Institution National Museum of Natural History, Washington, DC, pp 1–30

Lalli C, Parsons TR (1997) Biological oceanography: an introduction. Elsevier, New York

Lambert G, Steinke TD, Naidoo Y (1987) Algae associated with mangroves in southern African estuaries. I Rhodophyceae S Afr J Bot 53(5):349–361. https://doi.org/10.1016/S0254-6299(16)31090-0

Latheefa A, Lindsey S, Gardene B, Zuhair M (2009) Assessment of Eidhigali Kulhi and Koattey Area. Ministry of Environment Energy and Water, Malé

Mendonça IRW, Lana PdC (2021) Richness and biomass distribution of the mangrove macroalgal association in a subtropical estuary. Ocean Coast Res. https://doi.org/10.1590/2675-2824069.21006irwm

Ministry of Environment and Energy (2015) Fifth National Report of Maldives to the Convention on Biological Diversity. Ministry of Environment and Energy, Malé

Mukherjee AK, Acharya L, Panda PC, Mohapatra T (2006) Assessment of genetic diversity in 31 species of mangroves and their associates through RAPD and AFLP markers. Z Naturforsch C 61(5–6):413–420. https://doi.org/10.1515/znc-2006-5-618

Naeem I (2008) Environmental impact assessment notes for HA Thakandhoo harbor construction project H.A. Ministry of Construction and Public Infrastructure, Malé, Republic of Maldives. http://saruna.mnu.edu.mv/jspui/handle/123456789/7483. Accessed 23 July 2023

National Bureau of Statistics (2021) Statistical yearbook of Maldives. http://statisticsmaldives.gov.mv/yearbook/2021/. Accessed 23 July 2023

Neba G, Neculina A, Mumbang C, Fonge B (2021) Benthic Algal community in relationship to perturbation in the Tiko Mangrove Estuary Cameroon. Open J Ecol 11:540–564. https://doi.org/10.4236/oje.2021.117035

Nishan, A (2010) Alien species cultivated in the Maalhendhoo mangroves. Thimaaveshi environmental news and information from the Maldives. https://thimaaveshi.wordpress.com/2010/03/14/alien-species-cultivated-in-the-maalhendhoo-mangroves/. Accessed 23 July 2023

Ono J, Yong JWH, Takayama K, Saleh MNB, Wee AKS, Asakawa T, Yilano OB, Salmo SG III, Suleiman M, Tung NX, Soe KK, Meenakshisundaram SH, Watano Y, Webb EL, Kajita T (2016) *Bruguiera hainesii*, a critically endangered mangrove species, is a hybrid between *B. cylindrica* and *B. gymnorhiza* (Rhizophoraceae). Conser Genet 17(5):1137–1144. https://doi.org/10.1007/s10592-016-0849-y

Parani M, Lakshmi M, Senthilkumar P, Ram N, Parida A (1998) Molecular phylogeny of mangroves V. Analysis of genome relationships in mangrove species using RAPD and RFLP markers. Theor Appl Genet 97:617–625

Payri C, de Ramon NA, Mattio L (2012) Benthic algal and seagrass communities in Baa Atoll, Maldives. Atoll Res Bull 590:31–66

Phillips A, Lambert G, Granger JE, Steinke TD (1996) Vertical zonation of epiphytic algae associated with *Avicennia marina* (Forssk.) Vierh. Pneumatophores at Beachwood mangroves nature reserve, Durban, South Africa. Bot Mar 39(16):167–176. https://doi.org/10.1515/botm.1996.39.1-6.167

Polidoro BA, Carpenter KE, Collins L, Duke NC, Ellison AM, Ellison JC, Farnsworth EJ, Fernando ES, Kathiresan K, Koedam NE, Livingstone SR, Miyagi T, Moore GE, Nam VN, Ong JE, Primavera JH, Salmo SG III, Sanciangco JC, Sukardjo S, Wang Y, Yong JWH (2010) The loss of species: mangrove extinction risk and geographic areas of global concern. PLoS ONE 5(4):e10095. https://doi.org/10.1371/journal.pone.0010095

Post E (1936) Systematische und pflanzengeographische Notizen zur Bostrychia-Caloglossa-Assoziation. Rev Algol 9:1–84

Rifqa M (2022) Preliminary assessment and mapping of Maavah mangrove: report Ministry of Environment, Climate Change and technology. Ministry of Environment, Climate Change and Technology, Malé, Maldives. http://saruna.mnu.edu.mv/jspui/handle/123456789/13889. Accessed 23 July 2023

Saleem A, Nileysha A (2003) Characteristics, status and need for conservation of mangrove ecosystems in the Republic of Maldives, Indian Ocean. J Nat Sci Found Sri Lanka 31:201

Save Maldives (2020) Discovery of critically endangered *B. hainesii* and mass mangrove die-off in the Maldives. https://savemaldives.net/mangrove-die-off-maldives/. Accessed 26 July 2023

Scholander PF (1968) How mangroves desalinate seawater. Physiol Plant 21(1):251–261. https://doi.org/10.1111/j.1399-3054.1968.tb07248.x

Schulz E (1935) IV. Nematoden aus dem Küstengrundwasser. Schr Naturw Ver Schlesw-Holst 20(2):435–467

Selvam V (2007) Trees and shrubs of the Maldives. FAO Regional Office for Asia and the Pacific, Bangkok

Semprucci F, Frontalini F, Losi V, du Chatelet EA, Cesaroni L, Sandulli R, Coccioni R, Balsamo M (2018) Biodiversity and distribution of the meiofaunal community in the reef slopes of the Maldivian archipelago (Indian Ocean). Mar Environ Res 139:19–26. https://doi.org/10.1016/j.marenvres.2018.05.006

Shadiya F, Jauharee AR, ShazThe value of small mangrove patches. Sciencely A (2016) Environmental valuation of *K. huraa* mangrove: a case study of ecological, social and economic perspectives. Mangroves for the Future. http://saruna.mnu.edu.mv/jspui/handle/123456789/2426

Shazra A, Rasheed S, Ansari A (2008) Study on the mangrove ecosystem in Maldives. Global J Environ Res 2(2):84–86

Shi S, Huang Y, Zeng K, Tan F, He H, Huang J, Fu Y (2005) Molecular phylogenetic analysis of mangroves: independent evolutionary origins of vivipary and salt secretion. Mol Phylogenet Evol 34(1):159–166. https://doi.org/10.1016/j.ympev.2004.09.002

Sivakumar K, Rilwan A, Priyanka K, Salah M, Kathiresan K (2018) Mangroves of the atolls of the Maldives, rich among the atoll groups of the Indian Ocean. ISME/GLOMIS Electron J 16(3):11–18

Smith NF, Wilcox C, Lessmann JM (2009) Fiddler crab burrowing affects growth and production of the white mangrove (*Laguncularia racemosa*) in a restored Florida coastal marsh. Mar Biol 156:2255–2266. https://doi.org/10.1007/s00227-009-1253-7

Snelgrove PV (1997) The importance of marine sediment biodiversity in ecosystem processes. Ambio 26:578–583

Snelgrove PV (1998) The biodiversity of macrofaunal organisms in marine sediments. Biodivers Conserv 7:1123–1132

Spalding M, Parrett CL (2019) Global patterns in mangrove recreation and tourism. Mar Policy 110:103540. https://doi.org/10.1016/j.marpol.2019.103540

Srikanth S, Lum SKY, Chen Z (2016) Mangrove root: adaptations and ecological importance. Trees 30(2):451–465. https://doi.org/10.1007/s00468-015-1233-0

Steinke TD, Naidoo Y (1990) Biomass of algae epiphytic on pneumatophores of the mangrove, *Avicennia marina*, in the St Lucia estuary. S Afr J Bot 56(2):226–232. https://doi.org/10.1016/S0254-6299(16)31090-0

Stevens GMW, Froman N (2019) Chapter 10—the Maldives Archipelago. In: Sheppard C (ed) World seas: an environmental evaluation, 2nd edn. Academic Press, London, pp 211–236

Tomlinson P (1996) The botany of mangroves. Cambridge University Press, New York

Upadhyay V, Ranjan R, Singh J (2002) Human–mangrove conflicts: the way out. Curr Sci 83(11):1328–1336

Valiela I, Bowen JL, York JK (2001) Mangrove Forests: one of the world's threatened major tropical environments: at least 35% of the area of mangrove forests has been lost in the past two decades, losses that exceed those for tropical rain forests and coral reefs, two other well-known threatened environments. Bioscience 51(10):807–815. https://doi.org/10.1641/0006-3568(2001)051[0807:MFOOTW]2.0.CO;2

Wang L, Mu M, Li X, Lin P, Wang W (2010) Differentiation between true mangroves and mangrove associates based on leaf traits and salt contents. J Plant Ecol 4(4):292–301. https://doi.org/10.1093/jpe/rtq008

West J, Kamiya M, Goer S, Karsten U, Zuccarello G (2013) Observations on some mangrove-associated algae from the western Pacific (Guam, Chuuk, Kosrae, and Pohnpei). Algae 28:241–266. https://doi.org/10.4490/algae.2013.28.3.241

Zhang H, Wang T, Liu M, Jia M, Lin H, Chu L, Devlin AT (2018) Potential of combining optical and dual polarimetric SAR data for improving mangrove species discrimination using rotation forest. Remote Sens 10(3):467. https://doi.org/10.3390/rs10030467

Zuccarello GC, Yeates PH, Wright JT, Bartlett J (2001) Population structure and physiological differentiation of haplotypes of *Caloglossa leprieurii* (Rhodophyta) in a mangrove intertidal zone. J Phycol 37(2):235–244. https://doi.org/10.1046/j.1529-8817.2001.037002235.x