Mangrove management and climate change: a review in Indonesia

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Abstract. Mangrove deforestation and degradation have been occurring at alarming rates. Indonesia, a country with the largest mangrove coverage in the world, experiences the highest mangrove loss mainly due to mangrove conversion to aquaculture. If this destruction continues, loss of a very unique ecosystem that has multi-benefits ecologically, socially and economically will happen. This paper aims to unravel the sensitivity and potential mitigation capacity of mangrove ecosystem to climate change, describe how mangroves have been managed in Indonesia and how they should be managed in the future. Studies have confirmed the significant mitigation capacity of mangrove ecosystems to climate change, not only in terms of carbon storage and sequestration, but also the resilience and buffering capacity of this ecosystem to climate-induced catastrophic events. To ensure the existence of this ecosystem, mangrove management in Indonesia, which are mandated to Coordinating Ministry of Maritime and Investment, Ministry of Environment and Forestry, Ministry of Fisheries and Marine Affairs, Ministry of National Development Planning (Bappenas) and Coordinating Ministry for Economic Affairs, should be strengthened and improved by removing barriers and avoiding the business-as-usual practices that would lead to management failure.

1. Background
Mangroves are woody plants that are salt tolerant and commonly found in or adjacent to the intertidal zones in tropical and sub-tropical regions [1],[2]. They are adapted to survive in harsh environment of the intertidal zones by developing adaptations in morphology, physiology and reproductive strategies [3],[4]. This ecosystem has unique morphological and ecophysiological characteristics that are specific for mangroves such as pneumatophores, viviparous embryos, tidal dispersal of propagules, lack of understorey, ability to cope high water salinity and efficient nutrient retention mechanisms [5].

Mangrove forests provide important ecosystem goods and services especially to coastal community and marine ecosystems, such as breeding and nesting grounds for fish, nurseries, feeding habitat [6], protection of shorelines from erosion, storms, tsunamis and sea-level rise, water purification, and eco-tourism [7]. Another valuable role of mangroves that have been found recently is the large capacity of this ecosystem to sequester and store carbon [8],[9], [10],[11].

The total mangrove area in the world is estimated at 137,760 km² and it is distributed in 118 countries [12]. Indonesia, which has the highest mangrove coverage in the world (3.31 million ha[14]), has lost about 30% of the mangroves between the years of 1980 to 2005 or with a deforestation rate of 52,000 ha yr⁻¹[13]. Another analysis of mangrove cover loss data from the Ministry of Environment...
and Forestry (MoEF) shows a decline of 430,000 ha from 1985 to 2019, or equals to a deforestation rate of 12,647 ha yr\(^{-1}\)[14]. The rapid decline of mangrove forests is due to mangrove conversion for agriculture, aquaculture, oil and gas, and urban development [5],[15],[11]. Recently, mangrove conversion to oil palm plantation is becoming a new threat in Indonesia which has been dominantly observed in Sumatera[16].

Studies have found that mangrove deforestation in Indonesia leads to a significant annual loss of carbon to the atmosphere, ranging from 0.96 Pg CO\(_2\)e yr\(^{-1}\)[17] to 0.19 Pg CO\(_2\)e yr\(^{-1}\)[11]. The Indonesian mangroves comprising of 3.31 million ha (in 2019) consists of 66.4% that are in good condition and 33.6% that are degraded [14]. If mangrove loss is not halted, the Indonesian mangroves carbon storage of 3.14 billion tons that has a significant role in climate change, is under serious threat [11].

The Government of Indonesia has committed to combat adverse impact of climate change and to reduce the global emission of GHGs by pledging to reduce emission by 29% unconditionally and 41% conditionally by 2030 in Indonesia’s first Nationally Determined Contributions (NDC). In 2017 Indonesia’s Ministry of National Development Planning (BAPPENAS) launched Low Carbon Development Initiative (LCDI) to incorporate greenhouse gas (GHG) emissions reduction targets into the policy planning and integrated into Indonesia’s National Medium-Term Development Plan in 2020[18]. In line with the Government of Indonesia’s target to reduce emissions, mangrove ecosystems could contribute to the national climate agenda and it is included in the greenhouse gas accounting systems that are given their significant emission reduction potential.

This paper aims to unravel the sensitivity and potential mitigation capacity of mangrove ecosystem to climate change, describe how mangroves have been managed in Indonesia and investigate how they should be managed in the future to achieve the emission reduction targets.

2. Impacts of climate change to mangrove ecosystems
Climate change is expected to affect mangroves and intensify their existing pressures. Changes in sea-level, temperature, atmospheric CO\(_2\), precipitation patterns, intensity of storms, ocean circulation patterns are predicted to impact this ecosystem, where relative sea-level rise may be the greatest threat [19], [20],[21],[22].

2.1. Sea-level rise
Sea-level rise is the greatest potential threat of climate change that not only will affect millions of people but also mangrove ecosystems [22]. Recent study using Coastal DEM indicates that under high emissions, 630 million people will be living on land below projected annual flood levels for 2100 [23]. This study also reports that 70% of the total people worldwide living in China, Bangladesh, India, Vietnam, Indonesia, Thailand, the Philippines, and Japan, would be exposed to sea-level rise and annual storm surges [23].

Sea-level rise will affect salinity that surpasses their tolerance threshold and inundation duration and frequency [3],[22]. As mangroves are halophytes, salinity changes could impact propagules growth and alter the species composition [3]. Studies have reported the increase of coastal flooding in the future due to sea-level rise which are likely to increase by 0.28 and 0.98 m by 2100 [24]. Increases in inundation due to long term flooding may also lead to plant death and species composition shifts [3], [20]. Sea-level rise will lead to a gradual decline for some mangrove areas, survival of individual trees to local extirpation [20].

2.2. Atmospheric CO\(_2\) concentration
Net CO\(_2\) emissions of 5.2 ± 2.6 GtCO\(_2\) yr\(^{-1}\) has been estimated to derive from land use and land-use change during 2007–2016 (IPCC, 2019). These net emissions are mostly due to deforestation, partly offset by afforestation/reforestation, and emissions and removals by other land use activities[24].

Responses to elevated atmospheric CO\(_2\) levels to mangroves may vary and difficult to predict, but changes will occur in rates of photosynthesis, salinity, nutrient availability and water use efficiency
[3]. Studies have shown that increased atmospheric CO₂ levels may increase productivity of some mangrove species [3], [25]. Increased productivity such as increased biomass, stem length and total leaf area are resulted under elevated CO₂ in mangrove seedlings. These are associated with higher root-shoot ratios, relative growth rates and net assimilation rates [26]. Changes in species patterns, community composition and competitive abilities of mangroves are also observed as a result of rising CO₂, sea-level and temperature [27].

Nevertheless, the response of mangroves on elevated CO₂ varies between species, and depends on other environmental factors such as temperature, salinity, nutrient levels and the hydrologic regime [28]. Research on the effects of elevated CO₂ on mangroves are still lacking and poorly understood.

2.3. Temperature
From 1850–1900 to 2006–2015 the mean land surface air temperature increased by 1.53°C, while the global mean surface temperature (land and ocean) increased by 0.87°C [24]. The increased frequency, intensity and duration of heat-related events, and the increased heavy precipitation are the result of global warming.

Mangroves exhibit variation in their sensitivity to temperature. It is widely accepted that plant growth will be enhanced by the increased temperature, as long within the threshold of plant tolerance. Although little is known about the effects of changing temperature to mangrove growth, the optimum mangrove leaf temperature for photosynthesis is believed to be between 28- 32°C, while photosynthesis declines when leaf temperatures reach 38-40°C [3], [29].

Global warming that results in the increased surface temperature will affect mangrove ecosystems by: (1) altering their species composition, (2) changing phenological patterns (e.g., timing of flowering and fruiting), (3) increasing mangrove productivity, (4) expanding to higher latitudes where the range is limited by temperature, (5) increasing floral and faunal diversity and declining rates of sediment accretion [27], [28].

2.4. Storms
Storms and extreme weather events have been predicted to increase in intensity and frequency [24]. The impact of storms is proportional to their strength, frequency, size and duration. Hurricanes and cyclones can impact mangroves by uprooting trees, breaking branches and defoliating their canopy [22]. Extreme storms can lead to complete large-scale mangrove mortality and increase stress due to peat collapse and rapid decreases in soil elevation [30]. Mangrove sediment elevation could be altered by storms through soil erosion, soil deposition, peat collapse, and soil compression [30], [20]. Mass mangrove mortality with little survival of saplings and tress could lead to permanent ecosystem conversion as recovery that might be hindered due to sediment elevation and hydrology changes [30].

3. Mangrove resilience to climate-induced catastrophic events
The role of mangroves to cope and offer protection to catastrophic events such as coastal erosion, sea-level rise, storms, hurricanes, tsunamis have been acknowledged [27], [19], [31], [22]. Mangroves have demonstrated significant resilience capacity over times proportionate with shoreline evolution. This ecosystem is characterized with key features that contribute to their resilience to climate change such as: (1) a large below-ground nutrients storage to reload nutrient losses; (2) rapid biotic turnover due to rapid nutrient flux rates and microbial decomposition; (3) high rates of water-use and nutrient-use efficiency to enhance self-recovery; (4) simple tree composition and architecture leading to rapid reconstruction and rehabilitation post-disturbance; (5) redundancy of keystone species; and (6) numerous feedback pathways to help recovery to a more stable state [27].

Mangrove forests basically have the capacity to keep pace with sea-level rise through vertical accretion and supply of sediments to maintain soil elevation suitable for mangrove growth. Or in other words, mangroves can keep up with the sea-level rise when their surface elevation gains exceed the rate of sea-level rise [20], [21]. However, studies find, most of the study sites in the Indo-Pacific, that
lower surface elevation is gained than the current rate of sea-level rise [21]. This means that Indo-Pacific regions that have most of the mangrove forests could not keep up with sea-level rise due to anthropogenic activities [21].

If sea-level rise exceeds the mangrove surface elevation, mangroves will retreat landward to maintain their suitable hydroperiod. Mangroves migrate landward when new habitat becomes available through erosion, inundation and salinity change [20]. Their ability to colonize newly habitat depends on the rate of the relative sea-level rise, slope of adjacent land and presence of obstacles [20], [32], [21].

Mangroves can survive extreme storm events by providing rapid input of allochthonous sediment allowing rapid sediment deposition that in turn will increase and maintain soil elevation[27]; [22]. Intense storms can also provide nutrients to stimulate mangrove productivity and growth [32].

Mangrove forests attenuated the Indian Ocean tsunami waves and protected coastal communities in Indonesia, Thailand, India and Sri Lanka [33]. Studies in Indonesia, India and Sri Lanka reported the buffering protection offered by mangroves to the adjacent villages during the year of 2004 from Indian Ocean tsunami[34], [20], [33]. There is a significant negative correlation between the casualties and the area of mangroves and other coastal vegetation, the elevation from mean sea level and the distance of settlements. In Simeleu Island, Indonesia, close to the epicenter of the tsunami, the casualties are significantly low due to the presence of good mangroves. The dense mangrove cover in Sundarbans have saved West Bengal and Bangladesh from the tsunami disaster [33]. In a post-tsunami survey in Sri Lanka, true mangroves such as Rhizophora spp. or Bruguiera spp. were reported to survive the ocean surge better due to pneumatophores or prop roots that could attenuate tsunami waves [34].

The role of mangroves in reducing sea waves depends on the water depth, wave period, wave height, mangrove species, mangrove density and diameter [35]. A six-year-old mangrove forests of 1.5 km width will reduce 1 m high waves at the open sea and 0.05 m at the coast [35]. Another study shows that a mangrove density of 30 trees/100 m² in a 100-m wide belt can reduce the maximum tidal pressure by more than 90%, if the wave height is less than 4-5 m [36].

The wave attenuation capacity of mangroves is due to the fact that mangroves act as suspended sediment sinks as a result of the complex mangrove density and aerial root system flexibility[37]. Generally, Rhizophora spp. is more suitable to mitigate tsunami impacts due to their extensive stilt roots that exhibit more drag force and tolerance to flood submergence [33].

4. Mangrove management

4.1. National policies

Indonesia’s Government policy on mangrove management began in the early 1930s which was oriented towards exploitation of mangrove forest timber by designated all mangrove forests in Sumatera as production forest [38]. This policy had inflicted problems as the natural regrowth in degraded mangroves failed. To address this failure, experiments in mangrove rehabilitation was undertaken by Perusahaan Hutan Negara since 1932 [38].

In 1952, mangrove forests belonging to the State were managed by State forestry companies (PERHUTANI) where a combination of exploitation and rehabilitation management plan was applied. This new management plan that time was then designated as the official guidelines for mangrove forest management in Indonesia (Directorate General for Forestry decree SK No 60 of the year 1978) which is still being applied up to date [38].

Currently, there are several national regulations related to protection and use of mangrove Ecosystems, such as:

a. Law No 5 year 1990 on Conservation of Natural Resources and their Ecosystems emphasized on conservation of mangroves as natural resources to ensure the sustainability of its supplies while keep maintaining and improving the quality of diversity and value.

b. Law No 41 year 1999 on Forestry, then revised in Law No 19 year 2004 states that mangrove management falls under the Department of Forestry.
c. Law No 26 Year 2007 on Spatial Planning states that mangroves belong to one of the protected areas.
d. Law No 27 year 2007 on Management of Coasts and Small Islands states that coastal areas (including mangroves) management falls under the Ministry of Fisheries and Marine Affairs. This law causes overlapping authorities between The Ministry of Forestry and Ministry of Fisheries and Marine Affairs on mangrove management.
e. Law No 32 Year 2009 on Protection and Management of Environment describes the standard criteria for mangrove ecosystem deterioration.
f. The Presidential Decree Number 73 Year 2012 on National Strategy on Mangrove Ecosystem Management laid the basics for the common reference in order to coordinate and synergize policies, programs and activities for the management and utilization of Indonesia's mangrove ecosystems.
g. The Presidential Decree Number 9 Year 2016 on One Map as a Guidance for Mangrove Management emphasized on the acceleration of the implementation of the One Map Policy at the level of map accuracy of 1: 50,000 scale, to fulfill one map that refers to one geospatial reference, one standard, one database, and one geoportal to accelerate national development.
h. Regulation of the Coordinating Minister for Economic Affairs No. 4 Year 2017 on Policy, Strategy, Program and Performance Indicators of National Mangrove Ecosystem Management describes the strategy and performance indicators of mangrove ecosystem management where the target of mangrove rehabilitation is set at 1.82 million ha by 2045.

Up to the present time, there are 5 institutions that are responsible for mangrove management in Indonesia, i.e. Coordinating Ministry of Maritime and Investment, Ministry of Environment and Forestry, Ministry of Fisheries and Marine Affairs, Ministry of National Development Planning (Bappenas) and Coordinating Ministry for Economic Affairs.

Although mangrove management policy and regulations have existed almost for a century, mangrove deforestation have still occurred, due to weak law enforcement and conflicting policies [39], [38], [40].

4.2. Mangrove Conservation
Mangrove conservation is an effort to maintain and protect mangrove ecosystem, preventing mangrove destruction and increasing their coverage. In addition to mangrove destruction, mangrove degradation is becoming a key issue due to declining mangrove ecosystem quality that results in pollution, salinity changes and biodiversity loss[41].

In order to support Convention on Biological Diversity (Aichi Biodiversity Target) and the UN-Sustainable Development Goals, Indonesia needs to protect 3.3 million km² terrestrial and 23.7 million km² of marine ecosystems. To address deforestation and forest degradation problems, the Government of Indonesia c.q. Ministry of Environment and Forestry has designated 42 ecosystem essential areas totaling of 909,580.521 ha. The Ecosystem essential areas (EEA) are ecosystems outside conservation areas that are ecologically and socially, economically and culturally important for biodiversity conservation. EEAs comprises of 4 types of purposes, i.e. wetlands EEAs, biodiversity EEAs, wildlife corridor EEAs, and high value conservation EEAs. These areas are protected and managed according to forest management and conservation principles under the authority of the local Government[42].

From 42 EEAs, 6 mangrove ecosystem essential areas comprising of 1,826,207.05 ha have been designated in 5 ecoregions, namely (1) Jaring Halus in North Sumatera; (2) Pantai Cemara in Jambi; (3) Desa Mojo in Pemalang, Central Java; (4) Teluk Panggang, Banyuwangi - East Java; (5) Torosiaje in Pohuwato - Gorontalo and (6) Lombok Barat in Nusa Tenggara Barat. The management model of mangrove EEAs includes: (1) active community engagement in managing mangrove EEAs; (2) sustainable mangrove use; (3) function-based management (preservation, protection and utilization); and (4) multi-stakeholder participation[42]. The proportion of mangrove forests under conservation management is approximately 22% of the total mangrove extent in Indonesia [43].
Carbon storage in mangrove conservation areas in 2010 was estimated at 0.82–0.89 PgC (1 PgC = 10^9 tonneC)[44]. Studies have shown that conserving one hectare of mangroves will have significant impact on the carbon emissions than if they are otherwise converted into other land uses such as fish ponds [11], [44]. If the annual mangrove deforestation in Indonesia are halted by conserving mangrove areas, the total annual land-use sector emissions would be reduced by 10-31% [11]. Increasing mangrove conservation areas by 30% of the total mangrove extent would result in a greater potential for climate change mitigation, which is equal to about 1.2 PgC of CO_2 emissions [44]. Hence, prioritizing mangrove conservation in regions with high mangrove loss such as Sumatera and Kalimantan is highly recommended.

4.3. Mangrove Rehabilitation

Mangrove rehabilitation programs have been started since 1930 in Indonesia [38]. Rehabilitation of mangroves is becoming an important task as mangrove destruction occurs at alarming rates in developing countries, especially in Southeast Asia. Low survival rate of mangroves in many rehabilitation projects are becoming a common problem in these countries, including Indonesia. In the Philippines, although massive funds have been allocated for mangrove rehabilitation, the long term mangrove survival rate are very low at 10-20% [45].

Generally, the most common factors that contribute to the failure in mangrove rehabilitation are: (1) inappropriate species; (2) unsuitable planting sites; (3) infestation of pests and diseases; (5) flood, wave; (6) garbage and marine debris; (7) weak monitoring; and (8) human factors such as gleaning, fishing gears, fishing boats[45]. _Rhizophora_ spp. is the most preferred and common species chosen for rehabilitation projects due to its large propagules and that are easy to collect and plant. Naturally, _Rhizophora_ spp. is more appropriate to be planted in more protected zones behind _Sonneratia_ – _Avicennia_ zone or along muddy tidal rivers and creeks. Therefore, planting _Rhizophora_ spp. in seaward zones would result in low survival rates.

Unsuitable planting site is another factor that lead to mangrove rehabilitation failure. Many rehabilitation projects choose the lower intertidal – subtidal zones that include tidal flats and seagrass habitats as their planting locations because these areas are open access and have minimum threat of land tenure conflicts [45]. Reforestation attempts in the mudflats often fails due to problem of frequent flooding that is greater than the tolerance of mangrove. In some cases where planting in mudflats succeed would represent habitat conversion rather than habitat restoration[46]. Rehabilitation should therefore be conducted on middle to upper intertidal zones rather than in the lower intertidal zones. Although the middle and upper tidal zones are now mostly occupied by abandoned ponds, they have better chance for a successful rehabilitation as they were formerly mangroves [45].

Several rehabilitation techniques have been implemented in Indonesia such as (1) the guludan technique; (2) mangrove planting in the over-logged forest area and (3) agroforestry techniques (sylvofishery, agrosilvofishery, agrosilvofishery pastoral system)[46]. Guludan technique was implemented in coastal area of Angke Kapuk, North Jakarta, that is now being degraded due to conversion to airport, high way, urban facilities, resettlements, and fish ponds. Guludan technique uses bamboo with 10 m (length) x 4 m (width) x 2 m (depth) filled with soil sediment sacs and soil at least 50 cm depth to be planted with mangroves. The media for mangrove seedlings is a mixture of mineral soil (60%) and mud (40%). Spacings of 0.5 x 0.5 m resulted in the good growth of _R. mucronata_ seedlings are planted in guludan with 80% of survival rate[46]. Guludan technique is best applied at inundated areas with water depth between 1-2 m.

Sylvofishery is a traditional technology of aquaculture that combines fishery business with mangrove planting, followed by the concept of introducing a management system by minimizing inputs and reducing the impact on the environment. Sylvofishery system was introduced in 1970’s by Perum Perhutani as a forest state enterprise. This system which is called _empang parit_ was that time designed where mangroves stands in the middle of the pond surrounded by ditches/canals for aquaculture. The ratio area for one unit of fish pond is about 80% mangroves and 20% ditches. Progress with time, sylvofishery has developed to other systems such as agrosilvofishery and
agrosilvofisherypastoral systems which have been applied by local coastal communities. These kinds of environmental-friendly aquaculture systems are suitable for mangrove rehabilitation in a poor community. The highest income could be received when the farmer implemented agrosilvofishery pastoral system by combining oil palm, mangroves, aquaculture and chicken in one pond[46].

Figure 1a. Guludan technique in coastal area of Angke Kapuk, North Jakarta; 1b. silvofishery system in Serang, Banten [14].

Since 2010 the Indonesian Ministry of Environment and Forestry have put more emphasis on mangrove rehabilitation programs in Indonesia. The rehabilitation system implemented are (1) silvofishery; (2) intensive rehabilitation and (3) community nursery. Since 2015 onward, the mangrove rehabilitation target have significantly declined due to national re-prioritization and due to the fact that it is harder to find land tenure conflicts - free locations in the field for conducting rehabilitation programs.

In the mid-term national development plan 2020-2024, the Ministry of Environment and Forestry of Indonesia targets to rehabilitate 5000 ha of mangroves within 5 years or 1000 ha/year[46]. This target is considered low compared to the rate of mangrove degradation in Indonesia (52,000 ha/year) and is predicted not to be able to reach the national mangrove rehabilitation target of 3.49 million ha by 2045 as it has been stated in the Regulation of the Coordinating Minister for Economic Affairs No. 4 year 2017.

Relating to mangrove rehabilitation with their mitigation capacity to climate change, restored or rehabilitated mangroves have been reported to follow a trajectory to attain similar ecosystem functions and services as natural forests. A 10-year restored abandoned ponds in Perancak, Bali, shows similar NPP and soil C sequestration rate as the natural mangroves, which underscores the value and the potential benefits from mangrove restoration [47].

To reach the national mangrove rehabilitation target and NDC, several factors must be taken into account, i.e. (1) enhance coordination between sectors and stakeholders; (2) solve conflicting land tenure issues; (3) adhere to the appropriate mangrove growth ecological prerequisites; (4) prepare careful rehabilitation planning; (5) increase mangrove conservation areas; (7) put a halt on mangrove conversion to other land-uses; (8) allocate long term monitoring program; and (9) involve local communities in mangrove rehabilitation and management.

5. Conclusions
Mangrove ecosystems provide a wide range of ecological and socio-economic benefits and should be taken into account for their mitigation potential in climate change. Although this ecosystem would be the first to be impacted by climate change, when mangroves are in good quality, they have been proven to be able to cope and offer protection to their surrounding environments and communities. Their significant capacity to store and sequester carbon can make this ecosystem becomes a large carbon emitter when they are converted into other land uses, such as aquaculture. Therefore, mangrove
conservation should be prioritized because it is the cheapest and easiest way for reducing emissions in this ecosystem.

Mangrove management have been undervalued and overlooked for decades. Rehabilitation programs should consider mangrove ecological pre-requisites such as planting the right species at the appropriate locations. Participatory approach by involving communities in the rehabilitation/restoration programs would increase the success of the program. Removing barriers in mangrove management would take a strong effort and commitment from the Government and all the stakeholders.

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