# Contributions of mangrove conservation and restoration to climate change mitigation in Indonesia

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RESEARCH ARTICLE

# Contributions of mangrove conservation and restoration to climate change mitigation in Indonesia

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## Abstract
Mangrove forests are important carbon sinks, and this is especially true for Indonesia where about 24% of the world's mangroves exist. Unfortunately, vast expanses of these mangroves have been deforested, degraded or converted to other uses resulting in significant greenhouse gas emissions. The objective of this study was to quantify the climate change mitigation potential of mangrove conservation and restoration in Indonesia. We calculated the emission factors from the dominant land uses in mangroves, determined mangrove deforestation rates and quantified the total emissions and the potential emission reductions that could be achieved from mangrove conservation and restoration. Based on our analysis of the carbon stocks and emissions from land use in mangroves we found: (1) Indonesia's mangrove ecosystem carbon stocks are among the highest of any tropical forest type; (2) mangrove deforestation results in greenhouse gas emissions that far exceed that of upland tropical deforestation; (3) in the last decade the rates of deforestation in Indonesian mangroves have remained high; and (4) conservation and restoration of mangroves promise to sequester significant quantities of carbon. While mangroves comprise only ≈2.6% of Indonesia's total forest area, their degradation and deforestation accounted for ≈10% of total greenhouse gas emissions arising from the forestry sector. The large source of greenhouse gas emissions from a relatively small proportion of the forest area underscores the value for inclusion of mangroves as a natural climate solution. Mangrove conservation is far more effective than mangrove restoration in carbon emissions reductions and an efficient pathway to achieve Indonesia's nationally determined contribution (NDC) targets. The potential emission reduction from halting deforestation of primary and secondary mangroves coupled with restoration activities could result in an emission reduction equivalent to 8% of Indonesia's 2030 NDC emission reduction targets from the forestry sector.

KEYWORDS
blue carbon, carbon sequestration, climate change, $CO_2$ emissions, mangroves, mitigation, nationally determined contributions (NDC), natural climate solutions (NCS), nature-based climate solutions

## 1 | INTRODUCTION

Mangrove ecosystems occur in tropical and sub-tropical intertidal marine and brackish environments (Friess, 2016; Giesen et al., 2007; Lugo & Snedaker, 1974). Renowned for an array of ecosystem services including fish habitat, sediment regulation, and protection from storm surges and sea-level rise (Barbier et al., 2011), mangroves are carbon-rich ecosystems that warrant preservation and restoration because they capture and preserve significant quantities of carbon (C), thus counterbalancing anthropogenic greenhouse gas (GHG) emissions (Kauffman et al., 2017; Kauffman et al., 2020; Mcleod et al., 2011; Siikamaki et al., 2012).

Natural climate solutions (NCS) to climate change includes the conservation, restoration, and/or improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions from forests, wetlands, grasslands, and agricultural lands (Griscom et al., 2017). Given their large carbon stocks and high levels of greenhouse gas emissions when converted, mangrove conservation and restoration would be a valuable NCS.

As part of the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement goal of limiting warming to <2°C, Indonesia has committed to reducing national emissions by 29% and 41% under unconditional and conditional mitigation scenarios by 2030 (Ministry of Environment and Forestry Republic of Indonesia, 2021). The forestry sector is expected to contribute up to 60% to the total emission reduction target from all sectors. Indonesia also submitted its first Forest Reference Emission Level (FREL) to UNFCCC in 2015 as a benchmark document for assessing reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks (REDD+) implementation (Ministry of Environment and Forestry Republic of Indonesia, 2016). The first FREL covered avoiding deforestation, forest degradation, and peat decomposition as mitigation actions. Currently, a second FREL is being prepared by the Indonesian Government and will include mitigation activities, such as the reduction of soil mangrove emissions through forest conservation. As soils comprise the largest fraction of carbon stocks in the mangrove ecosystems (Kauffman et al., 2020), they are important for inclusion in national REDD+ strategies. A pantropical study from Griscom et al. (2020) reported that NCS potential in Indonesia from avoided mangrove loss and restoration could reduce GHG emissions ≈ 67 Tg $CO_2$e $year^{-1}$. However, they used global averages of carbon stocks, emissions, and emission factors (EFs). In this study, we reduced uncertainties by using site-specific EFs and official data activity from Indonesian mangroves.

Accurately predicting the values of conservation and restoration of mangroves requires knowledge of the carbon dynamics of intact and degraded mangroves (Figure 1). Ecosystem carbon stocks of intact mangroves and emissions associated with land use must be known. In addition, it is necessary to determine the net ecosystem productivity (NEP) of land cover types which can be accomplished through measurement of net primary productivity (NPP) and heterotrophic respiration (Chapin et al., 2011).

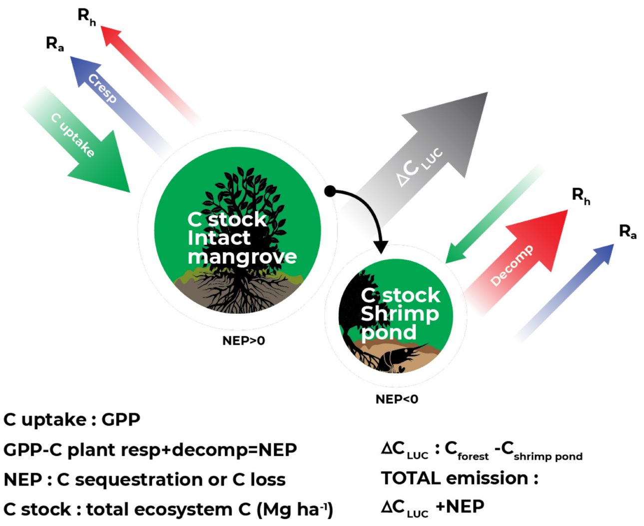


FIGURE 1 Ecosystem and anthropogenic processes that are necessary for the quantification of understanding carbon dynamics for climate change mitigation and adaptation. This is an example of conversion of a mangrove forest to a shrimp pond. The size of the arrows represents the relative size of the fluxes and the size of the C stocks (green circles) represent the relative size of the C stocks. The gray arrow represents the emissions from land use change (LUC). GPP is gross primary productivity, NEP is net ecosystem productivity, LUC is land use change, NPP is net primary productivity, rh is heterotrophic respiration, and ra is autotrophic respiration. When NEP is >0 the ecosystem is a net sink of carbon and when NEP < 0 the ecosystem is a net source of carbon

We compiled a comprehensive data set of the current and historical extent of Indonesian mangroves, as well as carbon dynamics associated with land use that could provide policy makers with the necessary information needed to determine the values of conservation and restoration with respect to climate change mitigation and adaptation strategies. The primary goals of this study were as follows: (1) to determine the EFs from conversion of Indonesia's primary and secondary mangrove forests to non-forest; (2) to determine the spatial extent of Indonesian mangroves, the magnitude of loss and the rate of conversion from 2009 to 2019 based on official spatial data; and (3) combining the ecosystem and spatial data, to quantify the total emissions from land use change in mangroves and the mitigation potential that could be achieved through avoided mangrove loss (conservation) and restoration of mangroves to fulfill Indonesia's NDC by 2030.

## 2 | METHODS

### 2.1 | Study sites

In this study we determined mangrove carbon stocks and EFs from seven major island groups as well as the country mean of Indonesia. The seven regions include: Java, Kalimantan, Bali-Nusa Tenggara Islands, Maluku Islands, Papua, Sulawesi, and Sumatra (Figure S1).

**TABLE 1** Vegetation dominance and geomorphic settings of the intact mangrove forests used in this study to estimate total ecosystem carbon stocks in each region

| Region | *N* | Dominance | Geomorphic settings | Source |
|---|---|---|---|---|
| Country-wide | 54 | | | Kauffman et al. (2020) |
| Java | 2 | *Sonneratia alba* | Fringing | Donato et al. (2011) |
| Kalimantan | 27 | *Rhizophora* spp., *Avicennia* spp., *Nypa fruticans* | Fringing, estuarine | Arifanti et al. (2019); Murdiyarso et al. (2015) |
| Papua | 13 | *Bruguiera gymnorrhiza*, *R. apiculata* | Fringing, estuarine, basin/interior | Murdiyarso et al. (2015) |
| Sulawesi | 6 | *Rhizophora mucronata* | Fringing, estuarine | Murdiyarso et al. (2015) |
| Sumatra | 6 | *Rhizophora apiculata* | Fringing | Murdiyarso et al. (2015) |

## 2.2 | Carbon stocks

For our analyses we limited inclusion to those studies that quantified carbon (C) stocks for the entire soil profile (or a default of at 3 m when soil profiles were >3 m depth). This is important as numerous studies have reported soil carbon losses from land use at depths of ≥3 m (Arifanti et al., 2019). Limiting estimates to 1 m depths has been found to underestimate both carbon stocks as well as the emissions from land use (Arifanti et al., 2019; Kauffman et al., 2017). We used published carbon stocks data from Arifanti et al. (2019), Donato et al. (2011), Murdiyarso et al. (2015) and Kauffman et al. (2020).

We used quantitative data from 54 mangroves throughout Indonesia (Table 1). The dominant geomorphic settings were fringing/oceanic and estuarine/riverine delta landscapes. The data presented here are mostly derived from intact mangroves and aquaculture ponds. There was limited data for other land-cover types such as degraded mangroves and silvo-fisheries.

Detailed methods to measure C stocks can be found in Kauffman and Donato (2012) and in the Supplementary text. We determined total ecosystem carbon stocks (TECS) of mangroves at the entire country scale as well as at the province scales from which they were collected (Figure S2). Carbon stocks of degraded and secondary mangrove forests varied due to the land use history as well as the time since disturbance. For example, secondary forests ranged from those occupying recently abandoned ponds or agricultural lands to mature forests decades following disturbance. As such, there would be wide ranges in both aboveground and belowground pools. Carbon stocks of intact (primary) and secondary (disturbed) mangrove forests were determined from data collected in 54 and eight sites respectively in Indonesia (Tables S1 and S2) using the same methods as described above. The secondary forests ranged in age from 3 to 14 years old (Arifanti, 2017; Table S2).

## 2.3 | Emission factors

The EF (the mean annual quantity of carbon emissions following forest conversion) in this study has two important sources: (1) the total emissions due to shifts in ecosystem carbon stocks due land-cover change and (2) the emissions associated with shifts in the NEP due to land conversion (Figure 1). We report the EF as the mean potential emissions due to land use based on a 20 year "committed emissions" accounting approach (Davis & Socolow, 2014).

Arifanti (2017) and Arifanti et al. (2019) determined the ecosystem C stocks, NPP, heterotrophic and autotrophic respiration of 10 mangroves paired with shrimp ponds in the Mahakam Delta of East Kalimantan. As the variation and mean of the TECS of the mangroves in the Mahakam Delta (1023 Mg C ha$^{-1}$) was well within the margin of error of the TECS of mangroves in Indonesia (1063 Mg C ha$^{-1}$), we believe these data offer a good approximation of losses due to land-cover change in Indonesia.

We defined the NEP as the differences between C gains (sequestration) and losses (emissions) of an ecosystem (Chapin et al., 2006; IPCC, 2006). NEP for mangroves and shrimp ponds was determined through measurements of NPP subtracted from heterotrophic respiration (Rh). NPP was determined though measurements of aboveground and belowground C sequestration, and litterfall (Arifanti, 2017). Autotrophic and heterotrophic respiration were determined through monthly trace gas emission measurements in trenched (heterotrophic) and untrenched plots (total respiration) (Arifanti, 2017).

## 2.4 | Emission factors of primary forests conversion to other non-forest land uses

Differences in carbon stocks between mangroves and shrimp ponds facilitated calculation of emissions arising from shifts in ecosystem carbon stocks due to land cover change. The C loss (i.e., emissions due to land conversion, Figure 1) was determined using a modified stock-difference approach (IPCC, 2006), also referred to as a biomass equivalence approach (Kauffman et al., 2017). Arifanti et al. (2019) found there was a mean ecosystem carbon stock loss of 51% due to primary mangrove conversion to aquaculture and we used this estimated percentage as the carbon lost due to land conversion. Carbon loss due to land cover change (primary and secondary mangrove conversion to other land uses) was estimated at both the country and province scale (Table 2; Tables S3–S5). Uncertainty of the EF from each land use transition was calculated using standard propagation methods.

TABLE 2 Emission factors (EFs) related to primary mangrove conversion to other land uses (non-forests), primary mangroves to secondary forests and conversion of secondary forests to other land uses in Indonesia. Numbers are mean ± SE

| Region | Primary mangrove conversion to other land uses (non-forests) | | Primary mangrove conversion to secondary forests | | Secondary mangrove conversion to other land uses | |
|---|---|---|---|---|---|---|
| | EF ($Mg\,CO_2e\,ha^{-1}$) | EF ($Mg\,CO_2e\,ha^{-1}\,year^{-1}$) | EF ($Mg\,CO_2e\,ha^{-1}$) | EF ($Mg\,CO_2e\,ha^{-1}\,year^{-1}$) | EF ($Mg\,CO_2e\,ha^{-1}$) | EF ($Mg\,CO_2e\,ha^{-1}\,year^{-1}$) |
| Country-wide | 2738 | 136.9 ± 8.3 | 1156.8 | 57.8 ± 10.2 | 833.4 | 41.7 ± 1.7 |
| Java | 1846 | 92.3 ± 15.7 | 626.5 | 31.3 ± 33.1 | 480.1 | 24.0 ± 5.4 |
| Kalimantan | 2618 | 130.9 ± 8.3 | 1090 | 54.5 ± 10.6 | 783.9 | 39.2 ± 1.8 |
| Papua | 3014 | 150.7 ± 10.7 | 1311.3 | 65.6 ± 18.6 | 944.8 | 47.2 ± 2.9 |
| Sulawesi | 2506 | 125.3 ± 25.4 | 1025 | 51.3 ± 58.2 | 739 | 37.0 ± 9.6 |
| Sumatra | 3218 | 160.9 ± 8.9 | 1429.5 | 71.5 ± 14.0 | 1026.8 | 51.3 ± 2.6 |

The change in NEP for mangroves and shrimp ponds was determined through measurements of NPP subtracted from heterotrophic respiration (Figure 1). NPP was determined through measurements of annual tree growth and litterfall. Autotrophic and heterotrophic respiration was determined through monthly trace gas emission measurements in trenched (heterotrophic) and untrenched plots (total respiration; Arifanti, 2017). EFs were calculated through summing the mean annual C emissions from mangrove conversion with the annual change in NEP between intact and converted sites (Figure 1).

## 2.5 | Emission factors of primary forests conversion to secondary forests

The EF of primary mangrove conversion to secondary forests was estimated as the mean emissions arising from the decline in carbon stocks when primary forests were shifted to secondary forests through deforestation (Table 2; Table S4). Here, we assumed that there was no change in the NEP between primary and secondary mangroves.

## 2.6 | Emission factors of secondary forests conversion to other non-forest land uses

Conversion of secondary forests to other land uses was estimated as the difference in the TECS between secondary forests and that of shrimp ponds (Table S5). There was a 29% difference in the ecosystem C stocks between secondary forests and shrimp ponds and we assumed these would be lost via GHG emissions (Arifanti, 2017). The EF for secondary mangrove conversion to other land uses was calculated as the emissions from conversion, and changes in the NEP between mangroves and aquaculture ponds (Table 2; Table S5).

## 2.7 | Activity data

Land cover data used in this study were derived from the Indonesian National Forest Monitoring System (SIMONTANA) data (https://nfms.menlhk.go.id/). This system is used by the Ministry of Environment and Forestry (MoEF) for planning, policy evaluation, and decision-making. The utilization of these data sets as activity data for GHG emissions accounting is in line with the country's effort to fulfill the principle of transparency, accuracy, consistency and comparability. A consistent national land cover data set was and readily available from 1990 to the present. Land cover maps are created annually by MoEF's regional offices using visual interpretation of satellite imageries.

The national land cover maps of Indonesia were made at the minimum scale of 1:250,000 using Landsat image mosaic data (Landsat 5 Thematic Mapper/TM, Landsat 7 Enhanced Thematic Mapper Plus/ETM + and Landsat 8 Operational Land Imager/OLI) with less than 50% cloud cover (Ministry of Environment and Forestry Republic of Indonesia, 2020a). Validation and quality assurance of the land-cover maps were conducted by comparing land cover maps with ground truthing (Margono et al., 2016). A total of 10,000 sample points were used as reference data that were randomly distributed to measure the accuracy of the MoEF's land cover data from 2009–2019. The accuracy assessment used high-resolution imagery including SPOT 6/7 and Google Earth Image was determined to be 91.2% (Table S6).

Mangrove forest changes were classified into four categories:

1. mangrove deforestation: the change of primary and secondary mangroves to non-forest areas or other land uses.
2. mangrove degradation: the change of primary mangroves to secondary mangroves.
3. mangrove growth: the change of secondary to primary mangroves.
4. mangrove reforestation: the change of non-forests to secondary mangroves.

We also reclassified the drivers of mangrove forest change into four classes (Arifanti et al., 2021): (1) aquaculture, (2) agriculture, (3) low statured vegetation or low-cover density vegetation (i.e., transitional vegetation from cleared mangroves before being converted to aquaculture), and (4) infrastructure development.

We calculated the area of mangrove forest change and net deforestation rates at both the national level and within seven regions of Indonesia from 2009–2019. Net deforestation or change in forest area was calculated by summing all changes due to deforestation and reforestation.

## 2.8 | Emission and removal factors from mangrove forest change

The $CO_2$ emissions ($CO_2$e year$^{-1}$) arising from land cover change in mangrove ecosystems were calculated by multiplying the EF ($CO_2$e ha$^{-1}$ year$^{-1}$) by the loss of mangrove area per year (IPCC, 2006). Carbon sequestration from mangrove restoration (forest removals) was calculated by multiplying shifts in EFs by the activity data for reforested areas. Carbon sequestration from forest growth was determined as the NEP for forests multiplied by their total area.

The forest reference level (FRL) is a benchmark to assess a country's performance in contributing to mitigation of climate change. The FRL includes both activities that reduce emissions and those which increase removals or enhancement of forest carbon stocks (UNFCCC, 2012).

## 2.9 | The range in mangrove climate mitigation potential

Mangrove pathways consist of land management activities that would reduce greenhouse gas emissions. We describe two possible pathways or strategies in which mangroves could function as part of Indonesia's NDC in 2030. The first includes all possible avoided mangrove deforestation and degradation (high end of projections) and the second is the current or projected government policies on mangrove reforestation/restoration (low end of projections).

## 2.10 | Avoided mangrove deforestation and degradation pathway

This pathway is one that avoids/ceases all mangrove deforestation and degradation that would include the participation of forestry, agricultural, and aquacultural sectors. Prevention of mangrove change or loss arises from two data activities: (1) halting deforestation defined as the change of primary and secondary mangrove forests to other land uses or non-forests and (2) halting forest degradation defined as a direct human-induced loss of forest values (particularly carbon), likely to be characterized by a reduction of tree cover (IPCC, 2006).

This pathway assumes that avoided mangrove deforestation and degradation activities in 2020–2030 is equivalent to, but opposite of, the historical deforestation and reforestation rates from 2009 to 2019. In this pathway we also included the enforcement of the implementation of the Presidential Instruction Number 5/2019 regarding the permanent cessation of the issuance of new licenses in primary forests and peatlands (The Government of Indonesia, 2019), where all primary mangroves should be protected from conversion activities and the commitment of Indonesia to protect 32.5 million ha of marine protected areas (including mangroves, coral reefs, seas, and sea shores) by 2030 (Ministry of Marine Affairs and Fisheries of the Republic of Indonesia, 2020).

## 2.11 | Mangrove restoration pathway

Indonesia has committed to restore its degraded mangroves covering about 638,000 ha (Ministry of Environment and Forestry Republic of Indonesia, 2020b). This pathway includes restoration programs as targeted by the Government of Indonesia from 2020 to 2030 including the following: (1) labor-intensive mangrove planting of 17,641 ha in 2020 (The Government of Indonesia, 2020a), (2) reforestation and restoration of 600,000 ha of degraded mangroves in Indonesia in 2021–2024 (The Government of Indonesia, 2020c), and (3) mangrove reforestation and restoration of at least 5000 ha per year in 2025–2030 as determined in the 2020–2024 Indonesia's Mid Term Development Plan (The Government of Indonesia, 2020b).

## 2.12 | Uncertainty analysis

We estimated uncertainty for maximum mitigation potential for avoided mangrove loss and mangrove restoration. The Monte Carlo simulation or IPCC (Ogle et al., 2019) approach was used by combining activity data and EFs to calculate the overall inter-pathway uncertainty. Standard errors of the mean were used to define Monte Carlo distribution using 100,000 iterations. We described uncertainty as the 95% confidence interval from results of the Monte Carlo simulations.

# 3 | RESULTS

## 3.1 | Carbon stocks

The mean TECS for Indonesian mangroves is 1063 ± 91 Mg C ha$^{-1}$ (mean ± 95% confidence interval; Table S1). There is a large range in TECSs from 408 to 2208 Mg C ha$^{-1}$ (Figure S2). The belowground carbon pool comprised a mean of 83% of the total stock. The range among the dominant sampled Indonesian islands ranges from 587 Mg C ha$^{-1}$ in Java to 1319 Mg C ha$^{-1}$ for mangroves of Sumatra.

## 3.2 | Carbon dynamics associated with land cover change

Shrimp ponds were net sources of carbon with a negative NEP of −1.4 Mg C ha$^{-1}$ year$^{-1}$. The differences in NEP between mangroves and shrimp ponds was 10.2 Mg C ha$^{-1}$ year$^{-1}$ (Arifanti, 2017). Adding losses due to changes in NEP to the stock losses due to land cover change allows us to estimate an annual EF for land use. Here we calculate that the EF for Indonesian mangroves related to primary mangrove conversion to other land uses is 2738 Mg $CO_2e$ ha$^{-1}$ or 137 Mg $CO_2e$ ha$^{-1}$ year$^{-1}$ (Table 2). At regional scales, the EF ranged from 92.3 Mg $CO_2e$ ha$^{-1}$ year$^{-1}$ in Java to 160.9 Mg $CO_2e$ ha$^{-1}$ year$^{-1}$ in Sumatra (Table 2).

## 3.3 | Mangrove forest change

During the 10-year period of this study (2009–2019) 261,141 ha of mangroves were affected, with 182,091 ha deforested (70% of the total loss) and 79,050 ha degraded (30% of the total loss) (Figure 2). In addition to mangrove forest loss, we also observed increases in cover of about 53,915 ha during this period. This majority of mangrove expansion was due to reforestation (the change of non-forests to primary/secondary mangroves; 52,415 ha) and shifts of secondary mangroves to primary mangroves occurred on about 1500 ha (Figure 2).

The total net deforestation or the net loss of mangrove forest area from 2009 to 2019 was about 128,176 ha (i.e., a net deforestation rate of 12,818 ha year$^{-1}$). Mangrove degradation totaled about 79,050 ha or 7905 ha year$^{-1}$. The greatest extent of mangrove deforestation from 2009–2019 occurred in Kalimantan, followed by Sulawesi, Sumatra, Bali and Nusa Tenggara Islands, Papua, Java, and Maluku Islands (Figure S3).

In addition to aquaculture, the major drivers of mangrove deforestation in Indonesia were conversion to low statured vegetation (transitional vegetation before conversion to aquaculture; 46%), agriculture (19%), and infrastructure development (3%; Figure 3). Almost all of the mangroves converted to agriculture (19% or 34,644 ha of the total deforested mangroves) had been converted to oil palm plantations.

## 3.4 | Emissions from mangrove forest change

The net $CO_2$ emissions from mangrove cover change during 2009–2019 shows a steady trend of mangrove emissions throughout this period, except for and abrupt peak in 2017–2018 followed by a sharp decline in 2018–2019. The Papua region had low net emissions prior to 2017, then showed a steep increase in 2017–2018. Sumatra has a steep increase of net emissions from 2014 to 2016 and Kalimantan had a steady increase in net emissions while others showed relatively constant trends (Figure 4).

Overall, the highest net emissions from mangrove forest change during 2009–2019 occurred in Sumatra (94.8 Tg $CO_2e$), Kalimantan (67.3 Tg $CO_2e$) and Papua (57.3 Tg $CO_2e$). The lowest net emissions from mangrove forest change were observed in Maluku Islands (11.6 Tg $CO_2e$) and Java (1.7 Tg $CO_2e$; Figure S4).

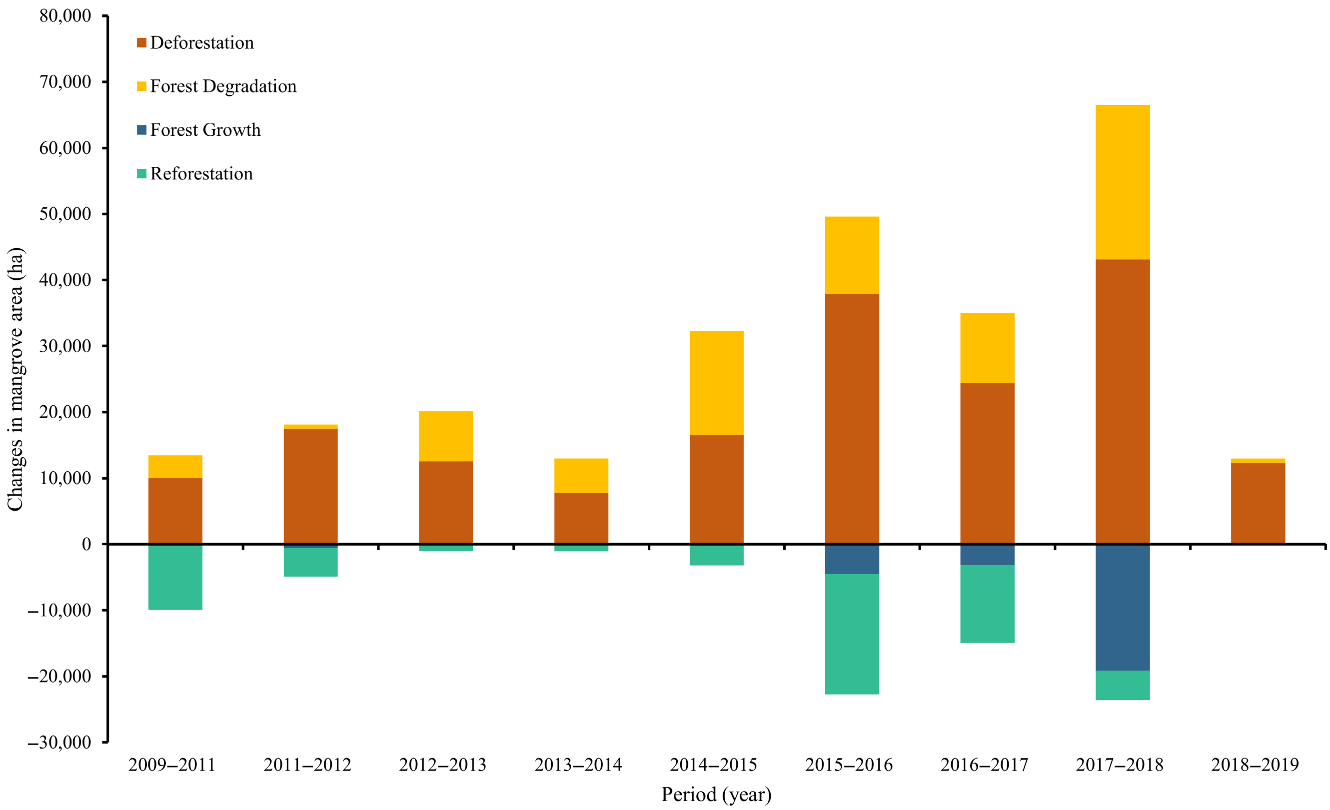


FIGURE 2 Mangrove forest change for Indonesia from 2009–2019 classified into four categories: (1) mangrove deforestation, (2) mangrove degradation, (3) mangrove growth, and (4) mangrove reforestation

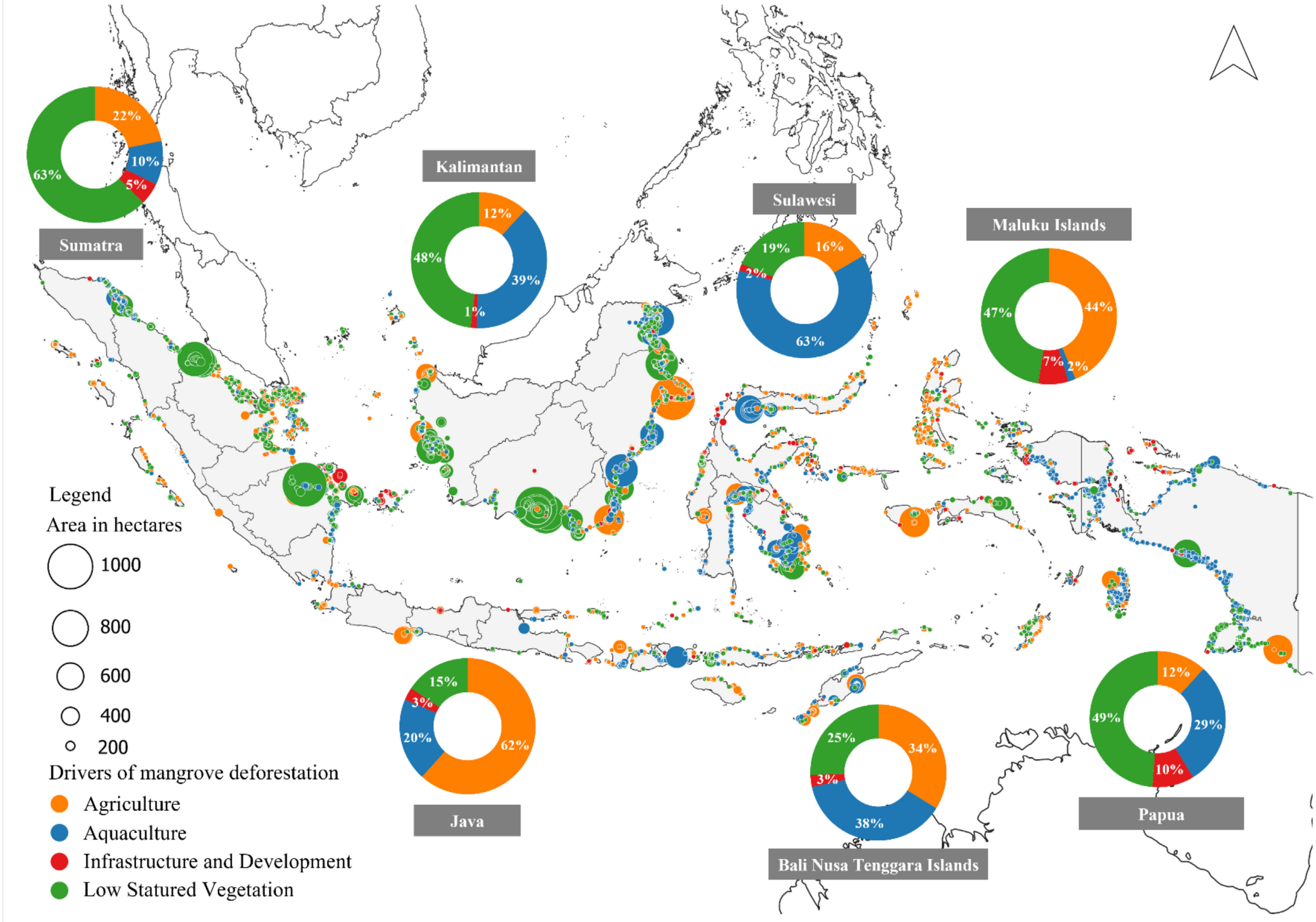


FIGURE 3 Map of Indonesia showing the proportion of the drivers of mangrove deforestation per region. The circle size represents the area of the landcover replacing the deforested mangroves. At the country scale, aquaculture accounted for 31% of the deforestation, and agriculture accounted for 19%

### 3.5 | Mangrove forest reference level

The potential FRL for Indonesian mangroves was constructed from averaging the historical net emissions of mangrove forest change from 2009 to 2019. This was estimated to be 280 Tg $CO_2$e (28 Tg $CO_2$e year$^{-1}$; Figure 5). This value is, therefore, assumed to be the mangrove emission reduction baseline for ongoing and future climate mitigation initiatives (2020–2030) (Figure 5).

### 3.6 | Potential of mangroves in climate change mitigation

#### 3.6.1 | Avoided mangrove deforestation and degradation

An estimated 32 Tg $CO_2$e year$^{-1}$ (Figure S5) or a total of 322 Tg $CO_2$e (Figure 6) could be mitigated through avoiding mangrove deforestation and degradation activities from 2020 to 2030. The uncertainty of avoided emissions from mangrove loss (deforestation and degradation) is estimated to be 28 ± 0.53 Mg $CO_2$e year$^{-1}$. This pathway includes protection of all primary and secondary mangroves in conservation areas as well as a country-wide moratorium of primary mangrove conversion. Avoiding mangrove deforestation and degradation activities comprises ≈78% of total mangrove emission reductions that can be accomplished to 2030. Although mangroves comprise about 2.6% about of Indonesia's total forest area, the emission reduction from this pathway could potentially contribute 6.5% (Figure 7) to the NDC target for the forestry sector in 2030 (497 Tg $CO_2$e) and 3.9% of the targeted NDC emission reduction from all sectors (834 Tg $CO_2$e) under Counter Measure 1 Scenario.

#### 3.6.2 | Mangrove restoration

This pathway only includes those current policy interventions that are planned to be implemented by the Indonesian government from 2020 to 2030. The pathway consists of continued existing regulations by respective Ministries and proposed policies or regulations to be implemented in 2020–2030, including national mangrove reforestation and restoration programs.

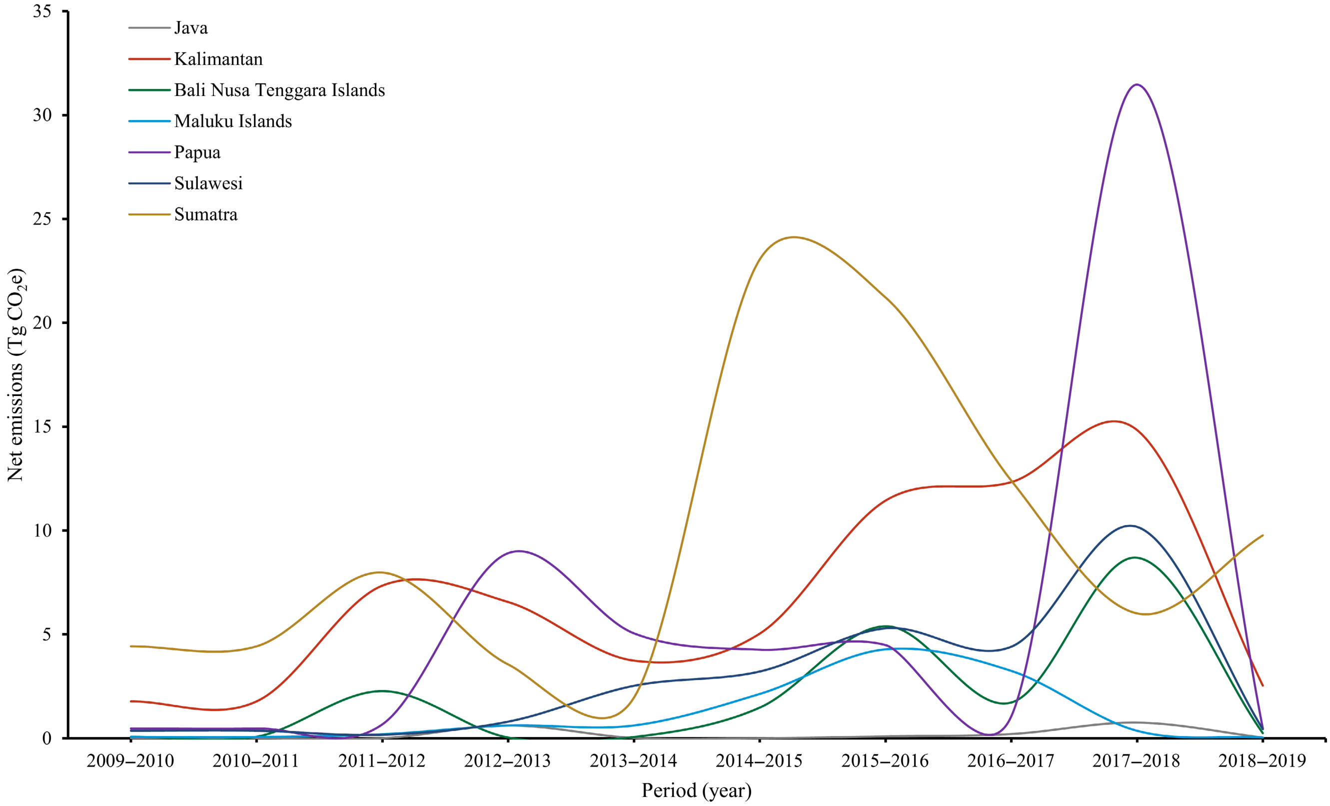


FIGURE 4 Total net emissions from mangrove forest change in 2009–2019 separated by regions in Indonesia

During the COVID-19 pandemic in 2020, the Ministry of Environment and Forestry, Republic of Indonesia (MoEF), enacted an operational plan of labor-intensive mangrove planting (Ministry of Environment and Forestry Republic of Indonesia, 2020d). This policy proposed mangrove reforestation projects to provide job opportunities and incentives for local communities with environmental benefits of restoring degraded mangroves (Ministry of Environment and Forestry Republic of Indonesia, 2020b). This initiative was implemented in 2020 by the Ministry of Environment and Forestry (MoEF), Ministry of Marine and Fisheries (MMF), and local governments. Through this initiative, about 18,041 ha of mangroves were planted. Assuming these plantings survived, this is equivalent to 7% of the total mangrove that had been deforested from 2009 to 2019.

This pathway also includes a planned national mangrove restoration project that would be implemented in 2021–2024 which has been targeted at restoring an additional 600,000 ha. The projected emission reduction that would occur from successful reforestation and restoration of 600,000 ha degraded mangroves in Indonesia in 2021–2024 is estimated at 7.5 Tg $CO_2$e $year^{-1}$. For the 2025 to 2030 period we assumed a conservative reforestation target of 5000 ha $year^{-1}$ as the minimum area that would be planted by the Government as had been determined in the 2020–2024 Indonesia's National Mid Term Development Plan (The Government of Indonesia, 2020b).

The mean mitigation potential of mangrove restoration in Indonesia is estimated to be about 8.9 Tg $CO_2$e $year^{-1}$ (Figure 6). The uncertainty of carbon sequestration following mangrove restoration is about 4.2 ± 0.1 Mg $CO_2$e $year^{-1}$. This is an optimistic number as we assumed that the entirety of the mangrove restoration program of 600,000 ha in 2021–2024 would be successful. If this assumption is true, about 22% of the total mangrove emission reduction is possible through mangrove restoration and would account for 1.4% of the NDC target for the forestry sector in 2030 (Figure 7).

The overall mangrove mitigation activities consisting of both avoiding mangrove deforestation and degradation activities and implementation of mangrove reforestation/restoration yield a total average mitigation potential of 41 Tg $CO_2$e $year^{-1}$ (Figure S5) or a total of 411 Tg $CO_2$e for 2020–2030 (Figure 6). Generally, all mangrove emission reduction activities would comprise about 8% to the NDC target for the forestry sector in 2030 under Counter Measure 1 Scenario (Figure 7).

## 4 | DISCUSSION

### 4.1 | Total ecosystem carbon stocks

Based on our analysis of the carbon stocks and emissions from land use in mangroves we found: (1) Indonesia's mangrove ecosystem carbon stocks are among the highest of any tropical forest types, (2) mangrove deforestation results in GHG emissions that far exceed that of upland tropical deforestation, (3) rates of deforestation remain high in the last decade in Indonesia, and (4) conservation and restoration of mangroves promises to sequester significant

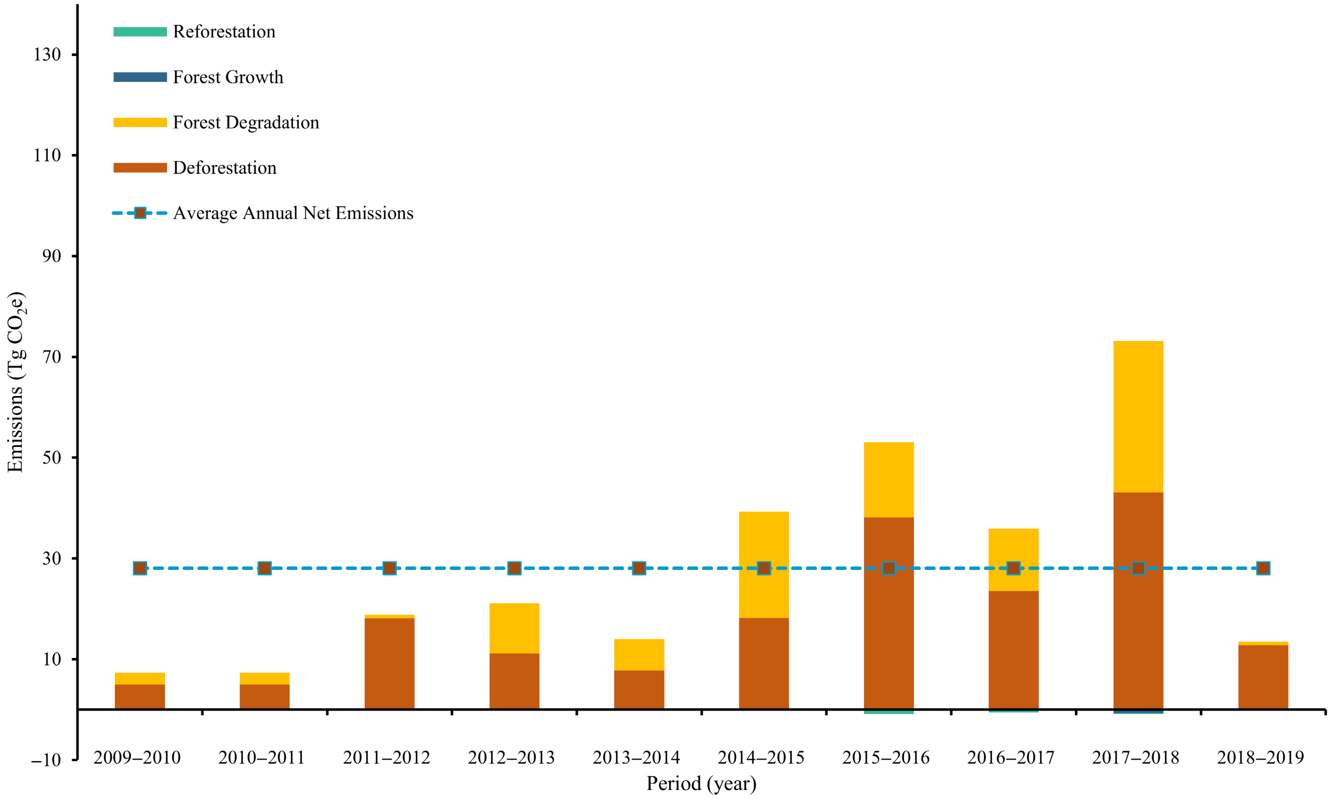


**FIGURE 5** Historical (2009–2019) carbon emissions from mangrove deforestation and degradation and carbon sequestration from reforestation and forest growth of mangrove forests. The average net emissions for mangroves in Indonesia from 2009 to 2019 (blue dashed line) is 28 Tg $CO_2e$ $year^{-1}$ and is set as the projected baseline or reference level for mangrove forest change in 2020–2030

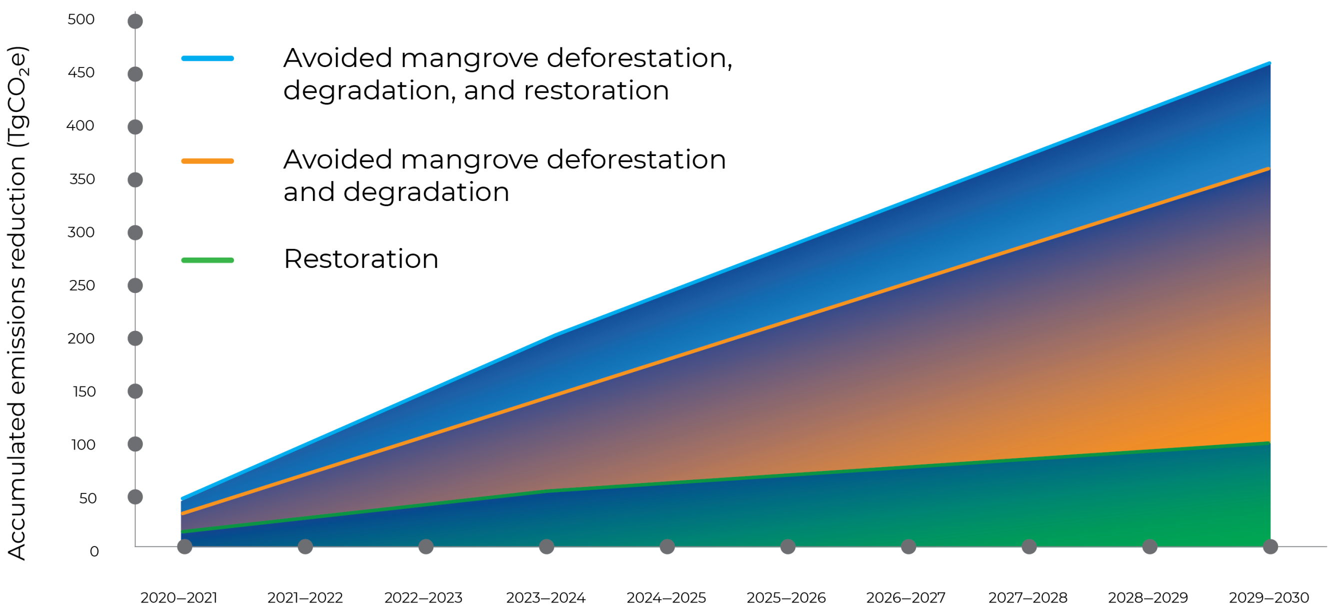


**FIGURE 6** Cumulative projected climate mitigation potential in terms of emissions reductions from avoided deforestation, degradation, and restoration of Indonesian mangroves (2020–2030). The detailed emission reduction values can be found in Table S7

quantities of carbon. Furthermore, IPCC default values are great underestimates of both carbon stocks and emissions from mangrove deforestation (Arifanti et al., 2019; Kauffman et al., 2020; Kauffman & Bhomia, 2017).

The mean C stocks for Indonesian mangroves (1063 Mg C $ha^{-1}$) is somewhat higher than global means for mangroves which have been estimated to be 856 ± 32 Mg C $ha^{-1}$ (Kauffman et al., 2020). Indonesia mangrove carbon stocks are substantially higher than the

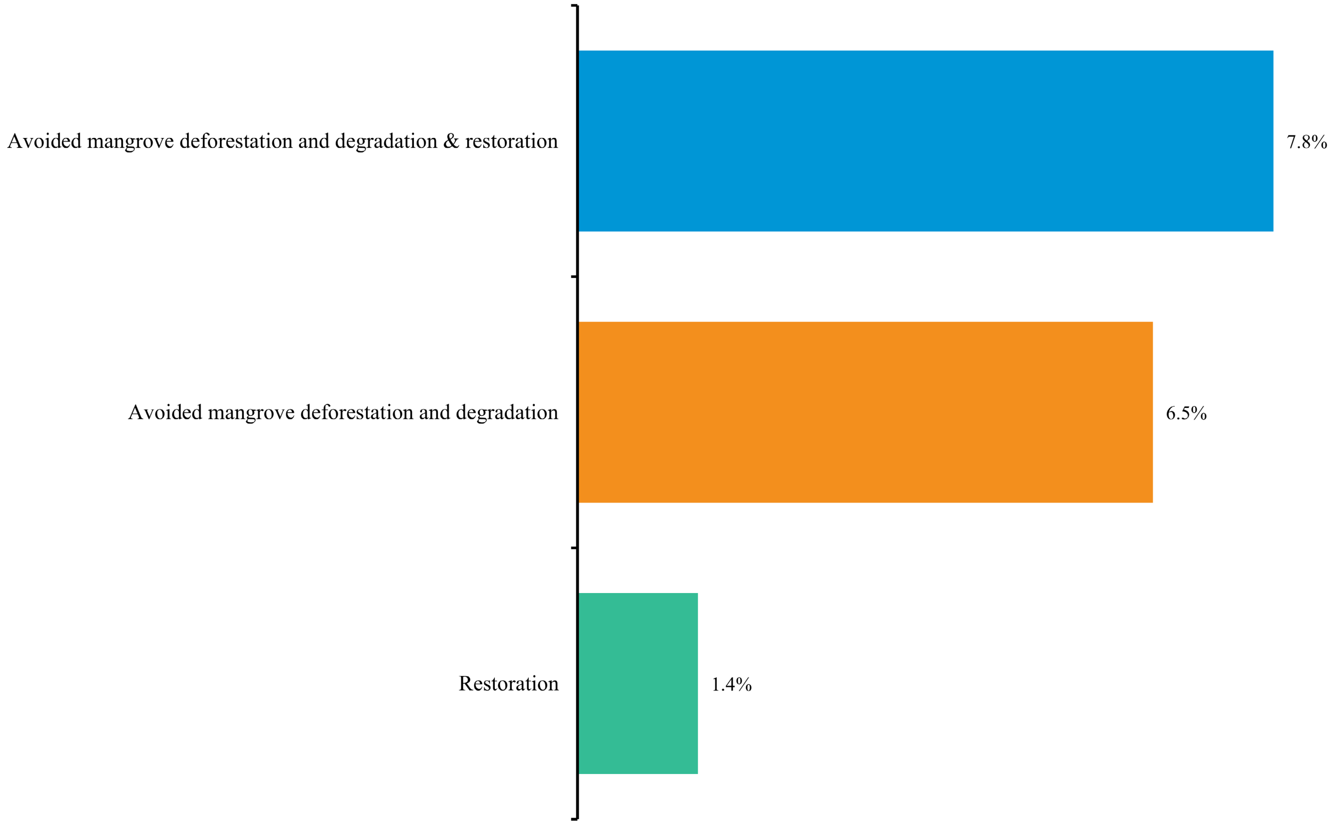


FIGURE 7 Emission reduction potential contributions of avoided deforestation, degradation, and restoration of Indonesian mangroves to the NDC target for the forestry sector in 2030 under counter measure 1 scenario

IPCC global default values (~511 Mg C ha$^{-1}$) (IPCC, 2014). Arifanti et al. (2019) reported that converting mangroves to aquaculture results in the loss of about 51% of the TECS of the extant mangrove. This is similar to estimates of Griscom et al. (2017) who predicted that 54% of the TECS is loss in the 20- year time period following disturbance. The mean carbon loss due to land conversion for Indonesian mangroves was 542 Mg C ha$^{-1}$. Over a 20-year period, this is a mean annual loss of 27.1 Mg C ha$^{-1}$ year$^{-1}$. Arifanti (2017) reported that intact mangroves were net source of carbon with a positive NEP of 8.8 Mg C ha$^{-1}$ year$^{-1}$. This was higher than the global average of mangroves reported by Alongi (2009, 2014) (i.e., 6.5 Mg C ha$^{-1}$ yr $^{-1}$).

In a NCS pantropical study (Griscom et al., 2020), mangrove loss from 1996, 2007, 2010, and 2016 was calculated from a global data set of Global Mangrove Watch (GMW) (Table 3). The study also applied a Tier 1-mean aboveground biomass of mangroves from Simard et al. (2019). Griscom et al. (2017) used literature values for mangroves totaling 563 Mg C ha$^{-1}$. Utilization of TECS estimates based on the IPCC Tier 1 and that of Griscom et al. (2017) will result in significant underestimations in both the ecosystem carbon stocks and in the greenhouse gas emissions arising from land use change in Indonesian mangroves. For example, in a study of land use change in mangroves, mean greenhouse gas emissions from conversion of mangrove to shrimp ponds and cattle pastures was 2033 Mg $CO_2$e ha$^{-1}$ (Kauffman et al., 2017). This carbon loss (equivalent to 554 Mg C ha$^{-1}$), exceeds the entire IPCC (2014) default value for ecosystem carbon stocks in mangroves. Using the ecosystem carbon stocks values of the mangroves presented here is suggested to be an improved estimation of default estimates (Tier 2 values) of mangroves for Indonesia.

The mean carbon storage in an Indonesian mangrove forest is 1063 Mg C ha$^{-1}$ (Table S1). Extrapolated to the total estimated current mangrove area of 33,100 km$^2$ the national carbon storage value is 3.52 Pg C. This estimate is slightly larger than estimates given by Alongi et al. (2015) for Indonesia. They reported that the median carbon storage in Indonesian mangrove forests was 951 Mg C ha$^{-1}$. When extrapolated to the total estimated mangrove area of 31,894 km$^2$, the national C storage value was estimated about 3.0 Pg C. Alongi et al. (2015) also suggested this was a likely underestimate as these habitats most often sequester carbon at soil depths >1 m.

## 4.2 | Mangrove forest change in 2009–2019

We found that 56,984 ha (31%) of mangrove deforestation was due to conversion to aquaculture with the highest peaks occurring from 2015 to 2018. This result is twofold higher compared with the mangrove loss to agriculture/aquaculture reported for the Sunda Shelf (including Malay Peninsula, Sumatra, Kalimantan, Java, Madura,

**TABLE 3** Sensitivity analysis of mangrove deforestation rates and total emissions from different studies. Deforestation rate from MoEF (this study) is compared with those from global mangrove watch, Goldberg et al. (2020), Hamilton and Casey (2016), Richards and Friess (2016). Averaged emission factor (EF) from this study is compared with the averaged EF compiled by Sasmito et al. (2019). Potential total emissions are calculated for each study source using their respective deforestation rates and EFs

| Sources | MoEF (this study) | Global mangrove watch | Richards and Friess (2016) | Hamilton and Casey (2016) | Goldberg et al. (2020) |
|---|---|---|---|---|---|
| Deforestation rate (ha $year^{-1}$) | 18,209 | 18,610 | 5075 | 6384 | 1295 |
| Data period | 2009–2019 | 2007–2016 | 2000–2012 | 2000–2014 | 2000–2016 |
| Deforestation drivers | Aquaculture, agriculture, infrastructure and development, low statured vegetation | No information | Aquaculture, erosion, mangrove, oil palm, recent deforestation, rice, terrestrial forest, urban | No information | Erosion, ECE, commodities, NPC, settlement |
| Avg. EF Arifanti et al. (2021; Mg $CO_2$e $ha^{-1}$ $year^{-1}$) | 78.8 | 78.8 | 78.8 | 78.8 | 78.8 |
| Avg. EF Sasmito et al. (2019; Mg $CO_2$e $ha^{-1}$ $year^{-1}$) | 50.2 | 50.2 | 50.2 | 50.2 | 50.2 |
| Total emissions using Arifanti's EF (Mg $CO_2$e $ha^{-1}$ $year^{-1}$) | 1,434,874 | 1,466,459 | 399,949 | 503,037 | 102,030 |
| Total emissions using Sasmito's EF (Mg $CO_2$e $ha^{-1}$ $year^{-1}$) | 913,822 | 933,937 | 254,713 | 320,367 | 64,979 |

Bali and their surrounding smaller islands) from 2000 to 2016 (2783 ha $year^{-1}$; Adame et al., 2021). Aquaculture practices contributed a significant proportion of mangrove deforestation in Sulawesi (63%), Kalimantan (39%), Bali and Nusa Tenggara Islands (38%), Papua (29%), Java (20%), and Sumatra (10%) (Figure 3).

Similar to shrimp, oil palm is a major export crop and may become a new driver of mangrove deforestation in Indonesia (Richards & Friess, 2016). If we compare the area of the oil palm plantations that are formerly mangroves with the extent of the existing oil palm plantations in 2019, an estimated 0.2% of oil palm plantations in Indonesia are derived from mangrove forests.

Secondary mangrove conversion to other land uses accounted for 62% of the total mangrove loss or covering about 161,725 ha. About 8% of primary mangroves were altered to secondary (disturbed) mangroves in the time period of this study. Mangrove deforestation and degradation occurred predominantly in disturbed or less dense mangrove areas managed by the local governments (provincial and/or district governments). Primary mangroves are now mostly found in conservation areas managed by the Central Government where deforestation is prohibited; however, these areas accounted for 30% of the total mangrove loss.

While comprising about 24% of the world's mangroves, Indonesian mangroves only comprise about 2.6% of the forested area of Indonesia and they remain vulnerable to deforestation. The net deforestation rate in Indonesia (2009–2019) is 1.3 times greater than that reported for all SE Asian mangroves (Richards & Friess, 2016). Indonesia's mangrove loss rate from 2009 to 2019 (12,818 ha $year^{-1}$) is much lower than the period of 1980–2005 (52,000 ha $year^{-1}$; FAO, 2007). This may suggest that the most accessible mangroves have been deforested as well as greater awareness and emphasis on their conservation. It is logical to assume that good access by human populations leads to increased mangrove deforestation. When the only remaining forests are not very accessible or conducive to development, the deforestation rates would likely decline. This is somewhat supported in our study where most of deforestation occurred in public lands designated for other purposes (APL) and areas with developed infrastructure and access.

Mangrove deforestation rates have also been reported by the GMW (https://www.globalmangrovewatch.org), Goldberg et al. (2020), Hamilton and Casey (2016), and Richards and Friess (2016). They conducted land-cover change classification from mangrove forests to non-forests from different periods ranging from 2000–2016 (Table 3). Deforestation rate calculated by this study is comparable with the results from the GMW, which is in the higher end compared with other studies. Richards and Friess (2016) and Hamilton and Casey (2016) obtained similar results, while Goldberg et al. (2020) had the smallest number of deforestation rates. The use of various satellite imageries, classification techniques and period of observations of these studies might have influenced the differences in mangrove deforestation rates.

Globally, about 27% of all forest degradation between 2001 and 2015 was due to commodity-driven deforestation (Curtis et al., 2018). Similarly, the principal cause of mangrove forest degradation is aquaculture (Figure 3). In 2009, the Indonesian Government issued a policy with a goal of positioning Indonesia as the world's largest aquacultural producer. The goal was to increase fisheries production by 353% by 2015 (Ministry of Marine Affairs and Fisheries, Republic of Indonesia, 2010; Rimmer et al., 2013). During 2012–2017 shrimp production increased by about 26% with the highest production increases in Bali Nusa Tenggara Islands (32%), Kalimantan (16%), Sulawesi (9%), and Sumatra (9%) (Ministry of Marine Affairs and Fisheries, Republic of Indonesia, 2018). Increased aquaculture production in this period came at the expense of mangroves and a concomitant increase in emissions from deforestation (Figure 3).

### 4.3 | Emission from mangrove forest change

In this study we determined EFs from conversion of primary forests to secondary forests as well as the conversion of secondary forests to other land uses (Table 2; Figure 8). This is important as secondary forest conversion is more widespread than loss of primary forest. It is also important to note that the EFs associated with conversion of primary to secondary mangroves exceeds that of conversion of secondary forest to other land cover types. In a previous study estimating emissions from Indonesian mangrove deforestation, Murdiyarso et al. (2015) used deforestation statistics provided by FAO (2014) to calculate mangrove deforestation from 1980–2005. In this paper, we used a more recent mangrove deforestation and degradation data set (2009–2019) collected by the MoEF, which provides updated context for with respect to climate policy. Furthermore, the use of unique EFs from conversion of both primary and secondary forest to other land uses should reduce uncertainties in the estimations of emissions from mangrove ecosystems.

The total emissions from land-cover change were calculated as the total emissions from carbon stock losses and the additional carbon emissions due to changes in NEP between mangroves and land cover types. Our estimate of the total flux from primary mangroves to other land uses was 137 Mg $CO_2$e ha year$^{-1}$ (Table 2). Griscom et al., 2017 estimated that 54% of carbon in coastal wetlands is lost within 20 years. This is similar to measured average losses of ecosystem carbon stock losses (51%) for Indonesian mangroves. However, as a result of lower estimates of TECS Griscom et al. (2017) estimated fluxes from mangrove conversion would be about 56 Mg $CO_2$e ha year$^{-1}$ (Figure 8). The IPCC EF estimates for land-cover change in mangroves is 26.7 Mg $CO_2$e ha year$^{-1}$ (IPCC, 2014). Based on published data from several countries (Malaysia, New Zealand, Philippines, Tanzania, Vietnam, Brazil, Sri Lanka, India, the Dominican Rep., Honduras and Costa Rica) compiled by Sasmito et al. (2019), we calculated a mean EF of mangroves conversion to be ≈50 Mg $CO_2$e ha$^{-1}$ year$^{-1}$ (Table 3). This is lower than the mean EF from this study (78.8 Mg $CO_2$e ha$^{-1}$ year$^{-1}$) and may reflect both inherent differences in mangroves (Kauffman et al., 2020) as well as methodological differences in sampling. The potential emission estimate from this study is similar to the GMW result and is about threefold higher than other studies. In contrast,

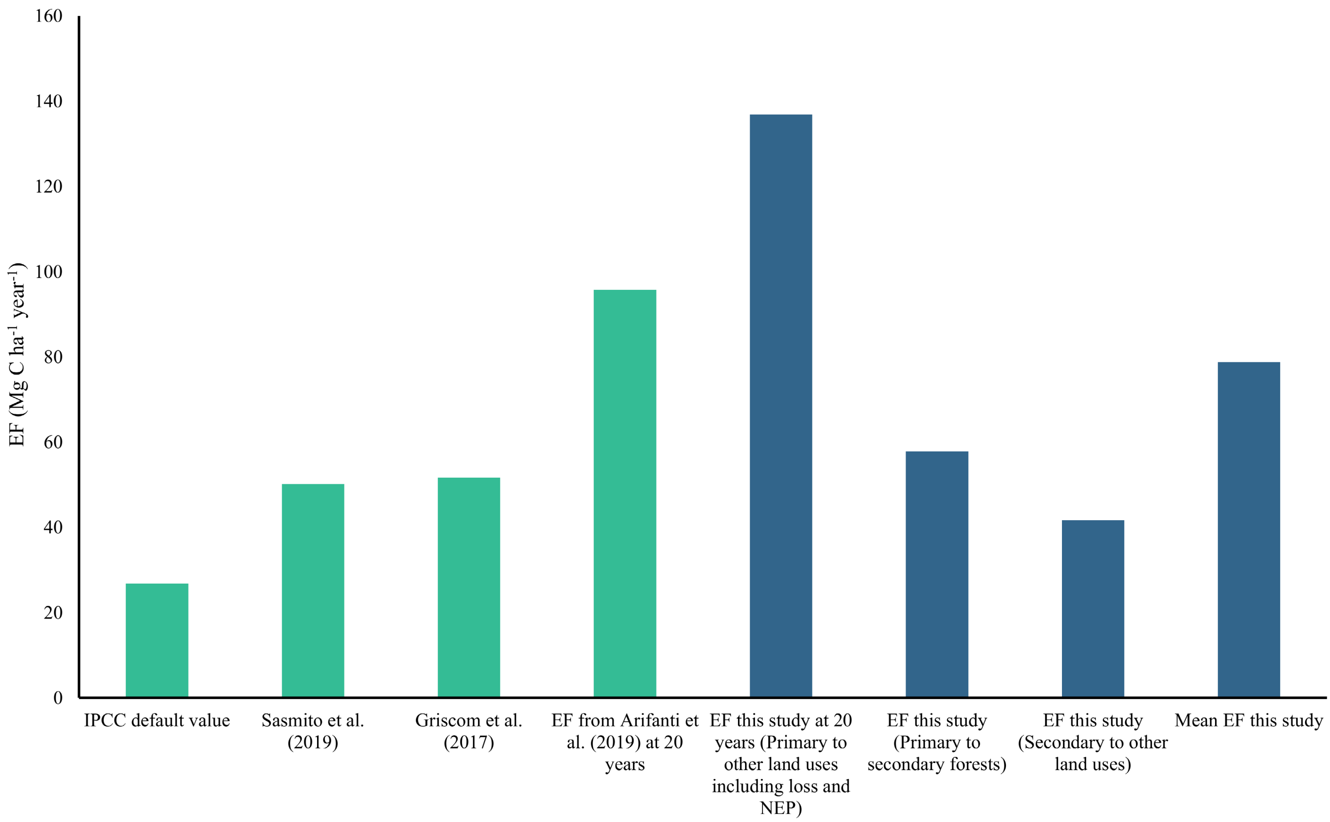


FIGURE 8 Estimates of emission factors due to land cover change in mangrove ecosystems. The IPCC, Sasmito et al. (2019) and Griscom et al. (2017) data are based on literature values. The dark blue bars (20 years emission factor estimate) are based on field measurements including loss and net ecosystem productivity from Indonesia

the potential total emission estimate from Sasmito et al. (2019) is about 64% of this study (Table 3). Methodological disparities affecting global stocks and emissions estimates include sampling soils at depths of only ≤100 cm, and lower estimates of the differences in carbon fluxes (NEP) between intact and converted mangroves sites (Adame et al., 2018; Bulmer et al., 2015; Cameron et al., 2019; Castillo et al., 2017; Gillis et al., 2017; Grellier et al., 2017; Griscom et al., 2017; IPCC, 2014; Pérez et al., 2017).

### 4.4 | Mangrove forest reference level

We determined the mangrove FRL as a baseline to assess the emission reductions that could be achieved through NCS pathways of halting or reducing deforestation and degradation coupled with reforestation. The FRL for country-wide mangrove emissions was ≈28 Tg $CO_2$ year$^{-1}$ (Figure S5). Recently, the Ministry of Environment and Forestry Republic of Indonesia (2020c) reported that the emissions from deforestation and forest degradation for the period of 2006–2020 was ≈278 Tg $CO_2$e year$^{-1}$. Hence, the average emissions of mangroves (2009–2019) comprise about 10% of the total projected emissions from the entirety of the Indonesian forest sector (2006–2020). The large source of greenhouse gas emissions from a relatively small proportion of the forest area (2.6%) underscores the potential value for inclusion of mangroves as a NCS for Indonesia.

### 4.5 | Achievable targets and policy implications

The emission reductions targets as laid out in the different pathways are assumed to be met when enabling conditions such as institutional and regulatory frameworks of mangrove management are in place. The optimum mangrove emission reduction would be achieved when successful protection is combined with restoration (Figures 6 and 7). To meet the emission reduction targets from mangrove conservation and protection, stronger regulations and enforcement of mangrove protection would have to be implemented. Implementation of the Presidential Instruction Number 5/2019 regarding the permanent cessation of the issuance of new licenses in primary forests and peatland and Indonesia's commitment to protect 32.5 million ha of marine protected areas (including mangroves, coral reefs, seas and shorelines) are important first steps leading to better protection of mangrove forests.

Mangrove restoration through planting has been used as the primary strategy to increase mangroves in many countries and organizations (Mursyid et al., 2021; Primavera & Esteban, 2008). Large-scale planting of mangroves could increase mangrove area, but the short-term success as well as the long-term efficacy of this program should be monitored. Although planting successes had been reported with mangrove survival rates of ≈90%, low survival rates of 10%–20% or lower are also common (Primavera & Esteban, 2008). Failures in mangrove plantings are often the result of a lack of baseline information on the causes of mangrove deforestation or degradation, land tenure issues, weak law enforcement, and complex governance on mangrove reforestation and conservation (Dale et al., 2014; Lee et al., 2019; Mursyid et al., 2021; Primavera & Esteban, 2008). Therefore, a comprehensive and scientific assessment on biophysical, and socio-economic factors that could limit recovery should be conducted prior to project implementation. Involvement of local governments and communities is also crucial for long-term sustainable mangrove management (Lee et al., 2019).

## 5 | CONCLUSION

Because of their capacity to store significant carbon stocks and a myriad of other ecosystem services, mangroves are recognized valuable components of NCS that would facilitate meeting NDC targets. While the net deforestation rate of Indonesian mangroves has tended to decrease in the last decade, high loss rates are still occurring. Current climate change mitigation planning for Indonesia mangroves is limited to large scale mangrove reforestation/replanting projects. However, large-scale mangrove planting will not result in a sufficient offset while continued destruction of the remaining mangroves is ongoing. Reforestation only contributes a small percentage of the total emission reduction possible in mangrove ecosystems. Mangrove conservation is far more effective in carbon emissions reductions and an efficient pathway to achieve NDC targets. Protection of extant mangroves coupled with efforts to restore degraded/deforested mangrove areas to become net carbon sinks would facilitate mangroves playing an outsized role in meeting Indonesia's commitment to reducing greenhouse emissions.

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**CONFLICT OF INTEREST**

The authors declare no competing interests.

**AUTHOR CONTRIBUTIONS**

Virni B. Arifanti served as the main contributor of this study. Virni B. Arifanti and J. B. Kauffman conceived and designed the study, analyzed the data and wrote the initial draft. Subarno analyzed the spatial data and did the modeling projections. Muhammad Ilman provided aquaculture data. Anna Tosiani provided the spatial land cover data. Nisa Novita was involved in project conception and analyzed the uncertainty data. All authors contributed to editing subsequent drafts.

## DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available at https://doi.org/10.5061/dryad.12jm63z0x.


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