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Natural climate solutions in Indonesia: wetlands are the key to achieve Indonesia's national climate commitment

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Abstract

Indonesia offers a dramatic opportunity to contribute to tackling climate change by deploying natural climate solutions (NCS), increasing carbon sequestration and storage through the protection, improved management, and restoration of drylands, peatlands, and mangrove ecosystems. Here, we estimate Indonesia's NCS mitigation opportunity for the first time using national datasets. We calculated the maximum NCS mitigation potential extent using datasets of annual national land cover, peat soil, and critical lands. We collated a national emissions factor database for each pathway, calculated from a meta-analysis, recent publications from our team, and available literature. The maximum NCS mitigation potential in 2030 is 1.3 ± 0.04 $GtCO_2e\ yr^{-1}$, based on the historical baseline period from 2009–2019. This maximum NCS potential is double Indonesia's nationally determined contribution (NDC) target from the forestry and other land use sector. Of this potential opportunity, 77% comes from wetland ecosystems. Peatlands have the largest NCS mitigation potential (960 ± 15.4 $MtCO_2e\ yr^{-1}$ or 71.5 $MgCO_2e\ ha^{-1}\ yr^{-1}$) among all other ecosystems. Mangroves provide a smaller total potential (41.1 ± 1.4 $MtCO_2e\ yr^{-1}$) but have a much higher mitigation density (12.2 $MgCO_2e\ ha^{-1}\ yr^{-1}$) compared to dryland ecosystems (2.9 $MgCO_2e\ ha^{-1}\ yr^{-1}$). Therefore, protecting, managing, and restoring Indonesia's wetlands is key to achieving the country's emissions reduction target by 2030. The results of this study can be used to inform conservation programs and national climate policy to prioritize wetlands and other land sector initiatives to fulfill Indonesia's NDC by 2030, while simultaneously providing additional co-benefits and contributing to COVID-19 recovery and economic sustainability.

1. Introduction

Indonesia is one of the most biologically diverse countries globally and has extremely high endemism across forests, peatlands, mangroves, and other unique natural ecosystems (Cleary and Devantier 2011). However, nearly half of the total greenhouse gas (GHG) emissions in Indonesia are from the forestry and other land use (FOLU) sector (0.92 out of 1.86 $MtCO_2e\ yr^{-1}$) (the Indonesian Ministry of Environment and Forestry [MoEF] 2020). The FOLU sector is expected to contribute up to 55% (500 $MtCO_2e$) of the total emissions reduction target (915 $MtCO_2e$) with a baseline year of 2010, based on Indonesia's enhanced *Nationally Determined Contribution* (NDC) under the unconditional mitigation scenario (MoEF 2022). Climate mitigation from natural climate solutions (NCS) in Indonesia can significantly contribute to achieving Indonesia's NDC commitment to reduce emissions by 31.89%–43.20% in 2030 compared to business-as-usual (MoEF 2022). Furthermore, the FOLU sector is set to be a carbon sink by 2030. Accordingly, MoEF has announced a strategy to utilize the mitigation potential from the FOLU sector to achieve the NDC and support Indonesia's long-term climate strategy to reach net zero emissions by 2060 or sooner. During the Conference of the Parties (COP) 26 in Glasgow in 2021, Indonesia joined the global declaration to halt and reverse forest loss and degradation by 2030. The subsequent plan issued in 2022 detailed the main mitigation actions, including avoided deforestation and degradation of forests and peatlands, sustainable forest management, forest rehabilitation, forest conservation, and peatland management.

There is growing awareness that NCS can provide a large portion of the climate mitigation needed to help countries tackle climate change in compliance with the Paris Agreement (Griscom *et al* 2017). As a subset of a much broader suite of 'nature-based solutions', we use 'natural climate solutions', or 'NCS pathways' here to refer to a nationally relevant subset of 20 land-based mitigation actions to conserve, restore, and/or improve the management of lands while also increasing carbon storage and/or avoiding emissions across forests, wetlands, grasslands, and agricultural areas (Griscom *et al* 2017). These NCS pathways also provide benefits in addition to GHG emissions reduction, including temperature regulation, biodiversity conservation, soil nutrient improvement, and surface flow management, among others (see supplementary figure 1).

We provide a comprehensive analysis of the maximum mitigation potential from nine NCS pathways in Indonesia. There have been several studies demonstrating the importance of NCS by using global datasets (Griscom *et al* 2020) or from specific ecosystem and mitigation strategies separately (Murdiyarso *et al* 2015, Leifeld and Menichetti 2018). Limited access to local datasets remains a challenge in conducting such studies at national levels, globally. To our knowledge, this is the first study to estimate Indonesia's NCS mitigation opportunity from all pathways in three different ecosystems and mitigation strategies (protect, manage, restore) using national datasets and country-level emission factors.

2. Methods

Yayasan Konservasi Alam Nusantara, the main partner of The Nature Conservancy in Indonesia, in collaboration with the Center for Instrument Standardization of Disaster Resilience and Climate Change (PUSTANDPI; MoEF), conducted a national workshop on NCS in Bogor, Indonesia in 2020. The purpose of the workshop was to gain perspectives on priority NCS pathways aligning with Indonesia's unique land use activities and needs. Cross-sector stakeholders attended the workshop (see supplementary table 1) and selected a subset of relevant NCS pathways based on scientific evidence, their implementation potential, the effectiveness of mitigation action, and alignment with national strategies. Nine NCS pathways emerged for inclusion: avoided forest conversion (AFC), reforestation, climate smart forestry (CSF), avoided peat decomposition, avoided vegetation loss on peat, avoided peat fires, peat restoration, avoided mangrove deforestation and degradation, and mangrove restoration. We define each pathway as shown in table 1 to avoid double counting in calculating the mitigation potential.

We calculated the extent for the maximum NCS mitigation potential using MoEF's annual land cover change maps (MoEF-LCM; Margono *et al* 2014) produced from 30 m Landsat satellite imagery based on visual interpretation of Indonesia's land cover classes (see supplementary table 2). We collated a national emissions factor database for each pathway calculated from a meta-analysis, recent publications from our team, and available literature. We quantified potential NCS contributions to national mitigation strategies by 2030 for each pathway using CO_2 equivalents based on the 2009–2019 baseline period. In addition, we estimated emissions reduction potential at regional levels: Sumatra, Kalimantan, Java, Bali Nusa Tenggara, Sulawesi, Maluku, and Papua.

We assessed the mitigation potential in drylands, peatlands, and mangroves. We use 'drylands' to refer to both forest and non-forest cover (excluding peatlands and mangroves) in lowland, upland, and montane areas (MoEF 2016). Wetlands include peatland and mangrove ecosystems. We define peatlands as areas which overlap Indonesia's peat soil map (Ritung *et al* 2011, Anda *et al* 2021) including areas with and without forest cover. Mangroves are identified as primary and secondary mangrove forests in the MoEF-LCM. We estimated the uncertainty for the maximum mitigation estimates using methods consistent with IPCC's Good Practice Guidance for the nine focal pathways (IPCC 2000). We combined emission factors and extent uncertainties for each pathway using a Monte Carlo simulation with 100,000 iterations using R software (R Core Team 2020). Furthermore, the three ecosystems were separated to avoid overlap and accounted separately to avoid double counting.

3. Results

The total NCS potential from the nine pathways in Indonesia is 1.3 ± 0.04 $GtCO_2e\ yr^{-1}$, where 76%

Table 1. Nine NCS pathways in Indonesia in three ecosystems (i.e. drylands, peatlands, and mangrove ecosystems) based on input from relevant stakeholders in Indonesia (AGB = aboveground biomass, SOC = soil organic carbon).

	Pathways	Definition	Gas measured	Carbon pool
Drylands	Avoided forest conversion (AFC)	Avoided CO_2 emissions from vegetation or aboveground biomass in non-wetland areas. We include deforestation (changes on forested area to non-forested) and degradation.	CO_2	AGB, Roots
	Reforestation	Increased carbon sequestration by replanting native species from assisted and natural reforestation/afforestation. We identified unproductive areas of land (i.e. shrub, open land) with highly degraded conditions as potential areas for reforestation. This pathway estimates CO_2 sequestration potential from aboveground, belowground biomass, and dead organic matter from planting in degraded drylands, including shrubs and bare ground. We do not include reforestation on peatlands and mangroves to avoid double counting.	CO_2	AGB, Roots
	Climate smart forestry (CSF)	Reduction of CO_2 emissions from Reduced Impact Logging for Climate Change (RIL-C) implementation. We used timber production data and developed a new emission factor based on primary data collection in Indonesia.	CO_2	AGB
Peatlands	Avoided peat decomposition	Avoided CO_2 emissions by preventing land cover changes in peatlands and hydrological disturbance such as canal development. Mass-balance approach is applied for calculating GHG emissions.	CO_2	SOC
	Avoided vegetation loss on peat	Avoided CO_2 emissions from aboveground loss due to land use conversion. Soil emissions are excluded.	CO_2	AGB, Roots
	Avoided peat fires	Avoided anthropogenic GHG emissions due to peat fires based on the estimate of peat burnt volume.	CO_2, CH_4	SOC
	Peat restoration	Reduced CO_2 emissions from peatland rewetting activities based on the most recent land cover maps and land tenure in the country.	CO_2	SOC
Mangroves	Avoided mangrove deforestation and degradation	Avoided mangrove emissions from above and belowground biomass including soil. Mangrove is assumed to be converted to aquaculture (the primary driver of mangrove loss in Indonesia).	CO_2	AGB, SOC
	Mangrove restoration	Increased carbon sequestration from regeneration of mangrove (where they have previously existed).	CO_2	AGB, SOC

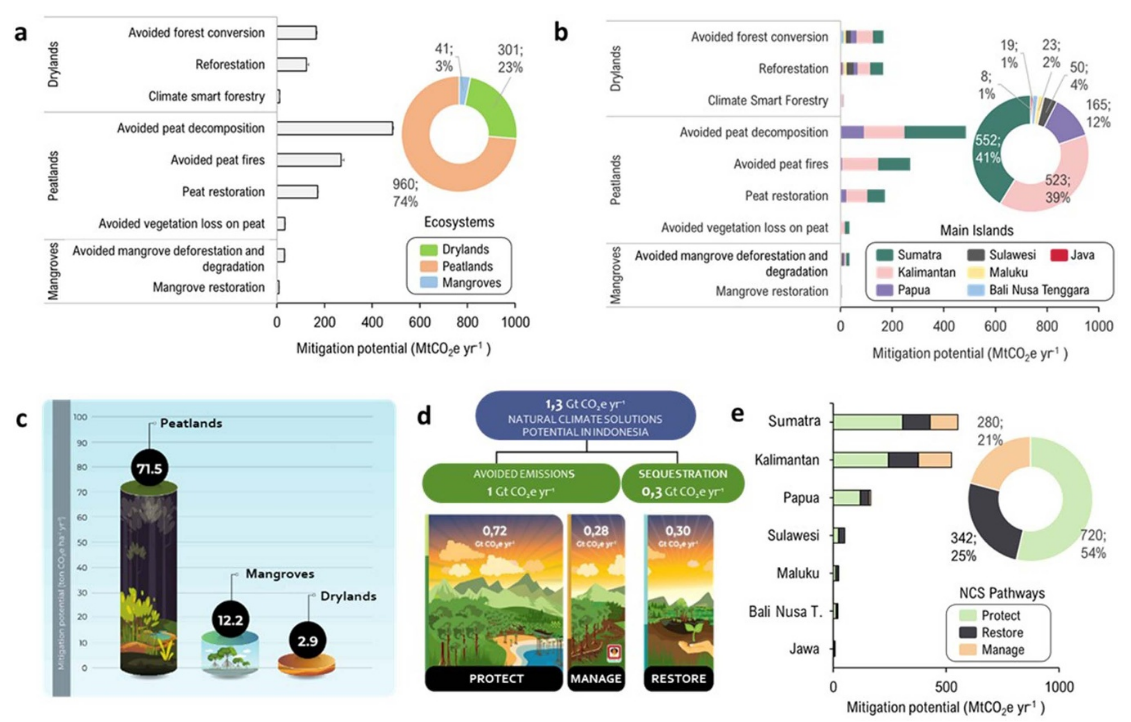

Figure 1. Total NCS mitigation potential in Indonesia from nine NCS pathways (a); total NCS mitigation potential in Indonesia from the selected pathways across major islands (b); mitigation potential per unit area (ton CO_2 ha^{-1} yr^{-1}) in drylands, peatlands, and mangroves (c); classification of mitigation potential based on the main NCS strategies (protect, manage, and restore) (d); total NCS mitigation potential based on the main NCS strategies (protect, manage, and restore) across the major islands (e).

is derived from avoided emissions mitigation activities from all ecosystems (figures 1(a)–(e)). This comprises 156% and 112% of Indonesia's NDC target by 2030 from all sectors under the unconditional and conditional scenarios, respectively. The highest total mitigation potential is from avoiding emissions and sequestering carbon from peatlands (960 ± 15.4 $MtCO_2e$ yr^{-1}; 74%), followed by drylands (300.7 ± 18.8 $MtCO_2e$ yr^{-1}; 23%), and mangroves (41.1 ± 1.4 $MtCO_2e$ yr^{-1}; 3%). The highest mitigation potential per unit area is found in peatlands (71.5 $MgCO_2e$ ha^{-1} yr^{-1}), followed by mangroves (12.2 $MgCO_2e$ ha^{-1} yr^{-1}), and drylands (2.9 $MgCO_2e$ ha^{-1} yr^{-1}) (figure 1(c)).

3.1. Drylands

Drylands have a total mitigation potential of 300.7 ± 18.8 $MtCO_2e$ yr^{-1} by 2030, or 23% of Indonesia's total potential (figure 1(a)). AFC can reduce 165.7 ± 4.1 $MtCO_2e$ yr^{-1}. Kalimantan has the highest mitigation potential from AFC (62.9 $MtCO_2e$ yr^{-1}), followed by Sumatra (40.8 $MtCO_2e$ yr^{-1}). For reforestation, the mitigation potential under the ambitious scenario (Basuki *et al* 2022) is 124.1 ± 12 $MtCO_2e$ yr^{-1}. Potential dryland restoration area is 9.5 Mha, 62% of which is in state-forest areas (Basuki *et al* 2022). CSF has the smallest mitigation potential compared to other pathways (10.9 ± 2.2 $MtCO_2e$ yr^{-1}). Among major regions in Indonesia, forest concessions in Kalimantan seem to have the highest annual log production, contributing to about 7.4 $MtCO_2e$ yr^{-1} (~4 million m^3 of logs yr^{-1}), followed by Papua (1.8 $MtCO_2e$ yr^{-1}; ~1 million m^3 of logs yr^{-1}). The lowest CSF mitigation potentials were derived from Bali, Nusa Tenggara, and Sulawesi, which altogether accounted for 1.7 $MtCO_2e$ yr^{-1} (see supplementary figure 2).

3.2. Peatlands

Overall, peatlands have the potential to mitigate 960 ± 15.4 $MtCO_2e$ yr^{-1} by 2030—74% of Indonesia's total NCS potential (figure 1(a)). Peatlands offer the most mitigation potential in comparison with other ecosystems and have the highest potential to deliver NCS on a per-hectare basis (71.5 tCO_2e ha^{-1} yr^{-1}; figure 1(c)). The most significant opportunities from peatlands are found in Sumatra followed by Kalimantan (figure 1(e)). We also ranked the mitigation potential from peatlands on a provincial basis. Central Kalimantan has the highest annual mitigation potential (253 $MtCO_2e$ yr^{-1}), followed by Riau and South Sumatra (252 $MtCO_2e$ yr^{-1} and 121 $MtCO_2e$ yr^{-1}, respectively) (figure 2). Avoided peat decomposition, which primarily conserves soil carbon stocks, represents the largest opportunity for NCS mitigation in Indonesia (485.6 ± 3.2 $MtCO_2e$ yr^{-1}). While significant carbon stocks are stored beneath the soil in peatland ecosystems, emissions from vegetation loss

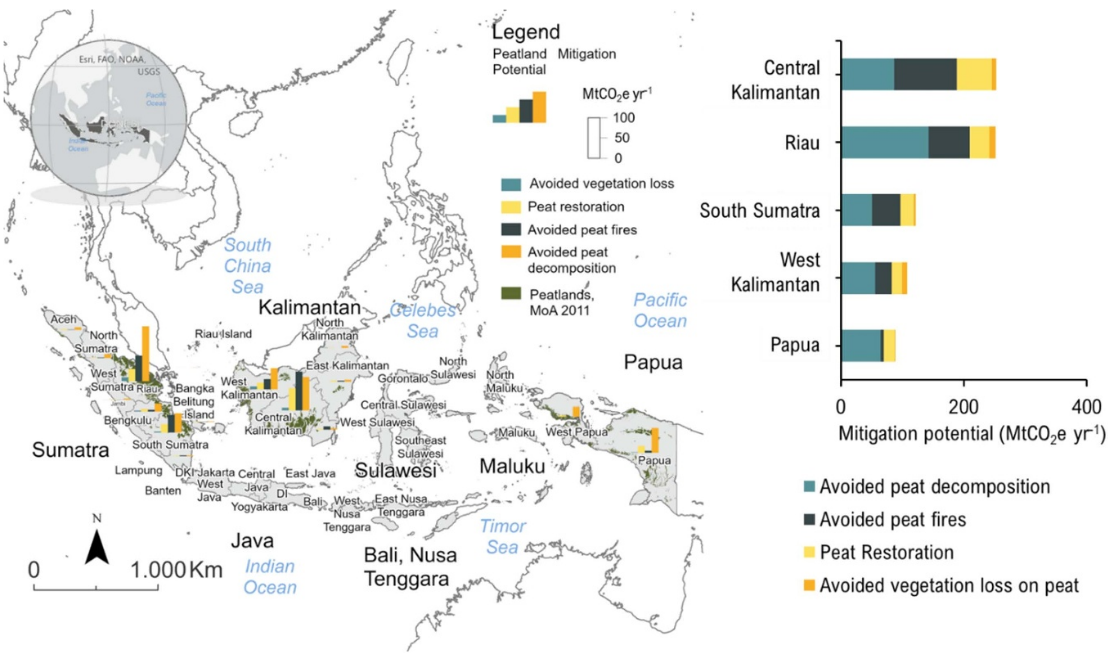

Figure 2. Mitigation potential from four pathways (avoided peat decomposition, avoided vegetation loss on peat, avoided peat fires, and peat restoration) for peatland ecosystems in Indonesia.

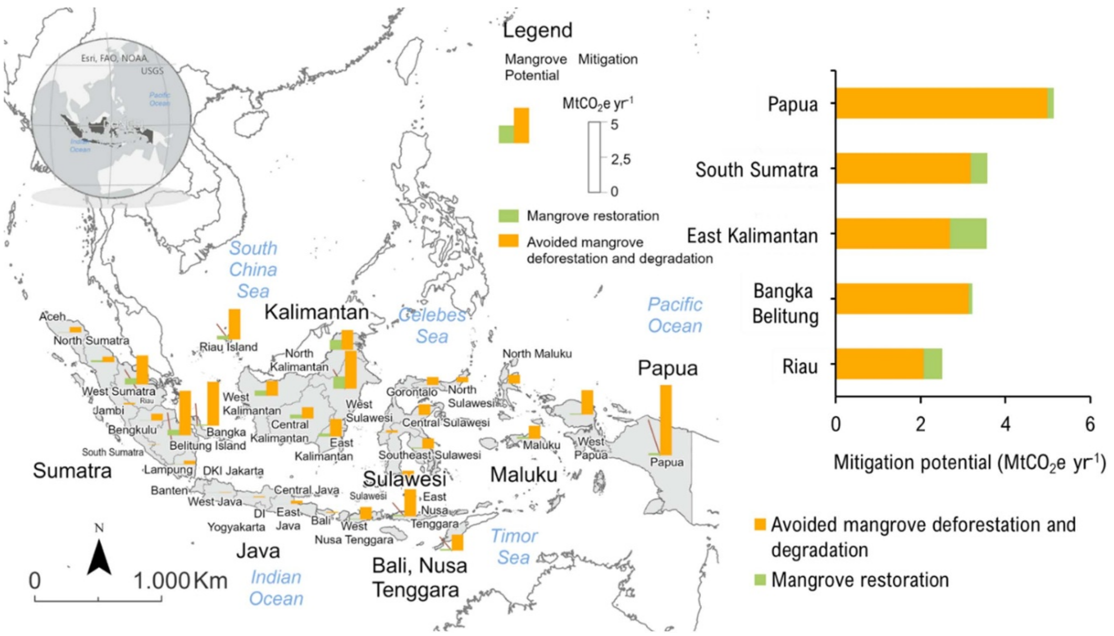

Figure 3. Mitigation potential from two pathways (avoided mangrove deforestation and degradation and mangrove restoration) for mangrove ecosystems in Indonesia.

due to deforestation on peatlands offer 33.6 ± 1.3 $MtCO_2e\ yr^{-1}$, 7% of emissions from peat decomposition. From 2009–2019, 68% of deforestation occurred inside peatland forested areas, and 32% occurred in peatlands designated for other purposes such as agriculture or estate crops (see supplementary figure 3). Avoided peat fires provide the next largest opportunity from peatlands with a mitigation potential of 268.8 ± 9.8 $MtCO_2e\ yr^{-1}$, nationally. Peat fires, a result of land clearing, mostly occur when peat swamp forests are drained and converted to oil palm or other extractive land uses. The highest peat fire emissions were recorded in 2014–2015, reaching 665 $MtCO_2e$, double the historical average annual peat fire emissions (see supplementary figure 4). Restoration of degraded peatlands represents the third largest NCS opportunity from peatlands in 2030, which could provide up to 171.6 ± 1.1 $MtCO_2e\ yr^{-1}$, assuming gradual rewetting across Indonesia's degraded peatlands.

3.3. Mangroves

Overall, mangroves have the potential to mitigate 41.1 ± 1.4 $MtCO_2e\ yr^{-1}$ by 2030, or 3% of Indonesia's total NCS potential (figure 1(a)). Avoided mangrove deforestation and degradation provide mitigation potential of 32.0 ± 1.0 $MtCO_2e\ yr^{-1}$ (figure 3). The regions in Indonesia with the highest potential for the mangrove pathways are Kalimantan, Sulawesi, Sumatra, and Papua. On a provincial basis, East Kalimantan had the highest annual deforestation and degradation rates over the last decade (Arifanti *et al* 2022a, 2022b).

4. Discussion

Our findings indicate several important points: (a) wetlands are the key to achieving Indonesia's national climate commitment, and (b) protection and conservation of ecosystems have a higher mitigation potential than restoration. The maximum NCS potential for Indonesia is 1302 $MtCO_2e\ yr^{-1}$, of which 1001 $MtCO_2e\ yr^{-1}$ come from wetlands. This is double the NDC target from the FOLU sector of 500 $MtCO_2e$ (MoEF 2021). Even without any mitigation efforts from other sectors, the NCS mitigation potential from wetlands alone would surpass Indonesia's emissions reduction target if implemented correctly and collectively. Furthermore, avoided conversion pathways in all ecosystems offer a total mitigation potential of 952 $MtCO_2e\ yr^{-1}$, of which over 80% are from wetlands, indicating that Indonesia's NDC has the potential to be realized using cost-effective NCS options. Our results support the NCS Mitigation Hierarchy which prioritizes protection efforts (followed by improved management then restoration), given the high per-hectare mitigation that can be realized quickly and at a comparatively low cost per tCO_2e from protection, typically with many co-benefits (Cook-Patton *et al* 2021). Preventing the loss of stored carbon by protecting ecosystems is estimated to be about twice as effective globally as restoring lost or damaged ecosystems: ∼4 Gt of CO_2 per year for protection compared with ∼2 Gt of CO_2 per year for restoration (Seddon 2022). However, the full range of NCS options must be considered in conjunction with the local political context to avoid unnecessary constraint of NCS implementation.

4.1. The importance of national-level data in NCS estimates

Our results indicate Indonesia can contribute ∼6% of the global NCS mitigation potential (Griscom *et al* 2017) and 10% of the potential across tropical countries (Griscom *et al* 2020). Our national NCS mitigation potential is comparable to that of Griscom *et al* 2020 (1390 $MtCO_2e\ yr^{-1}$). Specifically for the mitigation potential from wetland ecosystems in Indonesia, our estimates are higher than prior estimates (1001 $MtCO_2e\ yr^{-1}$ vs. 907 $MtCO_2e\ yr^{-1}$; Griscom *et al* 2020), representing 83% of the wetland mitigation potential in 79 tropical countries. Despite similar estimates of total mitigation with the pantropical study, the distribution of the mitigation potential among pathways diverges from our study compared to Griscom *et al* (2020) (see supplementary figure 5). Griscom *et al* (2020) report the highest mitigation potential from AFC (572.8 $MtCO_2e\ yr^{-1}$), three times more than our estimate (165.7 $MtCO_2e\ yr^{-1}$). The study also estimated the mitigation potential from the CSF pathway as 246 $MtCO_2e\ yr^{-1}$, more than twenty times larger than the results of our study (10.9 $MtCO_2e\ yr^{-1}$). Griscom *et al* (2020) included various CSF options and was not limited solely to RIL-C activities. However, in Indonesia RIL-C is the only feasible emission reduction activity from logging concessions. The mitigation potential from avoided peat impacts is underestimated compared to our study (514.2 $MtCO_2e\ yr^{-1}$ vs 788 $MtCO_2e\ yr^{-1}$), but Griscom *et al* (2020) used different baseline periods and sources for potential extent (see supplementary table 3) and only examined avoided peat impacts and peat restoration, not avoided peat fires, decomposition, vegetation loss, and considered peat restoration separately.

Perhaps the most important source of differences in our findings versus global findings is our use of national data. We used the annual MoEF-LCM from 2009–2019 generated from manual expert interpretation as the primary source to map cover class extent (Margono *et al* 2014). The accuracy of the MoEF-LCM is assessed using 10,000 sample points with higher resolution imagery (Tosiani *et al* 2020b) compared to global products. We used the Indonesia peat soil map published by Ritung *et al* (2011) with a scale of 1:250 000 for the peatlands analysis. Other maps included the 2019 Indonesia critical land map and the Indonesian burnt peat map from 2009–2019 (based on MODIS & MoEF datasets), and the official mangrove extent and deforestation rates published by MoEF. We also adjusted the potential area for forest conservation and restoration based on the National Development Plan to include additional aspects, such as policy intervention. Moreover, methodological disparities affecting global stocks and emissions estimates may affect the differences between these results (Arifanti *et al* 2022a).

In addition to the pathway and country specific datasets, we also applied country-level emissions factors to all pathways based on compiled studies in Indonesia to estimate the mitigation potential of each pathway while the global NCS study calculate emission factors based on forest biomes (Griscom *et al* 2017). Furthermore, we used historical data from the last 10 years (2009–2019) to provide mitigation potential estimates based on national emissions trends. As a final note about differences between this study and the global studies, we focused on several prioritized pathways for Indonesia developed during the initial 2020 workshop and did not include other NCS pathways from savanna and agricultural lands.

4.2. The contribution of dryland ecosystems to Indonesia's NCS mitigation potential

For dryland ecosystems, mitigation potential from CSF may be underestimated given the likely future trends in the forest sector. Over the last 10 years, only 73.2% of logging concessions remained active. There are still many production forest areas that have not been granted a concession license (Suryanto and Sayektiningsih 2020). Therefore, as more concessions become active and obtain their licenses, emissions from the forest sector are likely to increase, thereby increasing the amount of mitigation available from improved forest management.

The baseline forest conversion rate in drylands during the reference period was much lower than the 1990–2009 period as recorded in the FREL (270.5 $MtCO_2e\ yr^{-1}$; MoEF 2016). This indicates the mitigation potential from AFC can be augmented by managing deforestation drivers. The dominant deforestation drivers in Indonesia are large-scale oil palm and timber plantation development (which contributed to two-fifths of the total deforestation) and major fire events. The conversion of forests into shrubs contributes to one-fifth of Indonesia's deforestation (Austin *et al* 2019).

The potential for annual carbon sequestration from reforestation is much greater than found elsewhere, with ranges from 50–67 $MtCO_2e\ yr^{-1}$ (Bastin *et al* 2019, Griscom *et al* 2020). Our estimation of potential reforestation area (1.7–19 Mha) is larger than those of prior studies with (3.2 Mha and 4.9 Mha; Griscom *et al* 2017, Bastin *et al* 2019, respectively). If only critical and highly critical lands are included, reforestation areas would be 1.7 Mha with an emission reduction potential of 23 $MtCO_2e\ yr^{-1}$. Thus, maximum climate mitigation potential for reforestation could only be achieved with a large-scale restoration program (i.e. 19 Mha) potentially reaching 247 $MtCO_2e\ yr^{-1}$ (Basuki *et al* 2022).

4.3. The importance of wetlands in Indonesian NCS mitigation potential

Peatland pathways play the most critical role in achieving Indonesia's NDC. The combined peatland pathways could provide nearly double the emissions reduction target from the FOLU sector by 2030. Carbon sequestration can be achieved by avoiding drainage of high-density carbon organic or peaty soils or by re-establishing high water tables in disturbed areas (Freibauer *et al* 2004). Great efforts and investments have been made to monitor water table fluctuations and to implement rewetting by construction of canal blocking (i.e. peat restoration) as the third largest NCS pathway. However, GHG emissions calculations from rewetting are highly uncertain both for estimated impacted areas and the relationship between water table depth and emissions reduction. We recommend further research to better understand rewetting processes and their potential contribution to emissions reductions.

Mangroves provide numerous ecological and socio-economic functions, especially for climate change mitigation and adaptation (Murdiyarso *et al* 2015, Kauffman *et al* 2017, Sidik *et al* 2018, Alongi 2020, Arifanti 2020, Arifanti *et al* 2022b). Mangroves have the potential to mitigate 41.1 $MtCO_2e\ yr^{-1}$ by 2030, 8% of the NDC target for the FOLU sector under the unconditional mitigation scenario (Arifanti *et al* 2022a). The total mangrove mitigation potential is relatively small compared to dryland ecosystems due to the small extent of mangrove ecosystems (~2.6% of the total forest area in Indonesia). Despite their small extent, the mitigation potential per unit area for mangrove ecosystems (12.2 $MgCO_2e\ ha^{-1}\ yr^{-1}$) is four times higher than dryland forests (3.3 $MgCO_2e\ ha^{-1}\ yr^{-1}$), warranting consideration for implementation. Belowground carbon stocks play a significant role as most of the carbon in mangrove ecosystems is stored in soil (Murdiyarso *et al* 2015, Kauffman *et al* 2017, 2020, Arifanti *et al* 2019). The total mitigation potential from mangrove reforestation (8.9 $MtCO_2e\ yr^{-1}$) is far less than avoided mangrove deforestation and degradation (32 $MtCO_2e\ yr^{-1}$) (Arifanti *et al* 2022a). This underscores mangrove conservation as an important NCS component. Currently, only 22% of the total mangrove area in Indonesia has designated conservation status (Sidik *et al* 2018). Considering the mitigation potential of mangrove conservation is significantly higher potential than reforestation, expanding and strengthening mangrove conservation in Indonesia should be a high priority.

4.4. Policy considerations: alignment with Indonesia's climate commitment

4.4.1. Policy wins

Indonesia is committing to reducing GHG emissions through multiple policies. In 2011, a moratorium of new development and extraction licenses in primary forests and peatlands was issued. This moratorium was made permanent in 2019 and intends to protect around 66 Mha of primary forest and peatlands from conversion (MoEF 2020). After the major peatland fires of 2015, which included 1.72 Mha in drylands and 0.89 Mha in peatlands, the government strengthened its emphasis on the restoration of degraded peatlands. Peatland restoration policies on hydrological management and restoration were issued in 2017 and the National Planning Agency (BAPPENAS) established national low carbon development targets for priority sectors, including 1.6 Mha of restored peatlands and 50,000 ha of rehabilitated mangroves by 2024. Mangroves are also addressed in the Management of Coastal Areas and Small Islands law, which states any human use of mangrove systems must consider the sustainability of mangrove ecological function. The Peat and Mangrove Restoration Agency aims to restore 0.6 Mha degraded mangroves by 2024. Mangrove protection can also be achieved through spatial planning of terrestrial and coastal mangroves. For example, a recent law has facilitated the integration of terrestrial spatial planning at the district level and coastal zonation at the provincial level and the government has targeted the expansion of Marine Protected Areas to over 23 Mha. In a final step forward for NCS, the government has made efforts to transform land-based infrastructure development throughout Indonesia by considering environmental quality in development. The government now requires an environmental impact assessment for infrastructure development, which takes the interests of economic development and the need to reduce the rate of deforestation into account. These efforts also involve ministries, local governments, and related authorities in infrastructure, environment, forestry, economy, and local governments (GOI 2021).

4.4.2. Policy challenges

Despite these policy gains, there are challenges facing policy implementation. For example, the 2011 moratorium on forest clearing includes exemptions for nine categories of activities that bring uncertainty to the areas meant to be protected by this regulation. These exemptions include areas that have been issued licenses for exploration prior to the issuance of the moratorium and vital development areas (i.e. food estate and infrastructure development). This regulation also omits secondary forests, with an area of around 42.8 Mha. These exemptions make the effectiveness of this policy unclear (Busch and Ferretti-Gallon 2014, Nurrochmat *et al* 2020). Confusion in policy implementation can also arise from the multiple definitions of protection or conservation areas across different regulatory frameworks (Mursyid *et al* 2021) and a lack of clarity on the management authority of local law enforcement (Uda *et al* 2017).

Policy harmonization and integration are necessary for NCS implementation in all sectors. For example, an important emission reduction strategy from the energy sector is the transition from fossil fuels to renewable and more sustainable energy, which includes an increase in biofuel production from the oil palm sector. This may conflict with policies aiming to reduce deforestation, since increasing biofuel production may lead to an increase in forest conversion (Obidzinski *et al* 2012, Mukherjee and Sovacool 2014, Dharmawan *et al* 2020). In addition to streamlining, sectoral policies should also be harmonized and integrated to achieve decarbonization objectives in all sectors.

4.4.3. Other challenges

The government of Indonesia has recently issued regulations concerning carbon pricing to engage various stakeholders to participate in achieving the national emission reduction target. It is estimated that IDR 343.6 trillion per year, equal to 22.5 million USD, is needed to achieve the NDC target by 2030 (MoEF 2020). After the maximum NCS mitigation potential is calculated under this study, marginal abatement cost from each NCS pathway is needed for effective NCS implementation (Moran *et al* 2009, Lu *et al* 2018). There are also major challenges tied to the coordination, availability, and quality of forest data and monitoring systems. Even though carbon loss from deforestation on drylands, peatlands, and mangroves is available for monitoring at the national level using land cover data, assessing carbon gain from the reforestation and mangrove restoration pathways is more challenging as it can only be detected starting at least three years after planting using remote sensing techniques (i.e. high resolution satellite imagery). All related stakeholders, including national and local governments, scientists, local communities, and NGOs need to work together to address these challenges, improve monitoring, and ease data access.

4.4.4. NCS and COVID-19 recovery

If the challenges to NCS implementation are overcome, NCS could be a key tool in facilitating COVID-19 recovery. At the beginning of 2020, the government issued a national economic recovery program to reduce COVID-19 impacts on local communities. NCS can generate high-quality carbon credits with economic gains from voluntary and compliance carbon markets. Implementation of NCS may provide an opportunity for labor intensive restoration programs by engaging local communities. For example, the government has included labor-intensive mangrove restoration as part of the country's National Recovery Program, engaging communities while implementing NCS. Compared to emissions reductions from energy sectors, NCS may offer a lower cost for implementation (Griscom *et al* 2020), which is an important consideration given the economic pressures as a result of the COVID-19 pandemic. However, recent assessments from the National Development and Planning agency and the Ministry of Finance show that the forestry and peatland sectors receive far lower funding than other sectors. The government could develop a fiscal policy that can leverage non-government financing and incentivize high-quality and inclusive emission reduction activities in the FOLU sector.

Based on these mitigation policies and actions, we make several recommendations to achieve the maximum mitigation potential of NCS in Indonesia:

- Enhance ecosystem protection (including peatlands and mangroves) through expanding the current ban on the issuance of new licenses to include secondary forests.
- Enforce low emission land clearing methods (such as a no burning policy on peatlands), invest in fire prevention, and collaborate with local governments to mitigate fire risks.
- Harmonize and integrate policies across the FOLU, energy, and agriculture sectors to achieve optimized mitigation results.
- Develop fiscal policy to leverage non-government financing and incentivize emission reduction activities.
- Improve data coordination, infrastructure, and monitoring systems to allow for efficient and timely monitoring, management, and protection.

5. Conclusion

In this study, we provide a novel estimate of potential mitigation opportunity from nine NCS pathways in Indonesia. Our findings underscore the need for national, regional, or local datasets when calculating national NCS mitigation opportunity. We leveraged national extent data and emission factors that allowed a more refined estimate of Indonesia's NCS potential than previously available. Wetlands, primarily peatlands, are key for NCS in Indonesia—by exclusively conserving and restoring wetlands, the country's NDC can be achieved by 2030. Land development plans for food and energy in Indonesia should protect and restore wetlands to meet the ambitious goals of the NDC and FOLU net sink target by 2030. If Indonesia can build on the current momentum and rise to meet the challenges of broad-scale NCS implementation, Indonesia can build a sustainable future nationally and become a leader in NCS globally.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Author contribution

N N assembled and coordinated the multidisciplinary research teams. N N, S, N S L, M L, D H T analyzed data, N N, N S L, M L, A M wrote the original manuscript, S Y, A A, C A S P, R P R, A G, E P, J J, D D, P E contributed to writing the final manuscript, S undertook uncertainty analyses, N S L developed content for drylands, M L developed content for peatlands, V B A developed content for mangroves, I B developed content for reforestation, P E, N N for funding acquisition, P E, I A, G Z A reviewed manuscript.

Conflict of interest

The authors declare no competing interests.

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