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Challenges and opportunities for achieving Sustainable Development Goals through restoration of Indonesia's mangroves

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Indonesia, the most mangrove-rich nation in the world, has proposed the most globally ambitious mangrove rehabilitation target (600,000 ha) of any nation, to be achieved by 2024 to support multiple Sustainable Development Goals (SDG 1–3, 6, 13 and 14). Yet, mangrove restoration and rehabilitation across the world have often suffered low success rates and been applied at small scales. Here, we identify 193,367 ha (estimated costs at US$0.29–1.74 billion) that have the potential to align with the national mangrove rehabilitation programme. Despite being only 30% of the national target, our robust assessment considered biogeomorphology, 20 years of land-use and land-cover change and state forest land status, all key factors moderating mangrove restoration success which have often been neglected in Indonesia. Increasing subnational government representation in mangrove governance as well as improving monitoring and evaluation will increase the likelihood of achieving the mangrove rehabilitation targets and reduce risks of failure. Rehabilitating and conserving mangroves in Indonesia could benefit 74 million coastal people and can potentially contribute to the national land-sector emissions reduction of up to 16%.

Indonesia has the largest mangrove extent in the world (22% of global mangrove area)[1], of which ~800,000 ha have been removed and converted over the past 30 years[2]. To reverse the loss of this valuable ecosystem, civil societies, policymakers and the research community have urged mangrove conservation and rehabilitation and promoted a broader understanding of the environmental drivers of mangrove carbon storage, rates of carbon sequestration and the value of other ecosystem services[3]. In 2020, the national government of Indonesia announced its aim to rehabilitate 600,000 ha of mangrove between 2020 and 2024, concentrated in nine provinces: North Sumatra, Riau, Riau Islands, Bangka Belitung, West Kalimantan, East Kalimantan, North Kalimantan, Papua and West Papua[4]. Non-government stakeholders and government partners will implement these ambitious targets on the ground[5] but unfortunately many past restoration programmes have failed due to limited ecological knowledge and misunderstandings about the governance of coastal lands[6–8]. Improving the success of mangrove ecosystem restoration in Indonesia requires recovering ecosystem extent and functionality in areas where mangroves have been lost (going beyond rehabilitation, see Methods for detailed definition of restoration and rehabilitation used in this study), as well as developing the means to verify restoration success (and thus assess return on investment) through the implementation of

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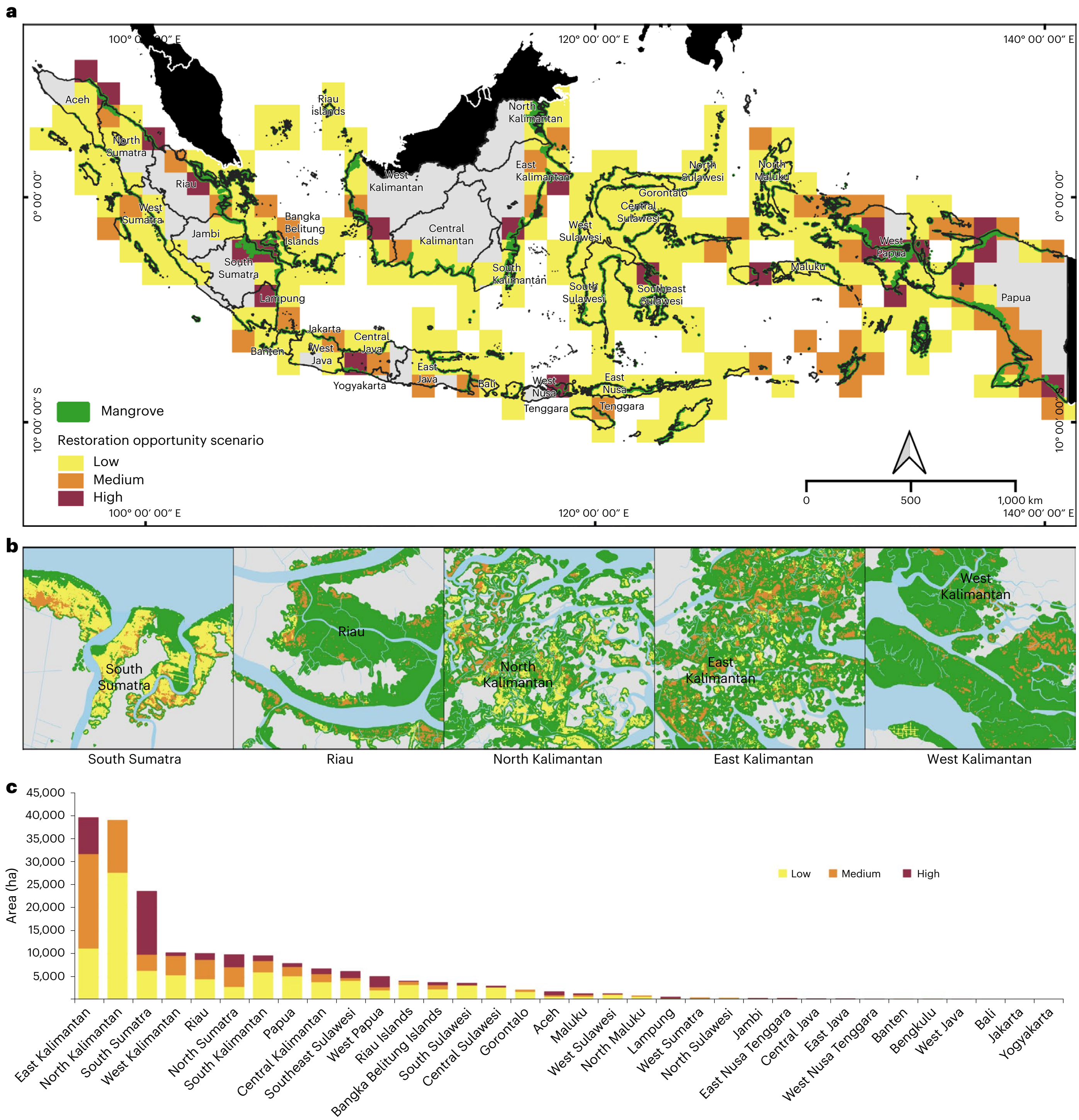

Fig. 1 | Distribution and potential area of mangrove restoration opportunity for three scenarios (low, medium and high) in Indonesia. a, Geographical distribution of restoration opportunity scenario area at 1° grid. **b**, Five grids of top five selected provinces for mangrove restoration opportunity area constituting 62% of national proportion. **c**, Restoration opportunity scenarios area at provincial level. The final restoration opportunity scenario was produced by considering the degree of mangrove restoration feasibility according to multiple factors, including mangrove loss area between 2001 and 2020 (Fig. 2), biogeomorphological coastal settings (Extended Data Fig. 4), mangrove loss drivers (Extended Data Fig. 2) and land ownership status (Extended Data Fig. 3). An online interactive map visualization for potential area of mangrove restoration opportunity is available through the following link: https://sdsasmito.users.earthengine.app/view/indonesia-mangrove-restore.

monitoring of change in mangrove extent, condition and the benefits to communities.

Mangrove conservation and restoration have been advanced as actions to achieve a range of international environmental targets. In line with the UN Decade of Ecosystem Restoration 2021–2030, a strong commitment was made by the global conservation community to increase mangrove cover by 20% by 2030[9]. Immediate action is required to meet this as well as the Sustainable Development Goals (SDGs) targets

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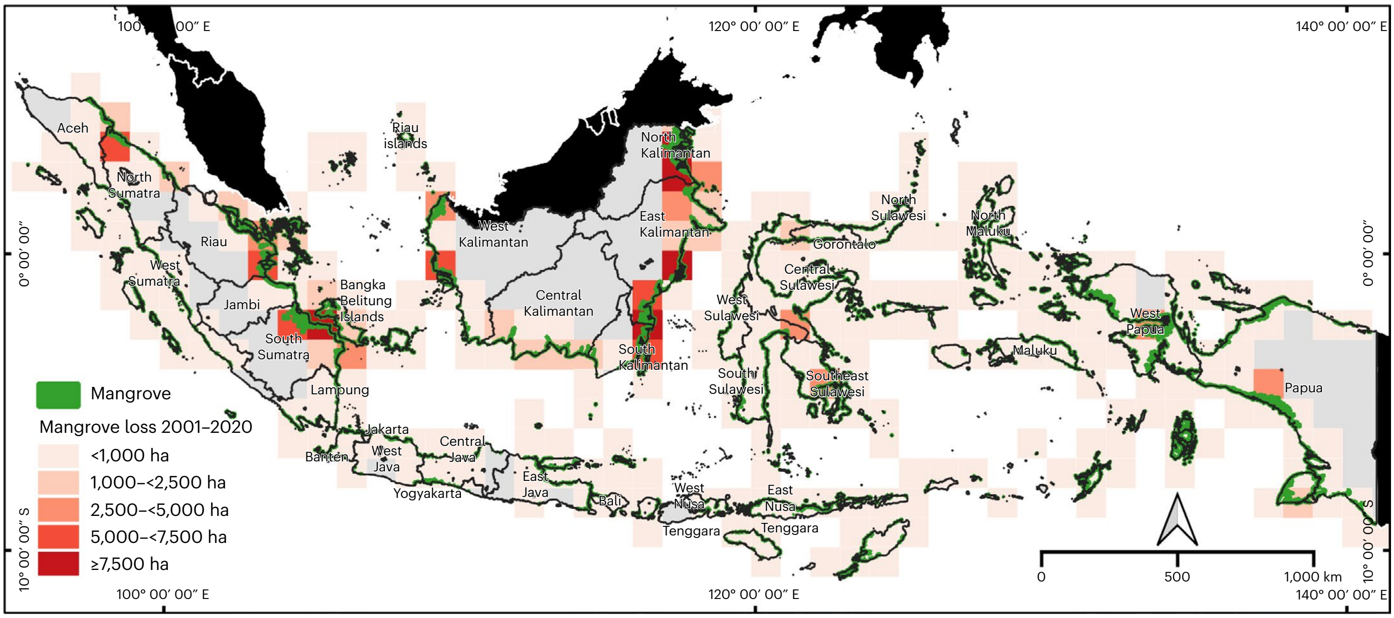

Fig. 2 | Location and area of mangrove loss across Indonesia between 2001 and 2020. Mangrove loss data at 1° grid are presented as the accumulation of loss area between 2001 and 2020. Total and annual mangrove area losses were generated by overlaying mangrove area baseline data in 2000 from ref. [1] with annual forest cover loss from ref. [33].

timeline, along with Aichi target 14 (improved ecosystem functionality) and target 15 (conservation and restoration of degraded ecosystems) of the Convention on Biological Diversity. Therefore, 2022 is a critical year to re-enforce mangrove conservation and rehabilitation management to achieve multiple goals over the next 8 years, including in Indonesia with its ambitious rehabilitation target. Globally, preventing further mangrove loss could potentially avoid nearly 424 $MtCO_2e$ by 2030 which is equivalent to 6% emissions generated by land use change in 2019[10,11]. The climate benefit of mangrove management (SDG 13) at global scale could be >424 $MtCO_2e$ if rehabilitation programmes can meet the target for increasing mangrove extent and thus achieve atmospheric carbon removal.

Natural mangroves deliver numerous ecosystem services which contribute directly and indirectly to achieving the SDGs. For instance, mangrove ecosystems regulate carbon storage more efficiently compared to other terrestrial forests (SDG 13), provide habitat for fishes and marine organisms (SDG 14) and provide fish products and important fishing grounds for coastal communities (SDG 2). Yet, despite recent reductions in rates of clearing and conversion of mangroves, mangroves remain among the most threatened ecosystems worldwide, including in Indonesia, due to land-use change, climate change and sea level rise[12,13]. Conserving the remaining mangroves and rehabilitating degraded ones may help mitigate climate change as well as reduce the impacts of climate change on 296 million people within tropical coastal communities, including Indonesia—the world's largest archipelagic country[14].

Here, we present an indicative nation-wide map of mangrove restoration potential and opportunity scenarios (Fig. 1). We identified the restoration potential and opportunity scenarios of landscapes, estimated the costs and calculated areas on the basis of historical mangrove cover losses (Fig. 2), biogeomorphological characteristics, state forest land status (land tenure) and mangrove loss drivers (land-use and land-cover change), all of which are key factors moderating mangrove restoration success and have often been neglected in Indonesia and worldwide. Further, we reviewed reported mangrove revegetation, restoration and rehabilitation studies between 1990 and 2020 (Fig. 3) and analysed the effectiveness of past restoration approaches and efforts, as well as mangrove governance-related policies and regulations in Indonesia. Our findings provide scientific evidence to support the Indonesian Government's goal to conserve and rehabilitate mangroves, particularly with the recent establishment of the Peatlands and Mangrove Restoration Agency (BRGM) whose role is to coordinate and implement Indonesia's ambitious mangrove rehabilitation targets[4].

Results and discussion

Restoration opportunity area and costs

Mangrove restoration programmes have a greater chance of being successful when implemented in areas where mangroves have previously grown[15]. These areas have either been subject to deforestation or degradation and may be under government management or private ownership. They are locations that have undergone forest conversion into other land uses, including aquaculture, crops or plantations and urban settlements. Land ownership status is an important factor to consider for determining the availability of land for mangrove restoration[7]. For example, a higher opportunity and priority would be given to unproductive aquaculture ponds located in the protected and production forest areas which are under government management or leasehold, rather than in areas with other land uses that may be under private ownership (Methods gives detailed forest land tenure classifications in Indonesia). Therefore, managing mangrove rehabilitation should consider factors that include land tenure status and land-cover type as well as biogeomorphology (for example, ensuring that the correct mangrove species are used in hydrologically suitable locations) across landscape scales.

We calculated that ~193,367 ha of land may be feasible for implementation of mangrove rehabilitation programmes (Fig. 4). This conservative assessment suggests that the potential for restoration may be only 30% of the current mangrove rehabilitation area target (600,000 ha). Depending on the challenges and opportunities for each of the biogeomorphological categories of land use and the forest land status we considered (see Methods for detailed mapping methodology), we identified that 9% of the potential restorable area was categorized as being within the high opportunity scenario, 33% as medium and 58% as areas falling within the low opportunity scenario. Among these scenarios, ~75% of identified areas have non-protected forest status, implying a greater tenurial challenge to establishing a rehabilitation

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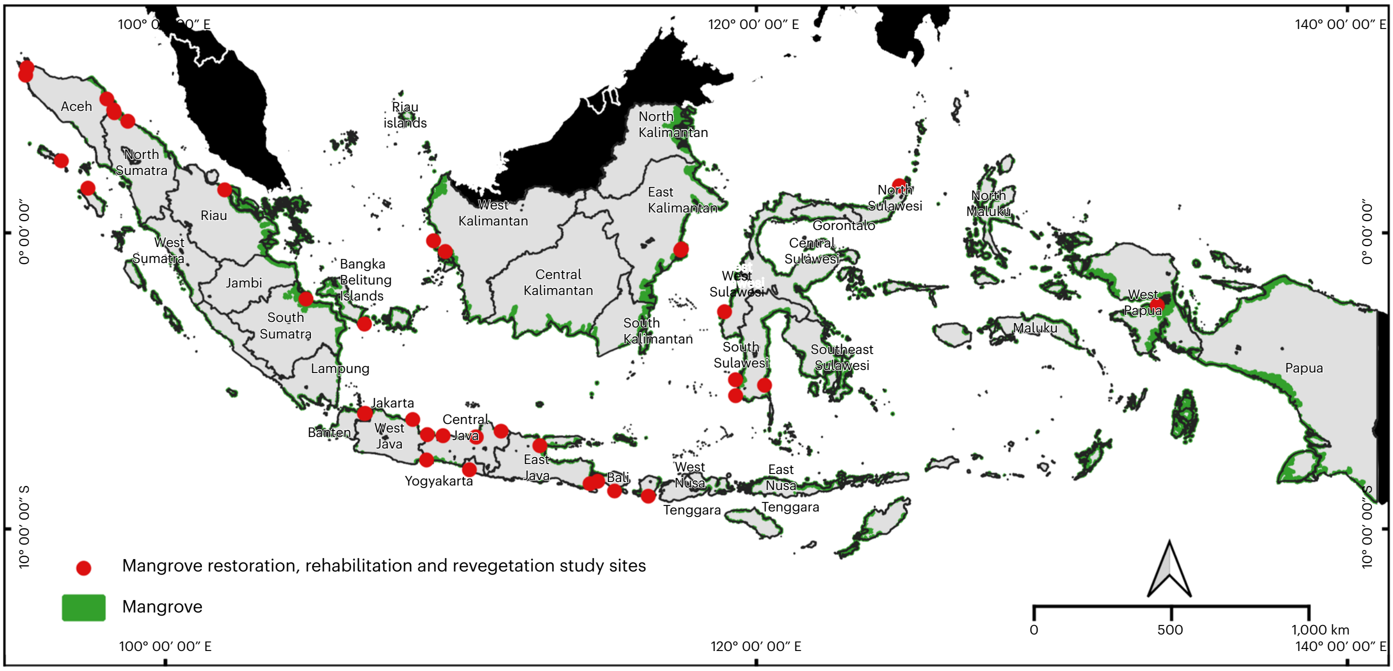

Fig. 3 | Geographical distribution of mangrove revegetation, restoration and rehabilitation study locations between 1990 and 2020 in Indonesia. The data were compiled through systematic review; further studies inclusion and exclusion criteria and the selection process are described in Supplementary Tables 12 and 13, respectively. Details of the study site and approaches (for example, revegetation, restoration and rehabilitation) for all compiled studies are provided in Supplementary Table 14.

programme. We identified the five provinces that are among the top ranked of high potential for mangrove restoration in Indonesia, namely East Kalimantan (20% of national restoration potential area), North Kalimantan (20%), South Sumatra (12%), West Kalimantan (5%) and Riau provinces (5%) (Fig. 1c). All of these provinces, except South Sumatra, are among the areas already identified in the current mangrove rehabilitation programme by the BRGM as having high opportunity for rehabilitation[4]. At the subprovincial scale, we identified the top six regencies with restoration area opportunity >10,000 ha, namely Banyuasin, Bulungan, Tana Tidung, Paser, Berau and Nunukan (Supplementary Table 1). Mangroves across these regions were commonly deforested after 2010 and converted into aquaculture ponds despite being designated as protected forest areas (Supplementary Table 1).

Considering that previous successful (85% survival rates) mangrove rehabilitation around the world has been achieved only at small landscape scales (10–400 ha) with costs varying between US$1,500 ha^{-1} and US$9,000 ha^{-1} (refs. [8,16]), the large-scale mangrove rehabilitation ambition of Indonesia must be carefully planned. Rehabilitating ~200,000 ha of degraded mangroves will require between US$0.29 billion and US$1.74 billion. The 2021 annual government budget allocation for mangrove rehabilitation under BRGM alone is ~US$0.10 billion[17], which is 66–94% lower than the estimated total required budget but with additional international investment[18] there is potential for scalable mangrove rehabilitation success.

Lessons learned from the past failures

In Indonesia, unproductive aquaculture ponds have become targets for mangrove rehabilitation programmes (Supplementary Fig. 1). However, metrics of rehabilitation success in these settings reveal low survival rates of planted seedlings, highlighting an urgency to develop new strategies for mangrove rehabilitation and strategies to assess the effectiveness of ecosystem rehabilitation[6]. For example, a silviculture approach—nursery-based mangrove planting using *Rhizophora* species—has been adopted for mangrove restoration and management for a long time in Indonesia[19]. When seedlings are directly planted in unused ponds (Supplementary Fig. 1), dense monoculture plantations often form, which despite providing some ecosystem services (for example, carbon sequestration[20]) have limited biodiversity value[21] and may be less resilient to stressors compared to a diverse assemblages of tree species[22].

Mangrove restoration projects have often suffered low success rates due to inadequate hydrological site assessments before revegetation[23]. For example, mangrove planting programmes initiated after the 2004 tsunami were focused on mono-species planting and on reporting the number of seedlings being planted in a given area[24]. These planting projects most often occurred on undisputed land, such as mudflats, which are inappropriate locations for long-term mangrove growth because of high inundation frequency, high water flow rates and hypersaline conditions that limit seedling establishment and survival[24]. Planting has also focused in mangrove areas where low canopy cover is observed. While some mangrove areas with low canopy cover may respond to plantings because they are degraded, many sites naturally support low canopy cover, reflecting suboptimal environmental conditions for growth of *Rhizophora* species, instead favouring growth of highly salt tolerant species such as *Avicennia* spp.[24]. Such failures in mangrove rehabilitation efforts, however, have been under-reported with more than 50% of rehabilitation studies not monitored over time (Supplementary Fig. 1).

Alternative restoration approaches through repairing hydrology, including excavation and removal of pond walls and tidal gates, have also been introduced[15], although this approach has been only practiced in Indonesia at limited scales, mostly in unused aquaculture ponds[25]. A comprehensive understanding of the opportunity for mangrove rehabilitation in Indonesia is largely unquantified. Additionally, with limited monitoring of mangrove rehabilitation projects, the effectiveness and functionality of mangrove rehabilitation in Indonesia remains largely unknown and therefore it remains challenging to assess rehabilitation effectiveness between approaches and locations in Indonesia. Yet such assessments provide important data to achieve the ambitious mangrove rehabilitation goals of Indonesia.

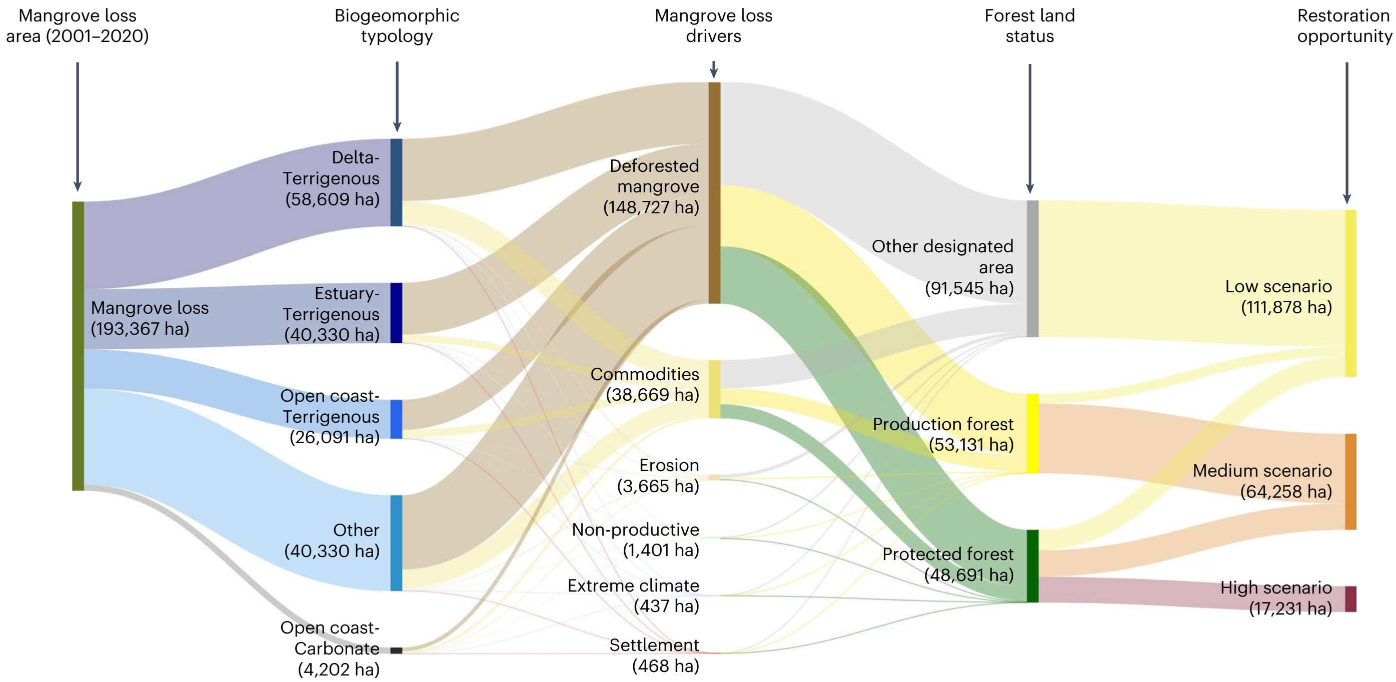

Fig. 4 | The distribution of mangrove loss area (in hectares) between 2001 and 2020 in Indonesia. Also shown are mangrove loss proportions within different biogeomorphological typology, loss drivers (land-use types), forest land status and identified scenarios of restoration opportunity (low, medium and high).

Mangrove governance in Indonesia

Mangrove conservation in Indonesia was formally adopted in 1990 (Extended Data Fig. 1 and Supplementary Table 2), when mangroves were designated as protected forests under Law 5/1990 and the Presidential Decree 32/1990. When the Asian tsunami hit Aceh province in 2004, the role of mangroves in wave attenuation and therefore minimizing disaster risks for coastal communities was recognized[26]. As a result, nearly 30,000 ha of damaged mangroves were rehabilitated to recover coastal resiliency through planting of nearly 24 million seedlings over 60 projects[24]. However, the success of these programmes was low due to a lack of planning, monitoring and critical supplemental actions[24,27]. Despite the failure of many mangrove rehabilitation projects post-tsunami, the implementation of the subsequent programmes have not fully adopted best-practice mangrove rehabilitation principles[6,7,15,23]. In 2007, similar approaches to mangrove rehabilitation and conservation were adopted at a larger, national scale under the Spatial Planning Law (Law 26/2007) and the Coastal Area and Small Islands Management Law (Law 27/2007).

In 2012, the National Mangrove Management Strategy (STRANAS Mangrove) was first established and followed by the formalization of the National and Regional Mangrove Working Group whose task was to guide mangrove conservation and rehabilitation. Its main goal was to involve more stakeholders, including civil society organizations and subnational government bodies, in mangrove conservation and rehabilitation[28]. Until 2017, the technical regulation of strategy and performance indicators for mangrove management was implemented with targets set to rehabilitate 3.49 Mha of mangroves by 2045[29]. In 2020, however, the Mangrove Working Group and its supporting regulations were abolished and the mangrove rehabilitation strategy was subsequently managed by BRGM[4]. This effectively removed the regional governments (subnational working groups) from decisions related to mangrove management and concentrated development of policy at the level of the national government. The new strategy includes a tenfold increase in the annual rehabilitation target (from 11,250 to ~120,000 ha yr^{-1}) with an overall target of 600,000 ha to be achieved within a shorter timeline (2020–2024). Without clear planning and appropriate strategies, these ambitious targets may not be feasible. For example, the annual mangrove rehabilitation area reached between 2017 and 2020 was only 5,318 ha (50% of the target) despite 2.6 million seedlings being planted (Supplementary Table 3). Given the lessons from the previous mangrove rehabilitation and the emerging processes of mangrove governance, it is timely to set an achievable restoration framework with improved planning, evaluation and monitoring.

Implication for international environmental agendas

A successful mangrove rehabilitation programme can directly contribute to reducing poverty (SDG 1) and maintaining food security and livelihoods (SDG 2), thereby increasing the health and well-being of 74 million coastal people in Indonesia (see Supplementary Table 1 for total population of regions with restoration potential area >5 ha). Additionally, mangrove rehabilitation will directly contribute to other relevant SDGs, such as improving water quality (SDG 6), providing healthy coastal habitats for fish and other marine biodiversity (SDG 14), contributing to emissions reductions and improving coastal resilience from sea level rise (SDG 13) and sustainably managing and protecting terrestrial ecosystems (SDG 15). Mangrove rehabilitation contributions to SDG 1 and 2 are particularly relevant as the current rehabilitation programme is delivered as cash-for-works activities under the National Economic Recovery strategy (PEN) as part of the social welfare payments to alleviate economic impacts of the COVID-19 pandemic[17]. With the current annual mangrove rehabilitation budget of US$0.10 billion[17], further implementation of scalable community-based mangrove restoration with technical support from subnational and non-government stakeholders could increase the benefits to local communities, if administered properly. Therefore, the large investments planned for coastal communities via a national mangrove restoration programme will not only contribute to the economy of coastal communities, potentially reducing poverty across 199 regencies but will also help in securing nearly 4% of the national greenhouse gas emissions reduction target from the land sector.

Restoring 193,367 ha of mangroves in the next 5 years (2021–2025) may contribute to carbon sequestration of 22 ± 10 $MtCO_2e$ by 2030 (see Methods for detailed estimate calculation and assumptions).

Moreover, stopping the current annual rates of mangrove loss of 7,436 ha yr^{-1} between 2021 and 2030 will reduce up to 58 ± 37 $MtCO_2e$ or 12% of the national land sector emissions reduction targets. Clearly, climate benefits from mangrove rehabilitation and conservation in Indonesia are substantial if rehabilitation and conservation can be implemented appropriately and large annual rehabilitation targets are achieved. Indonesia has submitted its updated Nationally Determined Contributions (NDCs) to the United Nations Framework Convention on Climate Change, within which integrated management and rehabilitation of mangroves is a component of the actions to enhance the resilience of coastal ecosystems[30]. Further ecological aquaculture practices such as silvofisheries which are commonly applied in Indonesia[31,32] may provide promising potential for climate change mitigation through mangrove biomass enhancement. With the increased potential for international investment to support mangrove rehabilitation in Indonesia, there is an opportunity for Indonesia to take the lead and show the world how mangrove conservation and rehabilitation can contribute to multiple international environmental agendas.

In the past three decades, the governance of mangrove conservation and rehabilitation in Indonesia has been highly variable in approach (Extended Data Fig. 1). The current approach is top-down[4] which has risks and may be ineffective at achieving landscape-scale increases in mangrove extent, as was demonstrated post-tsunami[24,29]. This top-down approach set by national-level agencies, which are responsible for achieving rehabilitation targets, has limited involvement (or investment) by subnational governments. While we have identified key factors that determine land available for mangrove rehabilitation, the success of mangrove rehabilitation is not necessarily assured because of the limited involvement of subnational mangrove working groups. A current 'one size fits all' strategy of the national government may not be appropriate to achieve successful mangrove rehabilitation and thus more flexible, localized approaches may increase the likelihood of success.

Methods

Datasets used in the analysis

We used multiple published datasets to develop maps and identify potential areas for mangrove restoration in Indonesia. These datasets include mangrove area baseline map in 2000[1] (accessed through UNEP WCMC Ocean Data Viewer and available at https://doi.org/10.34892/1411-w728), annual global forest cover loss between 2001 and 2020 v.1.8 (ref. [33]) (data publicly available and accessed through open access Google Earth Engine platform), the most up-to-date map of drivers of mangrove loss[12] (data publicly available and accessed through open access Google Earth Engine platform), a biogeomorphic mangrove typology[34] (accessed through UNEP WCMC Ocean Data Viewer and available at https://data.unep-wcmc.org/datasets/48), national forest land status digitized from the Ministry of Environment and Forestry public data portal[35], national population in 2020 from Statistics Indonesia[36], national mangrove rehabilitation activities between 2015 and 2020 and their budget allocation for 2021–2022 fiscal year[17] and the national emissions reduction targets by sectors updated from Indonesia's NDCs[30].

Mangrove forest losses between 2001 and 2020 were assessed from overlay analysis of the mangrove baseline map and forest cover loss data. In Indonesia, forest area ownership status (forest land status) is normally assigned into seven categories[35] and we simplified those categories into three classes for this study: (1) protected mangrove forests (for example, nature reserve area, marine reserve area and protected forest); (2) production mangrove forests (for example, production forest, limited production forest and convertible production forest); and (3) mangrove under other land-use allocation (Area Penggunaan Lain). Additional data on historical records of mangrove restoration approaches and policies were compiled through systematic review.

Mapping and analysis of potential areas for mangrove rehabilitation

The potential for national-scale mangrove restoration was assessed using a cross-analysis overlay processes and used spatial-based secondary data as described in the dataset section above. We assigned a range of scenarios (low, medium and high) indicating the degree of restorable land across land classification factors (land use types, national forest land status and biogeomorphic setting) for each identified pixel as described in Supplementary Table 4. For example, land where settlement replaced mangrove had low restoration potential as it may not be feasible to rehabilitate this type of land compared to a deforested mangrove land use type (Extended Data Fig. 2 and Supplementary Table 5). For the national forest land status factor, converted and degraded mangroves within protected and production forest areas were considered highly restorable due to their legal government land ownership rather than areas under other land-use allocation (Area Penggunaan Lain), which may be owned by the private sector (Extended Data Fig. 3 and Supplementary Table 6). We further defined the level of restoration scenario following the variation of carbon stocks between multiple biogeomorphological settings compiled across 97 datasets of undisturbed mangroves in Indonesia (Extended Data Fig. 4 and Supplementary Tables 7 and 8). We considered mangrove settings with higher carbon stocks as having a higher potential for future restoration success compared to those with lower carbon stocks, particularly in the context of climate change mitigation potentials. The restoration potentials for each land classification factor were subsequently summarized and presented as three restoration opportunity scenarios (low, medium and high). This scenario approach provides conservative assessments of restoration opportunity and are described in Supplementary Table 9. These spatial analyses were done through cloud-based spatial analysis operations using the Google Earth Engine and the final map layout for the figures were developed using open source QGIS software.

The limitation of our spatial analyses was mainly due to the coarse resolution and accuracy of global scale secondary maps. For example, we used the most recent global-scale product of the drivers of mangrove loss by ref. [12], which may not fully recognize local mangrove loss drivers such as the expansion of oil palm and coconut plantation[37,38]. Moreover, ref. [12] mapped the drivers of mangrove loss until 2016 and we assumed that the trends of the drivers were the same through to 2020, which was the last year of mangrove forest loss data used in this study. Therefore, we defined and assumed the land-use type for mangrove loss areas after 2016 within the deforested mangroves class. Further, the use of the worst-case scenario—rather than the best—for identification and mapping of restoration opportunity may provide conservative analysis and, thus, this approach will require ground verification before policy actions can be implemented. The limitations in our approach to identifying opportunities for restoration can stimulate future studies seeking to address these limitations as well as their application for other ecosystems (peatlands).

Calculation of emissions reduction potential of mangrove rehabilitation and conservation

We estimated annual emissions caused by mangrove loss between 2001 and 2020 in Indonesia by multiplying the calculated annual area of mangrove loss (Fig. 2) by the total living biomass carbon stocks (211 ± 135 Mg C ha^{-1}) obtained across eight study sites (excluding dead wood and soil carbon stocks) representing mangroves in Sumatra, Kalimantan, Java, Sulawesi and Papua reported by ref. [39]. These estimates were subsequently used to calculate avoided emissions potentials between 2021 and 2030, following future emissions reduction target timeline[30].

The potential of carbon removals following 5 years of mangrove restoration was also estimated using a similar approach. We first assumed that restoring 193,367 ha of degraded mangrove will be fully achieved by 2024/2025—reflecting the current BRGM target timeline for mangrove restoration activities implementation across Indonesia[4]. We subsequently used total living biomass carbon stocks (31 ± 14 Mg C ha^{-1}) from a 5-year-old regenerated mangrove which were previously reported from mangrove production forests in Bintuni Bay of West Papua Province[40,41]. We calculated potentials for carbon removals by multiplying the restoration area by the carbon stocks over a 5-year time frame, between 2025 and 2030. The potential contribution of mangrove conservation to avoided emissions and mangrove rehabilitation to carbon removals were summarized and compared with reported emissions reduction targets in Indonesia's NDC[30].

Systematic review of mangrove restoration in Indonesia

A systematic review approach was used to describe the status and distribution of past and present mangrove restoration and rehabilitation in Indonesia. Methodological steps for the systematic review used in this study were based on previous systematic reviews on mangrove ecosystems[42]. The systematic review was focused on studies that have reported on restoration or rehabilitation from degraded, converted mangroves, abandoned ponds and advances in restoration approaches, for example, those that examine ecological and hydrological factors. Data were gathered from published literature obtained through searches in preselected bibliographic databases, including Scopus and Web of Science, as well as the search engine Google Scholar. To determine the scope of the review, this study used a globally applied standard approach for systematic review, by first defining the population, intervention, comparator and outcome (PICO) of the review. The detailed descriptions of PICO used for this systematic review are: (1) population: mangrove ecosystems in Indonesia; and (2) intervention: any approaches and efforts used for mangrove re-establishment in degraded mangroves or land uses where mangrove existed before. These common approaches include restoration, rehabilitation, planting and silviculture: (3) comparator: any indicators used to monitor the success of mangrove restoration, such as seedling survival, species richness, forest structure, hydrological regimes, area of restoration and time since restoration; and (4) outcome: restored or recovered or rehabilitated mangrove.

We considered how stakeholders and policymakers have used different terminologies describing the process of ecosystem recovery in the scope of this study. International communities such as Society for Ecological Restoration, Aichi targets and the upcoming Post-2020 Global Biodiversity Framework, as well as the UN Decade on Ecosystem Restoration use the term 'restoration', which is defined as a process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed[43]. However, most of studies and programmes for mangrove recovery in Indonesia used the term 'rehabilitation', which is associated with the planting of seedlings, rather than the term restoration, where the restoration of the natural ecosystem is the goal (Supplementary Fig. 1). Therefore, in this study, we used the term restoration specifically for our data analysis and interpretation, as well as in the discussion related to international environmental agendas. The term rehabilitation was subsequently used to discuss activities and targets associated with Indonesia's mangrove rehabilitation programme.

Before conducting the literature search in the bibliography databases, we composed the search string by identifying the relevant keywords following recommendations in PICO. However, here we only considered keywords from the population and intervention categories to avoid a narrowed search string and low number of papers during the literature search. Literature searches in Scopus and Web of Science were conducted using a search string in English, while we used both English and Bahasa Indonesia search strings for Google Scholar (see Supplementary Tables 10 and 11 for detailed search string and literature search documentations). To avoid the inclusion of less-relevant studies in the search results from Google Scholar, we only selected the first 50 publications following the most relevant order. The cut-off date for the literature search was 20 October 2020.

Study relevance was determined by using the inclusion criteria presented in Supplementary Table 12. For inclusion in the review, studies must have met the following relevant criteria: population, intervention, comparator and outcome of interest. After duplicates were removed from the search results, all studies went through a two-stage screening process at the combined title and abstract and full text levels by three reviewers. All screening stages used predefined questions—formulated following PICO—to select which publications satisfied the scope of the review. The workflow of the publication screening is described in Supplementary Table 13. Initially, 423 publications were identified using the systematic literature search string described in Supplementary Table 10. Following the relevancy of the initial papers to the defined research questions for this study, the literature screening, consisting of title, abstract and full text screenings, resulted in 61 final papers for further data extraction as listed in Supplementary Table 14.

After the two screening stages, the included literature records also indicated an increase in the number of publications over time, particularly in 2017, 2018 and 2019. This observed trend suggests a growing interest or number of mangrove restoration projects in Indonesia over the past few years. All the 61 included publications reported mangrove revegetation from almost all provinces in Indonesia (Fig. 3). Approximately 75% of included papers were from Sumatra, Java and Sulawesi with each of 20, 16 and 15 papers, respectively. While mangrove restoration and rehabilitation interventions occurred on degraded and converted mangroves, this preliminary finding was consistent with an earlier study[2] where past mangrove degradations in Indonesia were extensively located in these three islands.

Approximately 60% and 30% of the included literature were published as journal articles and conference proceedings documents, respectively (Supplementary Fig. 2). The publication outlet is critical to examine the reliability of the study, particularly where some of the papers (proceedings and reports) have a limited peer review and transparency. This quality control may also be observed for studies which are published in local journals where the peer review process may not be as rigorous as for international journals. For example, many excluded studies during screening were due to unknown or incomplete information on when the restoration activities occurred, which approach was used and whether there was monitoring of a particular rehabilitated mangrove site, despite those studies mentioning that their study sites were used for restoration of mangroves or a mangrove conservation-related programme. Certainly, improving the quality of reporting on mangrove restoration in Indonesia should consider improving transparency in the following: (1) how the restoration is being conducted, (2) how the restoration is being monitored and (3) what the impacts are between before and after restoration in terms of the recovery of ecosystem functionality.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data are available in the main text or the Supplementary Information. Results data from this study on mangrove restoration potential area by region in Indonesia can be accessed through the following figshare repository link: https://doi.org/10.6084/m9.figshare.19636458. The generated spatial results data on mangrove restoration potential area in Indonesia can be directly accessed in Google Earth Engine using the following asset ID: projects/ee-mangroverestoration/assets/Indo_mangrove_restore.

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Author contributions

Conceptualization of this work was by S.D.S. and M.B. The methodology was developed by S.D.S., M.B., A.K. and M.F.S. Investigations were undertaken by S.D.S., M.B., A.K., M.F.S., C.E.L. and

D.M. Visualization was by S.D.S. and A.K. Funding was obtained by S.D.S. and M.B. The project was administered by S.D.S. and M.B. with supervision by C.E.L. and D.M. The original draft was written by S.D.S. and M.B. who, along with A.K., M.F.S., C.E.L. and D.M., were involved in reviewing and editing the final manuscript.

Competing interests
The authors declare no competing interests.

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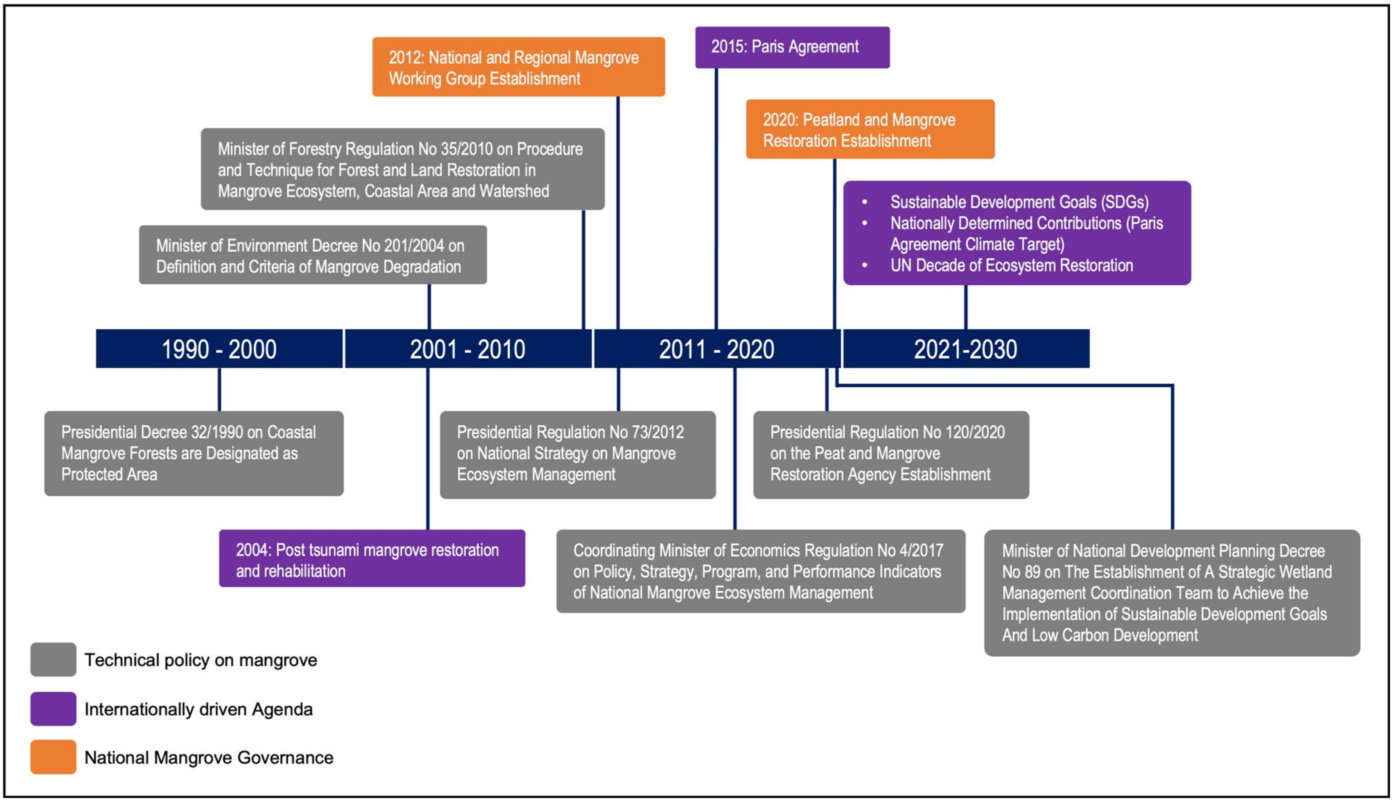
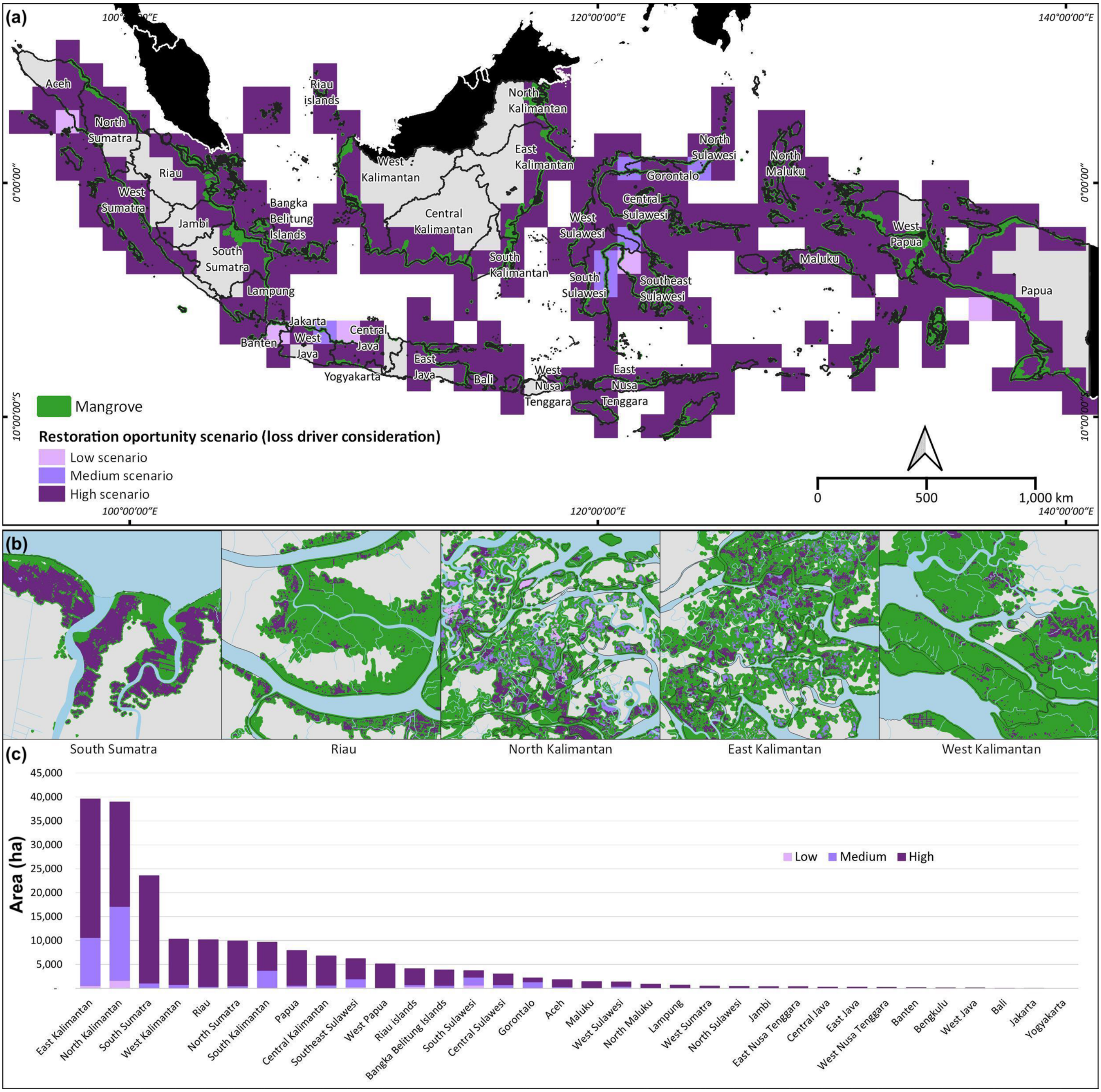


Extended Data Fig. 1 | Key mangrove management and conservation policies in Indonesia and relevant international environmental agenda between 1990 and 2030. A further detailed list of mangrove management policies in Indonesia is described in Supplementary Table 1.



Extended Data Fig. 2 | Mangrove restoration opportunity scenarios according to their loss drivers or the latest land use types, namely erosion, commodities, settlement, non-productive conversion, climate event and deforested mangrove. a, national distribution of restoration opportunity scenarios at 1 degree grid, **b**, selected grids of restoration opportunity scenarios distribution in South Sumatra, Riau, North Kalimantan, East Kalimantan, and West Kalimantan province, **c**, the proportion and area of restoration opportunity scenarios across all provinces in Indonesia according to loss drivers documented by Goldberg et al.[12] (see methods section for detailed description how this study overlaid loss drivers data with tree cover loss data by Hansen et al.[33]). Mangrove loss drivers such as erosion, settlement, and climate event were considered of having a low restoration opportunity scenario, while other drivers including commodities and non-productive conversion were a medium scenario. The high restoration opportunity scenario was only considered in areas where mangroves are deforested (living biomass is removed with minimal soil and hydrological disturbance). Further description of the scenarios classification for each loss driver is provided in Supplementary Table 4.

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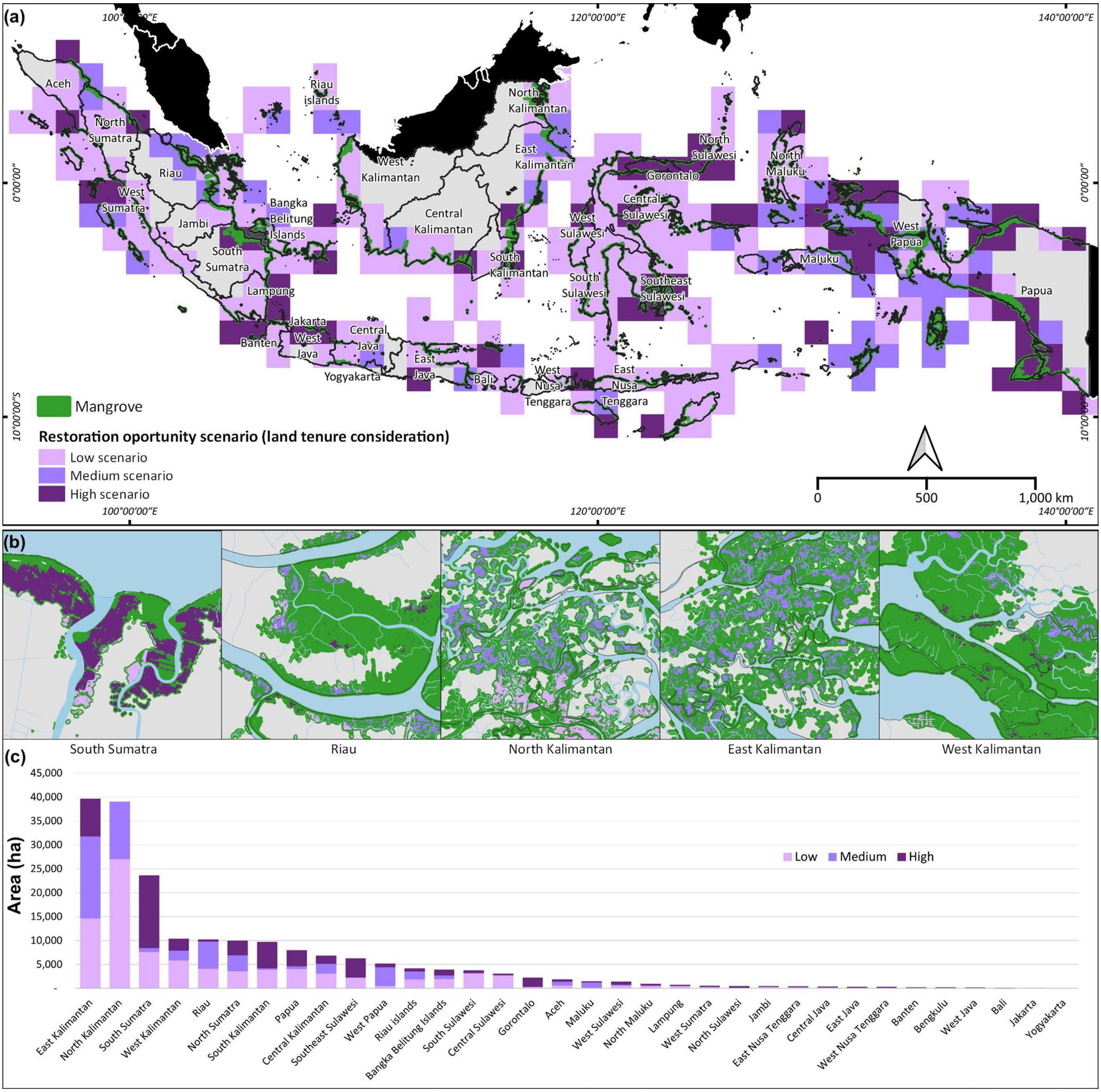

Extended Data Fig. 3 | Mangrove restoration opportunity scenarios according to their forest land status in Indonesia, namely other land use allocation, production and protected forests. a, national distribution of restoration opportunity scenarios at 1 degree grid, **b**, selected grids of restoration opportunity scenarios distribution in South Sumatra, Riau, North Kalimantan, East Kalimantan, and West Kalimantan province, **c**, the proportion and area of restoration opportunity scenarios across all provinces in Indonesia according to the national standard for land status by Ministry of Environment and Forestry[35]. A low opportunity scenario was given to areas belonging to other land use allocations (area penggunaan lain or APL), where this specific land status is commonly associated with private land ownership. Medium and high restoration opportunity scenarios were respectively assigned to areas under production forest (hutan produksi) and protected forest (hutan lindung) designations. Further description of the scenarios classification for each loss driver is provided in Supplementary Table 4.

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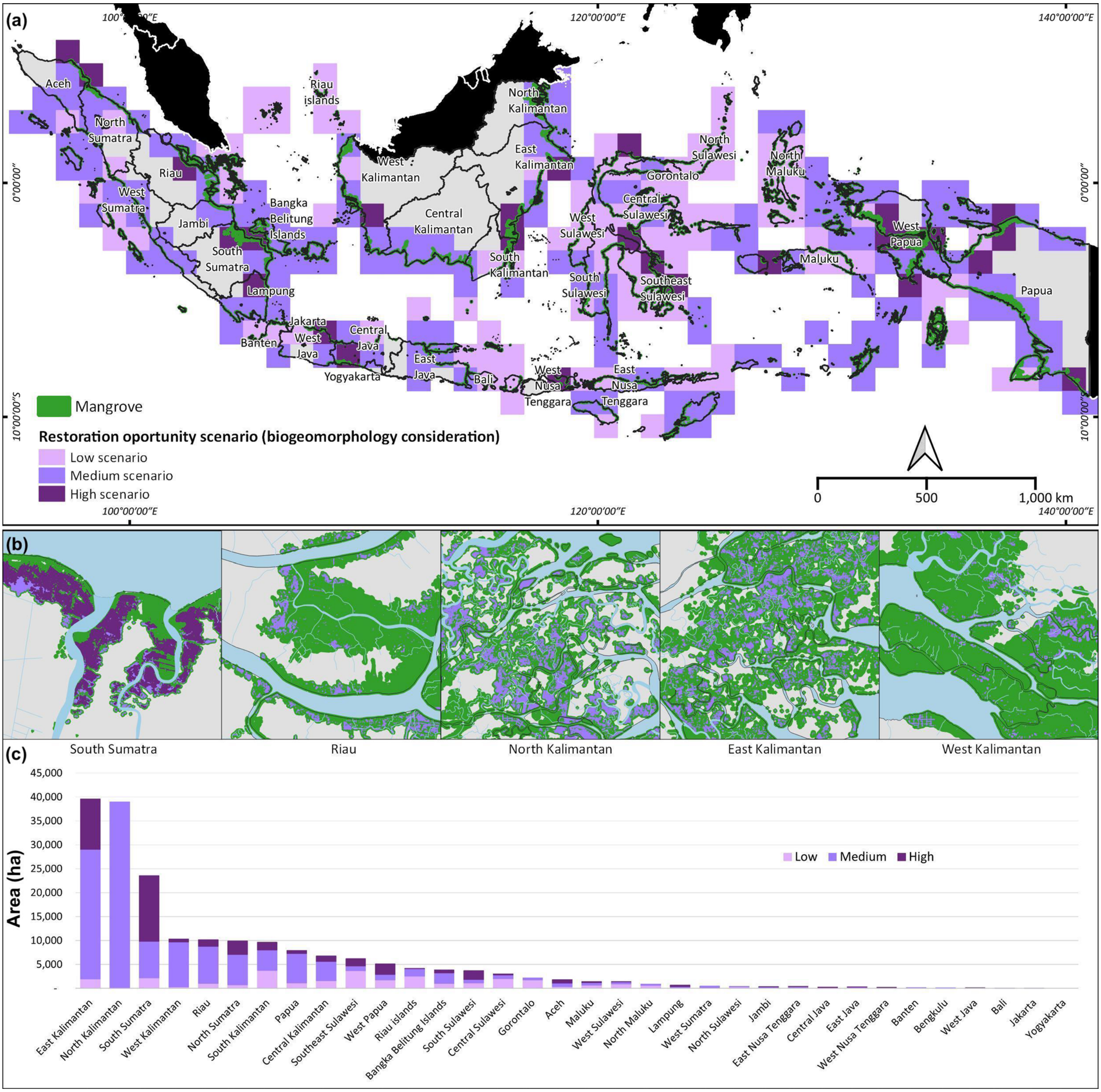

Extended Data Fig. 4 | Mangrove restoration opportunity scenarios according to multiple biogeomorphological settings. The mangrove typologies included in this study are delta-terrigenous, estuary-terrigenous, open coast-carbonate, open coast-terrigenous, and others (an area that does not belong to any settings described by Worthington et al.[34]). **a**, national distribution of restoration opportunity scenarios at 1 degree grid, **b**, selected grids of restoration opportunity scenarios distribution in South Sumatra, Riau, North Kalimantan, East Kalimantan, and West Kalimantan province, **c**, the proportion and area of restoration opportunity scenarios across all provinces in Indonesia according to biogeomorphological typology. The low scenario was assigned to areas located in both open coast-carbonate and open coast-terrigenous settings. A medium scenario was given to areas located in delta-terrigenous and other settings. Estuary-terrigenous was the only setting with a high restoration opportunity scenario. Further description of the scenarios classification for each loss driver is provided in Supplementary Table 4.

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Study description	This study mapped mangrove restoration potential and opportunity scenario, and reviewed mangrove management policies in Indonesia.
Research sample	We overlaid multiple spatial data including mangrove area baseline in 2000, tree cover loss, mangrove biogeomorphology setting, mangrove loss drivers, and land tenure to produce mangrove restoration potential and opportunity scenario. A systematic review on mangrove management policies in Indonesia was also applied.
Sampling strategy	Sampling for this study is described in the method section with particularly under Mapping and analysis of potential areas for mangrove rehabilitation, and Systematic review of mangrove restoration in Indonesia.
Data collection	Secondary spatial data used in this study were collected through public domain database. Data extraction for the systematic review was completed through reading the fulltext of included studies.
Timing and spatial scale	The spatial scale of this study is nation wide mangroves area in Indonesia
Data exclusions	Data exclusion for this study is explained in the Supplementary Table 13, with particularly this study excluded any studies that did not present any relevant data and information on mangrove revegetation, restoration and rehabilitation.
Reproducibility	This study used publicly available dataset and therefore future improvement studies are highly possible and encouraged.
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