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Opportunities and risk management of peat restoration in Indonesia: lessons learned from peat restoration actors

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Significant efforts have been invested to restore degraded peatlands in Indonesia considering the high mitigation potential as an effective natural climate solution. However, peat restoration in Indonesia faces challenges such as suboptimal planning and risk management. In this study, we assessed the national potential peat restoration area using spatial analysis and identified the associated risks based on lessons learned from past restoration efforts. We estimated the extent of potential restoration areas by analyzing canal networks, burnt areas, and critical land maps at the national scale. We conducted focus group discussions (FGD), in-depth interviews, followed by a national workshop with relevant stakeholders to assess the potential risks and develop risk management strategies for peat restoration. Our analysis estimated 6 Mha, or 45% of Indonesia's total peatland area, as potentially restorable areas for rewetting and/or revegetation efforts. Of this potential area, 50% falls under concession holder management. The identified risks consisted of technical (39%), management (38%), social (17%), and economic (6%) factors, with 15 and 22% classified as extreme and high risk, respectively. Policymakers can use these findings to strengthen regulations and improve the chances of successful restoration implementation, supporting Indonesia's emissions reduction target and providing economic benefits for restoration actors.

Key words: climate mitigation, peatland degradation, restoration potential, risk management, stakeholder analysis

Implications for Practice

- A comprehensive restoration plan, biophysical parameters, and governance aspects that vary across sites need to be taken into consideration for identifying suitable restoration areas.
- Our study highlighted that a landscape-based approach is key to successful peat restoration. Relevant policies should focus on strengthening the roles, collaboration, and capacities of the ground restoration actors, in addition, provisioning incentives for peat ecosystem services.
- Lessons learned from restoration actors can provide valuable information for identifying potential risks, but further research is necessary to fully understand risk interdependencies.

Introduction

Indonesia has 13.4 Mha of tropical peatlands, one of the largest amongst other tropical countries (Anda et al. 2021), with an approximate carbon storage of 28.1–57 GtC (Page et al. 2011; Warren et al. 2017). Despite its significant environmental value (Wösten et al. 2008; Thornton et al. 2018; Leng et al. 2019), more than half of Indonesian peatlands are degraded or drained (Miettinen et al. 2016) as a result of major anthropogenic drivers including forest logging, industrial plantation development, agricultural expansion, and recurrent fires (Miettinen et al. 2016; Dohong et al. 2017). This condition enhances peat decomposition rates (Hirano et al. 2014; Jauhiainen et al. 2016) and increases the vulnerability to wildfire (Torrent et al. 2016; Leng et al. 2019; Edwards et al. 2020), leading to substantial atmospheric greenhouse gas (GHG) emissions (MoEF 2021). In addition to negative climate consequences, peatland degradation also causes air pollution, negatively impacting human health (Betha et al. 2014; Uda et al. 2019), as well as exacerbating biodiversity loss (Syaufina & Hamzah 2021), and inducing further economic loss (Glauber et al. 2016; Kiely et al. 2021).

To achieve its national emission reduction commitment and fulfill critical co-benefits, Indonesia has put significant efforts

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and investments into restoring degraded peatlands. While the key principle of ecological restoration is to assist degraded ecosystem recovery (SER 2002), restoration goals also need to consider the provision of valuable benefits for people (Martin 2017), emphasizing the importance of restoration ecology as part of an integrated land management strategy (Fig. 1). As a response of the 2015 wildfires, where an estimated approximately 623,000 Mha of peat burnt, 692–748 $MtCO_2$ was emitted to the atmosphere (Huijnen et al. 2016; Heymann et al. 2017), costing at least $16.1–28.0 billion USD (Glauber et al. 2016; Kiely et al. 2021), Indonesia established a peat restoration agency (*Badan Restorasi Gambut* [BRG]) in 2016, aiming to restore 2.6 Mha of degraded peatlands in seven priority provinces: Riau, Jambi, South Sumatra, West Kalimantan, Central Kalimantan, South Kalimantan, and Papua. In 2021, the BRG mandate was extended to include mangroves, thus becoming the Peat and Mangrove Restoration Agency (*Badan Restorasi Gambut dan Mangrove* [BRGM]), with the peatland restoration target of 1.2 Mha (2021–2024) (BRGM 2021). BRGM aims to implement peat restoration through three core activities: rewetting, revegetation, and revitalization of livelihood-supporting activities. BRGM determines working areas as a function of land cover, canal network presence, ecosystem functioning, and burn impact from the 2015 wildfires. However, the actual potential area for peat restoration in Indonesia has not been fully elucidated.

To date, Indonesia's peat restoration program has been relying on funding from the state, international donors, and private sectors, including non-governmental organizations (Puspitaloka et al. 2021). Even though peat restoration is listed as one of the main climate mitigation strategies to achieve Indonesia's Nationally Determined Contribution and Forestry and Other Land Use Net Sink Target (MoEF 2022), with a recent study estimating that it could help reduce GHG emissions up to 269 $MtCO_2$/year (Novita et al. 2022), the government still prioritizes climate mitigation budget on the transportation and energy sectors (MoEF 2020). It is estimated that peat restoration in Indonesia needs a projected cost of $1.7–7.0 billion USD (Kiely et al. 2021; Sari et al. 2021) with an average cost of $1,866 USD per hectare for restoration (Hansson & Dargusch 2018). As a cost-efficient natural climate solution (NCS) strategy (Humpenöder et al. 2020; Kiely et al. 2021; Novita et al. 2022), several regulations have been enacted to support the implementation of peat restoration. However, existing regulations generally have low compatibility with the actual practices in the field (Uda et al. 2020).

Despite the development of strategic peat restoration action plans, achieving the target remains challenging. While several studies have identified national peat restoration challenges

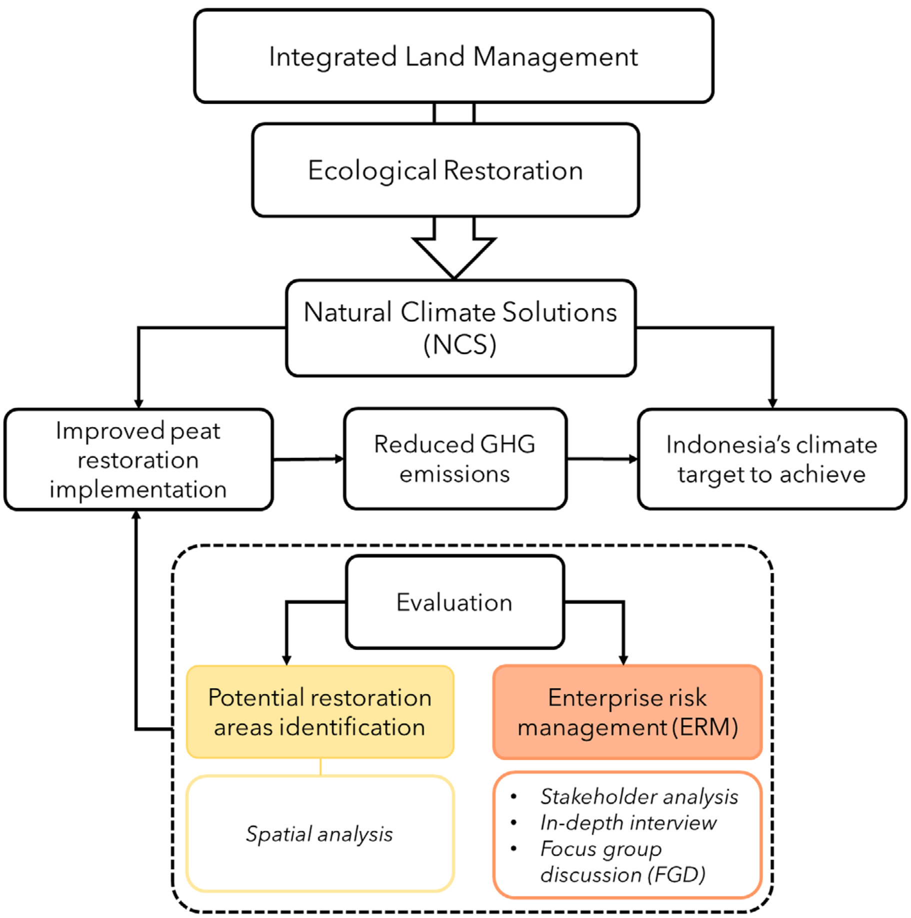


Figure 1. Conceptual framework of this study.

(Gunawan et al. 2021; Puspitaloka et al. 2021; Yuwati et al. 2021), incorporating these into actionable developments has yet to be implemented, a key strategy in avoiding failure and ensuring stakeholders' involvement in program implementation, reducing uncertainties, and improving resource allocation efficiency (Suedel et al. 2012; Abhilash 2021). Moreover, no prior study has identified potential areas for peat restoration at the country level, considered a critical first step in developing a restoration program. In this study, we conducted biophysical analyses to describe potential peat restoration areas at the national scale. We then assessed the potential risks of peat restoration implementation in Indonesia, based on peat restoration actors' experiences to develop risk management strategies for peat restoration. The results provide insights for policymakers to strengthen regulations to improve the probability of successful restoration, thus helping achieve Indonesia's ambitious climate commitment target.

Methods

This study's conceptual framework revolves around improving peat restoration implementation as a potential NCS for climate mitigation (Fig. 1). Here, we evaluated on the ground peat restoration implementation and provided lessons learned on areas of improvement to reduce GHG emissions, an essential element of climate mitigation efforts for achieving Indonesia's climate commitment.

Calculating the Potential Peat Restoration Area

We defined potential peat restoration areas as peatlands that have been either drained, burnt, or designated as critical land by the government. Here, four main datasets were used for the calculation:

(1) Peat extent map.

Peat extent was obtained from a recent national study published by Anda et al. (2021). This semi-detailed 1:50,000 scale map was developed from multisource satellite imagery, supported by peat depth observation points, and verified with rigorous ground-truthing.

(2) Canal network map.

Canal networks were obtained by merging canal network datasets across BRGM peat restoration areas in Indonesia (available online at https://prims.brg.go.id) and southeast Asia (Dadap et al. 2021). The BRGM data were developed through manual delineation of canal lines from a series of satellite imagery using Google Earth Pro, while Dadap et al. (2021) utilized automatic detection using 5 m resolution Planet imagery. For a conservative estimate in calculating drained peatland extent, a 300 m buffer was applied around the canals assuming these areas were affected by drainage (Evans et al. 2019).

(3) Burnt areas map.

MODIS's Burned-Area Monthly data product (Giglio et al. 2021) was used to determine burnt area extent in 2015 and 2019 in *Google Earth Engine*. This dataset has a spatial resolution of 500 m^2 with active fire observations (1 km^2), and burn date. Only pixels with uncertainty values of less than 5 were retained to avoid over-calculation of burnt areas.

(4) National critical land map.

Critical lands are defined as both forest and non-forest areas that have a reduced capacity for production and water regulation functions for the watershed (Minister of Forestry Regulation No. 32 of 2009). The national critical land map was obtained from the Ministry of the Environment and Forestry (MoEF 2018). This map is categorized into five categories from non-critical to very critical, based on productivity, land cover, slope, erosion risk, and land management scores. To be conservative in the analysis, we only used critical and very critical categories.

Priority areas for rewetting were determined by overlaying the peat extent and buffered canal network maps. Priority areas for revegetation were defined from the overlap between the peat extent and critical land maps. We also assumed vegetation loss from fire and considered burnt areas for revegetation.

Assessing the State of Peatland Degradation

We assessed the state of forested peatland degradation (conversion of forest to non-forest) in Indonesia from the last decade (2009–2019) due to anthropogenic activities including forest logging, conversion to industrial plantations including oil palm and forest plantation, agricultural expansion, and settlement construction. While field observations are recommended, we excluded this step since these are outside the scope of this study. Here, we used a 30 m resolution land cover map from Ministry of Environment and Forestry (MoEF) to categorize the state of peatland degradation into six classes: oil palm, plantation forest, shrubs, bare ground, agriculture, and others.

Assessing Peat Restoration Actors in Indonesia

Peat restoration actors, defined as stakeholders implementing restoration programs in the field, were identified and categorized following the four classes as defined by Government Regulation No. 57 of 2016 on Peatland Protection and Management and Minister of Environment and Forestry Regulation No. 16 of 2017 on technical guidelines for peat ecosystem restoration: concession holders, central government, local (provincial and district) governments, and communities. Concession holders were defined as private companies that hold permits on oil palm and forest plantations, as well as on logging and ecosystem restoration concessions. Maps from MoEF and Global Forest Watch were used to calculate the concession area extent. Then, we overlaid potential peat restoration areas and MoEF's forest status map, consisting of production forest, protection forest, conservation forest, and other-use areas. Production forest and other-use areas are categorized into concession and non-concession areas.

Risk Assessment

Risk assessment focused on what factors can cause peat restoration failure, including technical, social, economic, and policy aspects. Two focus group discussions (FGD), followed by an in-depth interview, were conducted in 2021 involving a total of 37 participants from various restoration actors. The FGD's brought together relevant stakeholders, including BRGM, provincial and district governments, concession holders, and local communities to discuss the implementation of peatland management and restoration. The inclusion of different organizational and community levels was to explore their insight and experiences in implementing peat restoration. The resource persons and their justifications for selection are presented in Table S1, while the interview questions are presented in Supplement S1.

The risk assessment, which combined Enterprise Risk Management and stakeholder analysis, was carried out in three stages (IRM, AIRMIC, & ALARM 2002; Wiryono & Suharto 2008): (1) risk identification, (2) risk assessment, and (3) risk mapping (Fig. 2). Following the two FGDs and the analysis of the results, a webinar was held to gather feedback as part of the validation process. We held interactive discussions to improve research findings and share preliminary findings on peatland restoration risks and strategies in Indonesia with three key peatland restoration experts from Tanjungpura University, the Indonesian Forest Concession Association, and International Centre for Research in Agroforestry. The webinar was also attended by 192 participants, consisting of policy makers, scientists, local community members, and NGO representatives.

Results

Potential Peat Restoration Area

Our analysis identified that drained areas account for the most substantial potential restoration areas (5.3 Mha), followed by burnt areas (0.8 Mha) and critical lands (0.5 Mha). Several of these areas overlap, resulting in a potential peat restoration area of 6 Mha (Table 1). These potential restoration areas are distributed across different regions, with the majority situated in Sumatra and Kalimantan. In particular, the Riau Province has

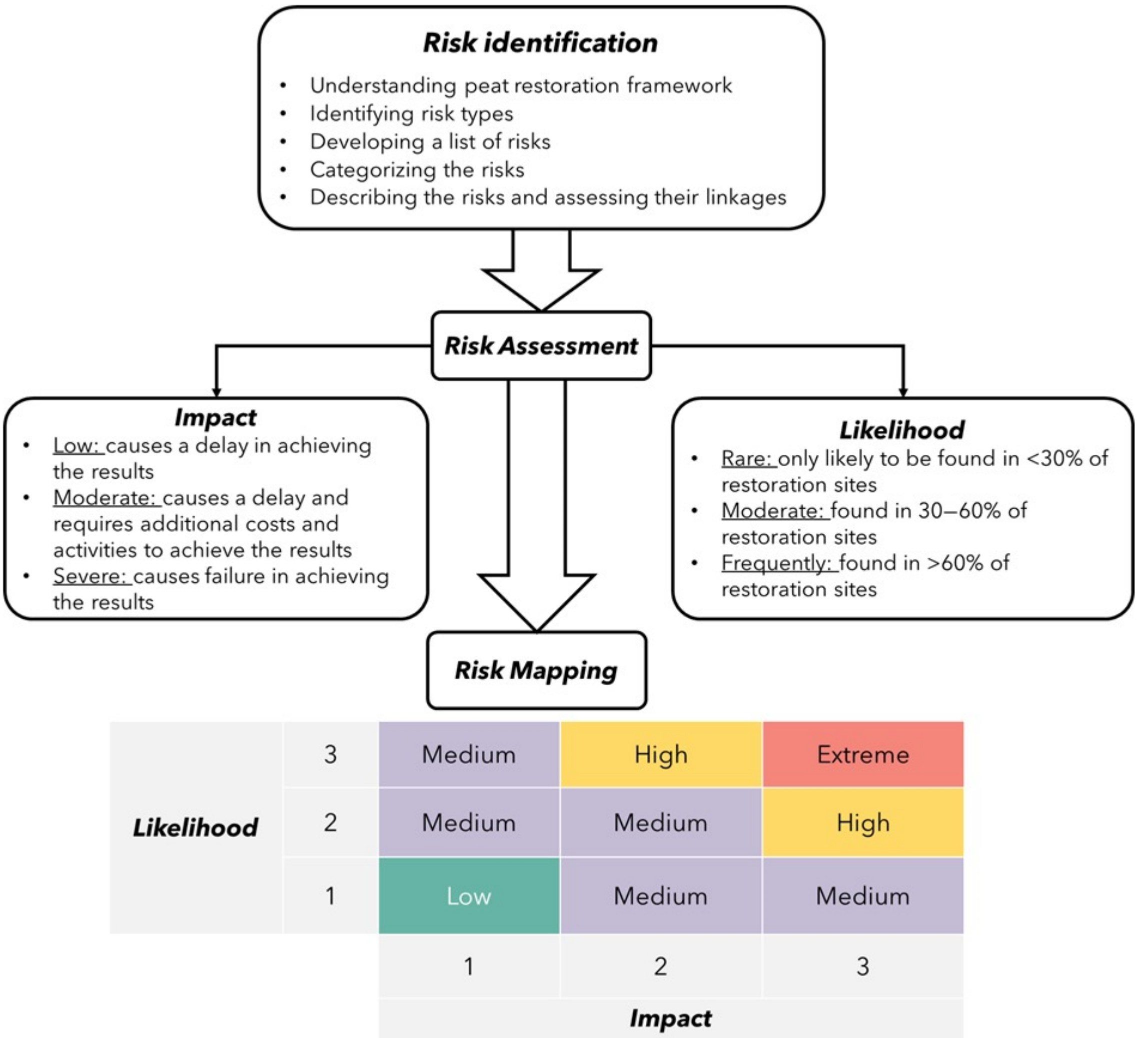
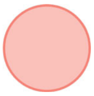
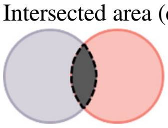
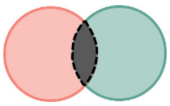
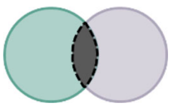
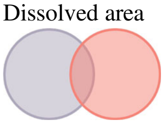
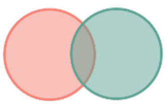
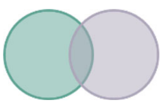
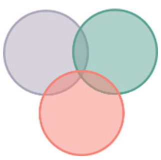


Figure 2. The stages of risk assessment.

Table 1. Category of area to define restoration potential.

Category	*Restoration potential parameters*	*Area (Mha)*
Individual area		
	Canal buffer	5.3
	Peat fire	0.8
	Critical land	0.5
Intersected area (dark-gray area with dashed line)		
	Canal buffer and peat fire	0.3
	Peat fire and critical land	0.1
	Critical land and canal buffer	0.2
Dissolved area		
	Canal buffer and peat fire	5.8
	Peat fire and critical land	1.2
	Critical land and canal buffer	5.6
	All restoration potential	6.0

the largest potential area of 2.4 Mha, or 39% of the total national potential for peat restoration, followed by Central Kalimantan (1 Mha; 16%), and South Sumatra (0.9 Mha; 14%) (Fig. 3A–E). Most of these potential areas can be categorized as priority rewetting areas (5.3 Mha), while the priority revegetation areas range from 0.5 to 1.1 Mha. We assumed that the revegetation areas also lie in degraded high conservation value (HCV) and retired production areas in peat domes within concession areas, as they are required for revegetation.

State of Peatland Degradation

In the last decade, peatland deforestation and degradation were substantial in Indonesia. The analysis of peatland forest cover from 2009 to 2019 revealed that oil palm (31%), shrubs (29%), and plantation forests (20%) were the land cover types most associated with peat degradation (Fig. 4A & 4C). Based on these results, forested peatlands were lost at an average rate of approximately 2.2% per year (142,492 ha/year). Amongst the five main islands, Sumatra experienced the highest deforestation/degradation rates (4.2%), followed by Kalimantan (1.7%). At the provincial basis, Riau had the highest deforestation rate (56,439 ha/year), followed by West Kalimantan (26,360 ha/year), Central Kalimantan (15,365 ha/year), Papua (8,492 ha/year), and South Sumatra (7,010 ha/year) (Fig. 4B).

Peat Restoration Actors

Based on our analysis, 3 Mha of potential restoration area is located within concession areas, 2.6 Mha within non-concession areas (designated for production forest and other-use areas), 0.2 Mha within protection forest, and 0.2 Mha within conservation forest (Fig. 5A). Concession holders are responsible for implementing the largest extent of restoration programs, accounting for 50% of the total potential restoration areas, including 1.5 Mha in oil palm concessions and 1.5 Mha in forest management concessions. Both local governments and communities, with support from BRGM, are responsible for restoring non-concession areas. While local governments are responsible for restoration within state-owned land, communities are responsible for restoration on privately owned land. Due to limited data, these areas could not be disaggregated. Local governments and communities contain 47% of the total restoration area, while the central government (under the jurisdiction of MoEF), is responsible for 3% of the potential restoration areas. The concession holders share the largest responsibility of 50% of the total potential restoration areas in the country (Fig. 5B.) At the provincial level, the largest potential restoration areas under the management of concession holders are in Riau (1.4 Mha), followed by South Sumatra (0.5 Mha) and West Kalimantan (0.5 Mha) (Fig. 5C).

Risk Assessment of Peat Restoration

Risk assessment in this study includes lessons learned from representation from the community, concession holders, and central and local governments. Each actor has different roles and challenges, as presented in Table 2.

Based on actors' experiences in implementing peat restoration, we identified 54 risks associated with peat restoration failure, both from internal (44%) and external (56%) peat restoration management units. Most risks are classified as related to technical (39%) and management (38%) aspects, while social and economic aspects contribute to 17 and 6%, respectively. Of the 54 identified risks, 15% were classified as extreme, 22% as high, 50% as medium, and the remaining 13% as low (Fig. 6). We also identified the detailed driver of risks and related stakeholders involved in determining the appropriate risk management through anticipated and further actions (Table S2).

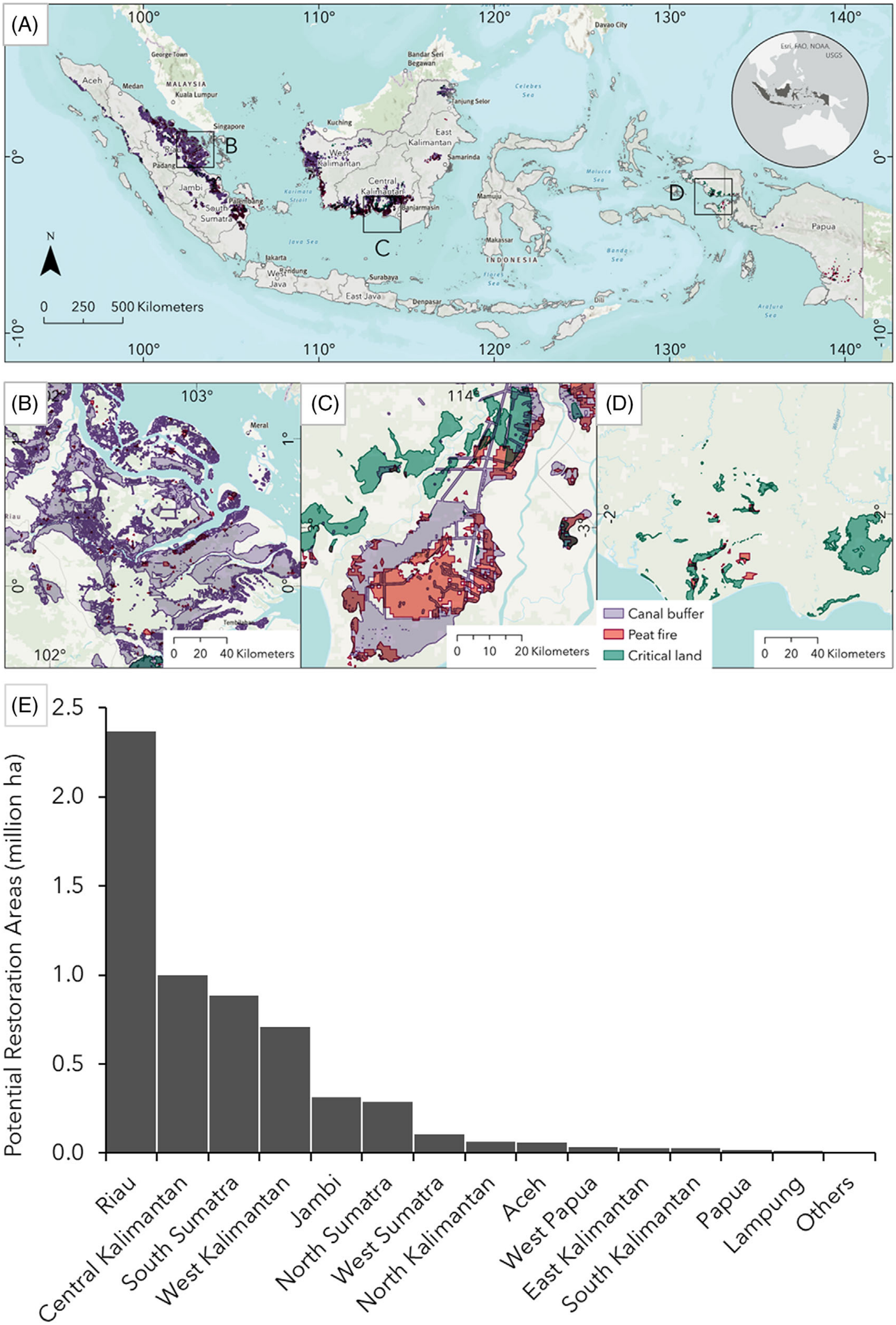


Figure 3. Potential peat restoration areas in Indonesia (A) with insets of Sumatra (B), Kalimantan (C), and Papua (D), along with the summary of potential peat restoration areas across provinces (E).

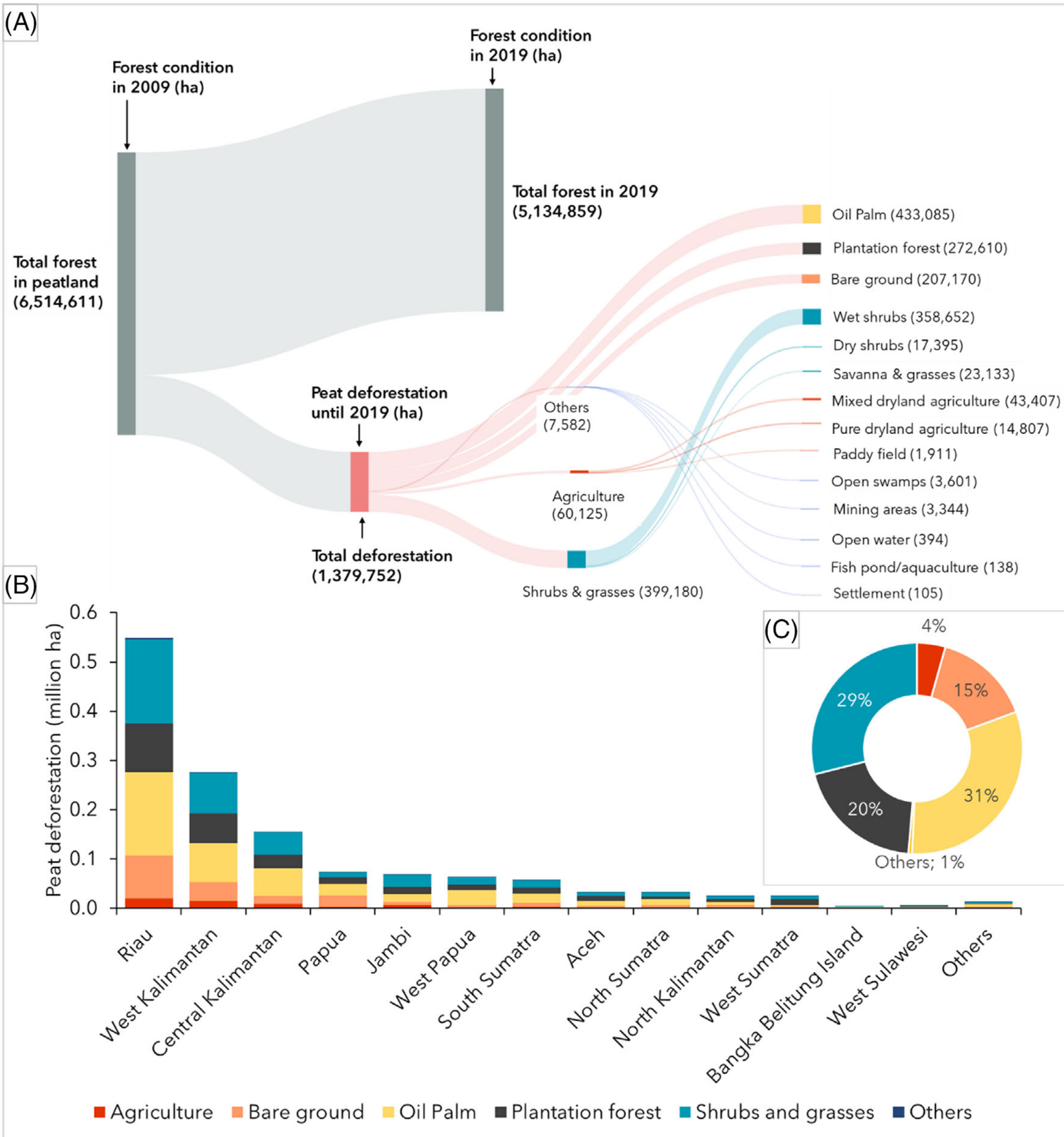


Figure 4. The state of peatland degradation in Indonesia from 2009 to 2019 (A, C) and peat degradation area by province (B).

Some options for restoration strategies including peat hydrological unit (*Kesatuan Hidrologi Gambut* [KHG])-based restoration, village-based restoration, and small-scale peat restoration approaches are outlined in Table S3.

Discussion

Comparison Between the Potential Restoration Area and Government Targets

The 6 Mha of the potential restorable area found in this study represents 45% of the total peatland area. This figure is smaller compared to the results presented in Miettinen et al. (2016), which found that 70.8–93.6% of the total peatland areas were degraded. Using a similar historical baseline, Novita et al. (2022) reported that 8.7 Mha of degraded peatlands in Indonesia have the potential to be restored through rewetting and improved water table management in agricultural sites. Nevertheless, both studies have several key differences in the datasets and methods used to determine the potential restoration areas.

In the seven BRGM priority provinces, we found that the total potential restoration area to be 5.4 Mha, one and a half times the government target of 2.6 Mha (2015–2020) and 1.2 Mha (2021–2024). Our findings show that the distribution potential restorable peat area is aligned with seven BRGM priority provinces, except for South Kalimantan and Papua. Even though 74% of peatland areas in South Kalimantan are considered for restoration, the province has a relatively small peatland extent

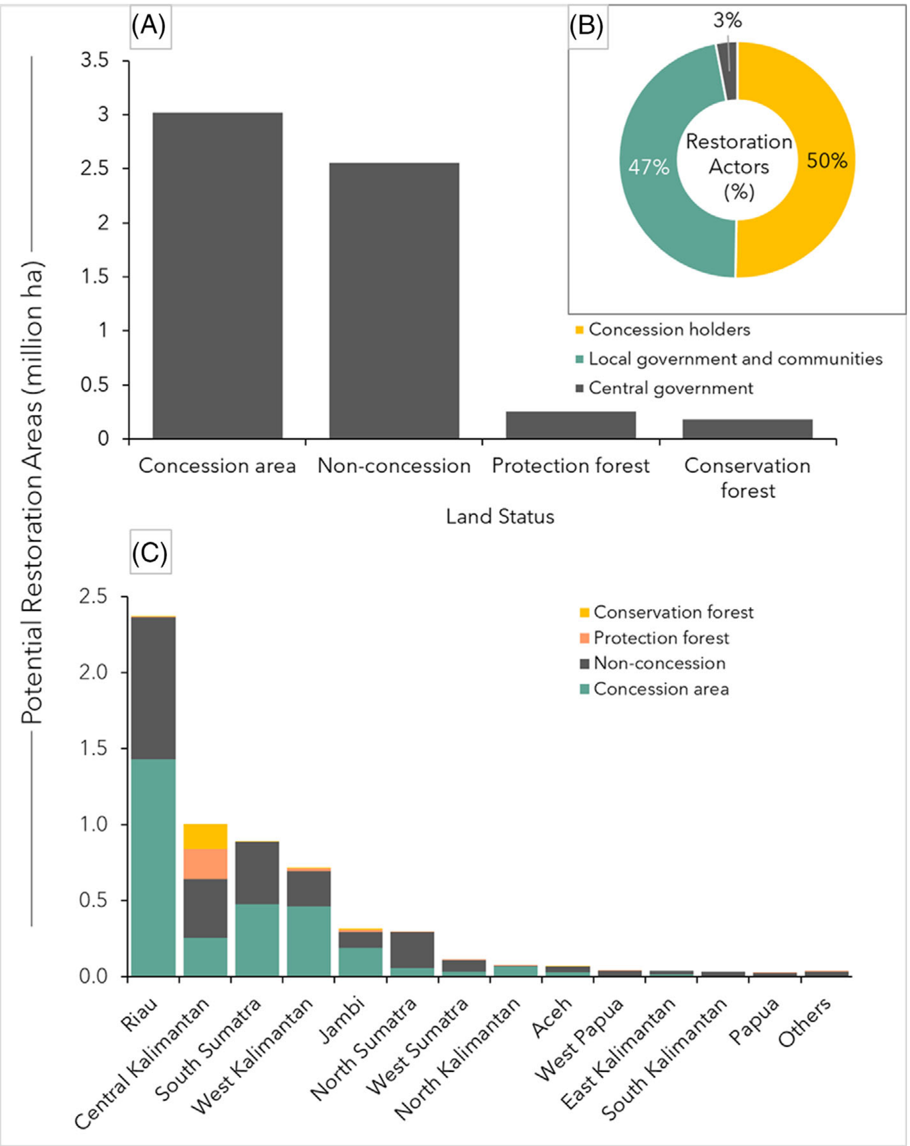


Figure 5. Distribution of potential peat restoration areas based on land status at the national level (A), restoration actors (B), land status at provincial level (C).

(<0.05 Mha). Meanwhile, Papua has very low degradation with 0.02 Mha (1% of the total Papuan peatland extent of 2.1 Mha). The provinces with relatively large restoration potential that are not considered priority provinces by the BRGM are North Sumatra and West Sumatra, with 0.3 and 0.1 Mha of potential restoration areas, respectively. There, we found that the majority of the peatland areas in North Sumatra were affected by drainage while peat fires can be considered the major cause of peatland degradation in West Sumatra.

Burnt areas are prioritized for restoration to prevent the recurrence of fires and further expansion of degraded areas. The land status of the burnt areas can impact the type of restoration intervention employed, as concession areas, which are mainly allocated for wood and oil palm production, prioritize rewetting, while non-concession areas can include revegetation in addition to rewetting as an intervention.

This study determined restorable areas based on the extent of canal networks, burnt area, and critical land status. While data were selected to best represent the potential restoration areas, this extent may be refined by improving the resolution and accuracy of the canal network map, redefining impacted drained area buffer size, considering the use of multiyear burnt areas map, and updating the critical land map. Given the extensive potential restoration area, implementing restoration programs in the field requires substantial resources. Additional analysis could prioritize these potential restoration areas based on urgency, with immediate action required to prevent further peatland degradation.

State of Peatland Degradation

Our land cover change analysis implies that socio-economic factors significantly affect land use on peatlands, as indicated by the

Table 2. Peat restoration actors, activities, and challenges in this study.

Restoration actors	*Activities*	*Challenges*
BRGM	(1) 20,821 units of peat rewetting infrastructure have been established, including 6,631 canal blocking, 324 canal backfilling, and 13,896 deep wells. Additional 895 units were established in 2021. (2) 1,947 ha of revegetation areas (up to 2021). (3) Delivering 1,063 assistance packages for revitalization of livelihood programs (up to 2021).	(1) Integrated restoration planning. (2) Conflicting interests in restoration areas. (3) Sustainability of community livelihood programs. (4) Coordination and collaboration with other restoration actors.
Local government	(1) Implemented by a regional peat restoration team, attached to the provincial environmental service. (2) Establishing canal blocking, deep wells, and replanting in degraded areas. (3) Delivering economic packages to improve community livelihoods.	(1) Limited information on restoration planning, restoration area status, village boundaries and peat hydrology map. (2) Improving community participation. (3) Lack of accessibility in several restoration locations. (4) Funding sustainability to ensure maintenance. (5) Mainstreaming peat restoration into a subnational development program (peat restoration is still considered an additional task).
Community	(1) Represented by the village forest management institution. (2) Constructing canal blocks for peat restoration using traditional materials such as coconut and galam woods.	(1) Insufficient funding for canal-blocking construction and maintenance. (2) Lack of technical assistance. (3) Conflict with concession holders working in upstream area in relation to their water management.
Concession holders (plantation and ecosystem restoration companies)	(1) Restores degraded peatlands in HCV areas and peat domes. (2) Water management in retirement production areas, which includes canal blocking construction. (3) Installing water table monitoring tools. (4) Using natural regeneration and replanting for revegetation strategies. (5) Protecting remaining peatland forests and restoring degraded peatlands (ecosystem restoration companies). (6) Support the improvement of community livelihoods through agroforestry and aquaculture development and micro credit provisions.	(1) Improving community participation. (2) Lack of regulatory support on environmental service business development (for ecosystem restoration companies). (3) Market uncertainty for ecosystem restoration products. (4) Difficulties in implementing landscape-based restoration approaches due to concession boundaries. (5) Lack of accessibility in peat dome areas.

high conversion of peatlands into plantation (plantation forest and oil palm) and agricultural land. This finding was further emphasized during the FGDs. In the last two decades, land cover changes indicate that conversion to industrial plantations is the principal direct driver of peatland degradation, followed by logging, drainage, and recurrent fires (Silvius & Diemont 2007; Dohong et al. 2017); while a combination of climate change, population density, and land use policy and governance are included as indirect drivers (Dohong et al. 2017; Lilleskov et al. 2019). Drainage canals are constructed to lower the water table for crop suitability (Dohong & Tanika 2021) and ease transporting both people and materials to harvesting sites (Jaenicke et al. 2010), increasing desiccation and fire risk. Local communities have traditionally practiced fishing and log hunting, using the canals for transport (Chokkalingam et al. 2005; Goldstein et al. 2020), however in modern times more intensive land use practices have been adopted. Burning, for example is used by local communities to clear the land, improve fertility and land productivity in preparation for agriculture (Purnomo et al. 2017; Hergoualc'h et al. 2018; Yuniati 2018). Additionally, abandoned lands are subject to land tenure-related conflicts (Uda et al. 2017).

Our research reinforces the findings of Koh et al. (2011) showing that the highest conversion of peatlands into oil palm plantations occurred in Riau, Central Kalimantan, and South Sumatra. The extensive global market for palm oil increases the conversion of peatlands (Koh et al. 2011) and incentivizes the private sector to expand plantations, particularly in Sumatra and Kalimantan, with these operations later adopted by smallholder farmers (Euler et al. 2016). On the other hand, paludiculture, an approach to shift dry land agricultural practices into peatland-adaptive practices to enrich and help the transition to fully restored peatland (Yuwati et al. 2021), is not yet thoroughly implemented by local communities (Budiman et al. 2020). This might be a consequence of the absence of technical guidelines for sustainable agricultural practices in peatlands (Syahza et al. 2020), inappropriate

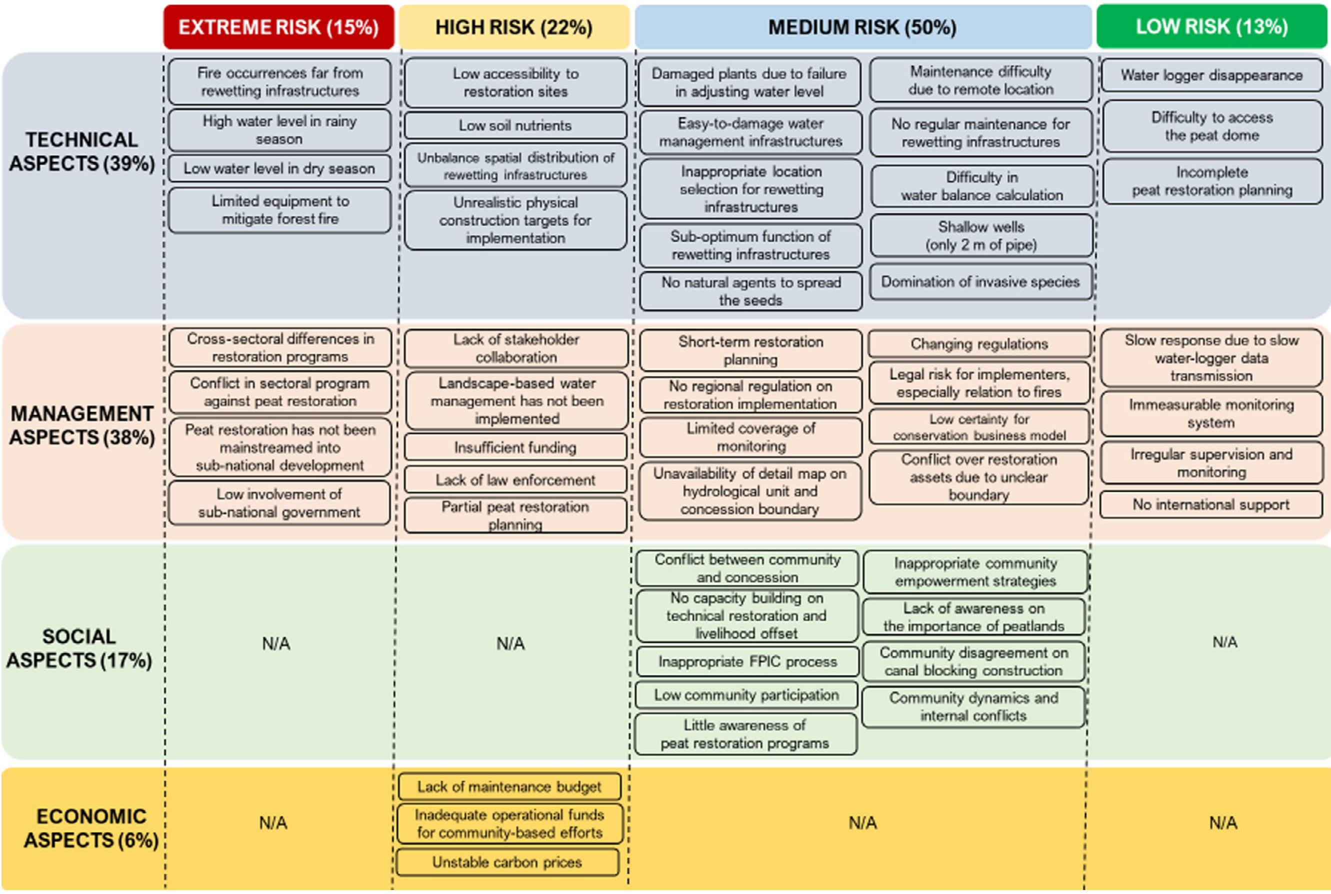


Figure 6. Risk assessment results based on risk categories.

species selection, causing a reduction in peatlands' direct economic benefits (Budiman et al. 2020; van der Meer et al. 2021), limited markets for restored peatland commodities (Salminah et al. 2021), and lack of co-benefits, such as rural infrastructure investment to increase living standards, when compared to oil palm plantations (Krishna & Kubitza 2021; Chrisendo et al. 2022). While many local communities favor revegetation of degraded peatlands using commercial crops (Puspitaloka et al. 2020), efforts are needed to promote protection, sustainable management, and essential functions of these ecosystems that align with the culture and interests of local communities.

The Importance of Identifying Peat Restoration Actors

Identifying restoration actors is crucial to ensure successful peatland restoration and enables us to acknowledge conflicting interests and uneven institutional capacities (Puspitaloka et al. 2021). For example, concession owners are required by law to maintain ground water level at no lower than 0.4 m. However, this regulation is difficult to enforce (Januar et al. 2021), as practices for plantation production tend to require the water table be kept below the regulation standard (Uda et al. 2020). To comply with the regulation, they must install rewetting infrastructure, which may result in water shortages in nearby villages during dry seasons and flooding during rainy seasons due to the close proximity of neighboring villages (Astuti 2020, 2021). Local governments and communities who play significant roles in restoring peatlands in non-concession areas are more likely to have limited resources and technical expertise, and the current provincial budget is unable to fully support restoration efforts. Improving this capacity for monitoring restoration activities appears necessary to assess the impacts of peat restoration at the landscape level (Harrison et al. 2020).

Restoration Strategies to Minimize the Risks

This study found that the extreme and high risks of peat restoration failure are dominated by technical and management aspects. In contrast, economic and social aspects are classified as high and medium risks only, respectively. This implies that peat restoration actors need to seriously underline the main technical risks (amongst others, fire and water levels in dry and rainy seasons), as well as the management risks, for instance, cross-sectoral differences in restoration programs and the absence of peat restoration in subnational development planning.

Extreme and high risks are prioritized as there are limited resources on the ground. For extreme risks, technical and management issues were the primary reasons for unsuccessful implementation, including conflicted sectoral/institutional programs and lack of subnational government involvement. For high risks, economics was an additional aspect contributing to unsuccessful implementation, such as unrealistic construction targets and insufficient funding. Socio-economic aspects are considered to be the foundation for peat restoration implementation (Pratama et al. 2022). These challenges echo previous studies highlighting that the governance issue in implementation is the lack of substantial coordination across stakeholders and disintegrating restoration planning (Budiman et al. 2021).

As the source of the risks is highly related to each individual actor, an integrated approach involving various actors, such as government agencies and restoration management units, is necessary to manage risks in peat restoration. Risk management should focus on restoring and maintaining critical hydrological, nutrient cycling, and energy flow processes (Maginnis & Jackson 2007; Dinesen & Hahn 2019). This can be achieved through constructing rewetting infrastructure based on hydrological studies and coordinating restoration planning with stakeholders at provincial and district levels.

Lessons learned from various actors show that peat restoration is highly complex. Based on our findings, options for restoration strategies include KHG-based restoration, village-based restoration, and small-scale peat restoration approaches. The hydrological function of peat will work optimally if the condition of the peat ecosystem in the KHG is well managed. The KHG approach needs to be placed as an integrated landscape (Jessup et al. 2020) and a basis for other local restoration actions (village-based and small-scale approaches). The village-based approach enhances livelihoods and community participation in peat restoration (Gunawan 2018; Puspitaloka et al. 2020), while the small-scale approach increases the likelihood of revegetation success (Blackham et al. 2014; Stanturf et al. 2019; Wijedasa et al. 2020). While a KHG-based approach is considered the most effective restoration strategy as it can diminish management-related risks through integrative planning and intensive coordination amongst peat restoration actors, implementation of the approach needs to be technically applied in smaller landscapes such as village or site level.

Indicators of Restoration Success

Specific and quantifiable indicators are required to measure intended restoration target achievements. Targets should consider the current status of degraded lands and baselines, which represent the initial conditions of restoration sites (Gann et al. 2019). Each target needs to have specific key attributes as the basis for determining restoration indicators to monitor restoration progress (CMP 2020). To have a shared understanding amongst stakeholders, ideal indicators should be defined clearly, consistent, and adaptive to changes that might occur in the implementation phase (The International Union for Conservation of Nature 2016; CMP 2020).

Unlike other ecosystems, the hydrological aspect plays an important role in peat restoration. Indicators used to monitor hydrology restoration progress include the water table, soil moisture, fire vulnerability, and subsidence rate (Bhomia & Murdiyarso 2021). While BRGM has developed a real-time monitoring system (sipalaga, https://sipalaga.brg.go.id/) for these indicators, the stations are still limited (Yananto et al. 2022). As the BRGM considers the amount of peat rewetting infrastructure a key indicator to evaluate restoration progress, it is therefore important to increase coverage of monitoring areas. Prior studies show that high-resolution satellite imagery is reliable for continuously assessing the change of water table depth and soil moisture to have a better understanding of hydrological dynamics in restored areas (Monteverde et al. 2022; Räsänen et al. 2022; Toca et al. 2022).

In addition to indicators of hydrology, additional measures of success include the number of wells, which is not directly related to hydrological restoration. Furthermore, a longer-term indicator of restoration success, such as GHG emission reduction from rewetting, is necessary. Progress for revegetation is reported by monitoring the total planting area in degraded peatlands and the survival rate of the vegetation. Long-term indicators of success should include species diversity, tree cover, and the ability to sequester carbon (FAO & WRI 2019).

Policy Support

The peat hydrological unit (KHG) approach is proposed to integrate peat restoration within varied landscapes encouraging all peat-related stakeholders to synergize restoration planning and implementation, with consideration of all interests. This approach also highlights the importance of integrated hydrological planning and peat restoration monitoring (Dohong & Tanika 2021). However, the lack of technical regulation to guide the implementation of KHG-based restoration approach on the ground has often caused conflicting peat restoration activities amongst the actors.

Coordination and synergy in peat restoration measures within a KHG should be improved by enhancing participation and collaboration amongst actors, particularly in developing peat hydrological management appropriate for a landscape with various land use zones (Applegate et al. 2021; Dohong & Tanika 2021; Gunawan et al. 2021). The role of BRGM might need to be strengthened to facilitate and control the synergy amongst peat restoration actors. Incorporating peat restoration into the work plans of relevant agencies in provincial and district governments, such as forestry, environmental, public works, and local development planning agencies, and integrating it into local spatial planning will help overcome bureaucratic obstacles and improve peatland governance in the country.

Sustainable peatland management and restoration requires enabling conditions including proper institutional arrangements, good governance, and provision of incentives (Nath et al. 2017; Rengasamy & Parish 2021). Given the interests of actors within a KHG and the direct economic values of peatlands, restoration should attempt to seek economic alternatives other than dry land-agricultural or forestry practices. Peatland-tolerant agroforestry business developed in the buffer zones of protected peatlands is proposed as both a sustainable livelihood option and an instrument of a fire prevention approach (Applegate et al. 2021). However, these efforts must be supported by institutional arrangements for smallholder farmers to facilitate coordination with other stakeholders as well as market access.

Requiring a net zero emission pathway in the global supply chain markets also opens opportunities for peat restoration actors to gain monetary carbon benefits. The government should include this opportunity in the carbon pricing regulations they are currently creating. Intergovernmental financing can be also proposed to encourage peat restoration measures carried out by provincial and district governments, further encouraging local governments that have successfully implemented sustainable peatland management. The extent of peat restoration or protected peatlands could be a variable in the consideration of the allocation of state budget that would be distributed to local governments in the framework of intergovernmental financing. To support mechanisms for financing peat restoration, it is necessary to measure total economic values generated from peat restoration including water regulation, biodiversity, and carbon. While significant economic benefits from peat restoration are widely recognized (Glenk & Martin-Ortega 2018), the economic return on peat restoration can be challenging due to the long timeframes involved, and the difficulty of quantifying several ecosystem services and indirect peat restoration costs (Martin-Ortega et al. 2014; Puspitaloka et al. 2021).

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Justification of the selected resource persons for focus group discussion (FGD) and in-depth interview.
Table S2. Detailed proposed risk management on peat restoration.
Table S3. Restoration strategies to minimize risks.
Supplement S1. Interview questions.

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