Peatland restoration as an affordable nature-based climate solution with fire reduction and conservation co-benefits in Indonesia

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Abstract

Ecosystem restoration is increasingly employed as a nature-based solution to a range of crises. Decisions over restoration must balance limited resources, land constraints, and competing demands. Peatlands in Southeast Asia have been heavily impacted by agricultural expansion over the past three decades, with Indonesia now accounting for a substantial proportion of degraded tropical peatlands globally. Using spatial linear programming, we focus on prioritizing peatland restoration sites in Indonesia for fire risk reduction, climate change mitigation, species conservation, and cost-effectiveness. The study finds that restoring peatlands at 1 km² planning units can generate multiple co-benefits such as reduced fire risks by 6%–37%, attenuated extinction risks of peatland specialist bird species and mitigated climate change potential of 0.002–0.36 Pg CO₂e yr⁻¹. These benefits were reduced but still of comparable magnitude when larger areas of planning (defined by village and catchment boundaries) were used. The results, although indicative, support tropical peatland restoration as a cost-efficient strategy for mitigating climate change, reducing fire, conserving biodiversity, and supporting sustainable development that can be offset by carbon prices of USD 2–37/Mg CO₂e.

1. Introduction

Recent decades have witnessed a rise in ecosystem restoration initiatives aimed at mitigating ecological degradation. Global estimates of degraded lands range from 1 to 6 billion hectare (Gibbs and Salmon 2015), with degradation concentrated in the biodiversity-rich tropics (Watts et al 2019). Initiatives such as the Post-2020 Global Biodiversity Framework demonstrate the urgent need to avoid irreversible damage to ecosystems and subsequent deterioration of social wellbeing, while pushing for more ambitious environmental goals and expanding markets for carbon and other ecosystem services (Koh et al 2021).

Over 140 Mha of tropical lands have been committed for restoration, with a median of 2 Mha per commitment, mostly in developing countries (Brancalion et al 2019, Fagan et al 2020) characterized by rapid land cover change, pressuring socio-economic and environmental challenges, and limited financial resources (Laurance et al 2014). Prioritizing restoration to deliver valuable ecosystem services can help build support for and alleviate constraints on restoration in economically marginalized countries while simultaneously contributing to (inter)national initiatives. Additionally, the various competing demands on land, e.g. for biomass production, biodiversity conservation, and climate change mitigation, present potential trade-offs. Evaluating and comparing the costs and benefits of each potential land use provides a means of selecting the most appropriate sites for restoration.
Indonesia accounts for around 36% of tropical and 80% of Southeast Asian peatlands (Evers et al 2016, Warren et al 2017b). Peatlands in Indonesia are mainly found in several provinces distributed across the islands of Sumatra, Borneo (Kalimantan), and Papua (figure 1). Commencing in the 1990s, extensive areas of peatland were drained and the forests they supported were harvested to facilitate industrial plantations and smallholder-based agriculture expansion (Miettinen et al 2016b). By 2015, more than 70% of peatlands in Sumatra and Kalimantan had been damaged (Miettinen et al 2016b) and the ecosystem services and benefits they provide in their intact state severely compromised. In addition, degraded peatlands are prone to burning and constitute the primary source of transboundary haze (fire-related air pollution) that periodically blights the region, which has become a major source of geopolitical tension (Marlier et al 2019). Haze presents a major health concern, and contribute to excess morbidity and premature mortality in the region (Koplitz et al 2016).

In the wake of a major haze episode in 2015, the Government of Indonesia established an ad hoc agency—the Peatland Restoration Agency (Badan Restorasi Gambut, BRG)—to oversee and facilitate the restoration of at least 2.5 Mha of peatlands by 2020 (BRG 2016), with an additional 1.2 Mha peatlands and 600 000 ha mangroves by 2024 under the new agency title Peatland and Mangrove Restoration Agency (BRGM). As BRGM represents a relatively new endeavor, this study focuses on BRG’s restoration framework, comprising the rewetting of peatlands to restore water table levels, revegetation of native peat swamp forest species, and the revitalization of peatland community livelihoods (Dohong et al 2018). A fourth activity, fire mitigation, was implicit in the three other restoration activities.

Spatial optimization has been used in Indonesia to determine the area for restoration needed to offset the impacts of harmful land uses (Budiharta et al 2016, 2018) and to target specific peatland restoration interventions, such as the blocking of drainage canals and the prevention of fire (Santika et al 2020, Urzainki et al 2020). Kalimantan has featured prominently in these studies (Budiharta et al 2018, Santika et al 2020), which have tended to focus on a singular objective (Marlier et al 2019, Santika et al 2020), paying limited attention to the economic costs of restoration. At the national level, identification of priority sites for restoration was based on past histories of fires, topography, canal infrastructures, and the functional zoning of peatlands (BRG 2016). While this method accounts for restoration feasibility, the fact that potential benefits are not explicitly considered led to a lack of clearly defined goals and metrics to evaluate restoration outcomes (Puspitaloka et al 2020).

This study builds upon an optimization of tropical forest restoration for carbon sequestration and biodiversity conservation (Budiharta et al 2014, 2018) by expanding the geographical scope of interest to the rest of Indonesia and including an additional fire risk reduction objective. Additionally, multiple objectives for restoration are considered rather than single objectives such as fire mitigation (Marlier et al 2019, Santika et al 2020) and canal block allocation (Urzainki et al 2020) in isolation, while potential trade-offs and synergies in restoration outcomes are identified. The study determines the benefits and financial costs associated with restoring degraded tropical peatlands in Indonesia, and where restoration sites may be allocated to maximize multiple co-benefits while accounting for trade-offs and cost-effectiveness. The multiple objectives considered comprise: (a) species conservation,
(b) climate change mitigation, (c) fire risk reduction, 
(d) cost minimization, and (e) cost-effective conserva-
tion, climate change mitigation, and fire risk reduc-
tion. Collectively the multiple objectives are hereafter 
referred to as the ‘multicriteria objective’.

2. Methods

Mathematical linear programming (Gurobi 
Optimizer 2021) was used to select for peatlands 
that yielded the highest ecosystem services bene-
fits in Sumatra and Kalimantan for the period of 
2015–2030. The period reflected the time from when 
the Government of Indonesia initiated national-
level peatland restoration, to the designated end 
points of the UN Decade on Ecosystem Restora-
tion and Indonesia’s Nationally Determined Con-
tribution (NDC) towards climate change mitigation 
(Government of Indonesia 2016, United Nations 
General Assembly 2019). Sumatra and Kalimantan 
were selected for study as the regions accounted for 
62%–75% of peatlands in Indonesia (Warren et al 
2017b), more than 50% of which have been degraded 
or converted to industrial plantations and small-
holder areas (Miettinen et al 2016a). Analyses were 
conducted across all priority provinces targeted by 
BRG for restoration (BRG 2017) (table S1 (available online at 
stacks.iop.org/ERL/17/064028/mmedia)), with the exception of Papua due to large uncer-
tainty in estimation for carbon fluxes and storage 
(Warren et al 2017b) and missing data for canals and 
species distribution.

A 1 km$^2$ grid was overlaid on cartographic data 
of peatland extent (Wahyunto et al 2003, 2004), 
producing 2080 921 km$^2$ cells, or planning units. The 
resolution represents a tradeoff between processing 
load and the scale at which land use decisions are 
made. Where necessary, all data were resampled to 
1 km$^2$ using nearest neighbor and bilinear interpola-
tion for categorical and continuous data, respectively. 
The following were determined for each planning 
unit: (a) restoration suitability; (b) potential climate 
change mitigation benefits for 15 years; (c) fire risk 
reduction potential; (d) overall species extinction 
risks; and (e) economic costs for restoration (table 1). 
Areas suitable for restoration were determined using 
a 2015 land cover map (Miettinen et al 2016a), where 
settled and permanently wet and seasonally flooded 
areas were deemed unsuitable for restoration and 
removed. Pristine peat swamp and mangrove forests 
were also removed as areas not requiring restora-
tion. The optimization algorithm was then run across 
increments of 10% of suitable peatlands for four dif-
ferent objectives (fire risk reduction, climate change 
mitigation, species conservation and cost minimiza-
tion), to explore the extent to which varying the area 
restored impacted the costs and benefits of restora-
tion. Additionally, the models were also run with 
BRG’s goal of restoring 25 000 km$^2$ of peatlands, as 
the constraint. This allowed the results to be situated 
and discussed in the context of a real-world policy. 
For the carbon offset price, potential climate change 
mitigation was divided by the total cost of restoration. 

The analyses were repeated with a second con-
straint limiting restoration to areas that would not 
affect current crop production level, assuming that 
the crop yield gap between current estimated pro-
ductivity and the maximum that is feasible (75% 
of projected possible productivity) could be closed 
with improved technologies and management prac-
tices (Mueller et al 2012). Actual and potential yield 
gap data for seven rainfed tropical crop groups 
(Carrasco et al 2017) were obtained from IIASA/ 
FAO (2012). Trade-offs and synergies of the objectives 
were explored further by combining species conserva-
tion, climate change mitigation potential, fire risk 
reduction potential, and restoration costs. Weight-
ings were applied to the pairwise combinations of cli-
mate change mitigation potential, conservation, and 
fire risk reduction objectives at intervals of 20% to 
explore a range of scenarios for trade-offs and syn-
ergies (Strassburg et al 2020).

Finally, the optimization and trade-off analyses 
were repeated using groupings of 1 km$^2$ grid cells 
into the coarser analytical scales defined by village 
and catchment boundaries (figure S1). This resulted 
in a total of 2334 villages and 389 catchments. Further 
details regarding model setup and the uncertainty 
analysis are provided in Supplementary Information.

3. Results

3.1. Impacts of restoration

Peatlands in Riau were commonly prioritized for 
fire risk reduction and species conservation, those in 
South Sumatra for climate change mitigation, and 
those in Central Kalimantan, West Kalimantan, and 
Riau for low costs (figure 2). The majority of selec-
ted sites were located on anthropogenic land covers, 
such as large plantations for pulpwood and palm oil 
production, and smallholder farms (figure 3), which 
are also highly degraded. Forests were unlikely to be 
prioritized except for the cost minimization objective.

Peatland restoration contributed substantially to 
ecological and social wellbeing through reducing fire 
risk by 6%–37% (figure 4(a)). Maximum annual cli-
mate benefit was 0.36 Pg CO$_2$ yr$^{-1}$, or a total of 
5.44 Pg CO$_2$e over 15 years, for the climate object-
ive (figure 4(b)). This annual climate benefit amoun-
ted to approximately 26% of total emissions from the 
agriculture, forestry and other land use sec-
tors in Indonesia in 2015 (Climate Watch 2021) 
(1.40 Pg CO$_2$e). Baseline extinction risk prior to restora-
tion was approximately 14% summed across all 
species. For the conservation objective, extinction risk 
dropped to 0% after more than 20% of peatlands, 
or all the lost habitats between 2000 and 2015, were 
restored (figure 4(c)). At the minimum, restoration
Table 1. Calculations for fire risk reduction, climate change mitigation, species conservation, and cost minimization objectives.

| Objective                  | Calculation                                                                 | Details                                                                                                                                 |
|---------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Fire risk reduction       | Fire risk reduction = Fire_{post} − Fire_{pre}                                | Fire risk reduction potential was predicted using a generalized linear mixed-effects model combining biophysical and social explanatory variables (table S2; Tan et al 2020). The year 2015 was used as a baseline, corresponding to the year of severe forest and land fires in Indonesia that sparked several peatland-related policies. |
|                           | where Fire_{post} = fire risk post restoration (%)                           |                                                                                                                                       |
|                           | Fire_{pre} = fire risk in 2015, pre-restoration (%)                          |                                                                                                                                       |
| Climate change mitigation | ∆C = C_{oxid} + C_{seq} + C_{burn} − C_{stock} − C_{CH4}                      | A gain-loss approach was used to estimate climate change mitigation benefits derived from restoration (Budiharta et al 2018, Zeng et al 2020). Values for the variables in the equation were taken from literature (table S3) and where possible, assigned according to land use classes. |
|                           | where ∆C = Net carbon gain/loss                                              |                                                                                                                                       |
|                           | C_{oxid} = Avoided emissions from peat oxidation                             |                                                                                                                                       |
|                           | C_{seq} = Carbon sequestration post-restoration                              |                                                                                                                                       |
|                           | C_{burn} = Avoided emissions from biomass fires                              |                                                                                                                                       |
|                           | C_{stock} = Initial carbon stock under land cover i                          |                                                                                                                                       |
|                           | C_{CH4} = Methane emission post restoration expressed as CO2_e                |                                                                                                                                       |
| Species conservation      | \sum_i^N B_i = S_{2000} − S_{2015}                                           | Maps of the distribution of ten peat swamp forest-dependent bird species (table S4) for the years 2000 and 2015 (Symes et al 2018) were used to estimate the potential area of habitat to restore. Extinction risk was calculated using the equation by Strassburg et al (2020) and Neeson et al (2015). |
|                           | where B_i = Conservation benefit for planning unit i                         |                                                                                                                                       |
|                           | S_{2000} = Suitable habitat for n species in planning unit i for the year 2000 |                                                                                                                                       |
|                           | S_{2015} = Suitable habitat for n species in planning unit i for the year 2015 |                                                                                                                                       |
|                           | \sum_i^N r = 1 − (\frac{A_{current}}{A_{crit}})^z                           |                                                                                                                                       |
|                           | where r = Extinction risk                                                    |                                                                                                                                       |
|                           | A_{current} = Restored habitat area and existing habitat area in 2015       |                                                                                                                                       |
|                           | A_{crit} = Original habitat area; i.e. species distribution in 2000          |                                                                                                                                       |
|                           | z = Rate of diminishing return for reducing extinction risk despite additional habitat, set at 0.25 as per literature (Strassburg et al 2020) |                                                                                                                                       |
| Cost minimization         | \sum_i^N cost = D_{rewet} + D_{revge} + D_{AR} + D_{fire}                    | The cost of restoration was set as the sum of four activities: rewetting, revegetation, revitalization (expressed as opportunity cost), and fire reduction (Dohong et al 2018). Values for the variables in the equation were taken from literature (table S5). For rewetting and revegetation, costs were stratified according to canal type (Hansson & Dargusch 2017) and forest degradation level (Budiharta et al 2014). The opportunity cost was derived from an agriculture rent map (Carrasco et al 2017) and firefighting cost was based on a fixed value derived from literature (Simorangkir 2007). |
|                           | where D_{rewet} = Cost of rewetting planning unit i                          |                                                                                                                                       |
|                           | D_{revge} = Cost of revegetating planning unit i                            |                                                                                                                                       |
|                           | D_{AR} = Agriculture rent in planning unit i; proxy for the opportunity costs of giving up current land use |                                                                                                                                       |
|                           | D_{fire} = Cost of firefighting in planning unit i                         |                                                                                                                                       |

could cost as little as US $7897–24 023 km⁻² yr⁻¹ depending on the area restored (figure 4(d)), but in return performed poorly for the other objectives. When crop production losses were constrained to be compensated with partial yield gap closure, restored area could not exceed 10%–40% of peatlands for groundnut, soybean, and wetland rice, and 60%–70% of peatlands for maize without compromising current crop production levels within peatlands. As the actual production of cassava, oil palm, and sugarcane has already exceeded 75% of potential within peatlands, the models were unable to select sites for restoration without compromising current production levels.

Restoration efforts that met BRG’s target of 25 000 km² could achieve relatively high fire risk reduction, climate change mitigation, and species...
Figure 2. Areas prioritized for restoration on Sumatra and Kalimantan for (a) fire risk reduction; (b) climate change mitigation; (c) species conservation and (d) cost minimization. Selection frequency was calculated as the percentage of number of times a planning unit was selected with target areas ranging from 10% to 100% of available peatlands.

conservation benefits (figures S2 and S3). Selected sites were predominantly located on smallholder and industrial plantation land covers for all objectives except cost minimization, which prioritized degraded peat swamp forest. Up to 30% of average fire risk could be reduced and net emissions of 9992 Mg CO\(_2\)e km\(^{-2}\) yr\(^{-1}\) mitigated for the fire and climate objectives, respectively. The latter amounted to a total of 0.21 Pg CO\(_2\)e sequestered and 3.54 Pg CO\(_2\)e emissions avoided for 2015–2030. Even though 25 000 km\(^2\) is only approximately 25% of available peatlands, prioritizing certain species may reduce extinction risk to zero. The total cost to restore this area ranged from US $8912–38 666 km\(^{-2}\) yr\(^{-1}\).

3.2. Multicriteria optimization
Combining objectives in a multicriteria optimization resulted in cost-efficient solutions at the expense of conservation, climate, and fire risk reduction benefits (figures S4–S6). Thus, when compared with their respective singular objectives at 25 000 km\(^2\), extinction risk reduction potential fell by 29%–71%, averaged annual climate benefit per area declined by 3%–80%, fire risk reduction potential was lowered by 24%–57%, whereas the minimum total cost required to restore the same area increased by 21%–89% (table 2).

3.3. Scales of restoration
Prioritizing restoration at the scale of villages and catchments, as opposed to a 1 km\(^2\) grid square, generated similar patterns of site selection. At 25 000 km\(^2\), average annual climate benefit per area at the village and catchment scales was reduced by 21%–29% and fire reduction by 43% for their respective objectives compared with restoring at the 1 km\(^2\) scale (figures S8–S21). Extinction risk reduction potential also decreased by 25%–30%, whereas the minimum total cost required to restore the same area increased by 21%–28%.

3.4. Economics of restoration
When the BRG’s target of 25 000 km\(^2\) of peatlands was restored, cost per unit carbon at the 1 km\(^2\) grid scale was priced at US $2–19/Mg CO\(_2\)e and at US $2–5/Mg CO\(_2\)e for the multicriteria objective. Whilst costs varied depending on the scale and area of restoration, results indicate that carbon prices are generally below US $37/Mg CO\(_2\)e. The only exception was a carbon offset price of up to US $84 at the catchment scale associated with the minimization of restoration cost objective. There was, however, a large uncertainty associated with the estimates due to varying costs for blocking canals of different sizes and carbon benefit estimations. For example, the maximum cost for blocking large, primary canals was estimated to be on average eight times that of small, tertiary canals (table S6).
4. Discussion

Restoring 25 000 km$^2$ of peatlands, the objective of the BRG in Indonesia, potentially reduces fire risk by up to 30% and also mitigates climate change by up to 0.25 Pg CO$_2$e yr$^{-1}$, offsettable by a highly affordable carbon price of USD 2–19/Mg CO$_2$e. Our analyses indicate that smallholders and industrial plantations are commonly prioritized across most objectives. These land covers are frequently drained and deforested, making them prone to fires, hence they hold the highest return benefit when restored. A previous study also reported prioritizing industrial plantation for fire mitigation (Santika et al 2020). Sites prioritized for fire risk reduction are located primarily in Riau, which in the recent past has been a major source of transboundary haze. Preventing peat fires can reduce atmospheric pollution in adjacent provinces and neighboring countries by an estimated 40%–70% and throughout tropical Asia by about 60% compared with a business-as-usual scenario (Marlier et al 2015). Restoration and resultant reduced risk of haze-producing peatland fires could thus avoid substantial health losses across the region each year (Marlier et al 2019) and has important implications for climate change mitigation at the global scale.

In addition to fire reduction and associated protection of health, the restoration of tropical peatlands has the potential to enhance biodiversity conservation. By targeting only 25 000 km$^2$ of peatlands, restoration can recover lost habitats for endemic birds and presumably other associated taxa. However, how a restored peatland is managed is, ultimately, likely to determine its contribution to biodiversity conservation. Thus, Runting et al (2019) showed that improved management strategies were the optimum way of deriving both conservation and production benefits from forests in East Kalimantan province, and that with careful management both benefits could be extracted simultaneously.
Figure 4. Restoration outcomes for (a) average fire risk reduction, (b) climate change mitigation, (c) species conservation, and (d) cost minimization. The negative extinction risk for (c) was due to species expanding beyond the original habitat area in 2000. As the extent of peatland restoration is increased, average fire and climate benefits decline as peatlands with lower benefits are restored. The vertical dotted line represents the 25 000 km$^2$ peatland restoration goal designated by BRG.

Peatland restoration can potentially contribute to Indonesia’s NDC by serving as a nature-based climate solution. NDCs are in effect national climate action plans that operationalize the 2015 Paris Agreement. The current research estimated a maximum climate benefit of 0.36 Pg CO$_2$e yr$^{-1}$ from carbon sequestration and avoided emissions when all peatlands are restored, comparable to estimates of 0.01–0.35 Pg CO$_2$e yr$^{-1}$ (Zeng et al. 2020) and 0.50 Pg CO$_2$e yr$^{-1}$ (Griscom et al. 2017) for restoring Southeast Asian and tropical peatlands, respectively. The extent of contribution is, however, constrained by the turnover time for restored peatlands to shift from carbon source to sinks. For example, sequestration benefit was substantially lower than avoided emissions. This is because peat swamp forest species are relatively slow-growing. As a result, the transition of a tropical peatland from a degraded carbon source to restored carbon sink can take many years (Taillardat et al. 2020). An estimated 75 years is required, post-restoration, to recover 1/3 of the peat carbon lost as a result of the changes associated with the sustained plantation-based cultivation of oil palm (Warren et al. 2017a). Carbon emissions from burning and oxidation are likely to decrease once all biomass has been depleted (Konecny et al. 2016), however, and avoided emission benefit is likely to decline over time instead of remaining constant. There is thus a lag between restoration of a degraded peatland and carbon accumulation and eventual saturation that is not accounted for in the models, which represent an ideal, but highly improbable, scenario of immediate restoration. Nevertheless, the long period for peatland ecosystems to become net carbon sinks again highlights the importance of protecting existing peat swamp forests and the need to consider including active management for enhanced carbon sequestration in restoration efforts (Taillardat et al. 2020).

A trade-off between conservation or fire risk reduction and climate change mitigation receives support from other studies; climate and conservation benefits do not always overlap, despite being consistently lumped together as goals of land interventions (Phelps et al. 2012, Budiharta et al. 2014, Law et al. 2015). Factoring in trade-offs therefore not only generates more realistic expectations for restoration, but also forces practitioners to explicitly account for diverse benefits. Adopting a multicriteria approach broadens the scope, allowing multiple ecosystem services and their interactions to be considered.

Difficult trade-offs are encountered at the intersection between maintaining livelihoods and peatland restoration. Models used in the current research prioritized smallholder and industrial plantations, or land covers that tend to be under active use. As such, there are limits to the extent of peatlands that can be restored without impeding levels of crop production after intensification. To better manage ecological benefits and economic functions, more transparent, scientifically-backed land use planning is needed to assign restoration and production functions. Mixed land use strategies combining restoration and agriculture can potentially reduce the magnitude of trade-offs (Law et al. 2017). An increasingly popular method
is paludiculture, or the production of biomass using native peatland species on rewetted peatlands (Tan et al 2021). Paludiculture can potentially achieve both ecological and economic objectives. However, the long-term feasibility and sustainability of paludiculture systems remains debatable (Budiman et al 2020), while in the short-term paludiculture is unlikely to be adopted by farmers without compensation for

Figure 5. Optimal outcomes for the multicriteria objective, showing (a) climate and conservation benefits, (b) potential fire risk reduction and conservation benefits, and (c) potential fire risk reduction and climate benefits. Each point on the Pareto efficiency frontier represents an optimal scenario for which there is no better solution as an improvement in one objective comes at the cost of the other. Each connected group of points represents the same area constraint, but with different weights for either the conservation or climate objectives.
reduced profits being made available (Schaafsma et al 2017). To this end, severe restrictions on the ability to close crop yield gaps to compensate production lost to restoration highlight the need to focus future agricultural intensification on existing agriculture lands.

Based on the respective objectives, increasing the geographical scales of analysis to the village and catchment level potentially reduced fire risks by 15%–18% and contributed 0.09–0.35 Pg CO$_2$e yr$^{-1}$ (6%–25% of the total emissions from the agriculture, forestry, and other land use sectors in 2015) to climate change mitigation. This contribution is comparable to the climate benefits obtained from restoring at 1 km$^2$. Despite their larger area, villages and catchments represent more ecologically- and socially-meaningful scales for capturing important ecological processes and distributing restoration resources. Moreover, whilst the 1 km$^2$ grid cell-level analyses produced optimal results, the coordination of restoration efforts and ability to derive benefits from economies of scale was rendered challenging by the often scattered and disconnected location of selected sites. Future optimization research exploring the effects of spatial scale and connectivity on restoration is needed to improve estimations of restoration costs and benefits.

Restoration costs could be partially offset through a market scheme, such as a system of carbon credits. A carbon price of US $2–37/Mg CO$_2$e was needed to offset restoration cost across all objectives at the grid scale emphasizing the potential of peatland restoration as a cost-effective nature-based solution compared to alternative negative emission technologies. Higher carbon prices of US $59–84/Mg CO$_2$e at the village and catchment scales reflect challenges with restoring across continuous landscapes that include areas with marginal carbon returns after restoration. Carbon credit schemes to pay for the reduction or removal of carbon emissions from the atmosphere via avoided emissions and sequestration are increasingly being promoted (Wei et al 2021). Depending on the estimation method, costs for removing carbon vary substantially for different negative emission technologies. For example, afforestation and reforestation are estimated to cost US $10–237/Mg CO$_2$ based on studies utilizing spatial optimization models. By comparison, costs as low as US $0.1–15/Mg CO$_2$ (Fuss et al 2018) have been established based on estimations of various cost components. In general, restoration is a cheaper option compared with the other, more technological, negative emission technologies such as ocean fertilization or direct air capture (Fuss et al 2018, Taillardat et al 2020) and produce, as shown, diverse co-benefits. Aside from utilizing carbon markets as a source of funding, restoration costs could also be offset through the use of alternative market-based schemes, such as ecosystem restoration licenses (Harrison et al 2020).

Table 2. Rounded outcomes of restoring 25 000 km$^2$ of peatlands at the 1 km$^2$, catchment, and village scales for their respective objectives.

| Scale of analysis | Fire risk reduction (%) | Climate change mitigation (Pg CO$_2$e yr$^{-1}$) | Extinction risk reduction (%) | Cost of restoration (US $/CO$_2$e km$^{-2}$ yr$^{-1}$) |
|-------------------|------------------------|-----------------------------------------------|-----------------------------|-------------------------------------------------|
| 1 km$^2$          | 30                     | 0.25                                          | 14                          | 8912                                           |
| Catchment         | 17                     | 0.18                                          | 10                          | 11 406                                         |
| Village           | 17                     | 0.20                                          | 11                          | 10 803                                         |

5. Conclusion

There are several caveats in this study. An understanding of local conditions on the ground, such as land tenure, political governance, and land management methods is critical to decision-making regarding site allocation. Failure to consider, fully, local conditions could result in exclusion of communities, resistance from local actors and delay and even reverse restoration. However, because of the sensitive nature of fire use, often highly dynamic policy environment, and difficulties in acquiring reliable data of an appropriate scale, variations in local conditions are often insufficiently captured in optimization studies. This is particularly an issue when it comes to projecting future conditions. Future land use competition was not accounted for in the models used in this study, for example. Competition over land is likely to be impacted by the effects of future policies, including the Indonesian government’s plans to expand the area of cultivated land in order to alleviate food insecurity concerns, with some of the expansion taking place on peatlands (SIIA 2021). Some areas designated under this program overlap with sites that are prioritized in our analyses for joint conservation and climate objectives. Social, legal, and economic factors therefore pose severe constraints to the realization of the restoration sites identified by the optimization models (Zeng et al 2020).

Spatiotemporal limitations in variables used in the models can also influence the estimates of restoration benefits and costs. For example, fire risk reduction was based on a dry El Niño year, despite differences in fire risks between dry and wet years (Tan et al 2020). The frequency and intensity of droughts and the risks of fire are likely to increase

Table 2. Rounded outcomes of restoring 25 000 km$^2$ of peatlands at the 1 km$^2$, catchment, and village scales for their respective objectives.
due to climate change (Turetsky et al 2015), hence projected fire risk reduction in the current paper can be viewed as conservative. Given that fire reduction confers health benefits by mitigating toxic emissions, future optimization research focused on peatland restoration could include health outcomes, such as disability-adjusted life years, to capture both local and transboundary costs and benefits.

In light of these challenges, results presented here are perhaps best viewed as providing a means of highlighting the potential costs and benefits of peatland restoration in Indonesia. Decisions over the actual siting, planning and implementation of restoration sites should also include fine-grained information on local actors, politics, and environmental and socio-economic conditions.

With large areas of degraded lands, restoration is needed more than ever to recover lost ecosystem services. Tropical peatland restoration is shown to be an affordable nature-based climate solution that generates climate change mitigation, conservation and health co-benefits in Indonesia. In addition to Indonesia, peatland restoration also features in the NDCs of several tropical countries, and forms part of the portfolios of many international climate and conservation initiatives. The current research found that the estimated cost of peatland restoration is less than other negative emission technologies, and thus has the potential to provide a highly cost-effective contribution to meeting sustainable development aims, particularly in less economically-advanced parts of the world. Nevertheless, the study indicates a weak trade-off between conservation or fire risk reduction and climate change mitigation objectives. By highlighting optimized co-benefits, the application of spatial optimization to rich datasets that include high quality information at the local scale is shown here to provide a means of prioritizing tropical peatland sites for effective restoration.

Data availability statement

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

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Conflict of interest

The authors declare no competing interests.

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References

Branclaison P H S et al 2019 Global restoration opportunities in tropical rainforest landscapes Sci. Adv. 5 eaaav3223
BRG 2016 Rencana Strategis Badan Restorasi Gambut 2016–2020 (Jakarta: Badan Restorasi Gambut) (available at: http://ir.obihiro.ac.jp/dspace/handle/10322/3913)
BRG 2017 Rencana kontinjensi 2017 (Jakarta: Badan Restorasi Gambut)
BRG Pranata Informasi Restorasi Ekosistem Gambut (available at: https://primis.brg.go.id/peta?q=e4iYXNBWfWfwfjoiZGkeV9 iYXNBWfWfwiwiZXh0ZW5jZGF0ZT1cLCoMc4wNj MoNzY1i1iLDDEO0C8xMjU5MTA0MDYzNDc2 NTYyNV01mnefWYyfpeyjypZC16dM4llicVYbGF5 ZXIlO0dV19)
Budiharta S, Meijaard E, Erskine P D, Rondinini C, Pacifici M and Wilson K A 2014 Restoring degraded tropical forests for carbon and biodiversity Environ. Res. Lett. 9 114020
Budiharta S, Meijaard E, Gaveau D L A, Struurbie M J, Wilting A, Kramer-Schadt S, Niedballa J, Raes N, Maron M and Wilson K A 2018 Restoration to offset the impacts of developments at a landscape scale reveals opportunities, challenges and tough choices Glob. Environ. Change 52 152–61
Budiharta S, Meijaard E, Wells J A, Abram N K and Wilson K A 2016 Enhancing feasibility: incorporating a socio-ecological systems framework into restoration planning Environ. Sci. Policy 64 83–92
Budiman I, Sari E N, Hadi E E, Siahaan H, Januar R and Haspari R D 2020 Progress of paludiculture projects in supporting peatland ecosystem restoration in Indonesia Glob. Ecol. Conserv. 23 e01084
Carrasco L R, Webb E L, Simms W S, Koh L P, Sodhi N S and Dobson A 2017 Global economic trade-offs between wild nature and tropical agriculture ed A Dobson PLOS Biol. 15 e2001657
Climate Watch 2021 Global historical emissions (available at: www.climatewatchdata.org/ghg-emissions? end_year=2018%26start_year=1990)
Dohong A, Abdul Aziz A and Dargusch P 2018 A review of techniques for effective tropical peatland restoration Wetlands 38 275–92
Evers S, Yule C M, Padfield R, O’Reilly P and Varkkey H 2016 Keep wetlands wet: the myth of sustainable development of tropical peatlands—implications for policies and management Glob. Change Biol. 23 534–49
Fagan M E, Reid J L, Holland M B, Drew J G and Zahawi R A 2020 How feasible are global forest restoration commitments? Conserv. Lett. 13 e12700
Fuss S et al 2018 Negative emissions—part 2: costs, potentials and side effects Environ. Res. Lett. 13 063002
Gibbs H K and Salmond J M 2015 Mapping the world’s degraded lands Appl. Geogr. 57 12–21
Government of Indonesia 2016 First Nationally Determined Contribution: Republic of Indonesia Griscom B W et al 2017 Natural climate solutions Proc. Natl Acad. Sci. USA 114 11645–50
Gurobi Optimizer L 2021 Gurobi optimizer reference manual (available at: www.gurobi.com)
Hansson A and Dargusch P 2017 An estimate of the financial cost of peatland restoration in Indonesia Case Stud. Environ. 21 1–8

Harrison R D, Swinfield T, Ayat A, Devi S, Sillahai M and Heriansyah I 2020 Restoration concessions: a second lease on life for beleaguered tropical forests? Front. Ecol. Environ. 18 567–73

IIASA/FAO 2012 Global agro-ecological zones (GAEZ v3.0) (available at: https://webarchive.iiasa.ac.at/Research/LUC/GAEZv3.0/)

Koh L P, Zeng Y, Sarira T V and Siman K 2021 Carbon prospecting in tropical forests for climate change mitigation Nat. Commun. 12 1–9

Konecny K, Ballhorn U, Navratil P, Jubanski J, Page S E, Tansey K, Koh L P, Zeng Y, Sarira T V and Siman K 2021 Carbon prospecting in tropical forests for climate change mitigation Nat. Commun. 12 1–9

Kopitz S N et al 2016 Public health impacts of the severe haze in Equatorial Asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure Environ. Res. Lett. 11 094023

Laurance W F, Sayer J and Cassman K G 2014 Agricultural expansion and its impacts on tropical nature Trends Ecol. Evol. 29 107–16

Law E A, Bryan B A, Mejiaard E, Mallawaarachchi T, Struiebig M J, Watts M E and Wilson K A 2017 Mixed policies give more options in multifunctional tropical forest landscapes J. Appl. Ecol. 54 51–60

Law E A, Bryan B A, Mejiaard E, Mallawaarachchi T, Struiebig M and Wilson K A 2015 Ecosystem services from a degraded peatland of Central Kalimantan: implications for policy, planning, and management Ecol. Appl. 25 70–87

Marlier M E et al 2019 Fires, smoke exposure, and public health: an integrative framework to maximize health benefits from peatland restoration GeoHealth 3 178–89

Marlier M E, Defries R S, Kim P S, Gaveau D L A, Kopitz S N, Jacob D J, Mickley L J, Margono B A and Myers S S 2015 Regional air quality impacts of future fire emissions in Sumatra and Kalimantan Environ. Res. Lett. 10 054010

Miettinen J, Shi C and Liew S C 2016a 2015 Land cover map of Southeast Asia at 250 m spatial resolution Remote Sens. Lett. 7 701–10

Miettinen J, Shi C and Liew S C 2016b Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990 Glob. Ecol. Conserv. 6 67–78

Mueller N D, Gerber J S, Johnston, R, Ray D K, Ramankutty N and Foley J A 2012 Closing yield gaps through nutrient and water management Nature 490 254–57

Nelson T M, Ferris M C, Diebel M W, Dornan P J, O’Hanley J R and McIntyre P B 2015 Enhancing ecosystem restoration efficiency through spatial and temporal coordination Proc. Natl Acad. Sci. USA 112 6236–41

Phelps J, Friess D A and Webb E L 2012 Win-win REDD+ approaches belittle carbon-biodiversity trade-offs Biol. Conserv. 154 53–60

Puspitaloka D, Kinn Y, Purnomo H, Hula P and Zubair P 2020 Defining ecological restoration of peatlands in Central Kalimantan, Indonesia Restor. Ecol. 28 435–46

Ranting R K et al 2019 Larger gains from improved management over sparing–sharing for tropical forests Nat. Sustain. 2 53–61

Sanjita T, Budihsrta S, Law E A, Dennis R A, Dohong A, Struiebig M J, Medrilzam M, Gunawan H, Mejiaard E and Wilson K A 2020 Interannual climate variation, land type and village livelihood effects on fires in Kalimantan, Indonesia Glob. Environ. Change 64 102129

Schaaf M, van Beukering P J H and Osokolokaitse I 2017 Combining focus group discussions and choice experiments for economic valuation of peatland restoration: a case study in Central Kalimantan, Indonesia Ecol. Serv. 27 150–60

SIIA 2021 Haze Outlook 2021 (Singapore: Singapore Institute of International Affairs)

Simorangkir D 2007 Fire use: is it really the cheaper land preparation method for large-scale plantations? Mitig. Adapt. Strateg. Glob. Change 12 147–64

Strassburg B N et al 2020 Global priority areas for ecosystem restoration Nature 586 724–9

Symes W S, Edwards D P, Miettinen J, Rheindt F E and Carrasco L R 2018 Combined impacts of deforestation and wildlife trade on tropical biodiversity are severely underestimated Nat. Commun. 9 1–9

Taillardat P, Thompson B S, Carneau M, Trottier K and Fries D A 2020 Climate change mitigation potential of wetlands and the cost–effectiveness of their restoration Interface Focus 10 20190129

Tan Z D, Carrasco L R and Taylor D 2020 Spatial correlates of forest and land fires in Indonesia Int. J. Wildland Fire 29 1088

Tan Z D, Lupascu M and Wijedasa L S 2021 Paludiculture as a sustainable land-use alternative for tropical peatlands: a review Sci. Total Environ. 753 142111

Turetsky M R, Benscoter B, Page S, Rein G, van der Werf G R and Watts A 2015 Global vulnerability of peatlands to fire and carbon loss Nat. Geosci. 8 11–14

United Nations General Assembly 2019 United Nations Decade on Ecosystem Restoration (2021–2030) (available at: https://un.org/RES/73/284)

Urzaizki J, Laurens A, Palvainen M, Haathi K, Budiman A, Basuki I, Netzer M and Hökkä H 2020 Canal blocking optimization in restoration of drained peatlands Biogeosciences 17 4769–84

Wahyunto, Ritung S and Subagio H 2003 Maps of area of peatland distribution and carbon content in Sumatra, 1990–2002 (Bogor: Wetlands International-Indonesia Programme & Wildlife Habitat Canada (WHC))

Wahyunto, Ritung S, Suparto and Subagio H 2004 Maps of area of peatland distribution and carbon content in Kalimantan, 2000–2002 (Bogor: Wetlands International-Indonesia Programme & Wildlife Habitat Canada (WHC))

Warren M, Froliking S, Dai Z and Kurnianto S 2017a Impacts of land use, restoration, and climate change on tropical peat carbon stocks in the twenty-first century: implications for climate mitigation Mitig. Adapt. Strateg. Glob. Change 22 1041–61

Warren M, Hergoualc’h K, Kauffman J B, Murdiyarso D and Warren M, Frolking S, Dai Z and Kurnianto S 2017a Impacts of land use, restoration, and climate change on tropical peat carbon stocks in the twenty-first century: implications for climate mitigation Mitig. Adapt. Strateg. Glob. Change 22 1041–61

Wei J, Zhao K, Zhang L, Yang R and Wang M 2021 Exploring development and evolutionary trends in carbon offset research: a bibliometric perspective Environ. Sci. Pollut. Res. 28 18850–69

Zeng Y, Sarira T V, Carrasco L R, Chong Y K, Friess D A, Lee J S H, Taillardat P, Worthington T A, Zhang Y and Koh L P 2020 Economic and social constraints on reforestation for climate mitigation in Southeast Asia Nat. Clim. Change 10 842–4

11