More field-based carbon monitoring of tropical peatland restoration is urgently needed: findings from a systematic literature review

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SUMMARY

The tropical peatland degradation crisis in Southeast Asia has triggered a surge in peatland restoration activity to reduce carbon emissions caused by biological oxidation of dry peat and recurrent peat fires. Monitoring the effects of restoration activities on carbon cycling is essential. We conducted a systematic literature review to determine where, how and by whom field-based carbon monitoring of tropical peatland restoration is being conducted. Our search focused on rewetting, revegetation of native plant communities, and interventions to reduce fire. Despite tropical peatland restoration activities occurring since the early 2000s, published studies monitoring their carbon effects are extremely limited, both temporally and geographically; only nine studies met the criteria of our systematic search. Concentrated in Kalimantan and Sumatra (Indonesia) and Selangor (Malaysia), all except one of these studies were published in the last six years. Southeast Asian academic institutions, nonprofit organisations, government and the private sector are interconnected in generating this research through authorship and the provision and/or management of land. Monitoring activities are heavily focused on flux chamber measurements of peat surface carbon fluxes. Monitoring of revegetation and fire reduction is very limited, and establishment of pre-restoration baseline conditions is lacking. In the detected studies, reported monitoring periods extended to a maximum of two years. Standardised reporting of the spatial extent of restoration activities would assist comparisons of restoration outcomes. There is an urgent need for longer term, continuous studies investigating the carbon outcomes of tropical peatland restoration that transcend existing funding and political time constraints.

KEY WORDS: peat swamp forest, reducing fire, revegetation, rewetting

INTRODUCTION

Recent carbon history of tropical peatlands

Tropical peatlands cover ~1.7 M km^2 of the Earth's surface across Africa, Asia and South America and store globally important amounts (~105 Gt) of carbon (Page *et al.* 2011a, Dargie *et al.* 2017). Peatlands form under waterlogged, anoxic conditions in which organic matter input rates exceed decomposition rates. Deposition of leaf litter, dead branches and roots from native tropical peat swamp forest provides the organic inputs (Dommain *et al.* 2015). This natural process has resulted in the accumulation of large quantities of carbon-rich peat over thousands of years (Page *et al.* 2004). Carbon is also stored in above- and belowground biomass of tropical peat swamp forests (Hergoualc'h & Verchot 2011), but this pool is considerably smaller than that of the peat soil. Overall, in their undisturbed state, tropical peatlands are a critical natural CO_2 sink due to their large pre-existing carbon stores and capacity at many locations for ongoing carbon sequestration (Page *et al.* 2004).

Southeast Asia has some of the deepest and most extensive tropical peatlands worldwide (Page *et al.* 2011a, Dargie *et al.* 2017, Gumbricht *et al.* 2017), but since the early 1980s the majority of peat swamp forests have been extensively logged for timber, cleared, and drained through construction of canals for conversion to agriculture and plantations (Miettinen *et al.* 2016). Drainage of the upper peat profile exposes it to oxygen, enabling biological oxidation which causes carbon emissions of ~146 Mt yr^{-1} (Miettinen *et al.* 2017). Dissolved organic carbon (DOC) is also lost through drainage via fluvial processes; total carbon loss estimates for a disturbed Bornean peatland increased by 22 % when fluvial carbon losses were included (Moore *et al.* 2013). Furthermore, dry peat is highly flammable and smouldering peat fires generate significant carbon emissions; in the ten years preceding 2016, carbon losses through CO_2 emissions from peat fires were estimated at ~122.1 Mt yr^{-1} (Miettinen *et al.* 2017). In 2015 alone, widespread peat fires, primarily in Indonesia, resulted in a toxic haze exceeding the fossil fuel CO_2 emissions of the entire European Union at that time (Huijnen *et al.* 2016). Thus, in recent decades, Southeast Asian peatlands have switched from being a carbon sink to a significant carbon source (Miettinen *et al.* 2017).

Towards restoration of tropical peatlands

The widespread degradation of tropical peatlands and the associated haze crisis have triggered a surge in peatland restoration activities throughout Southeast Asia. Peatland restoration initiatives began in the early-to-mid 2000s (e.g. Nuyim 2005, Suryadiputra *et al.* 2005, CKPC 2008, Jauhiainen *et al.* 2008, Ritzema *et al.* 2014). Following widespread peat fires in 2015, in 2016 the Indonesian Government established the Indonesian Peatland Restoration Agency, or 'BRG' (Badan Restorasi Gambut), tasked with restoring ~2 million hectares of degraded peat by 2020 (GoI 2016). Although a significant driver of peatland restoration in Indonesia has been to mitigate negative human health and geopolitical effects of the haze from peat fires, motivation to reduce associated carbon emissions has also gained momentum. For instance, the Indonesian government committed to reduce its carbon emissions under the Paris agreement; their enhanced nationally determined contribution cited peat fires as a major cause of emissions and peatland restoration as part of their mitigation strategy (RoI 2022). The growing voluntary carbon market is also drawing upon tropical peatland restoration to reduce carbon emissions and generate carbon credits (Box 1). In Malaysia, some of the most significant peatland restoration efforts have occurred in the North Selangor Peat Swamp Forest, a network of forest reserves established in 1990 by the Selangor State Authority, and management objectives include the minimisation of carbon emissions through peatland restoration (SSFD 2014). Peatland restoration efforts have also been undertaken in Sarawak, Brunei, Thailand, Vietnam, Laos and Myanmar (ASEAN 2021). While there are extensive tropical peatlands in Africa and South America, these are still largely intact (Ribeiro *et al.* 2021). However, there are urgent calls for early restoration interventions to mitigate carbon emissions amidst increasing reports of peatland degradation (UNEP 2022).

Dialogue and processes of tropical peatland restoration are commonly framed around the '3Rs' paradigm of 'rewetting', 'revegetation' and 'revitalisation' of local livelihoods, conceived by the BRG as a tropical peatland restoration implementation framework (Giesen & Sari 2018). Harrison *et al.* (2020) proposed a fourth R of 'reducing fires' for inclusion of fire prevention and mitigation strategies not implicit within rewetting and revegetation, and that may fall outside of the BRG's 3Rs remit. Recently, Terzano *et al.* (2022)

Box 1. Peatland restoration and the voluntary carbon market

Since adoption of the Paris Agreement under the United Nations Framework Convention on Climate Change in 2015, the number of companies seeking carbon credits has increased substantially (Kreibich & Hermwille 2021). The voluntary carbon market facilitates trading of carbon credits that permit the buyer to offset their carbon emissions (Kreibich & Hermwille 2021). A number of tropical peatland restoration projects generate carbon credits derived from their emissions-reducing activities; a search of the globally-popular Verified Carbon Standard Program public database (managed by the nonprofit corporation 'Verra') in July 2022 returned three registered peatland restoration projects in Indonesia. Methods for quantifying and monitoring project emissions reductions are developed by the individual offset standard and are typically informed by the peer-reviewed scientific literature. They may incorporate direct measurements (e.g. flux chambers), proxies such as land use type, land management practices, vegetation cover, water table depth and microtopography, or IPCC default emissions factors, with evidence of proxy validity required through reference to published data or expert judgement (e.g. VCS 2020a,b). Methodology details from specific projects verified by reputable offset standards are in theory publicly available, though we were unable to obtain consistent access to such data for inclusion in this review. Monitoring of carbon outcomes by for-profit ventures may primarily serve a commercial purpose, negating motivation to disseminate details beyond auditing compliance. However, peer-reviewed studies undertaken at the Katingan Mentaya Project site, which operates as a carbon financed peatland restoration project, demonstrate that carbon outcome findings from peatland restoration projects embedded in the carbon market can make valuable contributions to the scientific literature (Murdiyarso *et al*. 2019b, Darusman *et al*. 2022, Lestari *et al*. 2022), although this appears to be a unique case at this time. Ultimately, monitoring carbon outcomes from peatland restoration projects and disseminating results in peer-reviewed literature is essential to inform accurate carbon crediting of projects engaged in the voluntary carbon market.

introduced 'reporting and monitoring' as a fifth cross-cutting component. The "5Rs" provide a useful framework for tropical peatland restoration discourse and action.

A major objective of peatland restoration is to reduce carbon emissions from biological oxidation and peat fires associated with peatland degradation (Page *et al.* 2009). Peatland rewetting is a critical part of this process, aiming to reduce the incidence and extent of peatland fires and rates of biological oxidation by raising water table levels (Page *et al.* 2009). Above the water table biological oxidation occurs via rapid aerobic pathways, whereas below the water table only very slow anaerobic decomposition can occur (Rydin & Jeglum 2015). Reducing fire risk may also bolster aboveground carbon stocks from vegetation regrowth. Rewetting is achieved through canal blocking and backfilling or infilling; canal blocking involves construction of dams or weirs to stem or slow canal water outflow, while backfilling or infilling blocks canal sections with peat, woody debris, or other locally available materials (Dohong *et al.* 2017a).

Revegetation of tropical peatlands is essential to maximise the vegetative carbon sink capacity of tropical peatlands and replenish the peat-soil carbon pool. Restoring closed-canopy native forest vegetation can re-establish organic matter inputs, restore cooler, moister sub-canopy microclimate conditions, and restart peat accumulation while helping to prevent fire (Page & Hooijer 2016, Waldron *et al.* 2019). Revegetation activities comprise a continuum from preservation and restoration of native vegetation communities to establishment of paludiculture or agroforestry to support revitalisation of local livelihoods (Giesen & Sari 2018; Box 2). Methodologically, in Southeast Asia, 'revegetation' most often refers to reforestation of peatland through planting seedlings. However, in many circumstances, it may be appropriate or preferable to facilitate tropical peat swamp forest revegetation through other responses to landscape degradation processes (Graham *et al.* 2017, Giesen & Sari 2018). For example, preventing anthropogenic disturbances such as logging and fire that inhibit vegetation regrowth, weeding of invasive species, or enhancement planting to complement natural regeneration can facilitate regeneration and revegetation (Shono *et al.* 2007, FAO 2019). Rewetting and reducing fire are also inherently 'facilitated regeneration' strategies, as they remove barriers to vegetation recovery. The term 'assisted natural regeneration' is also used to describe aspects of facilitated regeneration in the tropical peatland context (Shono *et al.* 2007, FAO 2019, McDonald *et al.* 2023). This growing recognition that there is a spectrum of peatland revegetation activities aligns with the Society for Ecological Restoration's "International Principles and Standards for the Practice of Ecological Restoration", which state that ecological restoration is part of a continuum of restorative activities to be implemented as appropriate to the local ecological, social and financial conditions (Gann *et al.* 2019).

Reducing fire is an essential component of mitigating tropical peatland carbon emissions through peatland restoration. In addition to rewetting and revegetation, activities that reduce fire directly include early fire detection to facilitate rapid firefighting responses, firefighting to extinguish fire, peatland/forest protection from fire through land access or burning regulations, development of alternative non-burning methods for land clearing, resolution of land tenure and conflict issues, and

Box 2. Paludiculture in peatland restoration and carbon outcomes

The different 'Rs' of peatland restoration inevitably overlap in various ways. One important case is the intersection of 'revitalisation of local livelihoods' with 'revegetation', 'rewetting' and 'reducing fire' through paludiculture and agroforestry. Paludiculture is broadly defined as the productive cultivation of wet or rewetted peat (Wichtmann & Joosten 2007). In degraded peatlands, it is intended that paludiculture will create opportunities for local communities to derive subsistence and economic benefits through methods compatible with rewetting and without fire, and is often included in the definition of tropical peatland revegetation (Giesen & Sari 2018). When successful, paludiculture has the capacity to improve peatland carbon stocks through the same mechanisms as revegetation, although at slower rates due to inherent biomass removal through product harvesting. While paludiculture is undoubtably a key tool in the restoration of peatlands there is conjecture about the accepted definition, including whether paludiculture can include the cultivation of non-native species, and some concern that the term might be misappropriated to describe some degrading practices (Tan *et al*. 2021). Appropriate interpretation and implementation of paludiculture is essential to ensure that practices are compatible with long-term peatland restoration and will deliver positive carbon outcomes in that timeframe (Jessup *et al*. 2020, Tan *et al*. 2021).

raising public awareness and promoting behavioural changes to reduce fire (Harrison *et al.* 2020). Construction of 'deep wells' is a widely implemented fire-reducing intervention in Indonesia (Dohong *et al.* 2017a); these polypipe-lined boreholes provide access to groundwater to spray on the surface peat for fire prevention and firefighting, and are included in the BRG's 'rewetting' remit although there is no lasting effect on peat water table levels (Giesen & Sari 2018). Reducing peatland fires helps prevent carbon emissions while simultaneously bolstering carbon storage and sequestration potential in the peat and biomass carbon pools (Murdiyarso *et al.* 2010).

Importance of field-based outcome monitoring

As tropical peatland restoration continues to gain momentum, it is essential to include field-based measurements when monitoring the carbon outcomes of restoration activities. Remote sensing and modelling techniques are increasingly used to estimate peatland restoration carbon outcomes, but field measurements are critical to ground-truth these outputs (FAO 2020). However, validation data obtained directly from restoration activities is often unavailable (e.g. Günther *et al.* 2020, Urzainki *et al.* 2020). Field-derived carbon storage and flux data is also essential for assessing ongoing climate feedbacks and to support future policymaking and land management (FAO 2020). There is an urgent need for in situ emissions data from peatland rewetting areas to improve IPCC emission factors; current Tier 1 CO_2, CH_4 and DOC emission factors are based on surrogate data from undrained sites because data for rewetted tropical organic soils were unavailable (IPCC 2014). Quantitative information about the carbon effects of restoration activities is also required to inform the growing carbon market (Box 1). Recently, the Indonesian Government regulated its carbon market, introducing a framework for carbon pricing and trading (MoEF 2022). Accurate carbon accounting is essential for the effective integration of peatland restoration into carbon credit accounting for carbon trading (Box 1). Modelling is widely used to provide estimates for the above purposes, and carbon storage and flux values from field-based studies are essential to verify and calibrate model accuracy and efficacy (FAO 2020).

Aims

In response to the burgeoning tropical peatland restoration efforts and the increasing need for field-based carbon storage and flux data, we conducted a systematic review to provide a comprehensive overview of where, how and by whom field-based carbon monitoring has been undertaken in tropical peatland restoration. Specifically, the aims of this review are to:

(i) identify where and when monitoring of carbon outcomes of tropical peatland restoration has been undertaken;

(ii) identify which countries and institution types are the main drivers of tropical peatland restoration carbon monitoring research;

(iii) determine which forms of tropical peatland restoration are most and least commonly monitored for carbon outcomes;

(iv) determine what methodologies are used in the tropical peatland restoration carbon monitoring context, and the spatial and temporal extent of monitoring studies; and

(v) identify areas for future research focus based on these findings.

METHODS

Terminology and scope

In this review we focus on rewetting, revegetation and reducing fire as the restoration strategies most likely to capture carbon storage and flux outcomes of restoration activities. We acknowledge some restoration techniques fit into multiple categories; e.g. 'rewetting' is concurrently 'reducing fire' through reduction of peat flammability. For this systematic search, we partitioned definitions to align with the commonly used 5Rs terminology in restoration discourse and policy, and the biogeochemical and ecological outcomes of the restoration strategies (Table 1).

Screening of sources and database development

The international academic literature databases *Web of Science* (All Databases) and *Scopus* were used to identify relevant literature using the search terms in Table 2. The search included journal articles, books, book chapters, reports, theses, conference papers and conference proceedings. Peatland degradation is most widely documented in Southeast Asia, thus Southeast Asian countries with tropical peatlands as identified by Dohong *et al.* (2017b) were included as specific search terms to increase the likelihood of capturing relevant sources, though results from any tropical peatland worldwide would qualify for inclusion in our review.

We undertook an iterative relevancy screening process with the returned sources as shown in Figure 1. Specifically, duplicates returned in the initial search were excluded, and remaining sources were included in the review if they met all of the following criteria:

(i) reported original research;

(ii) investigated a tropical peatland context;

(iii) described a specific restoration strategy of rewetting, revegetation or reducing fire, or a combination;

(iv) reported the carbon storage and/or carbon flux outcomes of the restoration activity; and

(v) derived carbon storage and/or carbon flux findings from field monitoring data.

Review articles, meta-analyses, conference proceedings and books were reviewed to identify additional studies. This returned one extra conference paper; however, the same results were more fully disseminated in a subsequent peer-reviewed journal article, and so only the journal article was included in the final database. Non-English abstracts were translated to assess for relevance.

The details required to address the aims of this review were extracted from the selected sources (see Table A1 in the Appendix). In summary, for each source we recorded:

- year of publication and author details;
- study site details including location, land tenure/management, peat depth, land use description and restoration strategy implemented;
- implementation methods for rewetting, revegetation and reducing fire; and
- carbon flux and carbon stock monitoring methods.

Where studies reported on multiple sites under different land uses, only those under restoration were included in the final database. Studies were recorded as investigating rewetting, revegetation or reducing fire as stated in their primary aims (Table A1). We recorded the institutional affiliation of the first author as a proxy for which country and research sector (academic, government or nonprofit organisation) were the main drivers of the research, as the convention in environmental sciences is that the first

Table 1. Definitions used in this review.

Term	Definition
Rewetting:	canal blocking, canal backfilling and canal infilling.
Revegetation:	reinstatement of native vegetation communities[1] through planting seedlings or facilitated regeneration[2].
Reducing fire:	in addition to rewetting and revegetation, other activities that reduce fire and thereby contribute to peatland restoration include: - early fire detection to facilitate rapid firefighting response; - firefighting to extinguish fires; - peatland/forest protection from fire through land access or burning regulations; - developing alternative non-burning methods for land clearing; - resolving land tenure and conflict issues; - raising public awareness and promoting behaviour change to reduce fire; and - construction and use of ‘deep wells’ for firefighting and fire prevention purposes[3].

[1] While paludiculture and agroforestry are important tools in peatland restoration, they are omitted from the definition of revegetation in this review. In Southeast Asia there is inconsistent use of the term ‘paludiculture’ (inclusive of agroforestry) and ongoing discussion of the accepted definition (Box 2; Tan *et al*. 2021), which complicates monitoring and reporting of carbon outcomes. Therefore, this review focuses on revegetation of native vegetation communities.

[2] Our definition of facilitated regeneration is inclusive of secondary succession following cessation of previous anthropogenic peatland disturbance(s) on land designated as a restoration opportunity by relevant stakeholders.

[3] We have included deep wells under ‘reducing fire’ and not under ‘rewetting’, as their use has no lasting effect on water table levels but contributes actively in firefighting (Giesen & Sari 2018).

Table 2. Search terms used to find relevant publications for this systematic review. Searches in *Web of Science* (All Databases) and *Scopus* using these terms in May 2022 returned 1202 hits. Terms in each topic column were joined using 'OR'. Tropical peatland restoration is a relatively recent and rapidly evolving field, and it is common for initial study findings to be available in reports, conference papers and proceedings sooner than in journal articles. Therefore, the *Web of Science* ‘All Databases’ was used to ensure that all relevant sources were detected, and none missed due to exclusion from the curated *Web of Science* ‘Core Collection’.

Terms related to “peat”	AND	(	Terms related to "tropics"	)	AND	(	Terms related to “restoration”	Terms related to “rewetting”	Terms related to “revegetation”	Terms related to “reducing fire”	)
peat*			tropic*				restorat*	canal block*	reveg*	fire*prevent*	
			Southeast Asia*				rehabilit*	canal infill*	replant*	fire* manag*	
			Indonesia*					canal backfill*	reforest*	fire* mitigat*	
			Malaysia*					rewet*	regen*	fire suppress*	
			Philippin*					hydrol* manage*	tree plant*	fire fight*	
			Thai*						assisted natural regeneration	deep well*	
			Brunei*						ANR		
			Cambodia*								
			Singapor*								
			Myanmar*								
			Vietnam*								
			Lao*								

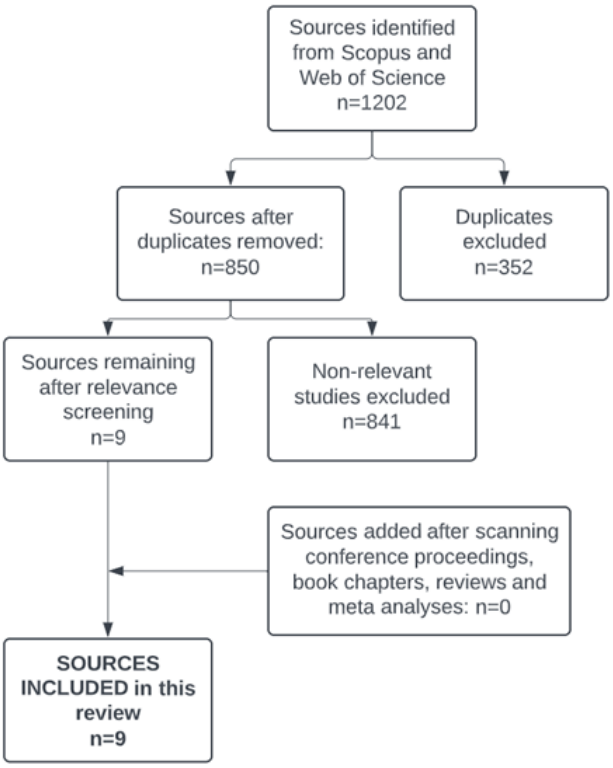

Figure. 1. Summary of the numbers of source articles included in, and excluded from, the review process.

author is usually the main contributor to the publication. To investigate local expertise contributions for each study, we determined the proportion of authors with affiliations to organisations within the studied country. Where an author had affiliations in two countries, each country was weighted at 0.5.

RESULTS

Where and when?

Despite tropical peatland restoration occurring since the early 2000s, the published literature on field-based monitoring of carbon impacts is extremely limited, both temporally and geographically. Only nine primary research journal articles (Table 3) met the systematic review criteria. Jauhiainen *et al.* (2008) reported the first field-based measurements of the effects of peatland rewetting on carbon fluxes, and the remaining eight studies were published only in the last six years. Seven of these studies were conducted in Indonesia (five in Kalimantan, two in Sumatra) and two in Malaysia (Selangor), which indicates the prevalence of peatland degradation and motivation for restoration in these regions (Murdiyarso *et al.* 2019a). Interestingly, although 80 % of the total area of Malaysian peatland converted to oil palm plantations is located in Sarawak (Murdiyarso *et al.* 2019a), no studies were found for this region.

Country and institutional drivers

Southeast Asian academic institutions are key drivers of this research, with governments designating, providing or leasing land for restoration purposes (Table 3). Specifically, the Malaysian studies were conducted in the North Selangor Peat Swamp Forest, which is managed by the Selangor State Forestry Department as a network of gazetted 'permanent forest reserves' that include management objectives of conservation and rehabilitation (SSFD 2014). Budiman *et al.* (2020) undertook research on land managed by the Environmental and Forestry Research and Development Institute, owned by the Indonesian Ministry of Environment and Forestry. All three of the remaining studies reporting land tenure details were conducted in the Katingan Mentaya Project peatland restoration and conservation area. The Katingan Mentaya Project is an emissions avoidance project certified through the Verified Carbon Standard programme and operates as a private company under an Indonesian Government ecosystem restoration concession licence (PT. Rimba Makmur Utama 2016). This intersection of private enterprise and government land ownership demonstrates that private business can play a role in generating opportunities for field-based carbon monitoring research. The multiple publications from the Katingan Mentaya Project also signal that commercialisation of the carbon market has potential to generate research in the restoration space (Box 1).

The authorship of studies detected through our systematic search indicates significant Southeast Asian academic contributions in this research field. Of the twelve first author organisational affiliations, nine were from Indonesia and one from each of Japan, Finland and the UK (Table 3). In six of the nine studies, ≥ 80 % of authors had organisational affiliations matching the country where the research was conducted, with four of these having 100 % representation by in-country organisations. All studies had at least one author with an in-country organisational affiliation. This suggests the research is of local value where undertaken, and that local expertise is critical. The majority of first-author affiliations were to academic institutions. Specifically, of the twelve first-author organisations, nine were academic institutions and three were not-for-profit organisations (Table 3).

Table 3. Details of studies reporting carbon outcomes of tropical peatland restoration, detected through a systematic literature search. Note that all forest sites have been previously subject to selective logging. Abbreviations: 'home authors' have country-of-study organisational affiliations; Rewet = rewetting; Reveg = revegetation; Fire red = fire reduction; MRP = Mega Rice Project; AC = academic, Gov = government; NFP = 'not for profit'; N.D. = 'no details'.

Source	Study location	Land tenure	First author affiliation	Home authors (%)	Land cover	Peat depth (m)	Rewet	Reveg	Fire red
Astiani *et al*. (2018)	Indonesia: West Kalimantan	N.D.	Indonesia, AC (×2)	80	Crops/ degraded shrubland	> 5	x		
Azizan *et al*. (2021)	Malaysia: North Selangor Peat Swamp Forest	Gov; managed as restored peatland by Selangor State Forestry Dept.	Japan, AC	12.5	Replanted forest	N.D.	x	x	
Budiman *et al*. (2020)	Indonesia: South Sumatra	Gov; managed by Environmental and Forestry R&D Institute, owned by Ministry of Environment and Forestry	Indonesia, NFP	100	Agri-silviculture	5–6.5	x		
Darusman *et al*. (2022)	Indonesia: Central Kalimantan (Katingan Project)	Private restoration concession leased from Indonesian government.	Indonesia, AC	100	Secondary forest	~ 4	x		
Jauhiainen *et al*. (2008)	Indonesia: Central Kalimantan (Block C Ex-MRP)	N.D.	Finland, AC	25	i. Secondary forest ii. Degraded shrubland	~ 4 ~ 4	x x		
Lestari *et al*. (2022)	Indonesia: Riau	N.D.	Indonesia, AC	100	Replanted forest	> 3 (~80 % of landscape)	x	x	
Murdiyarso *et al*. (2019b)	Indonesia: Central Kalimantan (Katingan Project)	Private restoration concession leased from Indonesian government.	Indonesia, NFP; Indonesia, AC	100	i. Secondary forest ii. Degraded shrubland	~ 3.2–4 ~ 3.2–4	x x		
Saragi-Sasmito *et al*. (2019)	Indonesia Central Kalimantan (Katingan Project)	Private restoration concession leased from Indonesian government.	Indonesia, AC; Indonesia, NFP	87.5	Secondary forest	3.5–4.5		x	x
Waldron *et al*. (2019)	Malaysia: North Selangor Peat Swamp Forest	Gov; gazetted forest reserve	UK, AC	8	Secondary forest	~ 3–6		x	

Forms of restoration monitored

Research involving field-based monitoring of the carbon outcomes of peatland restoration is dominated by rewetting studies. Seven of the nine studies detected in this review investigated rewetting, four monitored revegetation, and only one specifically referred to reducing fire (Table 3). The dominance of rewetting studies may reflect the general consensus that peatland restoration should begin with hydrological restoration in order to halt subsidence and prevent fire, and that water table level can be used as an indicator of progress towards restoration (Ward *et al.* 2020). Additionally, the capacity to reduce carbon emissions from biological oxidation and peat fires is arguably greatest from rewetting when compared to other restoration interventions (Jaenicke *et al.* 2010).

Monitoring of the carbon effects of peatland restoration was most commonly undertaken on forested deep peat (Table 3). All eight studies reporting details were conducted on peat of depth ≥ 3 m. Secondary forest was represented in five studies; and replanted forest, degraded shrubland, production landscapes and a degraded - production landscape hybrid were each represented in 1–2 studies.

Methodologies, duration and extent

Rewetting

In situ monitoring of carbon outcomes from peatland rewetting studies were predominately small-to-medium-scale canal blocking interventions (Table 4). Most rewetting studies specifically investigated canal blocking, although Azizan *et al.* (2021) only reference ‘rewetting’. Astiani *et al.* (2018), Jauhiainen *et al.* (2008) and Lestari *et al.* (2022) explicitly describe dams or weirs constructed of timber frames filled with compressed peat or sacks of sand, peat or mineral soil, consistent with recommended canal blocking methodology (Dohong *et al.* 2017a). Interestingly, we found no studies reporting on canal backfilling or infilling, which is usually reserved for blocking larger canals in conservation or protected areas (Dohong *et al.* 2017a).

Canal blocking in the reviewed studies involved up to eight blocks in one or two canals, though again not all studies reported details (Table 4). The three studies reporting the dimensions of canals blocked illustrated the significant variation in canal size, from 2 m wide and 1.5 m deep (Darusman *et al.* 2022) toup to 25 m wide and 3.5-4.5 m deep (Jauhiainen *et al.*2008). Total length of canals blocked was not reported, although Darusman *et al.* (2022) provided the average length of canals in the rewetted area, and several studies provided site maps with canal block locations (Jauhiainen *et al.* 2008, Budiman *et al.* 2020, Darusman *et al.* 2022). Most rewetting studies involved closed flux chamber monitoring campaigns of a few days repeated at least twice (Table 5), sometimes integrating additional elements such as seasonality (Darusman *et al.* 2022). Astiani *et al.* (2018) and Azizan *et al.* (2021) report relatively extended and consistent soil carbon flux monitoring of weekly and fortnightly measurements over 12 and 18 months, while Jauhiainen *et al.* (2008) undertook frequent measurements over two years, integrating 10 cm increments of water table level. Budiman *et al.* (2020) infer longer monitoring timeframes in the only subsidence study detected through the review, but its specific duration is unclear. The remaining three rewetting studies used closed flux chambers to monitor total soil respiration or heterotrophic respiration via trenching. Five rewetting studies investigated soil CH_4 fluxes, and only one rewetting study sampled DOC and POC (Table 5).

Several rewetting studies monitored other important carbon components including litterfall production, aboveground carbon, belowground carbon, soil organic carbon stores and dead wood (Tables 5 and 6). However, this was not always directly in relation to rewetting aims; for example, Murdiyarso *et al.* (2019b) compared differences in aboveground carbon stocks at clear-felled and secondary forest sites in the context of logging history rather than rewetting.

Revegetation

Despite widespread revegetation efforts throughout Southeast Asia, we identified just four studies monitoring carbon outcomes of peatland revegetation; one via replanting, two via forest protection, and one via replanting and subsequent forest protection (Table 7). Only Saragi-Sasmito *et al.* (2019) measured vegetative carbon storage and fluxes (Tables 5 and 6), as part of a baseline assessment of the Katingan Mentaya Project which involved undertaking restoration through forest protection. They reported aboveground and below-ground carbon stores, litterfall and stem productivity - all key components for a comprehensive understanding of revegetation carbon cycling trajectories (Hergoualc'h & Verchot 2011, Kauffman *et al.* 2016).

Other carbon components monitored in association with tropical peatland revegetation included total soil respiration, heterotrophic respiration, CH_4 flux, fluvial carbon components and peat soil carbon stocks (Tables 5 and 6). Only Waldron *et al.* (2019) measured fluvial carbon, a significant yet often overlooked carbon flux in tropical peatlands (Moore *et al.* 2013). Through a single sampling event, they used fluvial CO_2 efflux to determine how the carbon cycle changed when revegetation was facilitated by a successfully managed 30-year logging moratorium, providing critical insight into the long-term carbon effects of peatland revegetation, In contrast, Azizan *et al.* (2021) and Lestari *et al.* (2022) focused on monitoring of soil carbon fluxes.

Reducing fire

Studies reporting carbon outcomes of interventions to reduce fire through field-based monitoring were conspicuously absent from the results of our systematic search. Only Saragi-Sasmito *et al*. (2019) specifically mentioned reducing fire, stating "the ecosystem restoration program protects concession areas from any anthropogenic disturbances (e.g. wildfire, illegal logging, and agriculture)".

Table 4. Rewetting studies monitoring carbon outcomes. N.D. = 'no details'.

Source	Rewetting method	Material and construction details	Dimensions of canal	Number of canals	Number of blockings
Astiani *et al.* (2018)	Canal blocking; two-walled dams	Two-walled dam filled with sandbags and peat soil, excess water channelled over centre.	5–6 m wide; 3–4 m deep	N.D.	8
Azizan *et al*. (2021)	'Rewetting'; N.D.	-	N.D.	N.D.	N.D.
Budiman *et al*. (2020)	Canal blocking; N.D.	-	N.D.	1	2
Darusman *et al*. (2022)	Canal blocking; N.D.	-	2 m wide; 1.5 m deep; 3–5 m long	N.D.	N.D.
Jauhiainen *et al*. (2008)	Canal blocking; dams	Wooden framework and covering, filled with compressed peat.	25 m wide; 3.5–4.5 m deep	2	7
Lestari *et al*. (2022)	Canal blocking; U-notch weir	U-notch weir with plastic sacks filled with sand and mineral soil, placed deep in weir body for stabilisation and to prevent water leakage/peat erosion.	N.D.	1	1
Murdiyarso *et al*. (2019b)	Canal blocking; N.D.	-	N.D.	N.D.	N.D.

Table 5. Carbon flux monitoring reported and methods. Abbreviations: R_{total} = total soil respiration; R_h = heterotrophic respiration; DCC = dynamic closed flux chamber; SCC = static closed flux chamber; (D) = depression; (H) = hummock/high surface; DOC = dissolved organic carbon; POC = particulate organic carbon; DIC = dissolved inorganic carbon; δ13C-DIC = stable carbon isotope composition of DIC; WTL = water table level; N.D. = no details available.

Source	Land cover	CO_2 flux		CH_4 flux	Subsidence	Waterborne C	Vegetation	Monitoring start	Monitoring duration and frequency
		R_{total}	R_h						
Astiani *et al*. (2018)	Crops/degraded shrubland	DCC						Immediately post rewetting	12 months; weekly
Azizan *et al*. (2021)	Replanted forest	SCC		SCC				Six years post rewetting and commencement of revegetation	18 months; fortnightly
Budiman *et al*. (2020)	Agri-silviculture				X			N.D.	N.D.
Darusman *et al*. (2022)	Secondary forest		SCC	SCC		DOC and POC from peat pore water sampling	Litterfall production	N.D.	CO_2 and CH_4 flux: several days' sampling in wet season and dry season DOC and POC: once Litterfall: fortnightly for 12 months
Jauhiainen *et al*. (2008)	i. Secondary forest	SCC(D) DCC(H)		SCC (D)				14 months pre-rewetting	2 years; frequent measurements repeated at least three times for each 10-cm WTL change during both years of sampling.
	ii. Degraded shrubland	SCC(D) DCC(H)		SCC (D)					
Lestari *et al*. (2022)	Replanted forest	DCC	DCC	SCC				4 months pre-rewetting; 5 years post commencement of revegetation	CO_2: 4 sampling periods of several days, 2 before rewetting and 2 after rewetting CH_4: once 4 months before rewetting, once 8 months after rewetting
Murdiyarso *et al*. (2019b)	i. Secondary forest	DCC	DCC	SCC				~1 year post rewetting	R_{total} and CH_4: 2 occasions over 4 months R_h: 2 occasions over 2 months
	ii. Degraded shrubland	DCC		SCC					R_{total} and CH_4: 2 occasions over 4 months
Saragi-Sasmito *et al*. (2019)	Secondary forest	DCC	DCC				Litterfall and stem productivity	~2 years post commencement of restoration concession	CO_2: 12 months; 3 monthly Litterfall: 18 months; every 15 days Stem productivity: 12 months; measured once
Waldron *et al*. (2019)	Secondary forest					Fluvial DOC, POC, DIC, δ13C-DIC, CO_2 efflux and CH_4-C_{aq}		30 years post logging moratorium	Single sampling event

Table 6. Carbon stock monitoring reported and methods. Abbreviations: DBH = diameter at breast height; N.D. = no details available.

Source	Aboveground carbon (AGC)	Belowground carbon (BGC)	Soil organic carbon	Dead wood
Astiani *et al*. (2018)			Total carbon content (%); 1 m soil cores	
Azizan *et al*. (2021)			Total carbon content (%); composite sample taken from top 10 cm of peat profile	
Darusman *et al*. (2022)	Overstorey, saplings; allometric equation based on DBH (Manuri *et al*. 2014)	Roots; biomass calculated using root-to shoot ratio then converted to C (Suwarna *et al*. 2012)	Organic peat soil carbon stock; soil cores at intervals 0–15, 15–30, 30–50, 50–100, 100–200, 200–300 and >300 cm (Kauffman *et al*. 2016)	Wood debris; allometric equation (Novita *et al*. 2021). Standing deadwood; allometric equations (Manuri *et al*. 2014, Novita *et al*. 2021)
Murdiyarso *et al*. (2019b)	Trees, saplings, seedlings; allometric equations based on diameters (e.g. Manuri *et al*. 2014)	N.D., but root C presented	Peat soil carbon stock; soil cores at intervals 0–15, 15–30, 30–50, 50–100, 100–300 (Kauffman *et al*. 2016)	
Saragi-Sasmito *et al*. (2019)	"Living tree biomass"; allometric equation based on DBH (Manuri *et al*. 2014)	Roots; allometric equation based on DBH (Suwarna *et al*. 2012)	Organic peat soil cabon stock; soil cores at intervals 0–15, 15–30, 30–50, 50–100, 100–200, 200–300 and >300 cm, or until reaching mineral layer (Kauffman *et al*. 2016). Sampled with Eikelkamp soil auger	

Table 7. Revegetation studies monitoring carbon outcomes.

Source	Replanting	Forest protection	Description
Azizan *et al*. (2021)	x	x	Managed as restored peatland by Selangor State Forestry Department. Forest a combination of mixed swamp forest species, including replanted Tenggek burung (*Euodia redleyi*) and oil palm trees (previously cultivated illegally).
Lestari *et al*. (2022)	x		Community-initiated replanting of native species following fire.
Saragi-Sasmito *et al*. (2019)		x	Protected through restoration concession leased by PT. Rimba Makmur Utama (PT. RMU), operated as the Katingan Mentaya Project.
Waldron *et al*. (2019)		x	Protection through logging moratorium.

DISCUSSION

This review highlights a remarkable paucity of field-based research reporting carbon outcomes of tropical peatland restoration. Current research is highly concentrated in Kalimantan (Indonesia), Sumatra (Indonesia) and Selangor (Malaysia), thus research from other regions will contribute to a more comprehensive understanding of carbon dynamics following restoration. Local academia, non-profit organisations, government and the private sector collaborate to generate in situ research on carbon effects of tropical peatland restoration through authorships and provision and management of land for peatland restoration. Peatland restoration is a relatively new field of research, which has so far focused mainly on the fundamental efficacy of restoration strategies including (but not limited to) assessment of the capacity of canal blocking to effectively maintain a raised water table (e.g. Ritzema *et al.* 2014, Sutikno *et al.* 2020), selection of appropriate species for restoration, assessment of seedling survival, and revegetation strategy trials (e.g. Graham *et al.* 2013, Graham & Page 2018, Lampela *et al.* 2018, Smith *et al.* 2022). After restoration has been implemented, time is required for repeated sampling and monitoring of medium-term to long-term effects of the interventions (FAO 2020). Nevertheless, it is surprising that, given past and ongoing socio-political emphasis on peatland restoration and reduction of associated greenhouse gas (GHG) emissions, more studies have not been conducted which report field-based carbon effects of restoration efforts over the past two decades or across a wider range of provinces/states or countries. The studies detected through our systematic search represent crucial preliminary research in this space.

The focus of restoration monitoring on forested deep peat was unexpected given the strong emphasis on restoration of highly degraded deforested peatlands in Southeast Asia, particularly in Indonesia. This may be in part because the reinstatement of native vegetation is usually prioritised on deep peat, while shallower peat at the edge of a peat dome can be used for livelihood activities (Jessup *et al.* 2020). Indeed, Indonesian Government regulations state that peatland > 3 m deep should be considered a protected area where conversion to land uses including agriculture, agroforestry and plantations is prohibited (MoEF 2017). Monitoring carbon outcomes from restoration of more severely degraded non-forested landscapes is needed to represent the restoration activities taking place on the ground more comprehensively.

There is a critical lack of long-term monitoring of carbon storage and fluxes associated with tropical peatland restoration. Monitoring over multiple years is essential to capture the complexity of the processes at play. For instance, weather causes inter-annual variation in temperature, rainfall and light, which affect peat biogeochemical processes (Nijp *et al.* 2015) by influencing water table depth, soil temperature and plant growth (Teklemariam *et al.* 2010). Long time periods may also be required for the recovery of belowground microbial processes (Mishra *et al.* 2021) that influence peat soil carbon storage and flux. Longer term research determining effects of rewetting on peat soil carbon flux is essential to inform estimates of carbon storage change and reliable carbon emissions factors (Wilson *et al.* 2016b). Many tropical forest species are slow growing and long-lived (Smith *et al.* 2022), and when regenerating from a bare peatland state, vegetation communities move through different successional stages which may have varying carbon dynamics. Deriving conclusions from studies spanning only a few years risks drawing erroneous conclusions about the outcomes of peatland restoration (Joosten 2021). Overall, there is an urgent need for longer term, continuous studies that transcend funding and political time constraints and reflect the decadal-scale timeframes over which relevant ecological processes (i.e. forest recovery and peat accumulation rates) operate. In the case of peat surface carbon emissions, where continuous or near-continuous monitoring is not possible, repeated and/or seasonal monitoring should be implemented to ensure that results are representative of broader ecological contexts.

Baseline sampling of pre-restoration conditions, which is invaluable in establishing management objectives and enabling accurate monitoring of restoration effects (Gann *et al.* 2019), is also limited in the tropical peatland restoration literature. Carbon offset standards require a GHG emissions 'baseline scenario' prior to restoration activities, in order to convert emissions reductions to carbon credits (Richards & Huebner 2012). Although space-for-time comparisons (e.g. comparing a drained site with a rewetted site) can be used when pre-rewetting data are unavailable, baseline data have a unique role in generating accurate field data calibrated against the pre-restoration starting point, and would be of value in future research. Wherever possible, future research should include baseline monitoring undertaken before restoration begins.

Defining the spatial scale of restoration efforts is important to contextualise restoration efforts and to inform transferability to future restoration projects. However, the spatial extent (i.e. land area covered) of revegetation efforts for which carbon monitoring was representative was not reported in any of the studies identified for this review. Reporting the spatial extent of revegetation could, at a minimum, include the number of hectares over which revegetation is being undertaken. Reporting the number of individuals, vegetation total basal area, the number of species and survival rate over progressive years would also support contextualisation of ecosystem structure and complexity. Reporting the scale of rewetting efforts in tropical peatlands is challenging as there is currently no standardised unit of measurement to capture the extent or density of rewetting across a landscape. Standardised reporting of the spatial extent of restoration activities will assist in comparing the effects of different projects. Where multiple canal blockings are involved, standardised reporting of rewetting extent and density could be adapted from the formula used to calculate the optimum number and locations of dams for effective rewetting (Jaenicke *et al.* 2010). Specifically, we suggest that reporting of rewetting extent should include: (i) the width and total length of canal/s blocked, (ii) the types of blocking structures, (iii) the mean distance between blockings/dams, (iv) the number of blockings/dams and (v) the gradient or surface slope of the canal section being blocked.

The majority of field-based monitoring of carbon outcomes of peatland restoration focuses on rewetting, which was heavily weighted towards quantification of peat surface carbon fluxes using closed flux chambers. Because no single monitoring method can capture all elements of peat soil carbon fluxes (Table A2), it is vital that future research incorporates additional methods such as subsidence monitoring, eddy covariance and DOC/POC monitoring to assist in generating reliable carbon flux estimates. In other words, a holistic approach to carbon monitoring is important for complete carbon accounting, and to inform understanding of whole ecosystem carbon recovery.

The small number of revegetation studies returned through our systematic search may reflect that successful revegetation trajectories are often hampered by disturbance, especially recurrent fire and flooding, as well as social and political barriers (Harrison *et al.* 2020). Particularly, short funding periods and political terms are not compatible with the long timeframes required to adequately monitor revegetation trajectories, which can span decades (Harrison *et al.* 2020). While causal relevance exists for monitoring soil carbon fluxes associated with revegetation, both Azizan *et al.* (2021) and Lestari *et al.* (2022) concurrently investigated rewetting, which may have been the more prominent motivation for measuring these carbon components. Nonetheless, these studies provide urgently needed insights into carbon flux outcomes of peatland revegetation initiatives. Although the vegetative carbon pool of tropical peat swamp forests is smaller than the peat soil carbon pool, it is surprising that more revegetation studies did not monitor biomass carbon pool changes associated with vegetative carbon sequestration, arguably the most direct contribution of revegetation to the reduction of tropical peatland emissions.

Our review detected only one study incorporating field-based monitoring of fire reducing interventions. Quantifying reductions in carbon emissions from reducing fire activities through field-based methods is undoubtably conceptually and methodologically challenging. Eddy covariance flux towers are one potential tool, capable of measuring net ecosystem exchange during a fire event and throughout subsequent ecosystem recovery, and have been used to this end in other ecosystems (e.g. Beringer *et al.* 2007). Various field-based monitoring methods could also be combined to produce a measure of carbon outcomes from reducing fire; for example, incorporating locally-derived peat fire carbon emissions from burned depth and area estimates (e.g. Graham *et al.* 2022) or monitoring of biomass, peat soil carbon storage and greenhouse gas fluxes undertaken during post-fire landscape recovery**.**

Partitioning and correct attribution of tropical peatland carbon outcomes to specific fire reducing strategies, as well as partitioning from naturally occurring environmental correlates, also presents challenges. For example, La Niña years bring increased rainfall to the Southeast Asian region and, therefore, reduced peat fire occurrence (Van Der Werf *et al.* 2008), which must be considered when attributing emissions reductions to social or policy-driven fire mitigation activities. Partitioning carbon outcomes of social and policy-based activities (e.g. resolving land tenure and conflict issues or raising public awareness to promote behaviour change to reduce fires) may be difficult and unrealistic to achieve in many circumstances. The reductions in carbon emissions through reducing fire, and socio-political focus on peat fire mitigation (Syaufina 2018) warrants further exploration and application of field-based measurements for quantifying carbon outcomes of reducing fire interventions.

Carbon outcomes of temperate and boreal peatland restoration have been more extensively studied over the past 30+ years compared to tropical peatlands, yet similar challenges to those identified in our review persist. There are calls for longer term (> 5 years) studies quantifying how GHG emissions respond to restoration in North American and European peatlands, including appropriate baselines, controls, reference sites, and monitoring across a broader range of land use types and geographical regions (Andersen *et al.* 2017, Chimner *et al.* 2017). For example, despite an extensive review of both peer reviewed and grey literature, Wilson *et al.* (2016a) could not examine links between rewetted organic soil GHG fluxes and previous land use history, time since rewetting or vegetation composition, due to insufficient data from temperate and boreal field studies. Nugent *et al.* (2018) identified that, aside from their work in a Canadian peatland, long-term datasets of net ecosystem carbon balance had only been reported from several Irish restoration sites. One such study monitored GHG emissions at a rewetted industrial cutaway peatland 7–12 years post-rewetting, and demonstrated that multi-year monitoring is critical for accounting for inter-annual variation in carbon outcomes (Wilson *et al.* 2016b). However, funding constraints in both time and scope are cited as barriers to comprehensive monitoring in temperate and boreal regions (Halme *et al.* 2013, Andersen *et al.* 2017), illustrating that these issues are not unique to tropical peatlands. In their recent global meta-analysis of the effects of peatland rewetting on CO_2, CH_4 and DOC fluxes, Darusman *et al.* (2023) also call for extended monitoring periods and better integration of baseline measurements and control sites from all regions, particularly boreal and tropical climate zones. International efforts to address these issues and provide guidance on pathways for effective peatland restoration monitoring are ongoing, for example, by the Food and Agriculture Organisation of the United Nations (FAO 2020) and through the Global Peatland Assessment (UNEP 2022).

This systematic review provides a unique and timely appraisal of the status of tropical peatland research implementation. We hope the findings will encourage further research that continues to improve understanding of the carbon outcomes of peatland restoration efforts, in turn bolstering the available ground-truthed data that is fundamental to the implementation and evaluation of peatland restoration.

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ALS conceived the review concept, undertook the systematic review and wrote the manuscript; LLBG and SPG provided feedback and edited the manuscript. We thank the anonymous reviewers whose feedback improved this manuscript.

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Appendix

Table A1. Information recorded (where available) for all items returned by the systematic literature search.

Category	Information recorded
General details	• Authors • Year of publication • First author institutional affiliation (academic, government, NGO) • Proportion of authors with country-of-study organisation affiliation • Restoration strategy investigated (rewetting, revegetation, reducing fire)
Study site details[1]	• Study location • Land tenure details • Peat depth • Land use and land cover description • Restoration strategy implemented (rewetting, revegetation, reducing fire)
Rewetting	• Rewetting method - if canal blocking, materials and construction details • Dimensions of canal blocked • Number of canals blocked • Number of blocks
Revegetation	• Type of revegetation and context description • Total area revegetated
Reducing fire	• Type of fire reduction strategy
Carbon flux monitoring	• Type of carbon flux monitored, including: o soil CO_2 and CH_4 fluxes o dissolved organic carbon (DOC) and particulate organic carbon (POC), and other fluvial carbon components o CO_2 equivalents from peat subsidence o litterfall or plant productivity measures converted to carbon units • Monitoring method details • Monitoring start in relation to restoration implementation • Monitoring duration and frequency
Carbon stock monitoring	• Type of carbon stock monitored, including: o aboveground carbon o belowground carbon o soil organic carbon o dead wood o litter • Monitoring method details

[1] Of special note were two studies undertaken in the North Selangor Peat Swamp Forest (NSPSF). Though all of Selangor State was subject to a logging moratorium in 2010, challenges still exist within the NSPSF with respect to legal and illegal land development and recurrent fire, and some areas are managed as oil palm plantations (SSFD 2014). Thus, we report as relevant to our aims only findings from sites framed by the NSPSF researchers as restoration, to avoid erroneously applying assumptions of a restoration context. Similarly, three of the studies detected through our systematic search were from the Katingan Mentaya Project, which operates as an Ecosystem Restoration Concession to protect the area from anthropogenic disturbances (Saragi-Sasmito *et al*. 2019). While any study at this location incidentally includes an element of revegetation and fire reduction through protection from illegal logging and fire, we recorded each study as investigating only the restoration strategy that was the specific focus of the publication, thus aligning with the original research intent.

Table A2. Common field-based methods for quantifying peat carbon emissions and examples of benefits and limitations, summarised from Couwenberg *et al*. (2010) and Page *et al*. (2011b)

Method	Description	Benefits	Limitations
Closed flux chambers	• Measure surface-to-air gaseous fluxes within a small chamber on the peat surface. • Can be either 'static', in which multiple gas samples are taken over several time steps using a syringe and later analysed in a laboratory, or 'dynamic', in which air is circulated through a portable gas analyser.	• Portable. • Can be used to provide fine-scale data such as diurnal or seasonal fluxes. • Dynamic chambers enable real-time flux measurements in the field.	• Does not capture carbon lost as DOC or POC. • Changed temperature and pressure within the chamber space during long measurement periods may affect flux rates. • Variations in chamber headspace microclimate. • Sampling often biased toward diurnal measurement or one season.
Total respiration	• Closed chambers are most commonly used to measure total respiration, inclusive of both CO_2 flux from peat and litter decomposition (heterotrophic respiration), and root respiration (autotrophic respiration).		• In isolation, total respiration measurements cannot be used to quantify net CO_2 emissions because CO_2 from autotrophic respiration is generated through metabolism of recent photosynthates that do not contribute to net CO_2 emissions.
Trenching	• Used to partition heterotrophic and autotrophic respiration. Involves cutting the roots of plants that extend into the peat being sampled, often by inserting a physical barrier that also prevents growth of new roots into the section being sampled.	• Currently the most accessible field method for partitioning heterotrophic and autotrophic respiration.	• Cutting roots may alter peat thermal and hydrological properties, and disrupt the rhizosphere priming effect, in which plant roots and exudates stimulate heterotrophic processes. Cut roots can also continue to respire for months.
CH_4 fluxes	• Closed chambers can measure CH_4 emissions from organic matter decomposition.		• Care must be taken to avoid artificially causing sporadic spikes in CH_4 fluxes through disturbances.

Method	Description	Benefits	Limitations
Subsidence monitoring	• Measures peat subsidence (i.e. changes to the peat thickness) using poles inserted into the peat and anchored in the underlying substrate, which can then be used to estimate peat carbon stock changes by incorporating peat carbon concentration and bulk density. • Subsidence integrates carbon lost through gaseous CO_2 and CH_4, DOC and POC, reported as $CO_{2\text{-eq.}}$.	• Captures total carbon loss from peat soil. • Thought to be more robust than closed chambers when estimating peat carbon loss from drainage, as measures of peat net carbon balance are time integrated.	• Subsidence is a slow process that requires repeated measures over several years. • Cannot provide fine-scale temporal data such as diurnal or seasonal fluxes. • Cannot partition individual carbon fluxes. • Cannot investigate micro-scale peat characteristics such as topographical variation. • Requires accurate bulk density data. • Assumes drainage is the only contributor to subsidence, ignoring potential interactive effects of peat depth and type, land use history, temperature etc.
Eddy covariance (EC)	• Measures net ecosystem exchange and CH_4 flux using micrometeorological instruments and theory. Instruments are typically mounted on an EC ‘flux tower’ above the vegetation canopy.	• Widely acknowledged as optimum method for quantifying ecosystem-atmosphere GHG budgets. • Provides direct, continuous, whole-ecosystem, multi-year measurements. • Can obtain measurements over a large area (e.g. the hectares/km^2 scale at forest sites).	• Inevitable data loss necessitates gap filling. • In isolation, cannot partition autotrophic and heterotrophic respiration components. • Cannot provide small-scale carbon flux details. • Challenging to apply in heterogenous landscapes when wind direction is variable (alters sampled ‘footprint’). • Expensive and highly technical methodology, and instruments need a continuous power source. • Does not capture carbon loss as DOC or POC.
Dissolved organic carbon (DOC) and particulate organic carbon (POC) monitoring	• DOC and POC concentrations and fluvial discharge rates are combined to estimate fluvial DOC and POC flux.	• Reports an important, often overlooked carbon flux.	• Only measures fluvial carbon.