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ORIGINAL ARTICLE

Tropical peatlands under siege: the need for evidence-based policies and strategies

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Abstract

It is widely known that tropical peatlands, including peat swamp forests (PSFs), provide numerous ecosystem services in both spatial and temporal dimensions. These include their role as large stores for organic carbon, which when not managed well could be released as carbon dioxide and methane, accelerating climate warming. Massive destruction and conversion of peatlands occur at an alarming rate in some regions. We hope that the lessons learned from those regions currently under siege from conversion can inform other regions that are at the precipice of mass conversion to agriculture. Much has been learned about high latitude, northern hemisphere peatlands but less is known about tropical peatlands. We collate, analyze, and synthesize the evidence revealed from the set of articles in this special issue. This special issue is a step forward, presenting new information generated from a considerable amount of field data collected from peatlands across the tropics in Asia, Africa, and Latin America. The hard data collected using comparable scientific methodologies are analyzed and compared with existing published data to form a larger dataset as scientific evidence. The synthesis is then interpreted to generate new knowledge to inform the policy community on how to strategize the sustainable management of tropical peatlands. Carbon (C) stocks in tropical peatland ecosystems can be as large as 3000 Mg C ha^{-1}, but the rate of loss is also phenomenal, causing substantial emissions of greenhouse gases of more than 20 Mg C ha^{-1} year^{-1}. These losses have mainly taken place in Southeast Asia, particularly Indonesia, where peatland development for oil palm and pulpwood has accelerated over the past few decades. Although peatlands in the Amazon and Congo Basin are less developed, it is possible that the same unsustainable pathway would be followed in these regions, if lessons from the dire situation in Southeast Asia are not learned. Strong policies to halt further loss of tropical peatlands may be drawn up and combined with incentives that promote a global agenda under the United Nations Framework Convention on Climate Change 21st Conference of the Parties, Paris, France, Agreement. However, we also propose a framework to address national and local agendas that can be implemented under the nationally determined contributions (NDCs) by balancing conversion/development and conservation/restoration objectives.

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1 Introduction

Global change is a multifaceted phenomenon largely driven by human decisions, mainly in the energy and land use sectors. The effect of land use change on emissions of greenhouse gases (GHGs), which in turn drive climate change and global warming, is unprecedented. In the tropics, one of major land uses is the conversion of peat swamp forests (PSFs) to other uses, mainly oil palm and fast-growing tree plantations. Having large amounts of organic carbon, these vulnerable wetland ecosystems have become a major source of atmospheric carbon dioxide (CO_2). Traditionally, they were reported under the agriculture, forestry and other land use (AFOLU) scheme of the Intergovernmental Panel on Climate Change guidelines (IPCC 2006). More recently, the wetland sector has been directly addressed using the Wetlands Supplement (IPCC 2014), an updated GHG accounting guidance, which continues to improve as more accurate emission factors are made available.

The challenges and opportunities associated with tropical peatland conversions surfaced at the 15th International Peat Congress, which was held in the tropics for the first time in Kuching, Malaysia, in August 2016. Under the theme of *Peatlands in Harmony-Agriculture, Industry & Nature*, the outcomes of the Congress as portrayed by the media were not shared by a large group of scientists. The scientific community responded that the message ignored the long-term negative consequences of agricultural practices that have been documented in tropical peatlands (Wijedasa et al. 2016). Tropical peatlands in Southeast Asia continue to be converted at an alarming rate, threatening its large stock of carbon, estimated to be approximately 69 Pg C (Page et al. 2011). Following drainage of peatlands (Couwenberg et al. 2009; Hirano et al. 2012; Carlson et al. 2015) and fire (Jaafar and Loh 2014; Chisholm et al. 2016; Stockwell et al. 2016), the contribution of GHGs to global warming has accelerated and reaches a globally significant scale. For example, the daily fire emissions from Southeast Asia in one single El Nino event during September–October 2015 resulted in a daily emission rate of GHGs that exceeded that of 28 European Union countries combined (Huijnen et al. 2016).

A scientific session on tropical peatlands was organized at the 125th Anniversary Congress of the International Union of Forestry Research Organizations (IUFRO) held in Freiburg, Germany, in September 2017. This synthesis presents an overview of this set of scientific papers presented in a special issue of this journal with the theme of "Tropical peatlands under siege: the need for evidence-based policies and strategies." The special issue features cases across the tropics, especially from Indonesia, Peru, and the Republic of the Congo. The lessons learned from Indonesia can be shared with Peru and the Republic of the Congo in the context of mitigating climate change by reducing GHG emissions due to PSF deforestation and degradation. The information and data gathered, including emission factors generated from the work in these regions, may be directly used for GHG inventories under the new guidelines specially designed for wetlands, including peatlands (IPCC 2014).

Most tropical peatlands in Southeast Asia have been under siege since the 1980s and continued to be converted in the following two decades (1990–2010), with a total deforested area of 3.1 Mha (Miettinen et al. 2012a). Efforts to halt further deforestation and degradation were launched in Indonesia in 2011 by imposing a moratorium under Presidential Decree No. 10/2011. National policy efforts to restore degraded peatlands materialized 5 years later with Presidential Decree No. 1/2016, which established a new government unit, the Peatland Restoration Agency, which is tasked to restore more than 2 Mha of degraded PSFs (BRG 2016).

These ambitious top-down policies need the scientific community to help guide the policy to meet the multiple objectives envisioned, including GHG emission reduction. Multiple studies in this issue generated data that can be used to refine emission factors (e.g., Murdiyarso et al. 2018; Basuki et al. 2018; Saragi-Sasmito et al. 2018; van Lent et al. 2018), which are critical to quantifying the importance of tropical peatlands in global GHG budgets. The data reported in this special issue enrich existing information, including the published emission factors in the Wetland Supplement of the IPCC guidelines (IPCC 2014).

The method of our assessment in this special issue of papers is to understand the drivers of peatland conversion in Indonesia and then consider whether those drivers could lead to similar patterns in other tropical regions. The Peruvian Amazon, where extensive lowland peatlands occur, was hypothesized as a region that could be susceptible to mass conversion if drivers of change aligned that were similar to those in Indonesia (Lilleskov et al. 2018, this issue). Major questions guiding this assessment include: To what extent can the drivers of land use change be identified? How do land use change trajectories affect the release of stored carbon into the atmosphere? Can lessons learned from policy development in Indonesia inform the kinds of policies and measures that would be appropriate for other regions and countries? Similar questions may be asked for the less disturbed tropical peatlands recently discovered in the Congo Basin (Dargie et al. 2018, this issue).

This synthesis aims to connect options of policies and measures with Nationally Determined Contributions (NDCs) under the United Nations Framework Convention on Climate Change 21st Conference of the Parties, Paris, France, Agreement and mitigation strategies. Globally agreed mechanisms such as Reduced Emissions from Deforestation and forest Degradation (REDD+) and Nationally Appropriate Mitigation Actions (NAMAs) are also discussed.

2 Regional trends

The largest distribution of peat volume is found in South America, estimated to be 30, 100, and 5 times more peatland volume in Brazil, Colombia, and Peru than previously estimated, respectively (Fig. 1; Gumbricht et al. 2017). Clearly, these discrepancies call for greater levels

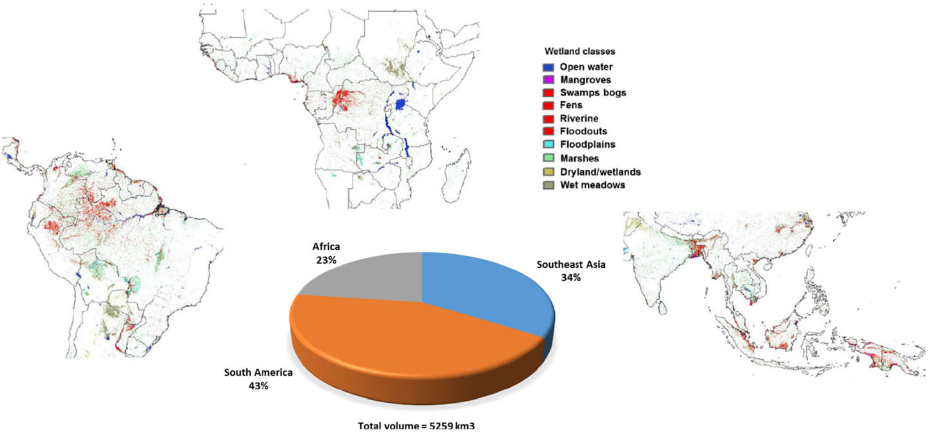

Fig. 1 MODIS-based tropical wetland distributions, including peatland distributions in South America, Africa, and Asia derived from an expert system model, and the associated peat volume (adapted from Gumbricht et al. 2017)

of ground-truthing of stocks, assessment of land use change, and the measurement of emissions of these remote peatlands.

Tropical peatland forest logging in Southeast Asia started in the late 1970s and early 1980s, but it mostly took place in lowland dipterocarp-dominated forests in Indonesia and Malaysia. This policy-driven logging was associated with land development for agriculture and human settlement. Since the early 1990s, peatlands in Sumatra, Indonesia, became very attractive to investors for oil palm and pulpwood plantations. The World Bank predicted that more than 5.5 Mha of peatlands would be converted into plantations; however, this estimate was not achieved and the area converted was only 2.5 Mha in 1998 due to the economic downturn in 1997 (Murdiyarso and Adiningsih 2007), despite the application for expansion in 1995 of 15.7 Mha (World Bank 1999). By 2010, oil palm plantations occupied around 2.5 Mha of peatlands and are projected to be more than 3.5 Mha in 2030 (Miettinen et al. 2012b). Another significant policy-driven land development was the conversion of approximately 1.4 Mha of peat swamp forests in Central Kalimantan during the mid to late 1990s (World Bank 1999; Murdiyarso and Adiningsih 2007). The issuance of Presidential Decree No. 82/1995, known as the Mega Rice Project, marked the creation of 0.5 Mha of rice fields and tree crops involving more than 1 Mha of peat swamp forests and the construction of 700 km of primary canals (25 m wide and 6 m deep) and numerous secondary canals. The project failed and left mounting ecological problems, including fires and long-lasting emissions of GHGs.

In Malaysia, of its 2.5 Mha of peatland, more than 1 Mha ha has been converted into oil palm, which is projected to occupy 2.3 Mha in 2030 (Miettinen et al. 2012b). Most of these activities (80%) have taken place in the state of Sarawak.

Gumbricht et al. (2017) showed that the extent of Amazonian peatlands (461,844 km^2) is more than double compared with those found in Indonesia (225,420 km^2); while the undisturbed peatlands are largely unquantified carbon sinks, they are potentially significant sources of carbon if disturbed by land use or climate change (Lähteenoja et al. 2009). Much of the Peruvian Amazon peatlands, which cover an area of 74,644 km^2, are dominated by economically important species of palm (*Mauritia flexuosa*) known as *aguaje*. The harvest of palm fruits by cutting the female trees affects the sustainability of the *aguaje* (see Bhomia et al. 2018, this issue). Besides this small-scale degradation, currently, there is not rapid conversion via policy-driven land use change as was experienced in Southeast Asia. However, the lack of explicit policies regarding peatland land uses, especially those that lead to oil and gas exploration, road expansion, agriculture, and peatland drainage, provides little protection as economic pressures mount (Lilleskov et al. 2018, this issue).

In the *Cuvette Centrale* of the central Congo Basin in Africa, a large area of peatlands was recently discovered, encompassing 145,500 km^2 and containing approximately 30.6 Pg C (Dargie et al. 2017). The potential threats to Congo Basin peat carbon stocks are hydrocarbon exploration, mining, logging, and plantations (Dargie et al. 2018, this issue). The low level of human intervention at present may be anticipated to provide improved and sustainable livelihoods for people depending on peatlands. In addition, the *Cuvette Centrale* peatlands, which have low rainfall compared with other tropical peatland regions, may be more susceptible to climate change impacts related to changes in rainfall intensity and frequency of drought (Haensler et al. 2013).

3 Some evidence and possible future research directions

Five studies on Indonesia, three studies on Peru, and one study on the Congo Basin published in this special issue were assessed to obtain information on drivers of land use change, emission factors, and pathways of GHG emissions. The evidence in terms of GHG fluxes and associated drivers was compared and the gaps are discussed to guide future research directions. The synthesis of these studies should inform peatland restoration policies and best practices such as those being implemented in Indonesia. Even if the current converted land use is going to persist, mitigation measures such as REDD+ may be proposed and guidance provided.

3.1 Emission factors

Among other parameters, the most important parameter the policy community and practitioners would like to elucidate is the peatland conversion emission factor (EF). The EF is a parameter that determines how changes in land management affect GHG emissions. Land managers need to base decisions on minimizing GHG emissions if they aim to have sustainable land uses that are environmentally friendly, economically viable, and socially acceptable. These emission factors need to consider changes in storage in both vegetation and peat, the latter of which is the much larger pool.

Considering only vegetation, along the trajectory of land use change from secondary PSF conversion to oil palm plantation, PSFs usually pass through a transition stage in the form of shrub or abandoned area in the land use trajectory. Table 1 summarizes the EF at each stage based on the stock difference approach for vegetation.

The factors summarized in Table 1 indicate that the more disturbed the ecosystem, the more emissions that resulted. Among other converted ecosystems that had large emissions (and hence were most degraded) were the deforested and drained PSFs that underwent fires, with emissions of 20.4 ± 2.9 Mg CO_2 ha^{-1} $year^{-1}$.

Examining the C stocks categories of the *aguaje*-dominated palm swamp forest ecosystems (*aguajales*) in the Peruvian Amazon, Bhomia et al. (2018) (this issue) developed an index of forest degradation level based on *aguaje* size distribution and amount of downed woody debris. They concluded that the *aguajales* did not differ significantly in degradation between the three sub-watersheds sampled. Within each watershed, there was a wide range of degradation scores. As degradation increased, *aguaje* biomass decreased significantly, whereas there was a non-significant trend to lower total forest biomass. It will take additional work, such as longitudinal studies in fixed plots, to translate these extractive disturbances to emission factors.

Alternatively, emission factors may be estimated using a gain–loss approach in a particular type of conversion. Estimations are based on the carbon balance between the gain (from carbon sequestration during photosynthesis causing growth in biomass, dead wood, and organic litter accumulation) and the loss (due to respiration, harvest, and fire). This approach includes both changes in phytomass and soil carbon. Large temporal and spatial variabilities

Table 1 Emission factors derived from C stock differences of vegetation from intact PSFs of 206.7 ± 37.6 Mg ha^{-1} into other land use types (adapted from Hergoualc'h and Verchot 2011)

Land use type	Initial biomass C (Mg ha^{-1})	C stocks difference (Mg ha^{-1})	Emission factor (Mg C ha^{-1} $year^{-1}$)*
Drained degraded secondary PSF ($n = 27$)	102.8 ± 27.8	116.9 ± 39.8	11.7 ± 4.0
Drained shrub that has undergone fires ($n = 55$)	15.7 ± 3.7	204.1 ± 28.6	20.4 ± 2.9
Oil palm (calculated)	31.6 ± 8.8	188.1 ± 29.8	7.5 ± 1.2

*25 years of rotation for oil palm and 10 years since conversion for other land use types will be inevitable, but they capture in situ processes, which represent the characteristics of the system as summarized in Table 2. The C balance may be converted into emission factors by multiplying with 3.67, which is the ratio of CO_2/C molecular weights.

3.2 Partitioning autotrophic and heterotrophic soil respiration

The use of the term respiration connotes the production of CO_2 by organisms, including plants. There are two different pathways that contribute to total respiration for ecosystems. Autotrophic (plant) respiration carried out by living roots and shoots is controlled by plant ecophysiological processes, while heterotrophic respiration in soils refers largely to microbial processes, and mediates the decomposition of soil organic matter. The latter is largely regulated by water tables and resultant limitations to oxygen availability, and secondarily by other environmental factors.

Direct soil respiration measurements conducted in drained forested peatlands that were converted to shrublands and underwent fires in Central Kalimantan emitted 52.4 ± 4.1 Mg CO_2 ha^{-1} $year^{-1}$, and from rewetted secondary PSFs emitted 42.9 ± 3.6 Mg CO_2 ha^{-1} $year^{-1}$ (Murdiyarso et al. 2018; this issue). These soil respiration measurements must be combined with other approaches (e.g., estimates of net primary production and DOC production) to close the carbon budget, and require additional partitioning approaches to provide estimates of heterotrophic soil respiration.

Partitioning of respiration into heterotrophic and autotrophic components is important for a number of reasons. By altering the environment to reduce heterotrophic and/or autotrophic respiration, there is an opportunity to reduce CO_2 emissions as part of mitigation actions. Reductions of heterotrophic respiration are particularly important to minimize carbon losses from ecosystems, and estimates of heterotrophic respiration are needed to calculate soil emission factors. Hence, it is important to partition heterotrophic and autotrophic respiration as components of soil respiration to understand the impact of management on heterotrophic fluxes. Trenching soils to exclude root respiration is one way to estimate the heterotrophic contribution to soil respiration. By subtracting heterotrophic respiration from total respiration, one may get estimates of autotrophic respiration. As shown in Table 3, in many cases, including those from this volume, heterotrophic respiration dominates total soil respiration, indicating that deforested PSF soils continue to decompose and remain a major source of CO_2. The fact that heterotrophic respiration in intact and drained areas does not appear to be significantly different merits further investigation.

Table 2 Emission factors derived from a gain–loss or flux change approach for land use change from PSFs to other land use types (adapted from Hergoualc'h and Verchot 2014)

Land use type	C gain (Mg C ha^{-1} $year^{-1}$)	C loss (Mg C ha^{-1} $year^{-1}$)	C balance	Emission factor (Mg CO_2 ha^{-1} $year^{-1}$)
Intact PSF (*n* = 33, 15)	8.9 ± 1.4	7.5 ± 1.1	− (1.4 ± 1.8)	− (5.1 ± 6.6)
Drained degraded secondary PSF (*n* = 62, 23)	5.1 ± 2.3	10.4 ± 1.1	5.3 ± 2.6	19.5 ± 9.5
Drained shrub underwent fires (*n* = 9, 24)	4.2 ± 1.0	15.4 ± 1.5	11.2 ± 1.8	41.1 ± 6.7
Oil palm (*n* = 8, 11)	5.0 ± 1.0	13.2 ± 2.7	8.2 ± 2.9	30.1 ± 10.6

Negative (emission) sign indicates net gain of CO_2 when atmospheric CO_2 is sequestered

The two numbers within the brackets indicate the number of sample to estimate C gain and C loss respectively

Table 3 Heterotrophic and total soil respiration from different types of land use before and after PSF conversion in Indonesia

Location	Soil respiration ($Mg\ ha^{-1}\ year^{-1}$)		Land use type	Reference
	Heterotrophic	Total		
Jambi, Sumatra	9.6 ± 7.7	20.2 ± 3.4	Primary peat swamp forest	Comeau 2016
	15.7 ± 1.0	18.7 ± 1.1	Degraded peat swamp forest	
	22.9 ± 2.0	26.4 ± 1.7	Oil palm plantation	
Ketapang, West Kalimantan	37.7 ± 2.4	48.5 ± 2.7	Peat swamp forest	Basuki 2017
	40.7 ± 1.2	50.2 ± 2.4	Logged peat swamp forest	
	30.7 ± 2.5	40.8 ± 2.3	Early seral (shrub)	
	38.7 ± 2.0	47.5 ± 1.6	Smallholder oil palm	
Tanjung Puting, Central Kalimantan	25.5 ± 1.0	35.1 ± 1.3	Primary peat swamp forest	Hergoualc'h et al. 2017
	29.8 ± 1.1	30.6 ± 1.6	Oil palm (2 years)	
	24.2 ± 1.0	37.3 ± 1.2	Oil palm (7 years)	
Katingan, Central Kalimantan	20.8 ± 1.3	42.9 ± 3.6	Secondary peat swamp forest	Murdiyarso et al. 2018 (this issue)
Sebangau, Central Kalimantan	–	73.1–74.4	Primary peat swamp forest	Jauhiainen et al. 2008
	–	27.8–26.1	Deforested peatlands	

By separating heterotrophic respiration from total respiration, we can test the effect that rewetting of drained peatlands has on soil CO_2 fluxes and help evaluate rehabilitation or restoration methods. Moreover, the calculated autotrophic respiration data may be used to help determine the species to be introduced in replanting activities. Figure 2 summarizes the pathways of carbon cycling from various compartments of carbon-rich peatlands.

3.3 Net primary production and net ecosystem production

As shown in Fig. 2, gross primary production (GPP) does not predict the carbon balance of ecosystems because of the importance of respiratory losses. The better indicators of the system productivity are net primary production (NPP) and net ecosystem production (NEP), which are respectively defined as:

$$\mathrm{NPP} = \mathrm{GPP}-\mathrm{Ra} \tag{1}$$

And

$$\mathrm{NEP} = \mathrm{GPP}-\mathrm{Ra}-\mathrm{Rh} \tag{2}$$

And, by substitution from Eq. 1

$$\mathrm{NEP} = \mathrm{NPP}-\mathrm{Rh} \tag{3}$$

where Ra is autotrophic respiration and Rh is heterotrophic respiration. Separating Rh from the total respiration reported in this issue (Murdiyarso et al. 2018; Saragi-Sasmito et al. 2018) is a useful approach to estimating NEP when combined with separate estimates of NPP. The latter

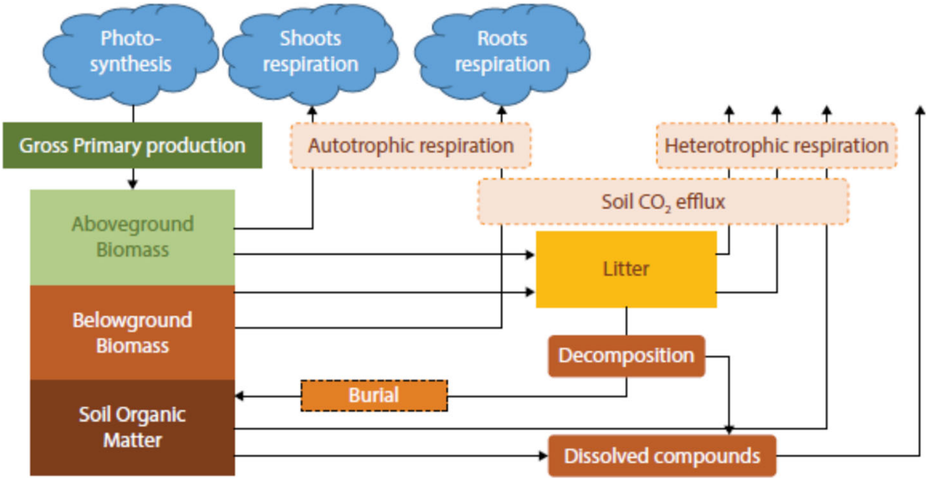

Fig. 2 Carbon pools and fluxes in peatlands and the processes and pathways that influence those pools and fluxes

is a close approximation to total ecosystem carbon balance, once other loss terms such as DOC export and loss of other gasses (e.g., CH_4) are accounted for.

Direct measurement of NPP, undertaken by Basuki et al. (2018) in this issue, provides insight into land use impacts on components of carbon cycling. Aboveground NPP was estimated by summing litter production and forest growth, and belowground NPP (BNPP) by allometry. The authors point out that the source for root allometry is from a different ecosystem type, suggesting the need for better estimates of BNPP in Indonesian peatlands to constrain ecosystem C budgets. The approach was applied in PSFs, logged PSFs, smallholder oil palm plantations, and shrub areas (early seral) following PSF conversion and indicated that NPP was highest in the intact peat swamp forests, and declined in logged, early seral, and oil palm stands.

Complementing these estimates with estimates of heterotrophic respiration (Basuki 2017) would provide an estimate of NEP (Eq. 3). Based on NEP, it was found out that logged PSFs and smallholder oil palm were net sources of CO_2. In contrast, PSF and early seral were net sinks (Basuki et al. 2018, this issue).

3.4 Water regimes and emissions

Measuring the entire hydrologic cycle is difficult and knowledge is limited to support and lead to improvements in existing regulations. However, several more easily measurable peat water properties are indicative of the water regime and have been explored in the present issue. Saturated hydraulic conductivity was found to be a useful characteristic to further describe peat properties with regard to water regimes (Kurnianto et al. 2018; this issue), information necessary to accurately model peatland hydrology. Additionally, van Lent et al. (2018; this issue) demonstrated that the wetness of peat is well represented by water-filled pore space (WFPS) and WFPS in turn predicted emissions of CO_2. Swails et al. (2018; this issue) successfully used remote sensing to estimate peatland water storage anomalies, which in turn explained a large percentage of the variation in soil respiration, providing a promising approach for landscape-scale estimates of peat water status, peatland fires, and greenhouse gas emissions.

4 Policy implications

The presence of water or waterlogged environments is essential for the stability of tropical peatlands. Understanding peatland hydrology and water regimes is key in framing strategies for the restoration or rehabilitation of degraded peatlands and conservation of intact peatlands. One of the most direct ways to restore degraded peatlands and probably the most effective means to reduce GHG emissions is rewetting drained peatlands. In the case of Indonesia, a number of compliance points were established and are being monitored by the government. These policy-driven regulations create incentives for those who comply and disincentives for those land managers who do not. Improved ability to model and remotely monitor peatland hydrology provided by several of the papers in this special issue will increase our ability to monitor the effectiveness of such policies.

Improved knowledge about peat characteristics would enhance a country's capacity in monitoring, reporting, and verification (MRV). The National Communication and Biennial Update Report (BUR) would benefit immensely from the availability of information addressing emission factors and ancillary data related to peat characteristics. Likewise, project-based activities such as REDD+ and NAMA would generate better outcomes and with their greater credibility, when directly adopting high-tier emission factors offered in this special issue.

Common themes seem to be emerging regarding threats to the relatively intact peatlands of Africa and South America. In the Congo Basin, which covers the Republic of the Congo (ROC) and the Democratic Republic of the Congo (DRC), Dargie et al. (2018; this issue) indicated the potential threats relating to peatland degradation include infrastructure development and support for hydrocarbon exploration and mining. Both disturbances would require strong policy aimed at the protection of national parks scattered in the region. Similarly, in Peru, the lack of policy to protect unique peat swamp forests (both *aguajales* and pole forests) in the Peruvian Amazon combined with plans to expand road networks in the area (Lilleskov et al. 2018; this issue) indicates a looming threat to peatland integrity. Table 4 summarizes the options of policy and measures to be explored in the abovementioned regions with different challenges.

If the scale of the activities is assumed to be closely linked with the geographic coverage, small-scale projects may be implemented at a subnational level, while large-scale projects or programs may be governed at a national level. A framework is needed to strategize the implementation to ensure the balance between conservation and development objectives is built around the climate agenda. It is necessary that such a framework is supported by the availability of technical support, legal arrangements, and financial mechanisms. Figure 3 shows technical support actions (MRV system), possible legal arrangements (regulatory framework), and financial mechanism (payment or incentives) directions.

It is obvious that the action at national level can be completely different in terms of the expertise needed, legal arrangement required, and the basis of benefit sharing. While peatlands are very important and yet vulnerable ecosystems globally, the challenges along the conservation and development nexus can be very different from one region or country to the other. Innovative ways of blending them are required and being mindful of the local context is crucial.

Peatland conservation is very much in line with mitigation measures, while restoration could be treated as adaptive management or adaptation to the changing climate. Globally, this approach is mandated under the Paris Agreement, namely the NDC, by which adaptation and mitigation may be implemented in a balanced manner.

Table 4 Summary of options for policy and measures to meet national and subnational agendas that align with the global agenda through adopted international treaties. See Lilleskov et al. (2018; this issue) and Dargie et al. (2018; this issue) for expanded discussion of policy options

Region and general peat type	Global agenda	National agenda	Subnational agenda
Asia Ombrotrophic, often deep	- NDC - REDD+ - Aichi Biodiversity Targets - Ramsar Convention - Green Climate Fund	- Restoration through rewetting and revegetation - Fire avoidance - Exploring C market	- Sustainable livelihoods based on non-wood forest products - Paludiculture practices
Latin America Ombrotrophic and minerotrophic	- NDC - NAMA - Aichi Biodiversity Targets - Ramsar Convention - Green Climate Fund	- Conservation of minerotrophic palm species-dominated system and ombrotrophic pole forests - Land use planning in a dynamic fluvial system - Explicit national policies regarding peatlands	- Non-wood forest products - Value chain of palm species - Sustainable fruit harvesting techniques
Africa Ombrotrophic, low nutrient status, relatively shallow	- NDC - NAMA - Aichi Biodiversity Targets - Ramsar Convention - Green Climate Fund	- Conservation program - Hydrocarbon exploration - Land use planning - Infrastructure development - Promotion of national park status	- Livelihood options of local community - Fish and aquaculture practices

NDC, nationally defined contribution; *REDD+*, reducing emissions from deforestation and forest degradation, and foster conservation, sustainable management of forests, and enhancement of forest carbon stocks; *NAMA*, nationally appropriate mitigation action

5 Concluding remarks: mitigation strategy options

Mitigation strategy options arising from the current issue include continued refinement of scientific understanding of peatland function and application of these findings to efforts for reducing greenhouse gas emissions in ways that address the specific regional threats and challenges.

First, the studies in the present issue will further refine higher tier emission factors and identify drivers of conversion as evidence to better estimate GHG emissions with acceptable uncertainties. Specifically, science-based knowledge and understanding of peat characteristics, such as chemical properties, microbial biomass, emission factors for all trace gases, hydraulic conductivity, water-filled pore space, and water storage anomalies, and their incorporation into models of ecosystem function, are keys to the success of landscape-level modeling of peatland greenhouse gas emissions, restoring/rehabilitating degraded peatlands, and conserving intact peatlands.

Second, evidence-based policy may be formulated, based on the studies in this issue and elsewhere, to allow the design of measures needed to implement national programs and/or

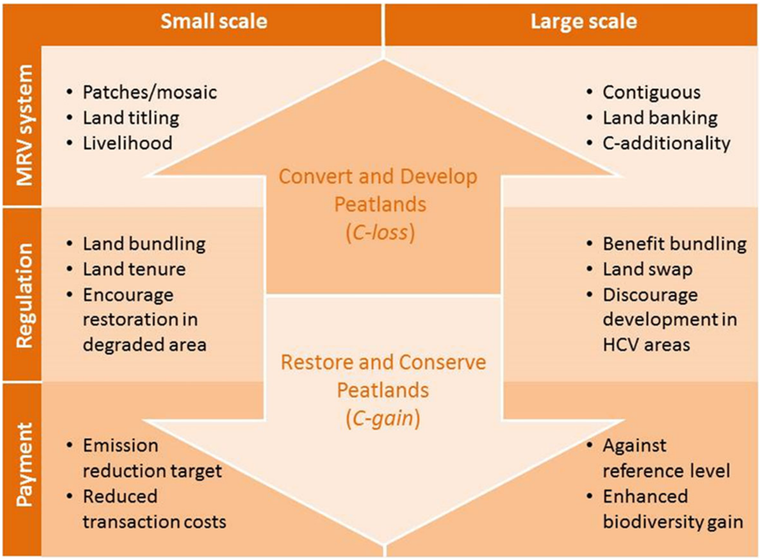

Fig. 3 Framework to balance development and conservation agendas to address national objectives (large scale) and local objectives (small scale) in high carbon storage peatlands while enhancing their high conservation value (HCV)

specific subnational projects that align with the global climate agenda. Moreover, they may be evaluated to improve the performance and be extrapolated for application elsewhere. Evidence-based policies will enhance the credibility of the activities for participation in rational compensation scheme. Given the differences among and within countries, strategies will be most effective if tailored to local conditions. For example, in areas presently subjected to extensive land use change (e.g., Sumatra and Kalimantan), strategies appropriately include efforts to restore peatland hydrology and sustainable forest practices; whereas in areas not yet subjected to extensive peatland land use change (e.g., Papua, Congo, and Peru), strategies to limit unsustainable land uses, such as peatland drainage and conversion to oil palm, are more appropriate. In the latter regions, there is a common theme of fairly extensive conservation areas that are vulnerable to lack of adequate enforcement under increasing economic pressures. Policies that recognize peatlands as hydrologically and ecologically unique and vulnerable ecosystem type at the national level, combined with appropriate valuation of their unique ability to store carbon over long time scales, could increase the likelihood that these peatlands will continue to be GHG sinks rather than serve as major GHG sources. More detailed mitigation strategy recommendations can be found in specific articles in this issue.

Evidence-based policy and measures such as REDD+ and NAMAs and other mitigation mechanisms guided by the NDCs of the Paris Agreement demonstrate how science and policy can work hand-in-hand.

Future research directions building on the present studies should allow the refinement of emission factors; provide a better understanding of the drivers of deforestation and peatland degradation, and of site-specific factors controlling emissions; and provide tools for cost-effective (e.g., remotely sensed) monitoring of peatland hydrologic status linked to modeling of GHG emissions. In addition to improving credibility, well-designed projects will in turn improve the livelihoods of the community and the resilience of peatlands to detrimental pressures.

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