Review

Towards an improved understanding of greenhouse gas emissions and fluxes in tropical peatlands of Southeast Asia

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Abstract: At present, there is insufficient data to understand the processes driving emissions and fluxes of greenhouse gases (GHGs) from tropical peatlands in Southeast Asia (SEA). In this review, we discuss fundamental factors controlling emissions of major GHGs (CO₂, CH₄, and N₂O) from tropical peatlands and their contribution to global climate change. Classifying peatlands in tropical and subtropical regions can aid in understanding their emission characteristics. The applicability of existing GHG emission factors to land use categories in SEA is discussed. We find that rewetting peatland can increase CH₄ emissions, and therefore more studies are needed to establish whether peatlands act as a net sink or net sources of GHGs. Few studies have investigated the effectiveness of liming toward reducing peat soil acidity. The review also finds that there is limited data on CO₂ concentrations in drainage and wildfire areas, N₂O fluxes in agriculture areas, and the impact and reduction of CH₄ in tropical peatlands. Addressing these research gaps could support the development of a framework for GHG emission measurements and abatement in tropical peatlands.

Keywords: Peat soil; Water management system; Greenhouse gases; Emission fluxes; Global Climate Change

Research highlights

- ▶ GHG emissions from peatlands and their contributions towards global climate are assessed.
- ▶ Southeast Asia is a significant region for peatlands; their restoration can reduce GHG emissions.
- ▶ CO₂ and N₂O emission fluxes from drainage, fire and agriculture areas are insufficiently known.
- ▶ Very little is known on drained peatlands and their GHG emission characterisation is required.
- ▶ Modern technology with traditional knowledge is important for peatland water management.

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1. Introduction

Climate change is a global issue that has been identified as a pressing concern over the past 30 years. Continuous emissions of GHGs (e.g., CO₂, N₂O and CH₄) have been linked to several environmental problems, including global temperature rise, alterations in precipitation patterns, changes in groundwater levels and soil conditions, and extreme weather events (Kumar and Imam, 2013; Isaksen et al., 2009). Therefore, researchers have been working to identify different sources of GHG emissions and develop strategies to mitigate them. Peatlands, however, are a key source of GHGs that remains poorly understood.

Peatland refers to land dominated by peats, formed from partially carbonised vegetable matter under waterlogged conditions (Worrall et al., 2010). As shown in Figure 1, the accumulation and decomposition of organic materials in unbalanced, low temperature, anoxic, anaerobic, and low-decomposability conditions favor the formation of peats (Rydin and Jeglum, 2013; Zinck et al., 2011; Couwenberg, 2009). Common stock materials for peat formation include woods, leaves, roots, and rhizomes. Mostly, peats are deposited photosynthetic matter that is buried under additional layers of litter, thereby creating the conditions for peat formation (Rydin and Jeglum, 2013).

Depending on region and history, the thickness of peatlands can vary between 30 and 70 cm, (Josten and Clarke, 2002). For example, the minimum thickness is 30 cm in England and Wales, 40 cm in Canada (Rydin and Jeglum, 2013), and 50 cm in Scotland (Holden et al., 2004; Johnson, 1963). Peats are examples of the soil type Histosol (Wösten et al., 2008; FAO-UNESCO, 1990). Histosols have a surface layer characterized by a minimum of 30% organic matter. Thus, their degree of humification is also influenced by hydraulic conductivity, water retention, nutrient availability, and load-bearing capacity.

Peatlands can be found in areas with various temperature levels, ranging from cool, temperate boreal regions to tropical or subtropical regions (Zinck et al., 2011). The boundaries between tropical-subtropical peats and temperate-boreal peats include Southeast Asia (SEA), Africa, Florida, North Carolina, Southern Brazil, and Uruguay (Zinck et al., 2011). These different peatlands can be distinguished by relevant form. For example, intertropical lowland peat has surplus rainfall and high temperature. Peat oxidation is accelerated by high temperatures, with little diurnal and seasonal variations. Peatland hydrology, controlled by rainfall, has an impact on vegetation type and composition. Peatlands in tropical lowland forests are commonly covered by peat swamps, unlike in temperate peatlands which are generally covered by sedges and moss. In the subtropical areas at mid-latitudes, the characteristic rainfall is important to peat formation, but annual temperature variations are more significant (Zinck et al., 2011). Page et al. (2011) reported an estimated tropical peatland area of 439,238 km² (≈11% of global peatland area), of which 247,778 km² (57%) is in (SEA).

Tropical peatlands in forests serve as one of the most efficient carbon sinks and are one of the largest near-surface reserves for terrestrial organic carbon (Marwanto and Agus, 2014; Anshari et al., 2004). In tropical peatlands, approximately 16.5 to 68.5 Gt of carbon is stored in a land area ranging from 275,400 to 570,600 km², with a thickness between 1-2 m and approximate carbon density of 60 kg m⁻³ (Zinck et al., 2011). When in a stable chemical form, peatlands store a large quantity of carbon which, upon degradation, can be released into the ecosystem as CO₂ and CH₄ (Page et al., 2002; IPCC, 2001). Their stability can be threatened by activities (such as the drainage and forest clearing) which render the land fire-susceptible (Page et al., 2002).

Peatlands are of interest due to their unique characteristics, including their CH₄ emissions. Peatlands are believed to contribute about 15% to 20% of global CH₄ emissions (Fan et al., 2014), which given the high warming potential of CH₄ suggest a significant impact on global climate (Fan et al., 2014; Worrall et al., 2010; Forster et al., 2007). Peatlands stability is directly related to GHG emissions potential (Sukarman et al., 2012). Losing carbon in peatlands via forest fire and land clearing accounts for about 4.5 and 7.9 t C ha⁻¹y⁻¹, respectively (Hooijer et al., 2014).

Fires in peatland are one of the most important environmental problems in SEA, especially in Indonesia, Singapore, Malaysia, Brunei, and southern Thailand (Nagano et al., 2013, Suzuki et al., 1999). Drainage and clearing on peatlands over recent years have resulted in an unprecedented increase in peat fires. For example, Kalimantan and Sumatra (in Indonesia) have experienced severe fire outrage over the years. GHGs and other toxic pollutants (e.g., CO, VOCs and PAHs) are emitted from the burning of peat soil, which can also endanger critical ecological systems (Jayaretny et al. 2017, Huijnen et al. 2016, Stockwell et al. 2016, Yokelson et al. 1997). These events can significantly impact human health. For instance, due to haze caused by peatland fires in 2015, about 100,300 excess deaths were reported over Indonesia, Singapore, Malaysia, and Brunei (Koplitiz et al. 2016). The related average inpatient health impact in Malaysia for 2005, 2006, 2008 and 2009 was valued at MYR 273,000 (US \$91,000) (Othman et al. 2014). In another example, wildfires affected Indonesia's island of Sumatra in June 2013 and triggered a severe air pollution episode in Singapore with daily PM_{2.5} concentration reaching 310 µg m⁻³ (Velasco and Rastan, 2015).

Experimental and numerical approaches have been used to investigate the role of peatlands in global climate and their GHG emissions. In 1997, between 0.87 and 2.57 Gt C (3-10 Gt CO₂ (Nusantara et al., 2014) was emitted from forest fires (Page et al., 2009; Page et al., 2002; Page et al., 1999). Annually, about 2-3 Gt CO₂ eq of CO₂ and N₂O are emitted from drained peatlands (Joosten and Couwenberg, 2009). Based on data collected by prior studies the role of peatlands in GHG budgets has been summarized as follows: (1) peatlands store carbon in their tissues in organic form; (2) when decomposed anaerobically, they release

CH₄ from the reduction of CO₂ (Setyanto et al., 2014); (3) via photosynthesis, peatlands sequester carbon as CO₂ during peat formation (Marsden and Ebmeier, 2012).

We consider these descriptions of the influence of peatlands on GHG budgets to be limited and incomplete. Beyond these simplified characterizations, tropical conditions, agricultural activities, land management, and drainage systems impact peatland GHG emissions in SEA. Therefore, we present a comprehensive review on the physical and chemical nature of tropical peatlands in SEA (specifically those in Peninsular Malaysia, Sumatra, Borneo and Papua), including their ecological features and the drivers and magnitude of associated GHG emissions within the region. Additionally, we identify emissions mitigation approaches for SEA peatland areas, particularly focused on the agricultural sector.

2. Peatland distribution in SEA

Globally, peatland area is estimated to be 4.26 M km², accounting for approximately 3% of total land mass (Zinck et al., 2011; Chimner and Karberg, 2008; Chimner and Ewel, 2005; Andriess, 1988; Mona, 1984) and capable of storing carbon at 3,000 t ha⁻¹ (Setyanto et al., 2014; Gorham et al., 2012), equivalent to 20% the world's carbon stocks. Global peatland distribution is shown in Figure 2a and the distribution in SEA is depicted in Figure 2b. Within the global peatland area, tropical peatlands cover about 45 Mha (12%) (Wösten et al., 2008; Page et al., 1999). Together, Indonesia (≈35% of global, i.e. 22 Mha), Malaysia, and Vietnam account for approximately 70% of tropical peatlands. Page et al. (1999) documented that Papua, Borneo, and Sumatra, three islands in Indonesia, cover 4.6, 6.8, and 8.3 Mha peatlands, respectively. Hooijer et al. (2010) reported that SEA has a lowland peatland landmass of about 27.1 Mha, out of which 22.5 Mha are in Indonesia. Central Kalimantan, for example, has an area of 153,564 km², consisting of 17.3% peatland (~2,651,724 ha) (Limin et al., 2007). Major peat areas in Peninsular Malaysia, Sumatra, Borneo and Papua are highlighted in Figure 3.

Unger (2012) and van Noordwijk et al. (2014), report that land use emissions in SEA account for 14% of global GHG emissions. Being the largest contributor in SEA, Indonesia could lead to the reduction of GHG emissions from land uses, although, there are still uncertainties about the relationship between GHG emissions to biomass burning and land cover change. Still, peatland restoration can be an important strategy to reduce of GHG emissions. One restoration approach is rewetting. However, peatland rewetting has been reported to cause CH₄ emissions, a drawback which needs to be addressed (Couwenberg, 2009). This review aims to comprehensively describe GHG emissions from SEA peatlands, as well as activities that can drive or mitigate their contribution to global warming.

3. Classification of peatlands

Based on the geographical location and tide movement, peatlands are broadly classified into two categories: (i) inland peat, which is uninfluenced by sea water, and (ii) coastal peat, which is generally influenced by sea water (Bourgeau-Chavez et al., 2018;

Anderson, 1983). Table 1 summaries the classification of peatlands based on some natural characteristics. According to Hooijer et al. (2010), there are insufficient data about peat thickness in some places where some content of domes lay deeper underneath sampled shallow peat. Moreover, subsoil beneath the inland peat (usually quartz, sand, and granite) lowers the soil nutrient significantly. On the other hand, coastal peatlands have a thickness range of 25-100 cm. As a result of seawater sedimentation, they produce some nutrients that improve soil fertility. At maturity, the inland peatlands are either hemic or sapric. However, because the subsoil is predominately marine, high acidity ($\text{pH} < 4.0$) ensues. Peatlands are also classified into fibric or hemic based on their decomposition and vegetative growth.

With respect to the source and nutrient types, peatlands can be classified as bogs (ombrotrophic) and fens (minerotrophic) (Worrall et al., 2010). Bogs are further sub-classified into blanket and raised bogs (Worrall et al., 2010; Lindsay, 1995), while fens are sub-classified into four: basin, valley, floodplains, and sloping fens (Charman, 2002). Another kind of classification based on the level of fertility, ash content, and content of P_2O_5 , CaO , K_2O was made by Polak (1949). This classification categorized peat into three types: eutrophic peat (with high fertility level), mesotrofik peat (with moderate fertility level), and oligotrofik peat (with low fertility level). Most peat soils are low in both macro and micronutrients (Hartatik et al., 2011). Peats formed near the coast, generally topogen peat, are more fertile than inland peat (i.e., ombrogen). Several factors responsible for peatlands' fertility include soil layer thickness, the composition of the parent peat plant, degree of decomposition, and minerals under the peat layer. So far, those are the available classifications of peatlands; they are detailed to improve their understanding, which in turn, could initiate further studies.

4. Properties of peatland soil

4.1 Physical properties

Pandjaitan and Hardjoamidjojo (2008) reported that the physical properties of peatlands are important, especially for their reclamation and water management, soil mechanics, soil engineering, and peat conservation. This section provides information on the important physical properties of peat deemed highly significant (Andriesse, 1988).

4.1.1 Water retention and water availability

Peats are highly hydrophilic; they can absorb water up to 13 times their dry weight (Hartatik et al., 2011). However, it was earlier reported that in saturated conditions, peatlands exhibit water retention between 4.5% and 30% of their dry weight (Andriesse, 1988). Table 2 shows their water content at different decomposition level. Such information on water availability is important to the agriculture sector. Also, the adequate information on the differences between mineral soil and organic soil are relevant to the water retention of peatlands. For example, (i) the volume soil solidity in organic soil is lower than in mineral soil; and (ii) at low pressure, organic soil has higher water retention than organic soil (Andriesse, 1988).

4.1.2 Hydraulic conductivity and water holding capacity

According to Andriesse (1988), knowledge about the hydraulic conductivity of peatlands to predict water flow behavior in the soil is important. Horizontally, the hydraulic conductivity is very fast but very slow in vertical flow, the latter is due to groundwater obstruction to vertical water flow (Pandjaitan and Hardjoamidjojo, 2008). Moreover, the water holding capacity in peatlands also depends on the level of decomposition (Table 2), which is the highest in fibric peatlands (Pandjaitan and Hardjoamidjojo, 2008). Furthermore, hydraulic conductivity is faster in fibric peatlands than in sapric peatlands, because of lower peatland porosity in the latter (Andriesse, 1988).

4.1.3 Bulk density (BD) and porosity

Because of high water content, peats have a low BD, rendering them flabby (i.e., having low tensile strength) (Widjaja-Adhi, 1988). Depending on the level of decomposition, the BD of topsoil peats varies between 0.1 and 0.2 g.cm⁻³. However, fibric peats (usually located in the bottom soil layer) have BD less than 0.1 g.cm⁻³, whereas due to the presence of the mineral soil, coastal peats and peats along river flow have BD less than 0.2 g.cm⁻³ (Hartatik et al., 2011). According to Widjaja-Adhi (1988), low BD peat causes low resistance-bearing capacity, making operations on the soft soil difficult for mechanical equipment. In addition, the porosity of peatlands influences the flow of groundwater proportionately, with fibric peat (having big pores) often exhibit high groundwater flow (Andriesse, 1988).

4.1.4 Irreversible drying characteristics

Upon exposure to heat, peats undergo irreversible drying, i.e., dried peats are unable to reabsorb water when wetted, becoming permanently hydrophobic. Also, peat shrinks significantly when drained (compaction by contraction). In addition to peat compaction, subsidence also occurs due to decomposition and erosion. In the first two years after peat drainage, subsidence rate may reach 50 cm.yr⁻¹. A year afterwards, the subsidence range from 2 to 6 cm.yr⁻¹, depending on the maturity and depth of peat drainage channels (Hartatik et al., 2011). Figure 4 illustrates the effect of continued drainage on peatlands.

Dry peats are easily eroded by water flow in wet conditions, and are highly flammable in a dry environment. When burning, peats produce higher thermal energy than wood or charcoal. Although, a burning mass of peat is difficult to control because the fire may spread under the surface, leading to a forest wildfire (Hartatik et al., 2011).

3.2 Chemical properties

The chemical content of tropical peatlands is predominantly associated with the percentage of organic carbon, which ranges from 35% to 60% (Melling and Henson, 2011). Further, Melling et al. (2013) observed that the total carbon in peat soil is between 52.3% and 58.2%, with the depth of 0-50 cm, whereas the ratio of C to N is approximately 28.2:41.6. The pH was found in a close range of 3.5 to 3.7. The chemical properties that

influence the availability of peat nutrients are divided into three categories: (i) eutrophic, (ii) mesotrophic, and (iii) oligotrophic (Table 3). They are based solely on the water source and water quality, and not determined by any property of the peat (Zinck et al., 2011). Chemical properties such as pH, ash content, contents of nitrogen (N), phosphorus (P), potassium (K), base saturation, and micronutrients are significant to the nourishment of peat plants (Hartatik et al., 2011). For example, some reported chemical properties of peatlands in Indonesia are summarized in Table 4.

Peat's organic matters have reactive, but weak acid groups (carboxylic and phenolic acids) that contribute about 85-95% of peat soil acidity. The acidity tends to decline with depth. Liming peat soil to increase its pH is ineffective because the aluminum content of peat is low. Generally, coastal peatlands are less acidic than inland peatlands due to the enrichment of tide-derived bases (Hartatik et al., 2011). The anaerobic decomposition of woody peat soils and rich lignin produces aliphatic acids and phenolic acids (Hartatik et al., 2011; Kononova, 1968). Most of these acids are poison for plants. Some of the phenolic acids commonly found in soil are vanilic acid, p-coumaric, p-hydroxybenzoic, salicylic, gallic, sinapic, and syringic acid. Hartatik et al. (2011) have shown that phenolic acids are phytotoxic to plants and cause stunted plant growth by inhibiting the provision of nutrients in the soil.

Oligotrophic peatlands (as found in Borneo) have a very low content of base cations (such as Ca, Mg, K, and Na). Lower base metal concentrations (i.e. higher soil acidity) are characteristic of thicker peats (Hartatik et al., 2011). The Cation exchange capacity (CEC) of peat soil is generally high (range of 90-200 cmol.kg⁻¹). This is largely due to the presence of carboxyl and phenolic groups, which are pH dependent. Therefore, the CEC increases with pH (Hartatik et al., 2011). The negatively charged site on peats is formed by the dissociation of the hydroxyl group. Naturally, peat soils have low fertility because of the large amount of toxic organic acids which inhibit most nutrients. To reduce the effects of the acids, polyvalent cations (such as Fe²⁺, Al³⁺, Cu²⁺, and Zn²⁺) could be added to the peat. These cations complex with the organic sites, thereby ameliorating the peat (Hartatik et al., 2011). Due to a large number of polyvalent metal ions required, the effectiveness of liming (addition of Mg²⁺ and Ca²⁺) peat soil to elevate its pH needs to be studied further.

In addition, there is a need to study, in details, the C and N cycles in tropical peatlands, due to finite data currently available about them. Such a study is essential because the available emission factors have an unclear relationship between the land use categories in SEA. Previous studies have shown that the C:N of peat soil is relatively high, and it increases with the depth. Usually, the total amino-based N content is relatively high. However, the availability of N for plant nutrition in peat soil is generally low. Therefore, to provide optimum N for plants, N fertilization is required (Hartatik et al., 2011). The microelement content of bottom peat soil is generally lower than at the top layer. However, the reverse could ensue if the bottom layer is mixed with mineral soil materials (Hartatik et al., 2011).

The microelement content can be increased by the addition of minerals or fertilizer. On peatlands, microelements (such as Cu) are usually unavailable to plants because they are absorbed strongly by peat soil.

5. Peatland ecosystem

Figure 5 provides an overview of peatland ecosystem services as influenced by both natural and anthropogenic activities, including climate change. Because of its capacity to store carbon, swamp forest is important to peatland ecosystem. Also, the tropical peat swamp forest is an important contributor to regional and global biodiversity (Wösten et al., 2008; Andriesse, 1988). In natural conditions, tropical peatlands serve as reservoirs for freshwater, maintain water level, reduce storm-flow, sustain the river flows, and prevent saltwater intrusion (Wösten et al., 2008). As a unique ecosystem, tropical peat swamp forest is a habitat for some rare or threatened species of aves, pisces, mammals, and reptiles (Wösten et al., 2008; Ismail et al., 1999). Moreover, Marsden and Ebmeier (2012) found that peatlands are important habitat for species with particular affinity for acidic, low-nutrient, and waterlogged conditions. Vegetation in peatland is responsible for the unrecognized changes in both the water level and water chemistry of their environment (Holden et al., 2004). Furthermore, ecological knowledge of response to vegetation after a fire incident is important to determining the actions related to planning for restoring or converting the area for efficient land use; the tropical secondary vegetation, being a carbon sink, is a potential regulator of climate change, (Hoscilo et al., 2008; Lucas et al., 2006; Castro et al., 2003).

In the last decade, tropical peatlands have been in steady condition, even though the peatland is negatively impacted by climate and land use (Wösten et al., 2008). Over 25% of peatlands (usually tropical peat swamp forest) are degraded by fire, drainage, logging, and land conversion (Page et al., 2008). For example, approximately 30 Mha (25%) of the Indonesian forest were lost in the past 15 years. In comparison to ecology and hydrology, fire and flooding are the most important ecological barriers in forest restoration. They could significantly hinder some important ecological phenomena such as pest control, pollination, water infiltration, etc. (Norowi et al., 2008). Developing peatlands while ensuring the sustainability of the ecosystem therein is challenging. Drainage (be it natural or artificial) and addition of fertilisers for the improvement of peatland's pH and nutrient levels are partly responsible for ecological restoration difficulties (Holden et al., 2004; Bragg and Tallis, 2001). If canal construction has caused some impairment on the peat layer, such significant change in the ecosystem will cause increased decomposition of peat, followed by the release of CO₂.

6. Hydrology and water management in peatlands

Hydrology is an important factor in keeping peatlands in a stable condition. In peat swamps ecosystem, hydrology depends on climate, topography, natural subsoil, and drainage base (Ritzema, 2008). Peatland hydrology is controlled by rainfall, which impacts

both vegetation type and composition (Zinck et al., 2011). With about 10% of global freshwater in the peatlands, it is important to maintain the water quality in the highland catchment areas (Marsden and Ebmeier, 2012; Josten and Clarke, 2002). For instance, in the 1960s, lowland development for rice cultivation was inspired by adopting traditional techniques combined with emerging engineering approach for systematic soil improvement in Indonesia. The result was remarkable: food crops (such as rice, corn, soybean, peanut, vegetables) and perennial crops (such as fruit trees, coconut, coffee and cloves) flourished (Rieley et al., 2008). Based on this development, similar projects were carried out at Sumatera, Kalimantan, and Papua. In 1996, one of such projects was the Mega Rice Project (MRP) in Central Kalimantan, with a total land area of 1,457,100 ha (Rieley et al., 2008). Varied dimensions of channels were constructed across the peatland landscape and completed in three years. According to Limin et al. (2007), the total length of the canals was 4,473.46 km, including main primary canals (187 km), primary canals (958.18 km), secondary canals (913.28 km), tertiary canals (900 km), and quaternary canals (1,515 km). However, the problem of insufficient water from the upper stream of three big rivers (Kahayan, Kapuas and Barito) has rendered the irrigation ineffective for the intended purpose (i.e., to create routes for transporting log out of the forest) (Rieley et al., 2008). Blocking canals is one of the solutions to recover hydrological status in peatland areas (Limin et al., 2007).

Due to the impact of the drainage system, the water content of peat soil depletes sharply, thereby affecting the temperature and humidity of the upper layer. In fact, in a year, the soil surface subsidence reaches between 1.0 and 3.0 cm, as influenced by hydrological conditions of the area. The peatland further subsidizes when it is over-drained with excavated giant canals in the area of MRP, constructed across the deepest peat area (i.e., peat dome) with thickness ≥ 3 m (Limin et al., 2007). Sometimes, without peat management sustainability systems (as used by Dayak people, such as the *handel* and *anjir*), the thickness could reach up to 8 or 10 m. Usually, the extreme environmental impacts are drought and flooding. Despite the information collected, there are limited data on peatland drainage for other countries in SEA. Therefore, additional research is needed as the water level continues to decrease in unused peatlands, and groundwater depths increases due to land use (Hooijer et al., 2010).

7. Land use and land-use change in peatland

Since the 1970s, tropical peatlands have been developed especially in the SEA, a region which dominates the coastal peatland for small-scale agriculture. However, ever since the 1990s when agricultural activities rose sharply, the peatlands have enlarged further into the inland (Rieley et al., 2008). More than 25 years ago, scientists from Indonesia and the Netherlands identified principal problems associated with tropical peatland reclamation. Such problems include chemical impoverishment, peat acidity, and extremely low ash content. As Rieley et al. (2008) opinionated about peat soils, “*No other soil type combines so many unused possibilities with so many unsolved difficulties... A multidisciplinary effort*

is needed to find ways to exploit the potentially suitable for peat formations in a non-destructing way". For example, peatland use for agricultural purposes in Central Kalimantan was unsuccessful. The failure was attributed to the carrying capacity, land ecosystem, culture, local wisdom, and crops market. Limin et al. (2007) inferred that the potentials of peatlands are not about thickness only, but also based on the underlay natural materials, the hydrology status, knowledge of peatland cultivation, culture of the community, and marketability of products from peatlands. In contrast, MRP policy has no consideration for the local people, who have first-hand and grounded knowledge about water management of the area, especially for successful rice cultivation.

For agricultural practices, Dayak people use shallow peat only because it is richer in nutrient rather than inland peat (UNEP/GEF, 2008). Shallow peats in upstream have the following characteristics: (1) peat thickness is between 20 and 50 cm; (2) decomposition condition is hemic to sapric; (3) bottom material is clay; (4) location is near river banks or between hills; (5) previous vegetation is dominated by grass; (6) water supply is from rainfall and river flood; and (7) soil becomes muddy after planting. Whereas, the characteristics of coastal areas used by the Dayak people are: (1) they are influenced by sea tidal movement, flooding the rice field incessantly; (2) location reaches about 2 km from the river bank; (3) maximum peat thickness ranges from 1.0 to 2.0 m; (4) clay is the underlay material; (5) decomposition status is mostly sapric; (6) nutrients are provided by tidal movement twice a day; and (7) the soil becomes muddy after planting.

Rice cultivation would flourish in the peatlands provided the land is irrigated by the fluctuation at river level. The rice cultivation of inland peat with peat thickness less than 100 cm introduces some constraints to the growth and yield of the rice. Lest, if the underlay material is sand or granite, the yield depreciates further. However, crops that grow in deep peat would exhibit low yield and shorter production periods. Such conditions can be improved by high lime input and fertilizers (Limin et al., 2007). Thence, standardized methods for the survey and evaluation of peatlands is needed, because each country has its own definitive philosophy about land use (Hooijer et al., 2010). Moreover, more study on tropical peatland water systems is needed.

8. Influence of emissions on peatlands

One of the areas of research interest on tropical peatlands is the emissions associated with the land type. Figure 6 provides the annual CO₂ emission values, categorized based on emission source (due to land use change and peat decomposition) in Indonesia and Malaysia, as reported by Agus et al. (2013). The CO₂ concentration values attributed to land use change and the oxidation of peat soils from drainage and conversion were also compared. Some peatlands in SEA have been deforested either through burning or conversion for oil palm and pulpwood plantation purposes. This situation has affected the net GHG balance of peatlands by some flux components: (1) net CO₂ uptake by vegetation, (2) CO₂ emissions from drainage-related peat decomposition, (3) huge CO₂ emissions from fires, (4) exports

of dissolved and particulate organic carbon, and (5) small-quantity emissions of CH₄ and, possibly, N₂O. Agriculture, as a potential source of GHG emissions in peatlands has been established, so also are the interrelationships among CH₄, N₂O, NH₃ and NO_x from the practice (Gurjar et al., 2015; Brink et al., 2005) .

8.1 Carbon dioxide (CO₂) emissions

Among all GHGs, CO₂ is the most important, because it has the highest atmospheric concentration, highest emission rate, and substantially longer atmospheric lifetime (Kumar and Imam, 2013). Still, CO₂ emissions will keep increasing because of the aerobic nature of agricultural practices (such as drainage) in peatlands (Beetz et al., 2013). The aerobic conditions also favour microbial activity and nitrogen mineralization in the peat profile above the water table (Hooijer et al., 2010). The directly proportional relationship between peatland utilization and CO₂ emissions in temperate and boreal peatlands have been confirmed (Minkinen et al., 2008). However, information on the relationship between tropical peatlands and CO₂ emissions is still insufficient. Kumar and Imam (2013) noted that CO₂ is produced by fossil fuel consumption, deforestation, and natural degradation of biomass sources, resulting in the oxidation of carbon compounds in marshes and forests. According to Hooijer et al. (2010), more studies are needed to complement the already-existing data toward achieving a reliable estimate of CO₂ emissions in drainage tropical peatlands. Huijnen et al. (2016) reported that in September and October 2015 where widespread forest and peatland fires burned over large parts of maritime SEA, a large amount of terrestrially-stored carbon was released into the atmosphere, primarily in the form of CO₂, CO, and CH₄. Then, a mean emission rate of 11.3 Tg CO₂ per day was recorded. The CO₂ emissions from these fires exceeded the rate limit recommended by the European Union (EU28) (i.e., 8.9 Tg CO₂ per day).

8.2 Nitrous oxide (N₂O) emissions

Another GHG with a long atmospheric residence time is N₂O. It is the fourth highest contributor to positive radiative forcing (Kumar and Imam, 2013; IPCC, 2007). Kumar and Imam (2013) also believed N₂O contributes indirectly to environmental dilapidation such as corrosion. Primarily, N₂O is produced by the burning of biomass and nitrogen-rich fuels (especially coal), decomposition of nitrogen fertilizers in the soil, livestock wastes, and of nitrate-contaminated groundwater. Still, continuous measurement, especially in agriculture areas with nitrogen inputs, is needed in peatlands to provide adequate information about N₂O emissions (Hooijer et al., 2010; Couwenberg, 2009). The N₂O emissions are higher in drained peatlands where fertilizers and manure are used (Beetz et al., 2013; Jassal et al., 2011).

8.3 Methane (CH₄) emissions

In terms of atmospheric concentration and emission frequency, CH₄ is second to CO₂, but 25 times more potent in global warming potential (Hooijer et al., 2010; Forster et al., 2007). CH₄ has a significant influence on the earth's climate; it plays an important role

in the formation of O_3 and influences climate parameter (Kumar and Imam, 2013). In the agriculture sector, CH_4 is produced from anaerobic degradation of organic matters in the rice field, natural wetlands, landfills, digestive tracts of a ruminant class of animals e.g., cattle, sheep, goats, deer, etc., production and utilization of oil and natural gas, and incomplete combustion of organics. CH_4 emissions from peatlands (either undrain or drained) are modest in comparison with CO_2 emissions (Hooijer et al., 2010; Couwenberg, 2009). Due to the significant role of CH_4 in the net GHG tropical peatland balance, continuous measurement of CH_4 flux over many years is needed (Hooijer et al., 2010). One of the activities for restoring drained peatlands is rewetting. However, rewetting peatlands to reach minimum water table would simultaneously increase CH_4 emissions. This arises when the water level rises, the environment tends towards anaerobic condition, therefore, methanogenic bacteria would produce more CH_4 (Beetz et al., 2013).

8.4 Emission flux in peatlands

Figure 7 shows peat carbon and GHG dynamics in a typical tropical peatland. There are limited data on CO_2 emission fluxes in peatlands over the years. Also unavailable are subsidence data which provide information about the deposition of particulate and dissolved organic matters into rivers and canals (Hooijer et al., 2010). Continuous measurements of CH_4 flux over many years would establish the role of CH_4 in the net GHG balance in the tropical peatlands (Hooijer et al., 2010). An example of such established facts is this: the concentrations of CH_4 in drained and undrained peatlands is moderate when compared to those of CO_2 (Couwenberg, 2009; Hooijer et al., 2010). Further, more measurements on N_2O are required, especially from agriculture-based emissions (Hooijer et al., 2010; Couwenberg, 2009).

GHG fluxes in SEA tropical peatlands influence water level, pH, C:N, soil temperature, vegetation cover, and land use. As an example, the water level impacts peatland subsidence; it increases 0.9 cm.a^{-1} for every 10 cm drainage depth (Couwenberg, 2009). Although some studies have reported on some biases, there are still some uncertainties regarding flux measurement criteria (such as chamber configuration, flux derivation, measurement frequency and time). Therefore, adequate and effective measurement of CO_2 fluxes should be continuous, or at least, consistent (Couwenberg, 2009).

With respect to CH_4 , Couwenberg (2009) found the flux balance in tropical peatlands is associated to water level, i.e., at the low water level of $\approx 20 \text{ cm}$, CH_4 flux values are generally negative. This means that the balancing value is gained by atmospheric uptake. However, at higher water levels, the values are usually higher and more variable as listed in Table 5. N_2O emissions from fertilizer-improved agricultural tropical peat soils are sometimes higher than those from temperate peat soil (Couwenberg, 2009).

The assessment of the contribution of radiative forcing to global warming in tropical peatlands depends on the robust net annual estimation of CO_2 , CH_4 , and N_2O emissions.

However, reliable estimates are still unavailable for CO₂ and N₂O emissions from tropical peat soils (Couwenberg, 2009; Forster et al., 2007). By rewetting drained tropical peatlands, CO₂ emission reduces, yet, the net carbon sequestration would not be reached. However, this does not apply to temperate and boreal peatlands because they have a low risk of increasing N₂O emission. Besides, during heavy rainfall, there is excessive rewetting of fertilized drained areas, resulting in increased emission of N₂O, and ineffective reduction of CO₂ emissions in these areas (Couwenberg, 2009).

To this end, adequate and reliable data of GHG emissions from peatland use and land use change are needed (Hergoualc'h and Verchot, 2014). Because 8% of global peatlands are in the tropics, there are 68% in the SEA which reserves about 6% of global peat carbon (Yu et al., 2010). However, between 1990 and 2000, peatland forest cover in Peninsula Malaysia, Sumatera, and Borneo decreased by 41% due to wildfires, land clearing, and cultivation in the drained peatlands, contributing to GHG emissions (Hergoualc'h and Verchot, 2014). So far, there is no confirmed quantitative estimation about atmospheric impacts because available data are limited and inconsistent (Frolking et al., 2011). The role of the tropical peatlands in global climate change in the future is still unclear, because of the yet-to-be-determined relationship among GHG flux estimates, future land use, land-use change trajectories, and responses to effects of climate change on ecosystems, be they short term or long term (Hergoualc'h and Verchot, 2014; Frolking et al., 2011). Table 6 shows the emissions of three GHGs (CO₂, CH₄ and N₂O) from seven land use categories (peat swamp forest (F), degraded forest (Deg F), croplands and shrublands (C&S), rice fields (R), oil palm plantation (OP), golden wattle plantation (A), and sago palm plantation (S)), and their annual uptake in SEA.

Although, the net GHGs (mainly CO₂, CH₄ and N₂O) exchange between the atmosphere and land at some SEA peatlands have been studied, some strong pulse of GHGs (such as N₂O and CH₄) by wildfires (especially during dry seasons), and vegetation changes are still unaccounted for (Hergoualc'h and Verchot, 2014). Hergoualc'h and Verchot (2014) further argued that the estimation approach used by Reducing Emissions from Deforestation and forest Degradation (REDD+) to avoid CO₂ emissions from peats on the basis of individual variables (such as depth of drainage) is incorrect. Moreover, alternative representatives of N value in soil can be used to assess soil GHG emissions. From their field study, soil GHG emissions should be considered along other environmental factors to achieve reliable results (Hergoualc'h and Verchot, 2014).

From quantitative research, more of CH₄ is produced in restored peatlands than in degraded peatlands. It was established that restored peatlands act either as sinks or sources for GHGs. Further, the assessment and estimation of carbon and general GHG budget in peatlands have been compiled in Table 7 (Worrall et al., 2010). In relation to GHG emission fluxes in tropical peatlands, CO₂ data are very limited, particularly with respect to drained and fire-exposed areas. Due to the rarity of long-term CO₂ flux data, there is a need for more studies

on the relationship between peatland utilization and CO₂ emissions, as well as improved estimation of CO₂ emissions from drainage areas. Finally, such detailed research should be extended to CH₄ and N₂O, especially in agriculture areas.

9. Conclusion and recommendations

Based on the reviewed literature on peatland GHG emissions, fluxes, and their global warming impact in SEA, we conclude the following:

- Classification, physicochemical properties, ecosystems, hydrology and water management, land use and land-use change, and GHG fluxes from peatlands are important to better management of peatland environment;
- Classification of peatlands could be based on geographical location, tides movement, water source, nutrients, levels of fertility and contents, or natural characteristics;
- For agricultural purposes, irrigation reduces the effect of toxic organics in peatlands. Soil liming improves soil physical condition and soil nutrients availability. Elaborate C and N cycles in tropical peatlands are needed to ascertain the influence of soil liming on peatlands. As a unique ecosystem, peatlands require some restoration, therefore, in-depth knowledge on peatland ecology is imperative.
- To develop peatlands appropriately, especially in the agricultural sectors and the water management system, a bridge between local wisdom and modern science is necessary to avoid culture offset.
- Canal blocking is a relatively clean method to restore water level in peatlands. However, rewetting peatlands would increase CH₄ emissions.
- There are insufficient data on GHG emissions fluxes, especially on CO₂ in drainage and fire areas, and on N₂O fluxes in agriculture areas.

Consequently, we recommend that future research focus on the study of GHG fluxes in drained, post-fire, restored, and agricultural areas. The relationship between GHG emissions in tropical peatlands and global carbon content should be further investigated. The measurement of GHG fluxes in drained peatlands, post-fire tropical peatlands, and in restored peatlands, during dry and wet seasons, should be carried out. Where real-time analysis is not available or impossible, field samples should be collected for laboratory analysis. Finally, based on the data gathered, a mathematical model should be built on water management system toward restoring peatlands, as related to mitigation of GHG emissions.

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List of Figures

Figure 1. A generalized scheme for the formation of peats (adapted from Andriesse, 1988).

Figure 2. Percentage distribution of (a) global and (b) Southeast Asia (SEA) peatlands (Page et al., 2012; Zinck et al., 2011; Andriesse, 1988; Mona, 1984).

Figure 3. Major peatland areas (in red) in Peninsular Malaysia, Sabah and Sarawak, Sumatra, Borneo and Papua (adapted from Page et al., 2011).

Figure 4. A scheme showing the progressive effect of drainage on peatlands.

Figure 5. A typical peatland ecosystem services under climate change and anthropogenic activities (adapted from Yang et al., 2017).

Figure 6. Estimated mean annual emissions stratified by the source of emissions for aboveground carbon due to land use change and the oxidation of peat soils from drainage and land conversion (Agus et al., 2013).

Figure 7. Peat carbon and greenhouse gas dynamics showing major peat carbon stocks, pathways, and processes in tropical peatlands (taken from Janhiainen et al., 2002).

Table 1. Types of peatlands based on natural characteristics (Pandjaitan and Hardjoamidjojo, 2008; Andriesse, 1988).

Nature characteristics	Type of peatlands
Topography and geomorphology	Based on the landscape: <ul style="list-style-type: none"> • Low moor peat • Transitional moor peat • High moor peat
Vegetation cover	Usually associated with management purposes
Origin vegetation	Based on the peatland-forming vegetation: <ul style="list-style-type: none"> • Moss peat • Saw-grass peat • Cyperaceae peat • Forest and woody peat
Chemical properties	Based on the level of fertility: <ul style="list-style-type: none"> • Eutrophic • Mesotrophic • Oligotrophic
Physical properties	Based on the extent of decomposition: <ul style="list-style-type: none"> • Fibric (if organic content is $>2/3$) • Hemic (if organic content is $\leq 2/3$ but $\geq 1/3$) • Sapric (if organic content is $<1/3$)
Genesis process	Based on the climate when the peatlands were formed: <ul style="list-style-type: none"> • Tropical and subtropical peatlands • Boreal and temperate peatlands

Table 2. The water content of peatlands at different decomposition level (Hartatik et al., 2011)

Level of peatland decomposition	% H ₂ O content (in oven-dried peat)
Fibric	850 to 3000 %
Hemic	450 to 850 %
Sapric	< 450 %

Table 3. Type of peat based on nutrients availability (Zinck et al., 2011).

Peat type	Nutrients availability	Nutrient Source
Eutrophic	Rich	Overland flow or river flooding
Mesotrophic	Moderately rich	Low molecular weight organic acids
Oligotrophic	Poor	Rainwater only

Table 4. Previous studies on chemical properties of Indonesian peatlands (Hartatik et al., 2011).

Author	Result/Found
Stevenson (1994); Tan (1993)	<ul style="list-style-type: none"> Organic content is < 95%; the rest are inorganics Organic fraction consists of 10% to 20% humic compounds (humic acid, humin and himatomelanat) Non-humic compounds found: lignin, cellulose, hemicellulose, wax, tannins, resins, suberin, and a small amount of protein. Chemical characteristics depend on mineral content, thickness, type of peat plant and peat substratum (base material), and degree of peat composition.
Andriesse (1974); Miller and Donahue (1990)	<ul style="list-style-type: none"> Peatland is mostly acidic with pH < 4.0 Due to the high acidity, content organic acids found are humic acid and fulvic acid
Driessen (1978); Driessen and Suhardjo (1976)	<ul style="list-style-type: none"> Peats are generally formed from timber, with lignin content higher than those of peat soils in temperate regions
Radjagukguk (1997)	<ul style="list-style-type: none"> Ombrogen is dominant, especially in inland peats which are thick and of low nutrients Peats are of an oligotrophic level Coastal peats are generally topogen and classified as eutrophic; rich in Ca, Mg, and K
Driessen (1978); Andriesse (1974)	<ul style="list-style-type: none"> Cation exchange capacity (CEC) of ombrogen peat in Indonesia is largely determined by the fraction of lignin and humic compounds

Table 5. Methane fluxes balance related to land-use (Couwenberg, 2009).

Land Use	CH ₄ flux (mgCH ₄ m ⁻¹ h ⁻¹)	Complement	Reference
Paddy fields	3.5-14	Without water level indicated	Hadi et al. (2002)
Rice plant	Up to 35	Paddies on peaty alluvium	Furukawa et al. (2005)
Waterlog previously drained and abandoned freshwater swamp	12.5	Attributed to ebullition	Ueda et al. (2000)
Cassava field	16.8	Biochar lowers CH ₄ production	Takakai et al. (2005)

Table 6. CO₂, CH₄ and N₂O fluxes (mean±SE (gm⁻²d⁻¹)) by land use types (Hergoualc'h and Verchot, 2014).

GHGs	Land Use Types						
	F	Deg F	C&S	R	OP	A	S
CO ₂	-5.3±5.8	19.4±9.4	41.0±6.7	25.6±11.5	29.9±10.6	71.8±12.7	5.2±5.1
CH ₄	2.7±0.9	0.4±0.2	0.5±0.5	10.3±5.8	0.0	0.2±0.3	1.9±1.4
N ₂ O	1.2±0.9	1.1±0.5	2.3±1.2	0.2±0.2	0.5		1.5±0.2
Net	-1.3±5.9	20.9±9.4	43.8±6.8	36.1±12.9	30.4±10.6	72.0±12.8	8.6±5.3
GHG	(-396, 204,91)	(93, 2, 5)	(94, 1, 5)	(71, 29, 1)	(98, 0, 2)	(100, 0, -)	(60, 22, 17)

Table 7. Estimation methods for carbon and GHG budgets of peatlands (Worrall et al., 2010).

Methods	Approach and Result	Characteristics
Dating of peat accumulation	To give a rate of C accumulation in peatland systems	<ul style="list-style-type: none"> • Cannot be used to estimate C losses in degraded peatlands unless an obvious eroded surface is present • Usually over long periods: 10 to 100 years • No indication of the temporal variation in C accumulation for shorter periods • Unsuitable for understanding the impact of land management change in C budget • Only used to provide baseline information, to indicate the typical function of active, relatively unmanaged peatlands
Measuring accumulation or loss of peat material	<ul style="list-style-type: none"> - To observe if peat mass loss is by using erosion pins or transects - To observe changes in peat surface elevation over time by using artificial structures - To estimate loss by using dated photographic evidence 	<ul style="list-style-type: none"> • Both approaches are based on measuring peat surface and rely on assuming the bulk density of the material lost • It may fail in the estimation of peat compression • Cannot estimate the impact of methane flux • Cannot give an accurate classification of peat loss between gaseous and fluvial pathways
Measuring C fluxes between the ecosystem and the atmosphere	To calculate a present day C budget	<ul style="list-style-type: none"> • Based on measuring/estimating fluxes C and GHGs with the atmosphere and C fluxes to fluvial system • Can capture all types of peat C and GHG fluxes with limitation of measurement and experimental design • Needs regular onsite measurement to fully capture temporal variability in the system • It is harder to integrate over long period

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