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Contents

1 Acknowledgments

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2 Executive summary

Conversion of tropical peat swamp forests to quench the desire for industrial plantation and agricultural production has triggered rapid and substantial carbon loss in the Asia-Pacific region. Various management practices are designed to reduce the emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) resulting from the land use change but their mitigation potentials in tropical peatlands have not been systematically synthesized. The components of this SRA project include a literature review, data mining, meta-analysis, and scoping study visit to Indonesia to understand the factors that affect soil carbon loss from systems undergoing land use change from native vegetation, and to assess the potential of management practice options to prevent or reduce soil carbon loss from land use change from native vegetation to farming activities.

Our literature review suggests that the conversion of peat swamp forests to industrial plantation, agricultural production and abandoned peatland generally increased carbon loss via deforestation, drainage, burning, peat subsidence and peat degradation. This is supported by the findings of our meta-analysis of 49 studies (mostly chamber-based) on greenhouse gas emissions from peat soils under different land uses. Compared to peat swamp forest, other land uses had significantly increased emissions of CO_2 and N_2O by 24 and 117%, respectively, whereas the increase in CH_4 emission (33%) was not statistically significant.

There is potential for large reductions in carbon losses from converted tropical peatlands. The Indonesian Government has taken arguably the most critical first step by placing a ban on further conversion of peatland. However, peatlands used for logging, cropping, and plantations, or that have been abandoned, will remain annual sources of carbon and continue to subside as long as water tables are artificially lowered and plant communities are not restored. In general, peat soil CO_2 emissions will decrease when water tables are managed closer to the surface. Our meta-analysis indicates that increasing water level significantly decreased CO_2 emission by 34% but increased N_2O emission by 54%; the response of CH_4 emission ranged from –46% to 104%. When these gases are converted into CO_2-equivalents and considered together, a decrease of 1.2 and 1.5 g C m^{-2} d^{-1} (or 4–5 Mg C ha^{-1} yr^{-1}) could potentially be achieved in bare peatland and oil palm/rubber plantation by raising the water level. Reducing fertiliser N input significantly decreased CO_2 (by 21%) and N_2O emissions (by 81%) in cropping systems, equivalent to 1.7 g C m^{-2} d^{-1} (or 6 Mg C ha^{-1} yr^{-1}).

Key knowledge gaps and recommendations are as follows:

1. Clearly, increasing water level (to <40 cm) effectively decreases CO_2 emission although it may increase CH_4 emission to a relatively minimal extent. Optimising fertiliser N input effectively decreases N_2O emission from peat soils and has the potential to increase crop productivity and carbon sequestration. There is a clear need of quantifying the greenhouse gas mitigation potential of various management practices for different peat depths, peat types, and peat substrates at the plot, farm and landscape scales.

2. Soil CO_2 fluxes are only one component of the net ecosystem carbon balance. The effects of these mitigation strategies on the other components of ecosystem carbon balance (e.g. gross primary production, ecosystem respiration, dissolved organic/inorganic carbon export and harvested biomass) remain unclear and must be quantified when considering the overall mitigation effects.

3. An objective of future work is therefore to comprehensively evaluate the potential of mitigation strategies by quantifying multiple components of a full net ecosystem

carbon balance of peatlands in different scales. This is essential to determine whether the reduction in soil greenhouse gas emissions seen in this SRA would be offset by increases, if any, in other components of the carbon balance.

4. To achieve the above objective, scale-appropriate methods and long-term measurements of CO_2, CH_4 and N_2O are needed, notably micrometeorological techniques (e.g. eddy covariance) coupled with measurements of lateral carbon flows and process-based modelling. Such approaches are complementary to measuring changes in peat but are more sensitive avoiding the challenges of detecting (small) changes in soil carbon stock due to varying peat bulk density, peat depth and hydrological conditions.

5. The expansion of abandoned peatlands cannot be ignored. The area of these abandoned lands is poorly mapped but the lands are more prone to fire and large carbon losses due to lack of management. The Peat Restoration Agency and the Indonesian Swampland Agriculture Research Institute manage 121 abandoned peatlands in Talio Hulu Village, Pandih Batu District, Pulang Pisau Regency, Central Kalimantan, which could be used for future projects on peatland restoration. There is huge potential to halt this substantial carbon emission by avoiding further land abandonment and restoring the abandoned lands, through a series of actions:

   (i) Farmers' motive for abandoning land should be studied. It is likely that they will not cultivate their land when the can no longer gain a profit and/or have insufficient capital to maintain the land. A better understanding is required of why the peat soils deteriorate over time and whether this can be effectively managed.

   (ii) The biophysical properties of abandoned peatlands should be better characterised. This will help in designing site-specific management options to avoid further degradation and/or aid restoration of the peatland. For example, land may be too acidic or the peat soil may be too compacted resulting from land conversion process, both of which affect crop growth.

   (iii) The stoichiometry of essential nutrients of the peat soil should be explored to understand the potential limiting factors for healthy plant growth. In particular, nitrogen is essential for crop growth but could be low/limiting in carbon-rich peat. While fertiliser N application is inevitable to sustain crop growth, enhanced efficiency fertilisers (urease inhibitors, nitrification inhibitors, and controlled release fertilisers) should be used to reduce N loss to the environment. Of course this may incur additional costs that require careful consideration. Surprisingly, there has been no study on the use of enhanced efficiency fertilisers in decreasing N_2O emissions from crops/oil palm cultivated on tropical peatlands.

   (iv) Appropriate land use e.g. growing paddy rice with balanced nutrient management appears promising to restore the degraded peatland, which not only halts C losses but also increases C sequestration and famers' income.

   Future projects should therefore identify strategies to avoid land abandonment and restore abandoned peatland, so as to stop further C loss, improve peat soil fertility and increase agricultural production of converted peatlands.

3 Introduction

Peatlands cover roughly 3% of the global terrestrial surface but store 20% of global soil carbon (C) (Joosten et al. 2009; Page et al. 2011). Peatland ecosystems play important roles in regulating climate, C cycling, hydrology and biodiversity (Danielsen et al. 2009; Koh et al. 2011). Tropical peatlands account for around 10% of global peatland area but 20% of the global peatland C stock (Page et al. 2011). Tropical peat typically accumulates under lowland rainforests, and consists of partially decomposed tree trunks, branches and roots. South East Asia harbours half of the tropical peatlands and three-quarters of the tropical peatland C stock, with C concentration ranging from 42–62% and depth reaching 20 m (Page et al. 2011).

However, conversion of tropical peatlands via deforestation, drainage and burning has led to substantial C emissions, with up to 30% of the global emissions from land use, land use change and forestry originating from these areas (Hooijer et al. 2006). Indonesia and Malaysia have lost more than 5 Mha of peatland between 1990 and 2010 (Miettinen et al. 2012; Margono et al. 2014). Oil palm plantation is a major cause of deforestation in peat swamp forests (Cooper et al. 2020). Because of the growing global demand of oil palm products, the area of oil palm plantation area has expanded by 10- and 3-fold, respectively, in Indonesia and Malaysia from 1990 to 2018 (FAOSTAT 2020). These two countries account for more than 80% of global palm oil production (Pittman et al. 2013). Apart from industrial plantations (oil palm, *Acacia*, sago palm and rubber) (Miettinen et al. 2012), the Mega Rice Project in Indonesia converted 1 Mha of peat swamp forest into cultivated land in Central Kalimantan from 1995 to 1998 to address food shortage. More than 4,000 km of drainage and irrigation canals were dug, and forest was removed by logging and fire (Putra et al. 2008). Unfortunately, the project failed to deliver its initial goal and was terminated in 1999; however, lasting damage to peat ecosystems has led to sustained C loss from the abandoned land (Hoscilo et al. 2011).

In 2009, Indonesia pledged at the G20 Summit to reduce its greenhouse gas emissions 26% below the business as usual (BAU) level by 2020 through unilateral actions, and by 41% with international support. However, little has been done in Indonesia to implement policies that would enable it to meet its 2009 G20 pledge, or indeed to meet its subsequent similar commitment under the Paris agreement.

While biomass loss, as the greatest source of emissions, has been the key focus of mitigation attention from land use change, halting or reducing the rapid loss of soil carbon that occurs during and after land clearing is a largely unexplored opportunity. The project utilises information in published literature, data mining, meta-analysis, and a scoping study visit to Indonesia to understand the factors that affect soil carbon loss from systems undergoing land use change from native vegetation, and to assess the potential of management practice options to prevent or reduce soil carbon loss from land use change from native vegetation to farming activities. The project will use Indonesia as a case study and the findings will have implications for other ACIAR target regions in the Asia-Pacific region.

4 Objectives

The objectives of the SRA are to:

(i) Understand and document the factors that affect the rapid release of carbon from systems undergoing land use change from native vegetation to production agriculture in tropical peatlands in the Asia-Pacific region,

(ii) Identify potential management options that prevent or reduce this rapid carbon loss,

(iii) Provide recommendations for future investments to address emissions avoidance in climate change programs in the Asia-Pacific region, and

(iv) Establish collaboration between Australia, New Zealand and Indonesia on reducing carbon loss following land use change.

The project will use Indonesia as the main case study, although the findings will have implications for other ACIAR and NZ Ministry target countries in the Asia-Pacific region.

5 Activities

Activities of the SRA include:

(i) Collate information on processes that contribute to the rapid loss of soil carbon during and following land use change from native ecosystems to production agriculture in the Asia-Pacific region,

(ii) Conduct a review on options to minimise the loss of soil carbon in systems undergoing land use change,

(iii) Conduct a meta-analysis on the effects of management practices on soil carbon loss following land clearing events to assess the potential of management practices to decrease carbon loss after land clearing,

(iv) Build collaboration between experts from Australia, New Zealand and Indonesia on the topic, and

(v) Produce a comprehensive report to ACIAR and the NZ Ministry and a scientific journal publication.

6 Literature review

6.1 Significance of peatlands

Peatlands cover roughly 3% of the global terrestrial surface but store 20% of global soil carbon (C) (Joosten, 2009; Page et al., 2011). Peatlands have the capacity to store and filtrate water, which can regulate the impact of flooding and improve water quality (Harenda et al., 2018). Peatlands are treasure troves of biodiversity and provide habitats for unique fauna and flora (Bobuľská et al., 2019). Therefore, peatland ecosystems play important roles in regulating climate, carbon cycling, water supply and biodiversity. Peatlands are widely distributed in diverse climatic zones (Szajdak et al., 2020). Boreal and temperate peatlands are located in cool climates, where the peat is primarily generated by residues of Sphagnum moss and covered in herbaceous vegetation (Rydin and Jeglum, 2013). In tropical areas, the peat is typically covered by tropical rainforest, forming peat swamp forests. Tropical peat is comprised of remains of woody plants under high temperature and high precipitation (Hirano et al., 2007; Rydin and Jeglum, 2013).

Tropical peatlands make up 10-12% of global peatland area but are estimated to hold around 20% of the global peatland carbon stock (Joosten, 2009; Page et al., 2011; Rieley et al., 2008). The majority of tropical peatlands are lowland, forested ombrotrophic systems, receiving water and nutrients only from rain (Page et al., 2004), with peat carbon content ranging from 45-60% (e.g. Shimada et al., 2001) and peat depths that can exceed 16 m (Evans et al., 2019). South East Asia holds 54% of the tropical peatland area and 76% of the tropical peatland carbon stocks, where peat depths can reach 20m but average approximately 4.5m throughout the region (Page et al., 2011, Page et al., 1999).

However, conversion, drainage, and burning of tropical peatlands have led to substantial carbon emissions, with up to 30% of the global emissions from Land Use, Land Use Change and Forestry originating from these areas (Hooijer et al., 2006). Indonesia and Malaysia, in particular have lost about 5.4 Mha (million hectares) of peatland between 1990 and 2010 (Margono et al., 2014, Miettinen et al., 2012a, Dohong et al., 2017) and about 12.5 Mha of Indonesia's 21 Mha of peatland had been drained for agriculture and forestry by 2008 (Joosten, 2009).

6.2 Conversion of South East Asian peatlands for other land uses

Timber was a major Indonesian export in the 1970s and 1980s (Brockhaus et al., 2012), leading to conversion or destruction of peatlands. Logging activities have led to estimated biomass C losses of 50-60%, relative to natural peat forest (Palm et al., 2000; Boehm et al., 2001). In addition to the actual harvesting of trees, both legal and illegal construction of roads and railways, contribute to soil degradation and fragmentation of the land, resulting in both immediate and lasting effects on the ecosystems (Dohong et al., 2017, Bohm and Siegert, 2001; Franke et al., 2012; Page et al., 2009).

More recently, large-scale agriculture and industrial plantations have driven a larger proportion of land conversion in Indonesia (Dohong et al., 2017). This has included rice (Page et al., 2009; Ritzman et al., 2014), palm oil (Miettinen et al., 2012b, c; Koh et al., 2011), Acacia, sago palm and rubber (Dohong et al., 2017). All of these land uses require drainage canals to lower water tables (Dohong et al., 2017; Hooijer et al., 2012; Jaenicke et al., 2010; Rydin and Jeglum, 2013; Holden et al., 2004; Parish et al., 2008; Suryadiptura et al., 2005; OuTrop, 2010; Dohong and Lilia, 2003; Hooijer et al., 2006; Joosten, 2009, Franke et al., 2012; Kool et al., 2006). Drainage has cascading effects leading to initial loss of surface structure and rapid subsidence, enhanced oxidation of peat carbon, desiccation, and changes to peat thermal properties, and higher fire risks (Nagano et al., 1996; Suzuki et al., 1997).

In particular, oil palm plantation has been identified as the main cause of deforestation in peat swamp forests, especially in Indonesia and Malaysia (Cooper et al., 2020). The tropical climate and high rainfall in Indonesia and Malaysia are highly suitable for oil palm plantation and around 80% of the world's oil palm trees are grown in these two countries (FAO, 2016). Oil palm is a high-yielding crop, producing 6-10 times as much oil as rapeseed, soybean, olive and sunflower per hectare (Murphy 2014). Moreover, the oil palm trees have a productive lifetime up to 30 years. The produced palm oil is a highly versatile raw material for cooking oil, margarines and confectionary in food industry, cosmetics, pharmaceuticals, industrial lubricants and biodiesel (Obidzinski et al., 2012; Paterson et al. 2013; Murphy 2014). Therefore, the global demand of oil palm products increased dramatically, and the oil palm plantation area subjected to an exponential expansion increasing 600% to 7.8 Mha from 1990 to 2010 in Indonesia (Carlson et al., 2012).

The Mega Rice Project (MRP) in Indonesia converted 1 Mha of peat swamp forest into rice paddy in Central Kalimantan from 1995 to 1998, aims to alleviate Indonesia’s food shortage. More than 4,000 km of drainage and irrigation canals were dug, and forest was removed by logging and fire (Putra et al., 2008). Unfortunately, the project failed to deliver its initial goal and was abandoned eventually. The project was terminated in 1999 but its damage to the peat ecosystem has never stopped. The roads and railways previously built for timber transportation have facilitated rampant illegal logging activities and the forest coverage continued decreasing since then. Water channels construction leaves behind a dried-out peatland that continues to burn on a large scale almost every year (Page et al., 2009; Dohong et al., 2017). The most severe fire happened in 2015, burning more than 2.6 Mha of forest, peat, and other land and emitting large amount of carbon, 11.3 Tg CO_2 emission per day during Sept-Oct 2015 (Field et al., 2016; Glauber and Gunawan 2016; Huijnen et al., 2016).

Processes associated with the degradation of tropical peatland are shown in Figure 6.1

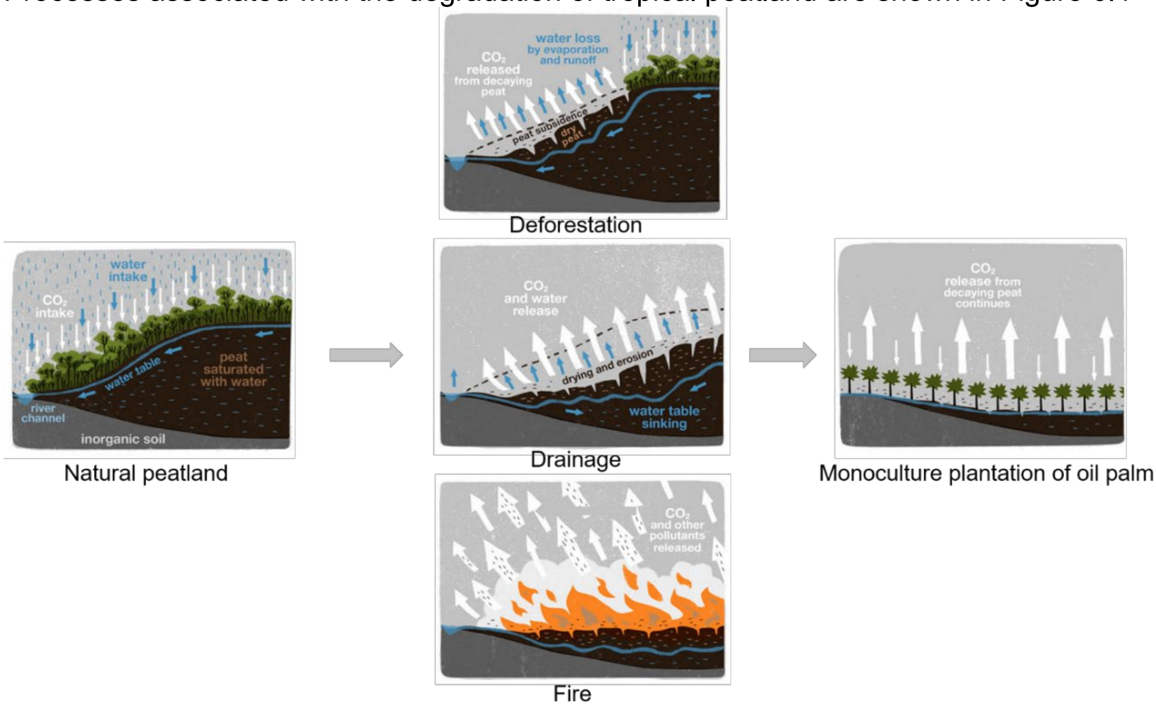

Figure 6.1. Degradation of tropical peatlands (Bell 2014)

6.3 Processes leading to carbon loss during land conversion

During the conversion of natural peatland to monocultural plantation, various anthropogenic activities are carried out on this land, such as forest clearance, recurrent fires, drainage, ploughing and fertilisation, which all contribute to losses of C and nitrogen (N) (Figure 6.2).

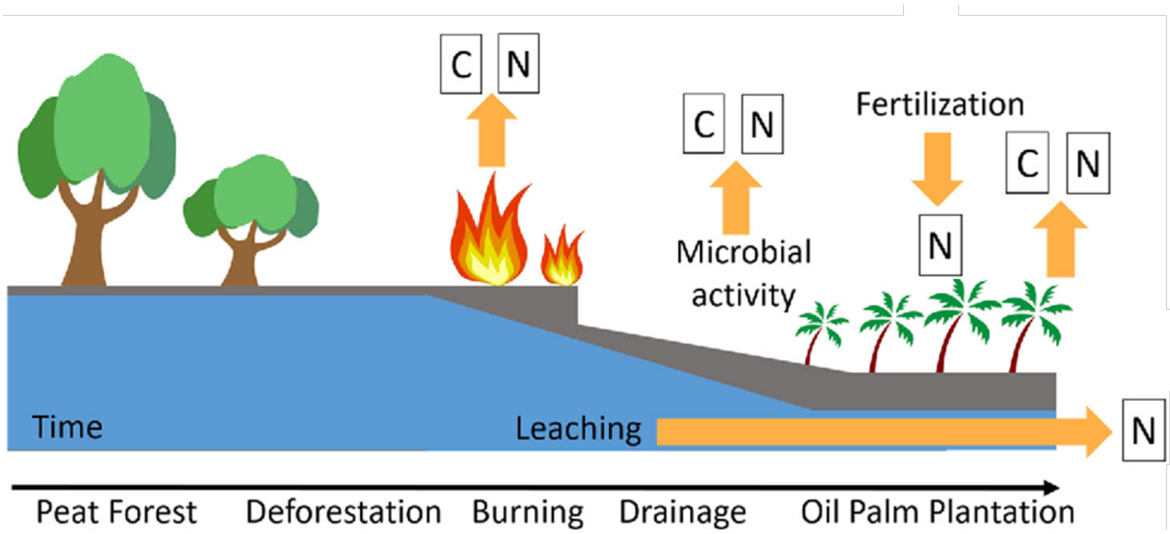

Figure 6.2 Losses of carbon and nitrogen as a consequence of the conversion of peatland into oil palm plantation (Swails et al. 2018)

6.3.1 Deforestation

Deforestation in the tropic area is one of the biggest contributors to CO_2 emissions. During 2000–2010, the estimated annual greenhouse gas emissions from deforestation and associated degradation of peatland ranged from 0.32 to 1.91 Gt CO_2-eq in Indonesia (Busch et al., 2015), relative to a global amount of 40–49 Gt CO_2-eq (IPCC, 2014). Deforestation results in a decreased input of plant litter, which is an important carbon source of peatland. By the early 2000s, a total of 0.88 Mha peat swamp forest in Peninsular Malaysia, Borneo and Sumatra were clear-fell for oil palm plantation, losing around 140 million Mg of aboveground biomass carbon (Koh et al., 2011). Moreover, loss of natural vegetation with aerial roots increases CH_4 emission due to deprivation of plant mediated oxygen supply (Hatano 2019).

Removal of trees leaves the land uncovered and more susceptible to erosion by heavy rain (Ekblad and Bastviken, 2019). Root loss resulted from deforestation increases surface run-off of soil particles and organic matter materials into rivers (Ekblad and Bastviken, 2019). A recent study further found that deforestation may release deep peat soil carbon which has been stable for millennia (Figure 6.3) (Drake et al., 2019). Apart from tree removal, the construction of roads and railways for logging and timber transportation further accelerates peat swamp forest degradation and peat subsidence (Dohong et al., 2017).

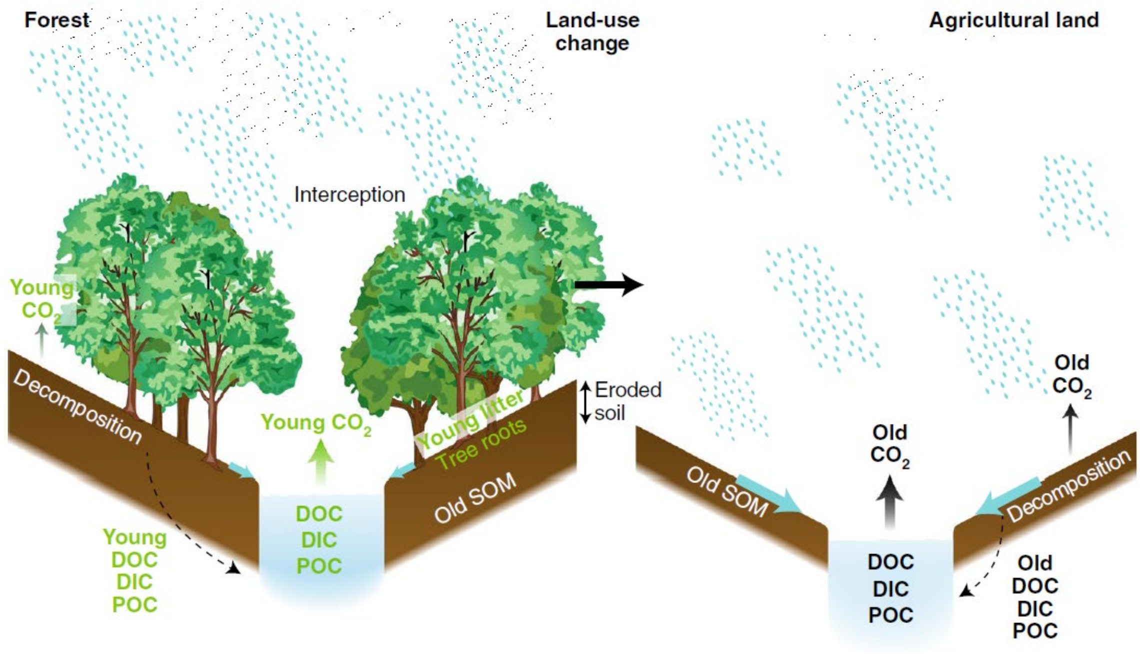

Figure 6.3. Deforestation releases old carbon (DOC, dissolved organic carbon; SOM, soil organic matter; DIC, dissolved inorganic carbon; POC, particulate organic carbon) (Ekblad and Bastviken 2019).

6.3.2 Fire

Pristine peatlands are naturally protected from burning due to their high moisture contents (Turetsky et al., 2015). Fires caused by lightning in non-degraded or non-drained peatlands are not common. Human disturbances in peatlands such as logging, agricultural conversion and peat harvesting drawdown water table, making the landscape more vulnerable to fire both horizontally to larger area and vertically to deeper layers (Huang and Rein 2017; Hu et al., 2018). Additionally, frequent human access and activities undoubtedly increase accidental and deliberate fire accidents (Turetsky et al., 2015). In Indonesia, peatland fires are mostly associated with anthropogenic land clearance before establishing crops (Page et al., 2002). Aside from the initial conversion of natural forest to agricultural land, fires have also been used as a cheap way to create ash fertiliser (Lee et al., 2012; Saharjo, 2007; Simorangkir, 2007; Chokkalingam et al., 2005; Dohong and Lilia, 2003), and also for clearing crops between rotations (Myllyntaus et al., 2002).

Because of the high biomass content, peatland fires can proliferate uncontrollably, consuming not only the surface vegetation, but also the underlying peat and tree roots. The combustion of deeper peat layers resulting from water table drawdown affects old carbon which has been thought stable for centuries to millennia (Turetsky et al., 2015). In 1997 and 1998, the catastrophic peat fires in Indonesia released approximately 0.95 Gt of carbon (Page et al., 2002; Van der Werf et al., 2010) and burned up to 50 cm depth of peat (Ballhorn et al., 2009). Peat fires can smoulder underground for weeks, months or even longer (Figure 6.4).

Comparing with flaming combustion, smouldering combustion is more readily to ignite and can persist in wet conditions, low temperature and low oxygen concentration (Belcher et al., 2010; Turetsky et al., 2015). The longer duration of flameless smouldering transfers more heat to surrounding and deeper soils, which could cause two orders of magnitude larger fuel consumption than flaming fires and irreversible damage to heat-sensitive plant roots and microorganisms (Treseder et al., 2004; Hart et al., 2005; Belcher 2013). Peat smoulder fires spread underground slowly, making them difficult to detect, locate and extinguish. Peat smouldering produces more smoke than flame combustion contributing to the dense haze and causing both severe deterioration in air quality and health problems (Page et al., 2002; Hu et al., 2018).

The frequency of unintended fires also increases when peatlands are drained as the surface organic-rich layers dry, and as drought frequency increases with climate change. Therefore, fire risk is particularly large during El Nino periods (Page et al., 2002). The depth of surface peat lost to fires is variable and depends on fire severity and peatland characteristics including vegetation type and height, peat depth, bulk density, and hydraulic conductivity and water table depth (Ballhorn et al., 2009, Langner et al., 2007; Langner and Siegert, 2009; Page et al., 2009; Page et al., 2002, Wösten et al., 2008; Hoscilo et al., 2008).

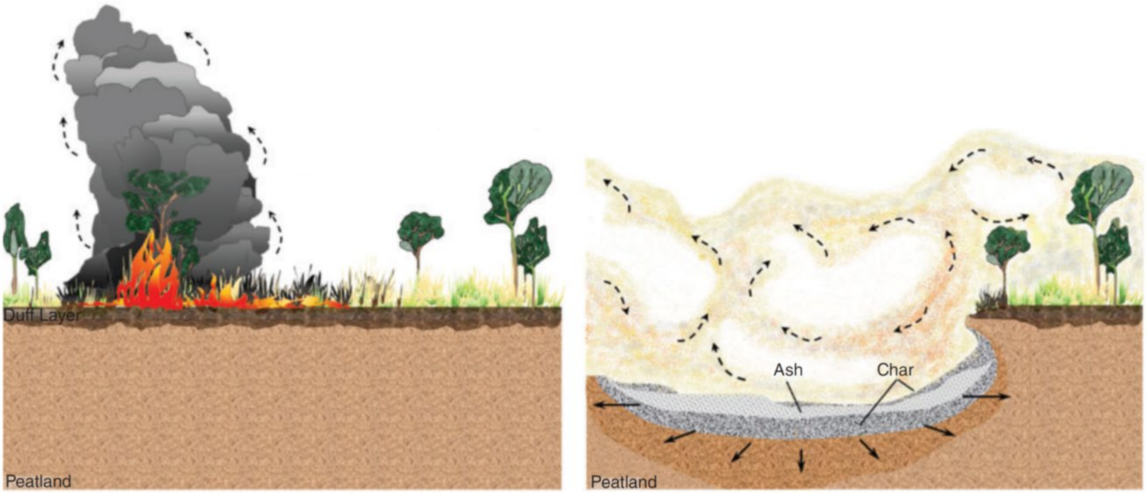

Figure 6.4. Forest flaming fire (left) and subsequent smouldering peatland fire (right). (Hu et al. 2018)

6.3.3 Drainage and subsidence

Carbon accumulation in natural peatlands hinges on the limited decay of recalcitrant plant litter in anoxic conditions created by high water tables (Ritson et al., 2017). Therefore, the stability of peatland is highly dependent on natural hydrological balance. However, artificial drainage by ditches construction has become a common practice to convert waterlogged peatlands to agriculture or other land uses, especially for oil palm plantation, which can thrive best when the water table decreases to 80 cm below the surface (Gewin 2020). Globally, approximately 10–20% of peatlands have been drained for their application in agriculture and for their stabilization in road construction as well as a support for heavy machinery for industrial activity in peatland (Frolking et al., 2011; Szajdak et al., 2020).

Water table decrease caused by drainage accelerates the decomposition of the peat layer above the water table due to the aeration of peat (Jauhiainen et al., 2008). The introduction of oxygen converts peat soil from anaerobic to aerobic system, which enhances rates of nutrient cycling and microbial activity. Higher microbial activity stimulates oxidation of soil organic matter and mineralisation of nitrogen, and subsequent emission as CO_2 and N_2O to the atmosphere (Wüst-Galley et al., 2016; Hu et al., 2017). Unlike CO_2 and N_2O, CH_4 is produced by methanogenic bacteria under strictly anaerobic conditions, especially in undrained peatland (Olefeldt et al., 2017; Hatano 2019). As well as direct gaseous losses, peatlands carbon can be exported to downstream via runoff as dissolved organic carbon and particulate organic carbon under drainage systems (Strack et al., 2008). The decomposition of drained peat and contraction of organic fibres when drying resulted in subsidence of peatland (Figure 6.5). The loss of buoyancy of the peat in the aerated layer above the water table compressed peat layers below the groundwater table extensively and further deteriorated peat subsidence (Eggelsmann 1984; Hooijer et al., 2012) (Figure 6.6).

Therefore, drainage has been identified as a main driver of peat subsidence and the subsidence rate has been proved to be linearly related to the depth of the ground water table (Wösten and Ritzema, 2001). Natural tropical peatlands typically have high water permeability due to their extensive woody materials contents (Hatano 2019) and serve an important hydraulic function in attenuating flooding and storing excess rainfall (Wösten et al., 2006). Drainage lowers the water storage capacity of peat soils, making them more susceptible to water-table fluctuations and droughts (Szajdak et al., 2020). In addition, drainage threats the biodiversity of peatland systems (Szajdak et al., 2020).

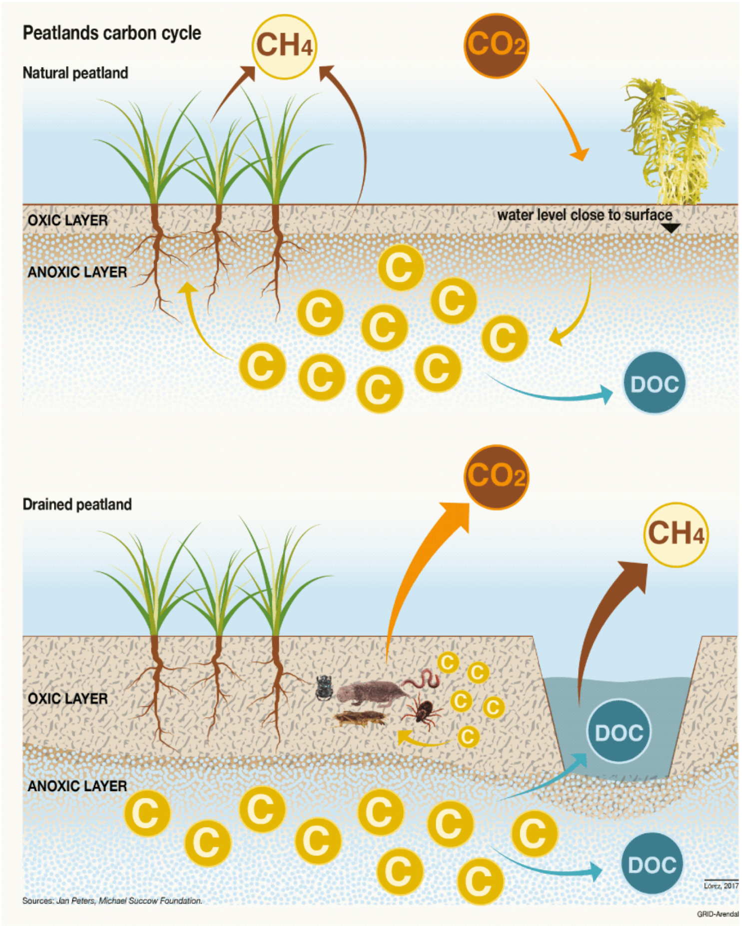

Figure 6.5 Increased carbon loss in drained peatland (United Nations Environment Program)

As mentioned, one of the consequences of lowering the water table depth of a peatland by drainage for cultivation is subsidence. Initial subsidence rates resulting from drainage and conversion are usually dramatic because of the loss of hydrostatic pressure, desiccation, and compaction of surface peat as well as oxidation of labile carbon (Figure 6.6). Subsequent, and long-term subsidence is related to continued oxidation of well-aerated surface peat (Wösten et al., 1997; Furukawa et al., 2005), particularly during droughts (Wösten et al., 2008; Hooijer et al., 2012), or other physical disturbance including fire or excavation. Additionally, deeper peat becomes consolidated or compressed as previously buoyant surface peat is lost or compacted.

A recent synthesis of data from tropical peatlands under Acacia plantation and adjacent conservation forest found average subsidence rates of 4.3 cm yr^{-1} (Evans et al., 2019). The authors showed that tropical peat subsidence rates are generally higher than northern hemisphere peatlands for the same water table depths, potentially related to differences in peat physical characteristics, water management, or higher temperatures and therefore decomposition rates (Andriesse, 1988; Stephens et al., 1984; Couwenberg and Hooijer, 2013). Subsidence rates are generally well-correlated with water table depth (Evans et al., 2019; Couwenberg et al., 2010), suggesting that management could help to reduce subsidence-driven peat loss. In a synthesis of both subsidence and greenhouse gas fluxes, Couwenberg et al. (2010) determined that losses of CO_2 resulting from long-term tropical peat subsidence range from 250 gC m^{-2} yr^{-1} to 1100 gC m^{-2} yr^{-1} depending on bulk density and the proportion of oxidative loss relative to physical shrinkage.

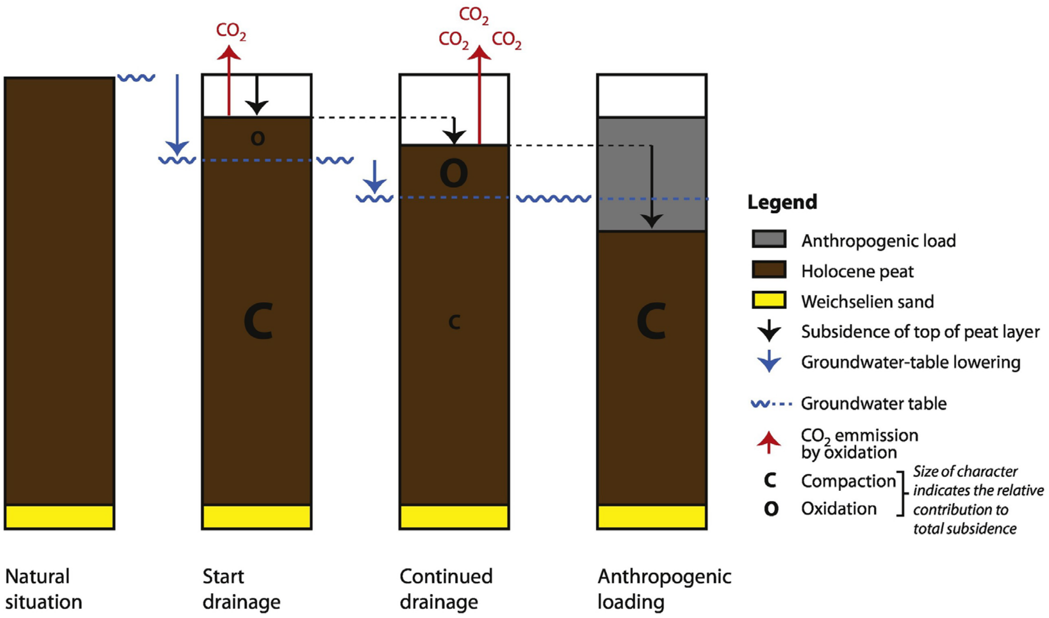

Figure 6.6 Schematic representation of temporal variations in the contributions of peat compaction and oxidation to land subsidence (van Asselen et al. 2018)

6.4 Carbon mitigation options

Mitigation or restoration initiatives in tropical peatland areas have primarily involved rewetting through canal blocking and damming (Suryadiputra et al., 2005; Dohong and Lilia, 2003; Page et al., 2009; Jaenicke et al., 2011; Ritzema et al., 2014; Limin et al., 2008; Dohong et al., 2018). The objective of these efforts is to maintain water table close to the surface in order to decrease surface oxidation, and therefore slow decomposition. Maintaining shallow water table depth also helps reduce fire occurrence caused by dry surface peat (Dohong and Lilia, 2008; Page et al., 2009). Despite being widely used for rehabilitating temperate and boreal peatlands, full canal infilling is usually not attempted in drained or degraded tropical peatlands since this is generally more expensive and labour intensive (Dohong et al., 2018). Generally, canal blocking is successful in raising water table levels (Limin et al., 2017; Dohong and Lilia 2008), but the monitoring of post-blocking water tables has been limited to relatively short-term campaigns, while long-term effects are not well understood. Furthermore, wooden dams are most commonly used to block canals despite having the shortest life span compared to other materials due to the fragility of the wood products and high flow rates in the canals (Susilo 2013; Ritzema et al., 2014; Suryadiputra et al., 2005). Generally, illegal drainage ditches are narrower than commercially dug canals and therefore easier to block, however locals who use canals for fishing or transport have been known to destroy dams in larger canals if they impede fishing activities (Dohong et al., 2018), and there are persistent issues of dams being destroyed by illegal loggers (Suyanto et al., 2009). Consequently, the development of mitigation strategies needs to take into account not only the biophysical constraints but also the associated cultural dimensions. It is critical that research and subsequent recommendations involve or, ideally, are led by local researchers.

In addition to canal blocking, there has been some work on revegetation of bare or abandoned tropical peatland through the production and transplantation of seedlings (van Eijk et al. 2009; Graham and Page 2018), promotion of seed dispersal tools (Graham and Page, 2012), and on understanding the potential of natural or spontaneous regeneration (van Eijk et al. 2009; Gunawan et al. 2012; Blackham et al. 2013; Blackham et al. 2014). There is some evidence that planting for the purpose of revegetating abandoned peatlands has been more successful if seedlings are inoculated with their corresponding mycorrhizas (Tawaraya et al., 2003; Hakim et al., 2017; Turjaman et al., 2008; Graham et al., 2013). Furthermore, the probability of regeneration and seed dispersal from natural sources is reduced with exposure to recurring fire or drought, stressing the importance and interconnectivity of multiple factors (i.e. water table and vegetative recovery). Despite the scope of tropical peatland carbon losses and complexity associate with mitigation options, very few studies have investigated management options with potential for reducing carbon losses from either managed peatlands or those abandoned after land conversion.

6.5 Quantifying the impacts of mitigation attempts on carbon loss

When considering the effects of carbon loss mitigation options in tropical peatlands, there are two major gaps in research to date. First, relatively few studies have specifically tested management strategies intended to mitigate carbon losses. There is a growing body of literature comparing carbon exchange from different land uses on tropical peatland, including undrained. However, these types of studies may not be sufficiently indicative of the mitigation potential of land already being managed a certain way.

Second, the vast majority of research on tropical peatland carbon losses has been based on soil chambers. Typically chambers cover an area less than a square meter and capture flux rates representative of a few minutes to an hour. Notwithstanding issues of spatially scaling plot-level measurements, soil CO_2 flux is only one component of the net ecosystem carbon balance that must be quantified when considering mitigation effects. In particular, there is very little information on gross primary production and dissolved organic carbon losses from tropical peatlands, particularly in the context of mitigation. Without a more complete understanding of the temporal and spatial variation in the full tropical peatland carbon balance, it will be impossible to determine whether mitigation efforts are successful, and it may be difficult to parse changes due to management from climate effects.

6.5.1 Components of tropical peatland net ecosystem carbon balances at relevant scales

The net ecosystem carbon balance (NECB) (Figure 6.7) of undisturbed peatlands is generally dominated by gross primary production, ecosystem respiration (soil and plant respiration), and dissolved organic carbon export (Goodrich et al., 2017; Gažovič et al., 2013; Koehler et al., 2011; Nilsson et al., 2008; Olefeldt et al., 2012; Roulet et al., 2007), while there may also be small contributions from particulate organic carbon and dissolved inorganic carbon export (Dinsmore et al., 2010). There is very little information on gross primary production and dissolved organic carbon losses from tropical peatlands, let alone in the context of mitigation or at relevant spatial scales.

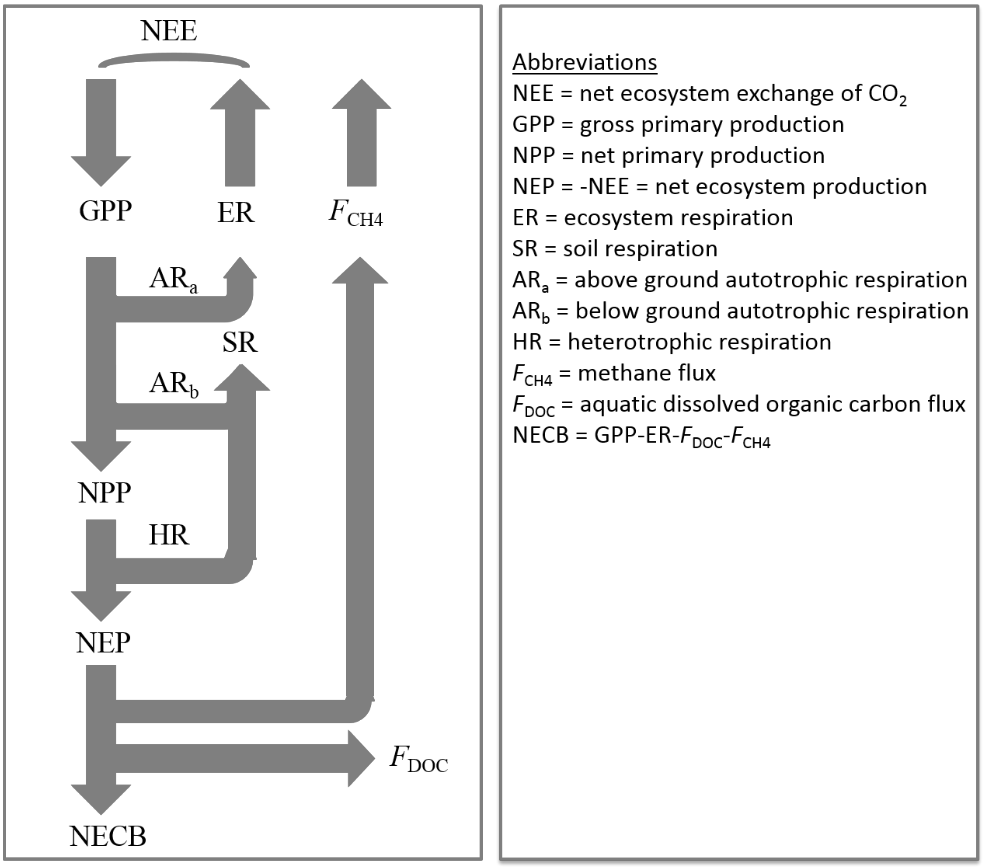

Figure 6.7. Illustration of the major net ecosystem carbon balance components for a natural peatland. Adapted from Luyssaert et al. (2007).

Eddy covariance flux towers capture hectare-scale ecosystem-atmosphere exchange continuously through time (Baldocchi et al., 2001). When coupled with other flows of carbon, eddy covariance provides a better scale measurement than chambers for determining ecosystem net carbon balance and the associated drivers of variability. There have been several ecosystem-scale studies utilising eddy covariance towers to measure ecosystem-atmosphere CO_2 exchange in tropical peatlands and plantations. Hirano et al. (2009) measured eddy covariance CO_2 exchange in a drained tropical peat forest and showed gross primary production (GPP) was consistently lower during periods when water table depth is increased. GPP was also the most variable component of net ecosystem CO_2 exchange from year to year, dependent largely on rainfall (and soil moisture). Furthermore, results from that study showed that when ecosystem respiration was highest, so too was gross primary production. Hirano et al. (2007) measured NEE with eddy covariance over a selectively logged and drained peat forest in Kalimantan for three years. They found very large ER that was remarkably similar among years. An El Niño year, which led to a drought and subsequent nearby fire, caused decreased GPP due to smoke-shading. Therefore, the magnitude of annual NEP was more driven by variability in GPP than ER, highlighting the need for better understanding of the role of vegetation in mitigation efforts. Annual ER from that study over the three years was 3848, 3844, and 3907 gC m^{-2} yr^{-1}, while GPP was 3246, 3461, and 3594 gC m^{-2} yr^{-1}, leading to net losses of 602, 382, and 313 gC m^{-2} yr^{-1}. Furthermore, GPP may also vary more spatially than ER. Comparing eddy covariance CO_2 exchange over similar peat forest types in Malaysia (Kiew et al. 2018) and Kalimantan, Indonesia (Hirano et al., 2012), showed larger differences in mean annual GPP (214 gC m^{-2} yr^{-1}) than ER (96 gC m^{-2} yr^{-1}).

Suzuki et al. (1999) also made micrometeorological CO_2 flux measurements over a natural and a secondary peat forest in Thailand (regenerating). They found that net CO_2 uptake by the natural ecosystem was largest during the dry season, but in the secondary forest, the dry season had lowest uptake due to plant water stress reducing GPP, and from higher nighttime respiration resulting from oxidized surface soil. The primary forest was a net C sink of 532 gC m^{-2} yr^{-1} and the secondary forest was also a net sink of 522 gC m^{-2} yr^{-1}, which highlights the potential for regaining C if a secondary forest can be established after a peatland has been degraded or partially drained. This handful of micrometeorological studies provide valuable information to the sparse literature on ecosystem-scale CO_2 exchange but much more work is needed in this area. For example, in the synthesis by Hergoualc'h and Verchot (2011) compiling carbon stocks and fluxes, they assumed that vegetation growth was similar between mineral and peat soils for rice, mixed croplands and shrublands, oil palm, and Acacia since there was almost no data available from relevant peatland systems.

Available estimates of fluvial (i.e. waterborne) C fluxes from tropical peatlands are quite variable, ranging from roughly 25 to 65 gC m^{-2} yr^{-1} (Yupi et al., 2016; Yule and Gomez 2009; Baum, 2008; Alkhatib et al., 2007; Moore et al., 2013; Evans et al., 2016). Most evidence confirms that total fluvial organic C losses are dominated by DOC, with less than 5% from particulates (Yupi et al., 2016; Cook et al., 2018). Despite variability, recent studies have demonstrated that disturbed or degraded tropical peatlands have larger fluvial C losses than their undisturbed counterparts. Moore et al. (2013) found that estimates of total carbon losses were increased by 22% when accounting for DOC losses. That study also showed that DOC lost from disturbed peatlands was dominated by older C, in contrast to the more recently derived C making up the DOC measured from undisturbed systems. Cook et al. (2018) was also able to show that fluvial C losses increased with drainage depth in tropical peatlands. Given that available results suggests that drainage and management of peatlands for lowered water tables leads to increases in fluvial C and that this may be derived from older sources, more work is needed to understand this component of peatland NECB as well as how and to what extent drainage is accelerating the peatland C cycle via fluvial losses.

In addition to fluvial C exports and ecosystem-atmosphere exchange of CO_2, contributions of other carbon imports and exports in managed systems (oil palm, Acacia etc) must also be accounted for. Other imports and exports of C may include crop harvest, pruning, mulching, and fertiliser application. Unfortunately none of these are included in any of the literature reviewed here. This is particularly important in agricultural and plantation systems given that these additional flows of carbon can dominate the annual NECB, depending on site conditions and management approaches, as has been shown for temperate agricultural grassland systems (Rutledge et al., 2015). To our knowledge there has been no attempt to quantify the NECB of a tropical peatland system. This represents a major gap in our knowledge of C losses from tropical peatlands given that oil palm yields, for example, average 3 t oil ha^{-1} yr^{-1} (300 g oil m^{-2} yr^{-1}) but have the potential to produce up to 1850 g oil m^{-2} yr^{-1} (Woittiez et al., 2017). Depending on the C content of palm oil harvests, these magnitudes may represent a substantial component of the full NECB and potentially even the dominant component. Clearly we cannot have a complete understanding of C losses from managed tropical peatlands without more information on these lateral C flows. Nonetheless, below is a discussion of those studies that seem to offer the most explicit information on effects of mitigation approaches on C losses from tropical peatlands, again mostly in the form of soil CO_2 exchange.

6.5.2 Water table

Most of the work explicitly testing C mitigation strategies in tropical peatlands has been conducted with chambers measuring bulk soil CO_2 emissions at naturally varying or managed water table depths. Astiani et al. (2016) conducted a bucket mesocosm experiment to estimate the effect of water table depth on soil CO_2 respiration in a forested and bare peatland in West Kalimantan. The authors experimentally manipulated mesocosm water table depths from 0–40 cm below the surface, showing that respiration increased more than 160% over that range. Astiani et al. (2018) demonstrated a similar result in the field by constructing dams to block drainage canal flows in a drained Kalimantan peatland used to cultivate corn, cassava, and pineapple. The authors successfully manipulated four different *in situ* water table depths ranging from approximately 30 – 65 cm, and observed a 50% reduction in soil CO_2 emissions from the site with WTD of 30 cm relative to that from the site with deepest WTD (65 cm) using static chambers. However, the authors also suggest that longer-term measurements were needed to determine the longevity of initial reductions in CO_2 losses when water tables are regulated. Nurzakiah et al. (2016) also performed a canal blocking experiment in a rubber plantation on peat in Central Kalimantan, and similarly found up to 50% reductions in soil CO_2 emissions in chamber plots where water table depths were reduced *in situ* (and soil moisture increased). Jauhiainen et al. (2008) examined the effects of peatland re-wetting on soil moisture and soil respiration fluxes using chamber measurements in a selectively logged forest and a burned fully cleared forest before and after canal blocking. Here the authors were again explicitly attempting to measure the effect of rewetting two different peatlands of varying degradation by damming the canals to manage water table depth for a year prior and a year post damming. Soil respiration was remarkably similar before and after re-wetting at both sites despite successfully increasing water levels, and was higher in the selectively logged site than the fully cleared burn. Annual respiration in the selectively logged site was 7305 and 7444 gC m^{-2} yr^{-1} before and after rewetting, respectively, and at the cleared site was 2781 and 2608 gC m^{-2} yr^{-1}, respectively. These studies, however, while offering some good information to a very sparse literature, does not adequately address vegetative influence or potential, solely focusing on soil respiration.

In contrast, Watanabe et al. (2009) found no significant water table effect on soil CO_2 emissions from Indonesian peatland planted with Sago palm. This may be a reflection of methodological limitations when measuring over heterogeneous peatland surfaces influenced by variable root and heterotrophic contributions to respiration that may react differently to changes in water table depth. To date, studies on this topic may be statistically underpowered with respect to determining differences that may otherwise be considered important. Handayani et al. (2010) found that peat soil CO_2 flux increased, decreased, or did not change with water table depth in a small-holder oil palm plantation on peat, with no clear mechanistic distinction between plots with or without roots. Despite few exceptions, it is clear that most research suggests that maintaining water table depth close to the surface will reduce soil CO_2 emissions from tropical peatland, regardless of land use. Such reductions in decomposition rates would be expected given our understanding of redox changes in the soil profile with water table fluctuations (e.g., Hoyt et al., 2019) and the associated oxygen limitation of aerobic respiration. However, quantifying the magnitude of water table effects on managed tropical peatland soil CO_2 emissions still needs further constraint with more manipulation experiments and field-scale measurements.

6.5.3 Cover crop and peat surface temperature

Other mitigation-relevant management changes that have been tested include reducing surface peat temperature and modifying fertiliser input on agricultural or plantation peat. While these alternate mitigation approaches have received even less attention that water table depth, there is some information available in the published literature. For example, Arifin et al (2015) explored the effects of leguminous cover crops on soil temperature and subsequent CO_2 emission in oil palm plantations. While the authors did conclude that cover crops can result in temperature-induced reductions in soil CO_2 losses, much more work is needed to determine how robust the result may be. For example, others have shown that additional nitrogen and labile carbon input to degraded tropical peat can stimulate carbon mineralization and increase CO_2 losses (Jauhiainen et al., 2016). Therefore, soil respiration may actually be stimulated by addition of cover crops if root exudation of labile carbon and added nitrogen stimulate microbial decomposition. Although, Jauhiainen et al (2014) also showed that shading with netting substantially reduced soil CO_2 emissions from vegetation-free tropical peat, and the reduction was larger on fertilized plots. Furthermore, Hoyt et al.

(2019) used automated soil chambers to measure CO_2 emissions from tropical peat, showing that water table depth was a dominant control over day-to-day variations, but surface temperature oscillations caused large diel amplitude in fluxes for unshaded locations. This reveals both the complexity associated with spatiotemporal controls on soil emissions, as well as methodological limitations of chamber studies that only measure during mid-day, which can lead to over-estimates of emissions, especially in more exposed systems. Clearly, more research is needed to disentangle the various biogeochemical interactions, as well as quantify effects on other components of the tropical peatland carbon balance, rather than limiting observations to soil exchange.

Information on primary production in tropical peatlands is particularly sparse. For example, in the synthesis by Hergoualc'h and Verchot (2011) compiling carbon stocks and fluxes, they assumed that vegetation growth was similar between mineral and peat soils for rice, mixed croplands and shrublands, oil palm, and Acacia since there was almost no data available from relevant peatland systems.

6.6 Summary

There is potential for large reductions in carbon losses from converted tropical peatlands. The Indonesian Government has taken arguably the most critical first step by placing a ban on further conversion of peatland. However, peatlands used for logging, cropping, and plantations, or that have been abandoned, will remain annual sources of carbon and continue to subside as long as water tables are artificially lowered and plant communities are not restored. In general, peat soil CO_2 emissions will decrease when water tables are managed closer to the surface. Most evidence also suggests that reducing surface temperatures can help reduce soil CO_2 emissions. However, the most practical method for achieving this through shading with cover crops is not well understood. The effects of fertilisers on soil carbon losses seem to be minimal, while CO_2 fluxes likely increase with addition of labile carbon. More data are needed to understand the combination of mitigation effects likely to impact peatland carbon exchange. Finally, there is insufficient data to determine the overall effect mitigation effects (water table depth, temperature, nutrient additions) on net carbon balance of tropical peatlands either in their natural or converted states. In particular, information on gross primary production, dissolved organic carbon export, and management related C inputs and outputs are needed for managed systems on tropical peatlands. This information will be essential for determining the most effective carbon mitigation strategies.

7 Meta-analysis

We conducted meta-analyses on published literature prior to May 2020 to examine:

(i) greenhouse gas emissions from different land uses in tropical peatlands in the Asia-Pacific region, and

(ii) the potential of various management practices to mitigate the emissions

7.1 Methodology

7.1.1 Database compilation

We performed comprehensive literature search of peer-reviewed publications through the Web of Science and Google Scholar databases, as well as the reference lists of the cited references. The keywords used in the search included carbon, peat, peatland, land use change, greenhouse gas (CO_2/CH_4/N_2O), fire, palm, water depth, water table, water level, mitigation, drain, fertiliser, abandoned peat, erosion, deforestation or their combinations. Studies were included if they met the following criteria:

a) studies were relevant to tropical peatlands within the Asia-Pacific region;

b) the sample sizes and means of greenhouse gas emissions or global warming potential following land use change or management practices were reported for both control and treatment groups; and

c) details on experimental location, design and conditions were given to enable cross-checking of duplicate publications. Greenhouse gas emissions were mostly measured in the field using chamber-based methods, with a small number under laboratory incubation conditions. Therefore, only soil fluxes were captured but not continuous ecosystem flux. A total of 510 observations from 49 studies (Appendix 1) were included in our analyses, with a majority conducted in Indonesia and Malaysia.

The observations were subdivided into two databases. The first database included studies on the effect of land use change on greenhouse gas emissions from peatlands (171 observations). We included categories based on the land use before and after conversions, viz. natural forest to oil palm plantation or agricultural land (including upland crops e.g. cassava, pineapple, maize, and flooded rice paddies); natural forest to abandoned land; and natural forest to bare land that was burnt or logged. We also categorized the observations according to the hydrological conditions of the land at different stages of land conversion, viz. remained undrained (water table depth ≤15 cm); undrained to drained (water table depth decreased from ≤15 cm to >15 cm); and remained drained (water table depth >15 cm). The second database included studies on the effect of management practices on greenhouse gas emissions (339 observations). We included the following management practices: increasing water table depth, decreasing fertiliser N input, shading, and growing cover crops. All data were extracted either directly from text or tables, or from figures using WebPlotDigitizer Version 4.2.

For each article, the following information was included in the compilation: data source, location (country, longitude and latitude), climate information (mean annual precipitation (MAP) and mean annual temperature (MAT)), soil information (soil texture, soil pH, carbon and nitrogen contents, water table and peat thickness).

7.1.2 Meta-analysis

We used the natural log of the response ratio ($r = \overline{x}_t / \overline{x}_c$, where $\overline{x}_t$ and $\overline{x}_c$ are the means of the treatment and control groups, respectively) as a metric for the analysis of treatment effects on CO_2, CH_4 and N_2O emissions. These results were reported as the percentage change under treatment effects ($(r - 1) \times 100$). Negative percentage changes indicate a decrease in gas emission compared with the control and positive values indicate an increase due to land use change and management practices. The effect of management practices on amount of CO_2-equivalent (CO_2-e) relative to the control was assessed as (amount of CO_2-e in the treatment plot – amount of CO_2-e in the control plot). CO_2-equivalent was calculated using the global warming potentials of 28 for CH_4 and 265 for N_2O (Myhre et al. 2013). We followed a commonly adopted randomization resampling procedure (Adams et al. 1997) and generated mean effect sizes and 95% confidence intervals by bootstrapping (4,999 iterations) (Lam et al. 2012; Xia et al. 2017) using the software MetaWin 2.1 (Rosenberg et al. 2000). Effect sizes reported in previous meta-analyses were weighted by the inverse of the pooled variance (Lu et al. 2011), replication (Lam et al. 2012) or unweighted (Guo and Gifford 2002). The studies collected in our database did not always include published variances or replications. Therefore, we followed the unweighted approach (Guo and Gifford 2002) in our analysis. The effects of land use change or management practices were considered significant if the confidence intervals did not overlap with zero.

7.2 Results

7.2.1 Soil emissions of CO_2, CH_4 and N_2O due to conversion of peat swamp forest

Overall, land use change from peat swamp forest to other land uses increased emissions of CO_2 and N_2O by 24% and 117%, respectively, whereas the increase in CH_4 emission (33%) was not significant (Figures 7.1–7.3). This change does not include fluxes that likely occurred during the conversion process itself as there are very few measurements during these conversions. Once converted to plantations or croplands there was a significant increase in CO_2 and N_2O emissions by 33% and 173%, respectively, and potential increase in CH_4 emission by 103%. Conversion to abandoned land significantly increased CO_2 and CH_4 emissions by 46% and 409%, respectively, but not for N_2O emission. After the peat swamp forest was logged or burnt, soil CO_2 and CH_4 emissions tended to decrease by 22% and 82%, respectively, whereas N_2O emission remained unchanged (Figures 7.1–7.3).

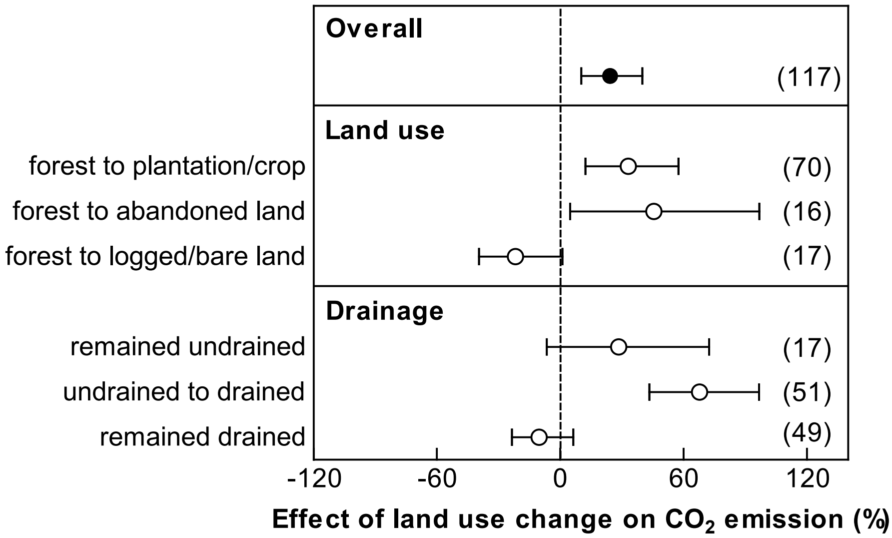

Figure 7.1 Response of CO_2 emission to land use change from peat swamp forests to other land uses under various drainage conditions. Numbers of experimental observations are in parentheses.

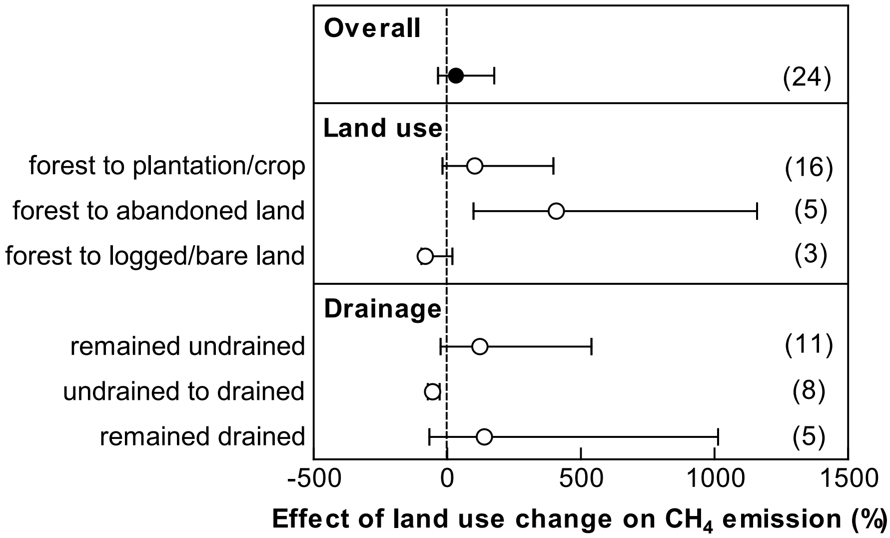

Figure 7.2 Response of CH_4 emission to land use change from peat swamp forests to other land uses under various drainage conditions. Numbers of experimental observations are in parentheses.

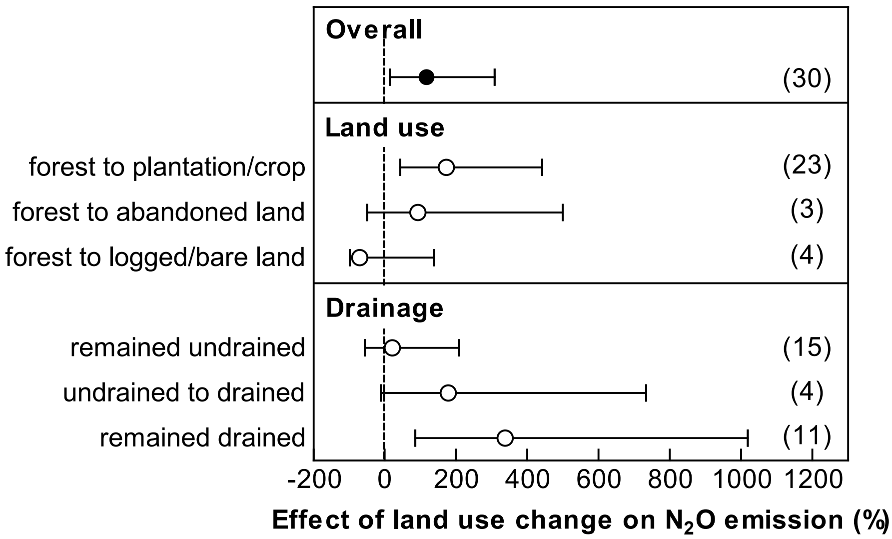

Figure 7.3 Response of N_2O emission to land use change from peat swamp forests to other land uses under various drainage conditions. Numbers of experimental observations are in parentheses.

Emissions of these greenhouse gases varied with hydrological conditions. If the land under comparison was both undrained or both drained, no significant changes in CO_2, CH_4 or N_2O emission was observed (Figures 7.1–7.3). In contrast, when the land was drained, CO_2 and N_2O emissions were increased by 68 and 178%, respectively, whereas CH_4 emission decreased by 55% (Figures 7.1–7.3).

7.2.2 Soil emissions of CO_2, CH_4 and N_2O under different management practices

Overall, increasing water level significantly decreased CO_2 emissions by 34%. The reduction in emission was 27% in oil palm plantations, 34% in bare peatland and 45% in forest systems. CO_2 emission was unaffected by change in water table level in cropland (Figure 7.4). In contrast, increasing water level increased N_2O emission by 54%, mostly contributed by the increase observed in bare peatland (Figure 7.5). Increasing water level overall did not significantly affect CH_4 emission but note that the response ranged from –46% to 104%. When the N input was decreased, the emissions of CO_2 and N_2O were decreased by 9 and 41%, respectively. The decrease was observed in cropping systems (–21%) for CO_2 emission and in oil palm/rubber (–32%) and cropping systems (–81%) for N_2O emission. Higher CO_2 emission was associated with a lower N input in abandoned land where N_2O emission tended to decrease. Shading decreased CO_2 emission by 33% but did not affect N_2O emission. Growing cover crops decreased CO_2 emission by 38 and 29% in oil palm and bare peatland, contributing to an overall 33% reduction. There were insufficient studies for analysing the percentage response of CH_4 emission because CH_4 uptake (negative values) was often observed in drained croplands, rendering the calculations of effect size using natural logarithm inappropriate. Instead, the effect of management practices on CH_4 fluxes (also CO_2 and N_2O) was expressed as the change in amount (Table 7.1).

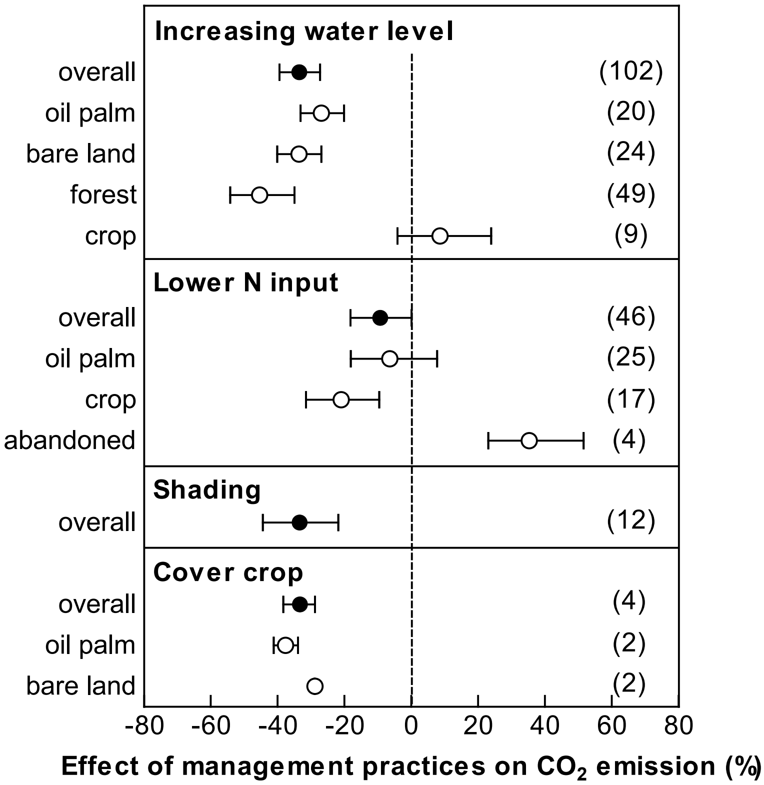

Figure 7.4 Effect of management practices on CO_2 emission under different end land uses. Numbers of experimental observations are in parentheses.

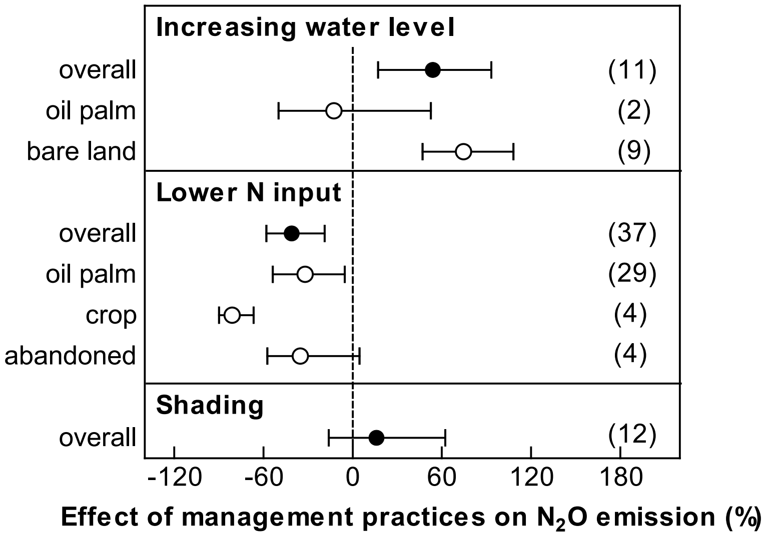

Figure 7.5 Effect of management practices on N_2O emission under different end land uses. Numbers of experimental observations are in parentheses.

Increasing water level decreased CO_2 emission by 3.1, 1.3 and 1.6 g C m^{-2} d^{-1} in forest, bare peatland and oil palm/rubber plantation, respectively, but generally increased CH_4 and N_2O emissions (Table 7.1). Considering the CO_2-equivalents, a decrease of 1.2 and 1.5 g C m^{-2} d^{-1} could be achieved, respectively, in bare peatland and oil palm/rubber plantation when the water table level was raised. A lower N input was associated with a decrease in CO_2 emission by 1.1 g C m^{-2} d^{-1} in cropland but an increase (0.38 g C m^{-2} d^{-1}) in abandoned land. When N input was reduced, CH_4 and N_2O emissions were decreased by 0.05–0.85 mg C m^{-2} d^{-1} and 0.18–5.5 mg N m^{-2} d^{-1}, respectively (Table 7.1). Overall, decreasing N input was the most effective for decreasing C loss (in CO_2-equivalent) in cropping system (by 1.7 g C m^{-2} d^{-1}) (Table 7.1). Shading overall decreased C loss (in CO_2-equivalent) by 0.47 g C m^{-2} d^{-1}.

Table 7.1 Changes in greenhouse gas emissions due to various management practices

Management practice[a]	CO_2 (mg C m^{-2} d^{-1})		CH_4 (mg C m^{-2} d^{-1})		N_2O (mg N m^{-2} d^{-1})		CO_2-equivalent [c] (mg C m^{-2} d^{-1})	
	mean	95% CI [b]	mean	95% CI	mean	95% CI	mean	95% CI
Increasing water level								
Bare peatland	–1288	–1788 to –829.5	0.075	–0.35 to 0.52	0.95	0.63 to 1.35	–1180	–1721 to –671.3
Oil palm/rubber	–1552	–1960 to –1151	0.006	0.002 to 0.010	0.45	–0.015 to 0.91	–1501	–1962 to –1048
Lower N input								
Oil palm/rubber	–108.8	–1047 to 734.4	–0.85	–1.13 to –0.58	–2.22	–4.34 to –0.33	–369.2	–1551 to 691.5
Cropping	–1086	–1768 to –460.6	–0.045	–0.28 to 0.14	–5.48	–9.05 to –2.78	–1709	–2799 to –774.8
Abandoned	376.4	261.8 to 490.9	–0.15	–0.59 to 0.21	–0.18	–0.38 to 0.042	354.5	212.5 to 497.8
Shading								
Cropping	–605.5	–878.2 to –360.0	0.090	–0.047 to 0.22	1.22	–0.63 to 3.20	–466.2	–950.6 to 5.23

[a] Only the categories with data available for all three greenhouse gases were included in this table, e.g. growing cover crop was not included because data was available only for CO_2 emission.
[b] CI: confidence intervals; negative (positive) values indicate a decrease (increase) in gas emissions due to management practices
[c] CO_2-equivalent was calculated using the global warming potentials (100-year time horizon) of 28 for CH_4 and 265 for N_2O (Myhre et al. 2013)

7.3 Discussion

7.3.1 Soil greenhouse gas emissions induced by changes in land use and hydrological conditions

Using tropical peat swamp forests for industrial plantation and agricultural production in South East Asia increases soil greenhouse gas emissions (Figures 7.1–7.3). The increased emissions from peat soils were consistent with effects of human disturbances, such as deforestation, drainage, and burning (e.g. Putra et al. 2008; Swails et al. 2018). The hydrological conditions of the land before, during, and after conversion are critical for the dynamics of gas emissions. It is important to note these studies were primarily from chamber measurements and so CO_2 uptake by plants is not included (discussed further below). Our work here provides an important first step in understanding effects of land conversion in the absence of more complete data that clearly needs collection in the future.

In general, for the land that remained undrained, no significant effects on soil greenhouse gas emissions were detected (Figures 7.1–7.3). While peat fire releases huge amount of CO_2 to the atmosphere (Huijnen et al. 2016), the land that was logged and/or burnt had lower CO_2 and CH_4 emissions compared to intact peatlands. This may be because the fresh organic matter from litter fall and root exudates in unburnt swamp forests was no longer available in burnt peatlands (Girkin et al. 2018). In addition, the amount of live roots decreased substantially when peatlands were burnt, thereby reducing CO_2 emission via root respiration (Ishikura et al. 2018). When the land was drained to establish crops and plantations, more CO_2 and N_2O but less CH_4 were emitted (Figures 7.1–7.3). Indeed, drained (aerobic) conditions favour microbial decomposition, root respiration (CO_2 emission), nitrification (N_2O emission) and methanotrophic activity (CH_4 consumption) (Arai et al. 2014; Wüst-Galley et al. 2016; Hu et al. 2017) whereas undrained (anaerobic) conditions are conducive to denitrification and methanogenesis (CH_4 emission) (Hergoualc'h and Verchot 2012; Adji et al. 2014; Ishikura et al. 2018; Hatano 2019). Enhanced denitrification may result in higher N_2O emission and/or N_2 emission depending on the peat soil water content and the availability of C and nitrate (Weier et al. 1993; van Beek et al. 2011). In addition to its direct effect on microbial processes and activities, the change in water table level exerts cascading (and potentially long-lasting) effects, leading to substantial CO_2 losses as observed in our study. For example, the drawdown of water table makes the landscape more vulnerable to fire both horizontally (larger area) and vertically (deeper layers) (Huang and Rein 2017; Hu et al. 2018). The combustion of deeper peat layers could release old carbon thought to be stable for centuries to millennia (Turetsky et al. 2015; Drake et al. 2019). Long-term tropical peat subsidence is estimated to result in losses of CO_2 ranging from 2.5–11 Mg C ha^{-1} $year^{-1}$ (Couwenberg et al. 2010). The substantial C losses consequent on tropical peatland conversion highlights the urgency of devising mitigation strategies to minimize further loss.

7.3.2 Potential of management practices to decrease soil greenhouse gas emissions

The available studies in the literature allowed us to quantify the effects of four management practices on greenhouse gas emissions in tropical peatlands, viz. increasing water level, decreasing N input, shading, and growing cover crops. Carbon accumulation in natural peatlands hinges on the limited decay of recalcitrant plant litter in anoxic conditions created by high water tables (Freeman et al. 2001; Ritson et al. 2017). In order to avoid the rapid loss of C through the breakdown of organics and encroachment by fire, the hydrology should be restored. This is evidenced by the decrease in soil CO_2 emission observed in our study under an increased water table level (Figure 7.4), also noted by Couwenberg et al. (2010). Raising water level reverts the aerobic conditions back to anaerobic. This process avoids the negative consequences of drainage on CO_2 loss via rapid decomposition, drying and burning of the peat. However, increasing water level potentially stimulates N_2O and CH_4 emissions (Figure 7.5; Table 7.1). This is because less aerobic conditions, as mentioned earlier, favour N_2O production from denitrification and CH_4 production by methanogens (Ishikura et al. 2018; Hatano 2019). Converting the emissions of N_2O and CH_4 into CO_2-equivalents and summing the CO_2-equivalents of the three gases, we found that increasing water level overall decreased soil C loss by 1.2–1.5 g C m^{-2} d^{-1} (4–5 Mg C ha^{-1} yr^{-1}) in oil palm plantation and bare peatland. This reduction in C loss partially offsets the total C loss (16 Mg C ha^{-1} $year^{-1}$) from converting peat swamp forests into oil palm (Murdiyarso et al. 2010). While the monitoring of water tables after hydrological restoration has been limited to relatively short-term campaigns, its long-term effect warrants further research. The non-significant effect of increasing water level on CO_2 emission in croplands could be attributed to contrasting mechanisms. On the one hand, a higher water level could reduce CO_2 emission due to anaerobic conditions as discussed. On the other hand, soil respiration could be enhanced during the rewetting period by the 'soil-drying effect' (Birch 1958), which occurs when labile organic matter, derived from dead microbes due to excessive drying of soil, is decomposed soon after its rewetting (Van Gestel et al. 1993). This effect was observed on a cropland on peat by Ishikura et al. (2017), who attributed the large variability of soil respiration rate to frequent occurrence of rewetting due to the temporal rise in ground water level.

Apart from water dynamics, the emission of greenhouse gases in particular N_2O is affected by N availability. It has been reported that unfertilized ecosystems in the tropics could emit substantial amount of N_2O emission (9 to >50 kg N ha^{-1} $year^{-1}$), mostly from drained peat soils (van Lent et al. 2015; Oktarita et al. 2017). This suggests that when peat is rich in N high N_2O emissions can occur during decomposition particularly in the tropics. However, considerable amount of fertiliser N is also applied to agricultural land on peat to secure crop production, which further stimulates N_2O emission via nitrification and denitrification. For example, N fertilisers are typically applied at 100–300 kg N ha^{-1} $year^{-1}$ for oil palm cultivated on tropical peat (Murdiyarso et al. 2010) and 35–115 kg N ha^{-1} $year^{-1}$ for croplands (Maftu'ah et al. 2016). We found that reducing fertiliser N input decreased N_2O emissions in croplands and oil palm plantations (Figures 7.4–7.5; Table 7.1). This is particularly important for drained peat soil (pH usually less than 4) because inhibition of N_2O reductase under acidic conditions would promote a higher N_2O:N_2 ratio during denitrification (Šimek and Cooper 2002; Liu et al. 2014). This highlights the importance of determining optimum N fertiliser rates and timing of application for these N intensive systems, and the need for developing N_2O mitigation strategies such as nitrification inhibitors and controlled release fertilisers that have been proven effective in other high N_2O emitting systems (Xia et al. 2017; Lam et al. 2018). Our meta-analysis suggests that decreasing N input also lowered CO_2 emission. Nitrogen fertilization promotes peat decomposition in tropical peatlands (Jauhiainen et al. 2014; Comeau et al. 2016) so lower N input results in less CO_2 emission. However, lower CO_2 emission was observed in degraded land when fertiliser N was applied (Figure 7.4). This might be because N was gradually lost in degraded land due to mismanagement such that N was required to stabilize C, which would otherwise be emitted as CO_2.

The limited studies on shading of the peat surface and growing cover crops are two other potential mitigation strategies for CO_2 emissions (Figure 7.4). While decomposition of organic matter in peatlands increases with temperature (Jauhiainen et al. 2014), the principle of both strategies is to lower the peat surface temperature and subsequent loss of peat C substrate. Compared to shading, growing cover crops offers the advantages of lower implementation cost, improved soil fertility and higher productivity (Arifin et al. 2015). Unfortunately, these two strategies have not been widely tested and more work is needed to explore their efficacy both in terms of mitigation and appeal to farmers and land managers in the region.

Apart from biophysical constraints, cultural or socioeconomic dimensions should also be considered for the development and implementation of mitigation strategies. It is critical that local researchers should be involved in research and subsequent recommendations on mitigation strategies. While studies on the socioeconomic barriers to adoption of mitigation strategies are limited for the restoration of tropical peatlands, we identify the positives and negatives of raising water table level and optimising fertiliser N input that might affect decision making on whether to adopt these practices based on socio-economic, environmental and biophysical considerations according to Robledo-Abad et al. (2017) (Table 7.2). A comprehensive cost-benefit analysis of potential mitigation strategies is warranted.

Table 7.2 Summary of positive and negative impacts of mitigation strategies

Mitigation strategies	Positive impacts			Negative impacts			Permanence
	Socio-economic	Environmental	Biophysical	Socio-economic	Environmental	Biophysical	
Optimising fertiliser N input	Improve soil resilience productivity; Reduce fertiliser and labour cost	Reduce pollution and improved soil quality	Improve soil, water and air quality	None	None	None	Reversible when the mitigation strategy ceases
Raising water table level	Employment, local livelihoods	Slow down peatland degradation and biodiversity loss, reduce carbon loss	Improve soil carbon, nutrient cycling, peat quality	May lower agricultural production, increase food prices	Possibly increase the prevalence of plant fungal disease; stimulate methane production	Excess water in the plant rooting zone may impact root growth	Reversible when the mitigation strategy ceases

8 Scope visit to Indonesia

To obtain first-hand advice and experience on the issues of C loss from land use change in Indonesia and to establish collaboration with Indonesian experts on these issues, we visited three institutions in Indonesia on 19-21 August 2019. Prior to the visit, we contacted Ms Mirah Nuryati, ACIAR Country Manager-Indonesia, regarding our plan for the scope study visit to Indonesia. We discussed in particular with whom we would collaborate on this project, and things to note before and during the visit. Ms Mirah arranged invitation letters for us (Appendix 2).

Through our discussion with Mirah, we realise that ACIAR works in Indonesia through three key Ministries ie. (i) Agriculture, (ii) Marine Affairs and Fisheries, and (iii) Environment and Forestry. ACIAR's main partner in agriculture is the Indonesian Agency for Agricultural Research and Development (IAARD) (see Appendix 3 for its organisation chart), which the Indonesian Centre for Land Research and Development (ICALRD) and the Indonesian Soil Research Institute (Dr Husnain Husnain) sit under. ACIAR is open and welcome for collaboration with various partners (including Universities such as IPB), the main Indonesian Delegate remains IAARD. So it would be good to talk to ICALRD, and we contacted Dr Husain and Dr Sulaeman regarding our visit. The IPB as a State University falls under different Ministry ie. Ministry of Research and Technology and Higher Education, and could be involved in any research activity, but not as a lead in ACIAR projects.

8.1 Indonesian Centre for Agricultural Land Resource Research & Development / Indonesian Soil Research Institute

We met Dr Yiyi Sulaeman, Saefoel Bachri, and colleagues on 20 August 2019 at ICALRD (2-4 pm) (Figures 8.1, 8.2). Through the meeting, we learnt that:

- Recent governmental moratorium on peatland conversion for any use but many issues surrounding current land-use permits remain.
- Peatlands now are under managed by either large companies or small holder farms, management strategies/suggestions could be different.
- The area of abandoned land is poorly mapped and these areas are more prone to fire and large carbon losses
- Abandoned lands, which are acidic with high organic C content, could be a future focus of land management to increase productivity, avoid wild fires and achieve sustainability and emission goals.
- It's farmers' decision as to when to abandon a peatland. When the farmers can no longer gain a profit and/or have insufficient capital to maintain the land they will not cultivate their land. Farmers' motivation for abandoning land should be studied.
- To avoid peatland degradation (abandoned peatland), we should first better characterise the biophysical properties of abandoned peatlands, and then can devise management options. More case studies are needed for this issue.
- Dr Sulaeman suggested that might be good to organise a workshop in Indonesia to gather relevant experts together in future for idea exchange.
- This institute has strong expertise in digital soil mapping in Indonesia.

Figure 8.1 Meeting at ICALRD

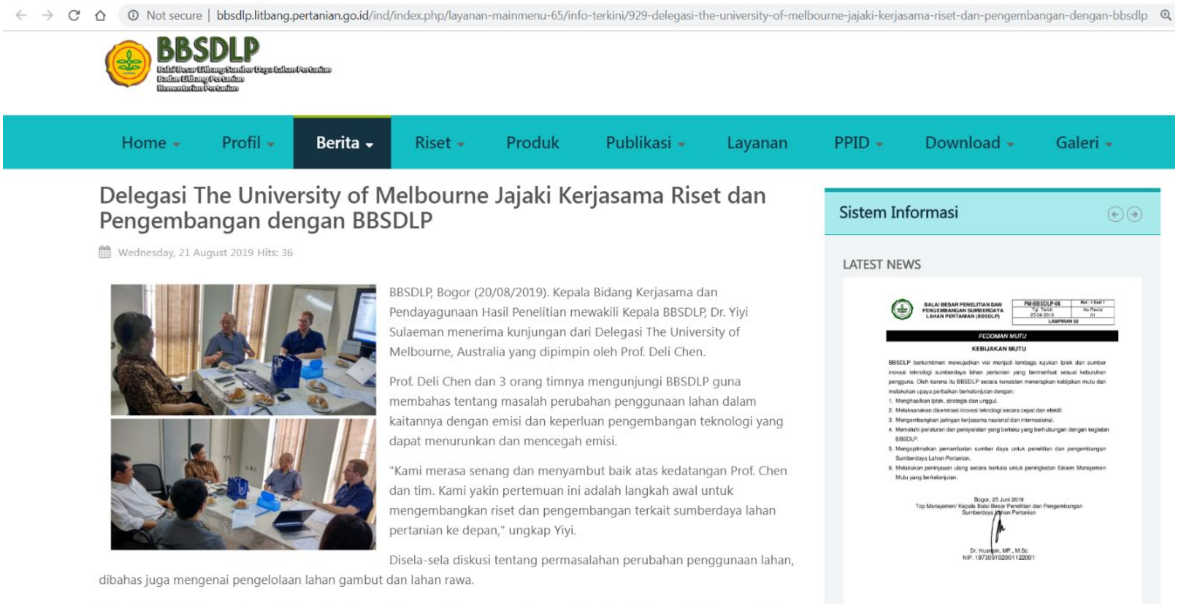

Figure 8.2 News on ICALRD website regarding our visit

8.2 Department of Soil Science and Land Resources, Faculty of Agriculture, IPB University

We met Prof Supiandi Sabiham, Dr Kukuh Murtilaksono and few PhD students on 21 August 2019 at IPB University (11am-2pm). We learnt that:

- This research group has set up one peatland flux tower in Lokasi Penelitian (Figures 8.3, 8.4) but will need more (at least one set) to get data for comparison and to quantify potential treatment (e.g. management options) effects.

- The major mitigation strategy to prevent or slow down the C loss from the peatland is water management, especially for dry season.
- Currently the primary guideline used for peatland management is to maintain water table depth within 40 cm of the surface.
- These researchers feel this is too simple and does not account for differences in peat physical structure that more directly controls surface soil moisture
- Some ecosystem scale CO_2 flux measurements over peat are being made and there is much interest in collaboration to expand (Figure 8.5).
- Measurements of components of C fluxes and net emission are important (Figure 8.6)

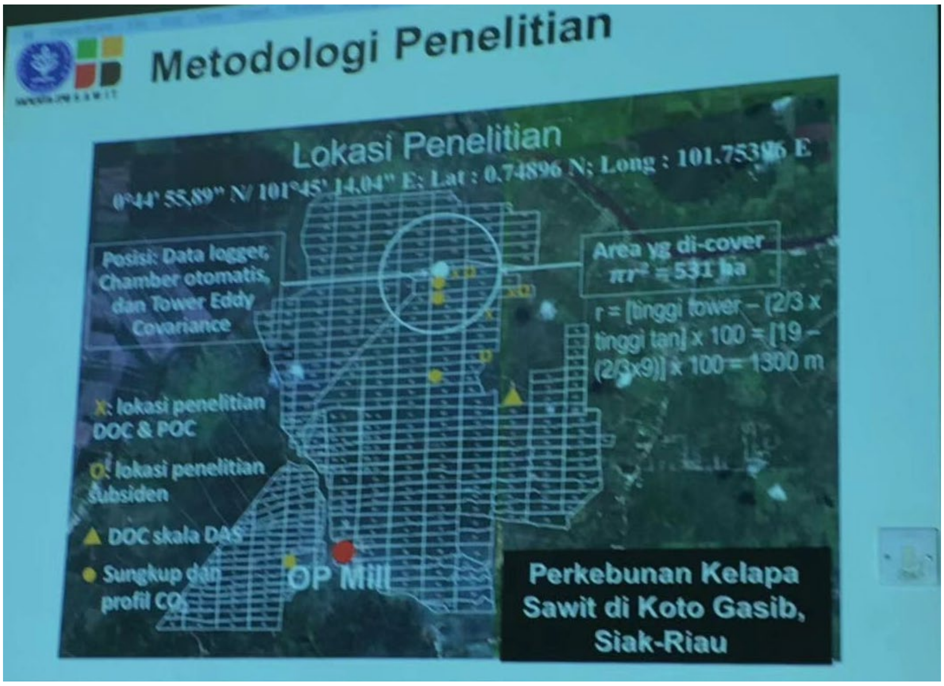

Figure 8.3 Location of the study site by Prof Supiandi

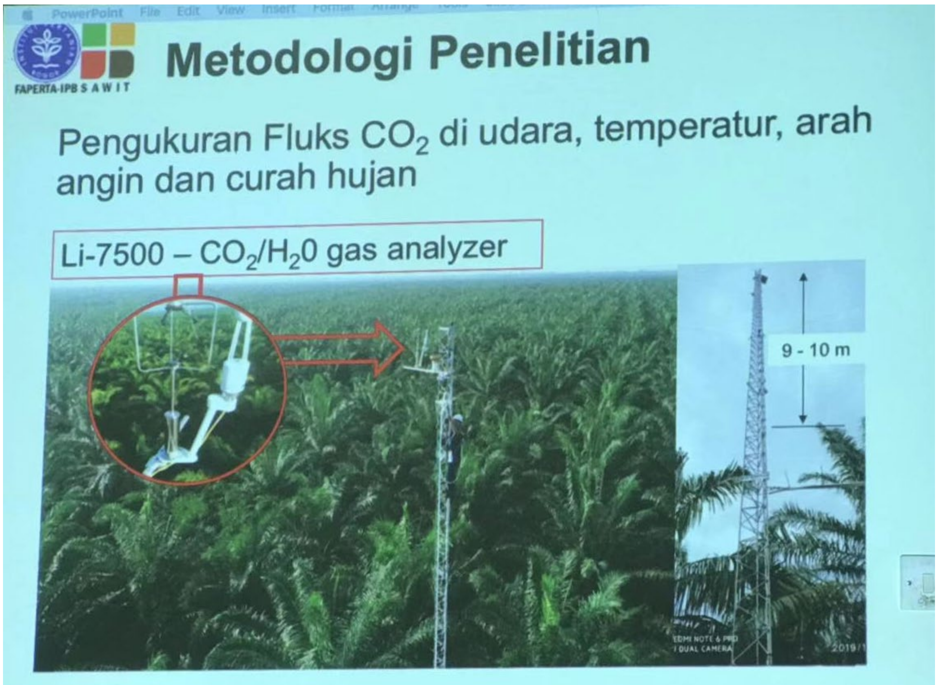

Figure 8.4 Flux tower for CO_2 measurement

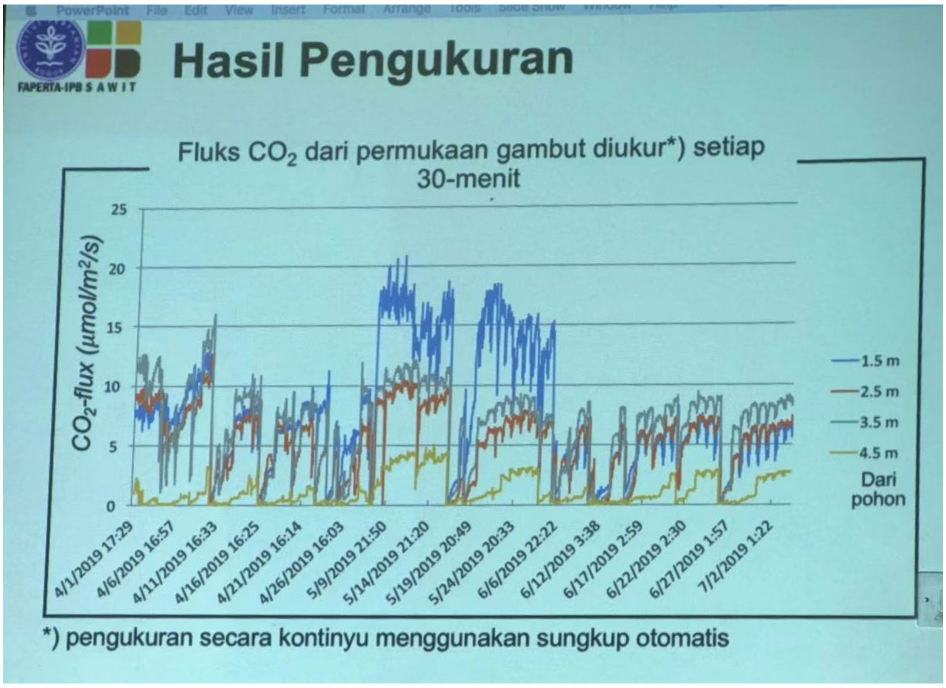

Figure 8.5 CO_2 flux observed from April to July 2019

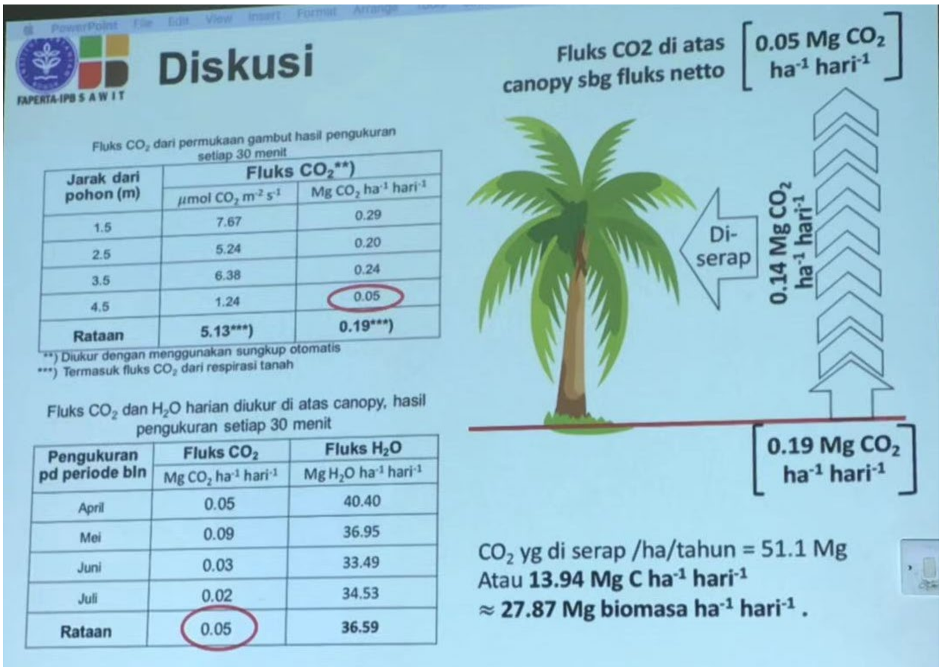

Figure 8.6 Measurement of various components of CO_2 flux

8.3 Center for International Forestry Research (CIFOR)

We met Professor Daniel Murdiyarso on 22 August 2019 at CIFOR (11.30 am - 2 pm) (Figure 8.7). We learnt that:

- CIFOR is a CGIAR Research Center, and leads the CGIAR Research Program on Forests, Trees and Agroforestry (FTA). CGIAR is a global research partnership and the world's largest global agricultural innovation network.

- Prof Murdiyarso also pointed out the major mitigation strategies for peatland is water management. The satellite data was used to observe the water table to detect the dangerous area to keep water table also within 40 cm of the surface.
- There exist issues of the introduction local species, management of abandoned land, fires induced by farms.
- We obtained online database/information from Prof Murdiyarso:
  - Sustainable Wetlands Adaptation and Mitigation Program (SWAMP) database: https://www.cifor.org/swamp/database/database-management/
  - Peat Restoration Agency: https://brg.go.id
  - International Tropical Peatlands Centre: https://www.tropicalpeatlands.org/
  - DG Climate Change: http://ditjenppi.menlhk.go.id/
  - DD Peat Conservation: http://ksdae.menlhk.go.id/

Figure 8.7 Meeting with Prof Daniel Murdiyarso at CIFOR

9 Conclusions and recommendations

9.1 Conclusions

The conversion of peat swamp forests to industrial plantation, agricultural production and abandoned peatland generally increased greenhouse gas emissions. The emissions are dependent on the hydrological conditions of the land at different stages of land conversion. In general, for the land that remained undrained, no significant effects on soil greenhouse gas emissions were detected. However, when the land was drained to establish crops and plantations, more CO_2 and N_2O but less CH_4 were emitted due to aerobic conditions.

The Indonesian Government has taken a critical step by banning further conversion of peatlands. This will be the most effective way of mitigating further C loss from deforestation and peat destruction. On lands that have already been converted, the water table level should be restored to reduce soil CO_2 emission from oil palm and rubber plantations. Although raising the water level may increase N_2O and CH_4 emissions, the magnitude of increase (in CO_2-equivalents) is much lower than that of decrease in CO_2 emission. Currently the primary guideline used for peatland management in Indonesia is to maintain water table depth within 40 cm of the surface, but this does not account for differences in peat physical structure that more directly control surface soil moisture. Other strategies such as decreasing fertiliser N input and growing cover crops also have the potential to lower greenhouse gas emissions, but their impacts were less studied.

The findings of our study provide important information on maintaining soil carbon stocks upon peatland conversion. They are highly relevant to the global action on climate change mitigation through international initiatives and research networks such as the “4 per 1000” Initiative (e.g. Minasny et al. 2017) and the Soil Carbon Sequestration network of the Integrative Research Group of the Global Research Alliance on Agricultural Greenhouse Gases (e.g. Smith et al. 2020), and possibly the Farm & Regional Scale Integration Network. However, measurements were mostly conducted using chamber-based methods; ecosystem-scale assessment of mitigation strategies is certainly lacking (see section 9.2 for further details). More mitigation strategies for greenhouse gas emissions should be explored and validated in the field at ecosystem scales over longer time periods, and ultimately these observations should be integrated with process-based modelling. Furthermore, the development of mitigation strategies needs to take into account not only the biophysical constraints but also the associated cultural dimensions. It is critical that research and subsequent recommendations involve or, ideally, are led by local researchers.

9.2 Knowledge gaps and Recommendations

Key knowledge gaps and recommendations of this SRA are as follows:

1. Clearly, increasing water level (to <40 cm) effectively decreases CO_2 emission although it may increase CH_4 emission to a relatively minimal extent. Optimising fertiliser N input effectively decreases N_2O emission from peat soils and has the potential to increase crop productivity and carbon sequestration. There is a clear need of quantifying the greenhouse gas mitigation potential of various management practices for different peat depths, peat types, and peat substrates at the plot, farm and landscape scales.

2. Soil CO_2 fluxes are only one component of the net ecosystem carbon balance. The effects of these mitigation strategies on the other components of ecosystem carbon balance (e.g. gross primary production, ecosystem respiration, dissolved

organic/inorganic carbon export and harvested biomass) remain unclear and must be quantified when considering the overall mitigation effects.

3. An objective of future work is therefore to comprehensively evaluate the potential of mitigation strategies by quantifying multiple components of a full net ecosystem carbon balance of peatlands in different scales. This is essential to determine whether the reduction in soil greenhouse gas emissions seen in this SRA would be offset by increases, if any, in other components of the carbon balance.

4. To achieve the above objective, scale-appropriate methods and long-term measurements of CO_2, CH_4 and N_2O are needed, notably micrometeorological techniques (e.g. eddy covariance) coupled with measurements of lateral carbon flows and process-based modelling. Such approaches are complementary to measuring changes in peat but are more sensitive avoiding the challenges of detecting (small) changes in soil carbon stock due to varying peat bulk density, peat depth and hydrological conditions.

5. The expansion of abandoned peatlands cannot be ignored. The area of these abandoned lands is poorly mapped but the lands are more prone to fire and large carbon losses due to lack of management. The Peat Restoration Agency and the Indonesian Swampland Agriculture Research Institute manage 121 abandoned peatlands in Talio Hulu Village, Pandih Batu District, Pulang Pisau Regency, Central Kalimantan, which could be used for future projects on peatland restoration. There is huge potential to halt this substantial carbon emission by avoiding further land abandonment and restoring the abandoned lands, through a series of actions:

   (i) Farmers' motive for abandoning land should be studied. It is likely that they will not cultivate their land when the can no longer gain a profit and/or have insufficient capital to maintain the land. A better understanding is required of why the peat soils deteriorate over time and whether this can be effectively managed.

   (ii) The biophysical properties of abandoned peatlands should be better characterised. This will help in designing site-specific management options to avoid further degradation and/or aid restoration of the peatland. For example, land may be too acidic or the peat soil may be too compacted resulting from land conversion process, both of which affect crop growth.

   (iii) The stoichiometry of essential nutrients of the peat soil should be explored to understand the potential limiting factors for healthy plant growth. In particular, nitrogen is essential for crop growth but could be low/limiting in carbon-rich peat. While fertiliser N application is inevitable to sustain crop growth, enhanced efficiency fertilisers (urease inhibitors, nitrification inhibitors, and controlled release fertilisers) should be used to reduce N loss to the environment. Of course this may incur additional costs that require careful consideration. Surprisingly, there has been no study on the use of enhanced efficiency fertilisers in decreasing N_2O emissions from crops/oil palm cultivated on tropical peatlands.

   (iv) Appropriate land use e.g. growing paddy rice with balanced nutrient management appears promising to restore the degraded peatland, which not only halts C losses but also increases C sequestration and famers' income.

   Future projects should therefore identify strategies to avoid land abandonment and restore abandoned peatland, so as to stop further C loss, improve peat soil fertility and increase agricultural production of converted peatlands.

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10.2 List of publication produced by project

- Lam, S.K., Goodrich, J.P., Liang, X., Zhang, Y., Pan, B., Schipper, L.A., Sulaeman, Y., Nelson, L., Chen, D. Mitigation of greenhouse gas emissions resulting from land use change in tropical peatlands in the Asia-Pacific region: A meta-analysis (submitted to *Regional Environmental Change*, under review)

10.3 List of presentations

- Annual Science Meeting presentation to New Zealand Ministry for Primary Industries, 6 August 2020
- Results update presentation to ACIAR, 5 June 2020
- Progress update presentation to ACIAR, 13 September 2019

11 Appendixes

11.1 Appendix 1

Studies included in the meta-analyses:

1. Adji FF, Hamada Y, Darung U, Limin SH, Hatano R (2014) Effect of plant-mediated oxygen supply and drainage on greenhouse gas emission from a tropical peatland in Central Kalimantan, Indonesia. Soil Science and Plant Nutrition 60:216-230.
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11.2 Appendix 2

Formal invitation letter from ACIAR Indonesia regarding our visit.

Australian Government
Australian Centre for International Agricultural Research

Australian Embassy
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INDONESIA

T (62 21) 2550 5555
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15 August 2019

Husnain SP, MSc. PhD
Director
Indonesian Centre for Land Resources Research & Development
Jl. Tentara Pelajar 12
Bogor

Dear Dr. Husnain

Re. Proposed meeting with University of Melbourne Team, 20 August 2019

I am pleased to inform of the upcoming visit to Indonesia by a Team of the University of Melbourne and University of Waikato, New Zealand in August 2019. The team will consist of the following personnel:

- Professor Deli Chen, M, University of Melbourne, Australia
- Dr Shu Kee Lam, M (Raymond), University of Melbourne, Australia
- Dr Xia Liang, F (Emma), University of Melbourne, Australia
- Dr Jordan Goodrich, M, University of Waikato, New Zealand

The teams will explore potential collaboration opportunities with ICALRD on Emissions avoidance of soil carbon from lands undergoing practice change. For this purpose, they are seeking to meet with you and relevant officials/researchers of ICALRD on Tuesday, 20 August 2019.

I hope that the subject would be of interest for further collaboration with ICALRD and thanking you for any supports you may be able to provide.

With best wishes,

Mirah Nuryati
Country Manager
ACIAR Indonesia

11.3 Appendix 3

Organisation chart of the Indonesian Agency for Agricultural Research and Development