COMPARISON OF CARBON OXIDATION LOSSES FROM A BARE DRAINED PEATLAND USING DIFFERENT TECHNIQUES

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by

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LIST OF SYMBOLS

$A\lambda$	Absorptance
F	Flux
hz	Hertz
mph	Miles per hour
$\boldsymbol{\rho}_d$	Mean product of air density
s	Dry mole fraction / Second
Tair	Air Temperature
u	Wind component (parallel to the x axis)
μ	Micro
v	Wind component (parallel to the y axis)
w	Vertical wind speed
λ	Wavelength
λε	Molar extinction coefficient
$<$	Less than
$>$	More than
Ω	Ohm
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalent
H_2O	Water vapour
N	Nitrogen
N_2O	Nitrous Oxide

LIST OF ABBREVIATIONS

ABS	Acrylonitrile butadiene styrene
ASCII	American Standard Code for Information Interchange
BD	Bulk Density
CSI	Campbell Scientific Incorporated
GHG	Green House Gas
GWL	Ground Water Level
EC	Eddy covariance
EGM	Environment Monitoring System
HFP01SC	Soil Heat Flux Plates 01 Self Calibrated
IPCC	Intergovernmental Panel on Climate Change
IRGA	Infrared Gas Analyser
MPOB	Malaysian Palm Oil Board
MSPO	Malaysian Sustainable Palm Oil
MUCOS	Malaysian Unified Classification of Organic Soils
NDIR	Nondispersive Infrared Sensor
NEE	Net Ecosystem Exchange
PVC	Polyvinyl Chloride
RH	Relative Humidity
S	Subsidence
SOM	Soil Organic Matter
SOP	Standard Operating Procedure
SRC	Soil Respiration Chamber
UK	United Kingdom
USA	United State of America

USDA	United State Department of Agriculture
VDC	Voltage, Direct Current
WFPS	Water-Filled Pore Space
WPL	Webb-Pearman-Leuning
XML	Extensible Markup Language

PERBANDINGAN KEHILANGAN PENGOKSIDAAN KARBON DARIPADA KAWASAN TANAH GAMBUT TERSALIR TERDEDAH MENGGUNAKAN PELBAGAI TEKNIK

ABSTRAK

Saliran dan penanaman tanah gambut akan menyebabkan penurunan dan mineralisasi bahan organik yang meningkatkan kehilangan karbon apabila lebih banyak CO_2 dikeluarkan. Pengukuran pelepasan CO_2 telah dibuat di kawasan paya gambut yang baru diterokai dan bebas daripada tumbuh-tumbuhan. Tiga kaedah berbeza digunakan; eddy covariance, kebuk tanah dan ukuran penurunan tanah untuk memperoleh pelepasan CO_2 dalam kajian ini. Purata kadar fluks CO_2 yang diukur dengan teknik eddy covariance adalah kira-kira 5.13±0.12 µmol CO_2 m^{-2} s^{-1} (atau 71.18 tan CO_2 ha^{-1} $tahun^{-1}$). Kadar efluks CO_2 tanah yang diukur dengan teknik kebuk tanah adalah kira-kira 3.88±0.15 µmol CO_2 m^{-2} s^{-1} (atau 53.84 tan CO_2 ha^{-1} $tahun^{-1}$). Penurunan gambut pula adalah sebanyak 1.21±0.13 cm $tahun^{-1}$ yang bersamaan dengan 24.60 tan CO_2 ha^{-1} $tahun^{-1}$. Perbezaan dalam anggaran kehilangan karbon tidak bergantung secara eksklusif pada kaedah pengukuran, tetapi juga pada kawasan dan tempoh pengukuran. Ini boleh dikaitkan dengan kebolehubahan spatial dan temporal, teknik pengukuran, keadaan persekitaran, dan kepelbagaian sifat gambut. Teknik kebuk tanah dikenalpasti teknik yang sesuai dan kos efektif untuk menilai kehilangan karbon di dalam kajian ini. Kajian ini menyediakan maklumat mengenai garis dasar pelepasan karbon daripada gambut akibat pengoksidaan yang disebabkan oleh saliran yang tanpa melibatkan komponen respirasi akar tumbuhan. Maklumat ini berguna untuk membantu dalam membuat keputusan mengenai pembangunan tanah gambut untuk pertanian di Malaysia pada masa hadapan.

COMPARISON OF CARBON OXIDATION LOSSES FROM A BARE DRAINED PEATLAND USING DIFFERENT TECHNIQUES

ABSTRACT

Drainage and cultivation of peatlands will lead to subsidence and mineralization of organic matter that increases C loss as more CO_2 is emitted. Measurement of CO_2 emissions were made at a newly logged-over peat swamp area that has been cleared of vegetation. Three different methods were used; eddy covariance, soil chamber and soil subsidence measurements to derive CO_2 emissions in this study. The average above ground CO_2 flux rate measured by the eddy covariance technique was 5.13±0.12 μmol CO_2 m^{-2} s^{-1} (or 71.18 tonnes CO_2 ha^{-1} $year^{-1}$). The soil CO_2 efflux rate measured by the soil chamber technique was 3.88±0.15 μmol CO_2 m^{-2} s^{-1} (or 53.84 tonnes CO_2 ha^{-1} $year^{-1}$). Subsidence amounted to 1.21±0.13 cm $year^{-1}$ over the measured year, which corresponds to 24.60 tonnes CO_2 ha^{-1} $year^{-1}$. Differences in estimated C losses might not depend exclusively on the method of measurement, but also on the area and period of measurements. This could be attributed to the spatial and temporal variability, measuring techniques, environmental conditions, and heterogeneity of peat properties. In this study, the soil chamber method was found to be a reliable and cost-effective approach for assessing carbon loss compared to eddy covariance and subsidence techniques. The study provides valuable information on carbon emission baseline from peat due to drainage-induced oxidation that excludes the plant root respiration component. The data will be helpful in making decisions about Malaysia's future peatland agricultural development.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Malaysia has about 2,426,600 hectares (ha) of tropical peatland, and about 65 % or 1,588,142 ha is found in Sarawak. The remaining areas are in Peninsular Malaysia, 716,944 ha; and Sabah, 121,514 ha. It was reported that Malaysia's total peatland area cultivated with oil palm was about 666,038 ha, where 37.45% were in Sarawak (Wahid et al., 2010).

Tropical peatland is known for its unique ecosystem and plays a vital role in storing a large amount of carbon. Once the peat is drained, the conversion of tropical peatland to cultivated areas will result in carbon emissions (Couwenberg, 2011; Hooijer et al., 2010; Page et al., 2011). Carbon loss from tropical peatland is a major concern since they contribute to climate change.

There is much debate on the magnitude of drainage-induced carbon fluxes from tropical peatlands (Hirano et al., 2007; Hooijer et al., 2006; Hoyt et al., 2019), which serves as a compelling motivation for undertaking this study. Tropical peatlands are unique and sensitive ecosystems that play a crucial role in the global carbon cycle. It stores a substantial amount of carbon in their organic soils. Drainage and land use changes in these areas can have significant impacts on carbon emissions, climate change, and overall ecosystem health. When these peatlands are drained for activities like agriculture, forestry, or development, the previously waterlogged conditions change. This can lead to increase decomposition of organic material, releasing stored carbon in the form of carbon dioxide (CO_2) and methane (CH_4) emissions. Drainage-induced carbon fluxes from tropical peatlands can contribute to greenhouse gas emissions, exacerbating global climate change. Understanding the magnitude and dynamics of these emissions is crucial for accurate climate modelling and policy decisions. This study can provide critical insights for land use planning and management in tropical peatland areas by quantifying carbon fluxes subsequently, can help guide sustainable practices that minimize carbon emissions while allowing for responsible development.

Tropical peatlands are biodiversity hotspots and provide important ecosystem services. A thorough understanding of carbon fluxes can aid in conservation efforts and inform strategies for restoring degraded peatlands to their natural, carbon-sequestering state. This study also has the potential to contribute to the scientific understanding of this complex issue, potentially resolving uncertainties and informing future research directions. The findings could be used to inform international agreements and policies related to carbon emissions, climate change mitigation, and sustainable land use. This is particularly relevant in the context of global efforts to reduce greenhouse gas emissions under agreements like the Paris Agreement. Besides that, this research may engage local communities, stakeholders, and decision-makers. Collaborative efforts can lead to informed decisions that balance economic development with environmental sustainability.

It has been known that the growth of oil palm plantations on tropical peatland requires drainage with a water table of about 60 cm below the peat surface (Othman et al., 2011; Singh, 2004). Drainage and cultivation on peat soils will lead to peat subsidence (Berglund & Berglund, 2011; Wösten et al., 1997). Peat subsidence is partly due to consolidation and compaction, but peat oxidation adds a considerable proportion. The oxidation of peat results in CO_2 that is emitted to the atmosphere. The exchange of carbon between the atmosphere and terrestrial ecosystems is governed by soil respiration, which accounts for the second-largest carbon flux. Components of soil respiration consisted of two major parts, i.e., autotrophic, and heterotrophic respiration (Luo & Zhou, 2006). The autotrophic respiration is live root metabolic respiration, related mycorrhiza, and symbiotic N-fixing nodules. Microbial degradation of root exudates in rhizospheres, above-ground and belowground litter, and soil organic materials all contribute to heterotrophic respiration (Luo & Zhou, 2006). However, there are less information on soil heterotrophic respiration from tropical peatland.

There are several methods to assess CO_2 fluxes from the peat soil to the atmosphere. Most common are the eddy covariance technique (Deshmukh et al., 2021; Hirano et al., 2007; Kiew et al., 2020), soil chamber measurements (Dariah et al., 2014; Hergoualc'h et al., 2017a; Kusumawati et al., 2021) and subsidence-based assessments (Hooijer et al., 2012; Wösten et al., 1997). A study was conducted to determine the CO_2 emissions from a peat swamp that had been logged over and purposefully kept left without any plant cover. The measurement of CO_2 emissions from a bare drained tropical peatland was conducted using all three of these methods (eddy covariance, soil chamber and subsidence-based techniques). The purpose of this research is to report CO_2 emissions from a bare drained peatland that was developed for oil palm plantations. This information is needed to determine the CO_2 emission contributed by microbial activity during peat decomposition, which refers to soil heterotrophic CO_2 fluxes.

The large amounts of carbon stored in tropical peatlands, which also sustain a variety of species, make them significant carbon sinks (Hooijer et al., 2006; Page et al., 2011). CO_2 emissions, peat subsidence, and biodiversity losses are all major concerns associated with the usage of peat soil. However, there is a scarcity of studies on the rate of CO_2 flux from peatlands especially at oil palm plantations (Page et al., 2011). Once the peat has been drained, the issue of peat carbon emissions has been much disputed. The extent of soil heterotrophic respiration from oil palm plantations on peat is currently limited and further research is needed to address this issue.

The study of soil CO_2 respiration from tropical peatlands is an important component of environmental research because of its potential impact on future climate change. One is the unavoidable subsidence that occurs as a result of the drainage required to provide favourable growing conditions for crops (Wösten et al., 1997). Furthermore, the peat productive life is limited due to the decline in peat depth (Tie, 2004). Shallow peats might gradually disappear subsequently revealing the underlying mineral soil that contain acid sulphate and be harmful to crop development. The subsidence is partly due to oxidation of the substrate, with the carbon in the peat being converted to CO_2 and then emitted to the atmosphere. This contributes to increased atmospheric concentrations of GHG.

There is currently much debate concerning the magnitude of such drainage-induced carbon fluxes (Hooijer et al., 2006). Previous measurements (Melling et al., 2005) did not distinguish peat soil surface CO_2 emission arising from microbial respiration (which equates to peat oxidation) or from autotrophic root respiration. The latter contribution will vary depending on the type of vegetation present and the location of sampling points with root biomass distribution (Henson & Harun, 2005). A recent study by Hergoualc'h and coworkers (Hergoualc'h et al., 2017) has addressed this issue but more measurements are still needed to confirm the results. Other example of studies on CO_2 measurement such as Cooper et al. (2020); Couwenberg & Hooijer (2013); Dariah et al. (2014); Gusmayanti et al. (2019); Hooijer et al. (2011); Husnain et al. (2014); Ishikura et al. (2018); Jauhiainen et al. (2012); Kiew et al. (2020); Kusumawati et al. (2021); Manning et al. (2019); McCalmont et al. (2021); Melling et al. (2013); Mos et al. (2021); Nagano et al. (2013); Wakhid et al. (2017) were conducted on cultivated and Hanson et al. (2000); Hergoualc'h et al. (2017b); Hirano et al. (2014); Jauhiainen et al. (2014); Matysek et al. (2018); Melling et al. (2013) were conducted on bare lands or root exclusion for accessing soil heterotrophic respiration.

The urge to find information regarding the actual carbon flux at drained tropical peatland in Malaysia motivates this study. Therefore, this study provides information on carbon loss or emission baseline from peat due to drainage-induced oxidation that excludes the plant root respiration component. The information will be helpful in decision makings in relation to the future development of Malaysian's peatlands for agriculture.

1.2 Problem Statement

Rising CO_2 emissions have the potential to accelerate global warming. However, the available information is comparatively limited regarding the actual carbon fluxes measurements from drained tropical peatlands that were kept free of vegetation, particularly in Malaysia. Although many studies have been conducted on measuring carbon losses using different measurement techniques, but relatively few studies have compared the various approaches that have been used. The understanding on the carbon losses of Sarawak's bare peat soil, without vegetation or plant roots, due to soil heterotrophic respiration is limited.

1.3 Research Objectives

The primary goal of this research is to quantify carbon (C) as CO_2 emission rate from the one-hectare bare drained peatland using three different methods of measurements, i.e., (1) eddy covariance, (2) soil chamber, and (3) peat subsidence method. Secondly, it aims to relate the oxidation rate to peat properties and conditions, particularly the water table and the subsidence rate. Lastly, the objective of the study is to compare methodologies: direct (eddy covariance & soil chamber) versus indirect (peat subsidence) measurement for estimating C loss by determine the carbon loss (as CO_2) over time.

The research objectives are:

1. To evaluate the microbial (soil heterotrophic) respiration of total soil respiration using vacant un-cropped drained peat land.
2. To relate the oxidation rate to peat properties and conditions, particularly the water table and the subsidence rate.
3. To compare methodologies (eddy flux versus direct soil measurements) for estimating C loss over time.

CHAPTER 2

LITERATURE REVIEW

2.1 Peatland

Peat is formed from partially decomposed plant material that has accumulated over time due to specific environmental conditions such as waterlogging, lack of oxygen, low pH, and nutrient deficiency. Peat in temperate region is created from mosses, shrubs, herbs, and small trees under slow decomposition process due to low temperatures (Moore et al., 2007). The tropical peat is made up of partially decomposed plant material, such as leaves, branches, trunks, and roots, that has exposed to nearly constant high temperatures and built up over many thousands of years. (Page et al., 1999).

There are several peats reserves in the world (Figure 2.1). The total area of pre-disturbance peatland is assessed to be around 4 million km^2, or comparable to 3% of the world's land area (Joosten & Clarke, 2002). Majority of peatland is found in North America and northern Asia, with substantial sections in northern and central Europe and Southeast Asia, as well as tropical Africa, Latin America, and the Caribbean. Four countries namely Russia, Canada, the United States, and Indonesia, amounted for 85 percent of the peatland area in the world. Large portions of peatland in Europe have been used for agriculture and forestry, covering 450 000 km^2 (11% of the total global area). Immirzi et al. (1992) estimate that the use of 40% of peatland in Europe and 5% of peatland worldwide, despite the fact that significant areas of peatland in Indonesia and Malaysia have been cleared, drained, and utilised for plantations and arable farming.

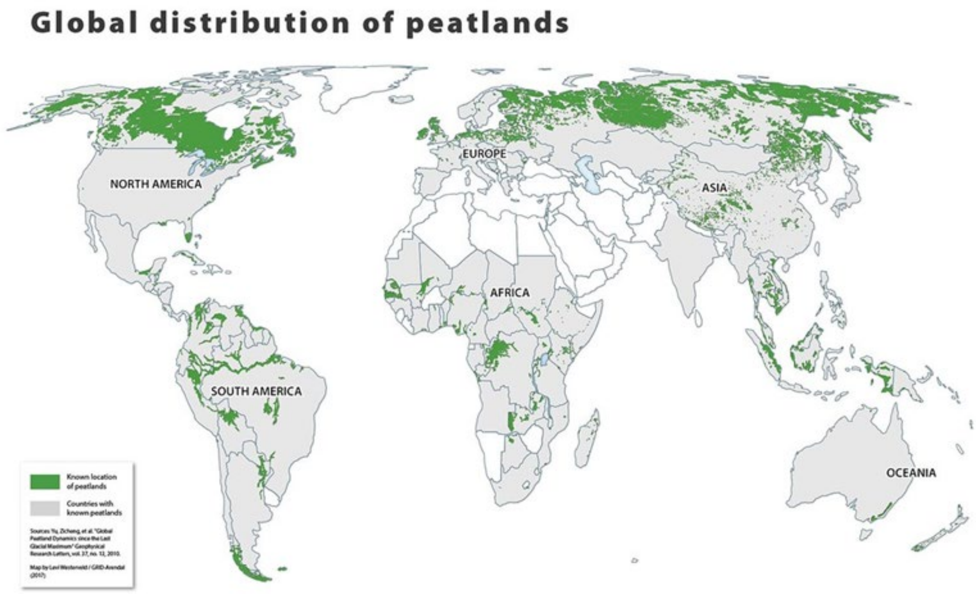

Figure 2.1 Global distribution of peatlands. Green is known location of peatlands and grey is countries with known peatlands. Source: (Yu et al., 2010).

Peat has a wide range of applications such as for energy as fuel for electricity or heat generation, horticultural and agricultural (i.e., as a compost element, cowshed, soil enhancer, or growth medium) and other uses (i.e., as a source of organic and chemical goods like activated carbon, resins, and waxes, pharmaceutical goods like steroids and antibiotics, and therapeutic uses like peat baths). Peat is harvested as sods which traditionally cut by hand, but now mostly mechanically milled into fine granules or picked mechanically. These peat extractions were used for energy usage, which is then utilised to generate power or heat. Briquettes are made from a fraction of the milled peat and are a convenient domestic fuel. Indonesia, Estonia, Belarus, Ireland, Finland, Russian Federation, and Sweden are the largest producers and users of fuel peat. In situ peat comprises around 90% water, with part of it being washed away by drainage and the rest being dried by the sun and wind. The moisture percentage of the air-dried peat is 40-50 percent.

The duration required for a rested, cleared peatland to replenish its carbon stocks and ecological functions can vary significantly depending on several factors, including the peatland's initial condition, the extent of degradation, the restoration techniques used, and the local environmental conditions. Peatlands are unique ecosystems, and the restoration process can take decades or even longer to achieve full recovery. The extent of peatland degradation plays a crucial role in determining the replenishment duration. Lightly degraded peatlands might recover faster compared to severely degraded ones, which could require much longer periods of restoration. The specific restoration techniques applied can influence the recovery timeline. Techniques might include rewetting the peatland, re-vegetation with native species, and implementing erosion control measures. Some restoration actions can have more immediate effects, while others might take longer to show significant results. Different types of peatlands (e.g., raised bogs, fens, tropical peat swamps) have varying natural regeneration rates and responses to restoration efforts. Tropical peat swamps, for instance, may recover more slowly due to the unique characteristics of tropical peat. Local climate and hydrological conditions are also the key factors. Adequate water management is essential to restore water levels in the peatland, as maintaining a high-water table is crucial for peatland health. The establishment of a diverse and sustainable plant community is vital for peatland recovery. Native plants, especially sphagnum mosses and other peat-forming vegetation, play a crucial role in carbon sequestration and overall ecosystem health. The time it takes for these plants to establish and thrive can impact the restoration timeline. Some aspects of peatland recovery, such as the accumulation of new peat layers, are gradual processes that naturally occur over time. Peatlands accumulate peat at relatively slow rates, often on the order of millimetres per year. Given these variables, it is difficult to provide a specific duration for peatland replenishment. However, it is important to approach peatland restoration with a long-term perspective, as the recovery process is typically measured in decades rather than just a few years. Adaptive management strategies that monitor progress and adjust restoration efforts as needed are commonly employed in peatland restoration projects.

2.1.1 Tropical Peatland

At present estimates of 4.41 x 105 km2, tropical peatlands make up about 11% of all peatlands (Page et al., 2011). Lowland regions of Southeast Asia, particularly Indonesia, have the biggest areas of tropical peatlands which accounted for 20.6 million hectares (Page et al., 2011; Rieley & Page, 1996), and the Pastaza-Marañón foreland basin in Amazon approximately 12 million hectares (Lähteenoja et al., 2009; Wang et al.,2018). Malaysia has about 2,426,600 hectares (ha) of tropical peatland, and about 65 % or 1,588,142 ha is found in Sarawak. The remaining areas are in Peninsular Malaysia, 716,944 ha; and Sabah, 121,514 ha (Wahid et al., 2010). Tropical peatlands in Malaysia are managed for agriculture especially for oil palm, housing, and development areas and some of the peatlands are gazetted and reserved as national park or biodiversity conservation areas. Wahid et al., (2010) reported the peatland's total area cultivated with oil palm in Malaysia was about 666,038 ha, where 37.45% were in Sarawak.

Tropical peatland is known for their unique ecosystem and plays a vital role in storing a large amount of carbon. The majority of tropical peats are distinct dome-shaped deposits that can occasionally be more than 10 metres deep. They evolved from organic soil components or the residues of woody materials (Wahid et al., 2013). The U.S Department of Agriculture defines peat as an organic carbon content of at least 12% and thickness of 40cm or more but less if directly atop bedrock (Soil Survey Staff, 2015). The tropical peatland forest in Sarawak's surface vegetation served as the basis for previous peat classification (Anderson, 1963). According to Anderson (1963), there were six phasic peats of Tropical Peat Forest community; Mixed peat swamp (PC1), Alan Forest (PC2); Alan Bunga Forest (PC3); Padang Alan Forest (PC4); Padang Selunsur Forest (PC5) and Padang Keruntum Forest (PC6) as the centre of the peat dome. Paramananthan created the Malaysian Unified Classification of Organic Soils (MUCOS) in Malaysian Soil Taxonomy (Paramananthan, 1998, 2010; Paramananthan et al., 1984) in 1984 for further efforts and improvement in peat classification and mapping tropical peatland soil in Malaysia. In addition to international classification schemes, this classification system takes into account depth, peat maturity, morphology, the presence or absence of wood, the nature of the wood (decomposed or undecomposed), and the underlying mineral substratum. Peat is described as organic soil with more than 50 cm of organic material thickness inside the upper 100 cm soil layer and a loss of ignition greater than 65%, according to MUCOS.

2.2 Oil palm Cultivation on Peat

Oil palm (*Elaeis guinensis Jacq*.) is an important crop or known as a golden crop in Malaysia due to its economic value that can help elevates socio-economy and eradicated poverty among smallholders. This multi-million-dollar industry have led to rapidly expansion of land for oil palm planation in Malaysia and Indonesia. Planting of oil palm on peat is unfavourable but due to insufficient arable land for agriculture, peatland has been chosen for agriculture development especially in Sarawak. Oil palm has been grown successfully on peatlands in Southeast Asia since the 1980s (Maltby & Immirzi, 1993). Wahid et al. (2010) reported the total area of Malaysian peatlands covered by oil palm trees was accounted for 666,038 ha, where 37.45% were in Sarawak. Oil palm cultivation on peat presents a number of issues, including CO_2 emissions, peat subsidence, flooding, and productivity loss. Planting oil palm on peat requires drainage with water table i.e., 40-60 cm below the surface for optimum growth and to support oil palm. Besides that, the peat soils need to be compacted before planting oil palm due to low bulk density of peat soils. Compaction and drainage cause peat oxidation subsequently peat decomposition and subsidence, which will make the soil susceptible for fires and floods. Typically, when peatlands are drained for establishment of new plantation or agriculture area, methane emissions cease but CO_2 emissions increase substantially, due to the creation of aerobic conditions and peat oxidation. Planting productive oil palm species best adapted to peat soils and maintaining drains to limit methane emissions and maximize oil palm growth can reduce initial CO_2 emissions related with drainage on peat soils. These processes are partially offset by the uptake of CO_2 by the growing oil palm, and the accumulation of carbon in woody tissue and frond litter on the plantation floor.

Despite the environmental effects owing to land use change for oil palm planting, the best management for oil palm production on peat need to be implemented to minimize peat disturbance in term of greenhouse gas (GHG) emissions, and biodiversity losses. Many initiatives have been done to ensure that peat ecosystem services are being taken care despite of unavoidable of anthropogenic effects caused by opening peatland areas for agricultures. One of the efforts by the Malaysian government is to safeguard that all oil palm plantations including smallholders were certified by Malaysian Sustainable Palm Oil (MSPO) scheme by year 2020. This scheme was developed to address sustainability issues and challenges in the relation to the multi-stakeholders involves in the industry. If tropical peatlands are deforested for agricultural purposes, block drains to increase the water table and inhibit peat decomposition. This is done to reduce soil disturbance and avoid the formation of aerobic conditions, which are excellent for peat decomposition. Besides that, efforts can be made by minimizing disturbance of natural vegetation by maintaining few species to encourage recolonization of natural plants in the plantation. The regeneration of natural vegetation or native woodland species such as *Shorea albida, Ramin Gonystylus bancanus, Dryobalanops rappa, and Dactylocladus stenostachys,* (Wetland International, 2010) should be allowed to compensate for peat decomposition and harvest residue losses. Planting legumes cover crop such as *Mucuna breacteata* in peatland along with oil palm trees. Moreover, peatland conservation through gazetted national permanent peatland forest reserves to protect peatland biodiversity.

Other than that, a standard operating procedure (SOP) for oil palm on peat has been published in 2011 by Malaysian Palm Oil Board (MPOB) for simply guidance and reference. Various aspects were covered including land preparation techniques and mechanisation, drainage, water management, planting density, fertiliser requirement, peat and disease management control and biodiversity conservation based on the science underlying recommended practices (Haniff et al., 2011). This is to ensure the sustainability of oil palm cultivation on peat by considering the ecological function of peatlands thus increasing the socio-economic benefits.

2.3 Soil Respiration from Microbes

Over the past twenty years, approximately 25% of Malaysia's peatlands have been transformed for industrial agricultural growth, with the main focus being on cultivating oil palm plantations (Padfield et al., 2015). In order to assist oil palm growth, oil palm development in tropical peatlands frequently requires the drainage of already saturated peat by lowering the ground water level to a depth of 50-70 cm. Lowering the water level, on the other hand, induces aeration, which stimulates soil organic matter breakdown and results in C losses from peat soil (Laiho, 2006) and enhanced oxidative enzymic activities (Itoh et al., 2017). Peatland clearing and draining cause a shift from anaerobic to aerobic conditions, resulting in increased microbial activity and CO_2 emissions. Soil respiration, which refers to the emission of carbon dioxide from the soil surface, serves as a valuable indicator of biological activity and decomposition in the soil. Carbon dioxide is generated through various mechanisms, one of which is the aerobic microbial decomposition of soil organic matter for energy production and functioning, also known as microbial respiration. The biological activity of soil organisms generates a substantial carbon dioxide flux in the global carbon cycle, emitting roughly ten times more CO_2 into the atmosphere annually than fossil fuel combustion (Bond-Lamberty & Thomson, 2010; Le Quéré et al., 2014).

Soil microbes, which include bacteria, fungi, protozoa, and algae, play a crucial role in various essential soil processes, such as soil respiration, nitrogen cycling, and nutrient cycling. The composition of the microorganism population in soil can vary significantly based on factors such as soil type and depth, as each species of microbe thrives under different environmental conditions (Bhattarai et al., 2015). Despite peat material being a valuable research subject, there has been little exploration of the microbial population and activity within it, leading to a poor understanding of the subject (O'Kelly & Pichan, 2014). Soil respiration also indicates the soil's potential to support plant growth. Organic nutrients in organic matter (e.g., organic phosphorus, nitrogen, and sulphur) are transformed to inorganic forms that are available for plant absorption during the decomposition of soil organic matter which known as mineralization (Chapin et al., 2011). Carbon mineralization is another term for soil respiration. Soil respiration is a measure of the soil's capacity to sustain soil life, encompassing plants, soil fauna, and microorganisms. Soil respiration is a measure of the level of microbial activity and the rate of degradation of soil organic matter. It is a useful tool in the laboratory for assessing soil microbial biomass and providing insights into nutrient cycling within the soil. Following tillage, excessive respiration and decomposition of soil organic matter are common due to the disruption of soil aggregates and the increased aeration of the soil. This influences yields through decreasing soil organic matter, restricting nutrient availability, and depleting soil organic matter. This observation agrees with the higher CO_2 emissions for the first two years of measurement after study site has been cleared as shown in this study.

Respiration decreases in dry soils due to the lack of moisture for microbes and other biological activities (Schimel, 2018). This is happened after few years of measurement as the site is exposed and became dried following the drainage. As soils become dry, the larger pores tend to drain first, causing a significant reduction in soil diffusivity as the moisture content decreases (Tecon & Or, 2017). Soil drying reduces diffusion rates, resulting in the precipitation of semi soluble minerals. Water scarcity creates a resource-limited environment for microbes, restricting their ability to undergo physiological acclimation processes such as the synthesis of compatible solutes that require energy and carbon (Schimel, 2018). Total microbial activity and respiration decrease in dry soils according to several studies (Carbone et al., 2011; Manzoni & Katul, 2014; Wu et al., 2011). Though, it is generally understood that microbial activity decreases due to oxygen deficiency as the soils become saturated (Davidson et al., 2012).

2.4 Peat Subsidence

It has been recognized that draining of peatland area induce permanent sinking of peat surface known as subsidence. Subsidence is caused by peat shrinkage and biological oxidation that the latter can cause a reduction in the carbon stock. Overall drainage-induced peat subsidence can be separated into three components: oxidation, compaction and shrinkage, and consolidation.

Decomposition of organic materials causes peat to oxidise in the aerated zone above the water table, losing carbon by the release of gaseous CO_2 into the atmosphere (Hirano et al., 2009; Jauhiainen et al., 2005, 2008) and removal as dissolve organic carbon and particulate organic carbon in drainage water (Baum et al., 2007; Cook et al., 2018; Jauhiainen et al., 2005; Yupi et al., 2016). However, the oxidation process does not increase the peat bulk density and may even lower it. Compaction and shrinking, causes the volume of peat in the aerated zone above the water table has decreased. The compression imparted on the peat surface during planting, drainage, and deforestation activities causes compaction while shrinkage happens as organic fibres compress as they dry. In practice, these two processes cannot be distinguished and are referred to as compaction. Peat bulk density rises because of these processes.

Consolidation refers to the compaction of waterlogged peat that is saturated below the water table as a result of the upper peat loss it's buoyancy, putting more pressure on the underlying peat. Peat macropores experience water loss, leading to the initiation of primary consolidation. It happens speedily when peat water is evacuated with a high absorbency with high intensity of drainage systems. Secondary consolidation is caused by the compressive strength of peat in its solid state. Peat consolidation is a gradual process that contributes only a minor fraction to overall consolidation (Mesri & Ajlouni, 2007) yet it results in a significant increase in bulk density. The peat subsidence process begins with an initial phase of consolidation, which is then followed by a gradual phase of oxidation and shrinkage (Wösten et al., 1997). The process of moving from one element to the next is fairly gradual and water management determines the intensity of these processes. The main cause of subsidence is peat oxidation, according to reports (Couwenberg & Hooijer, 2013; Wösten et al., 1997). After the initial subsidence phase, which is the primary stage, the peat undergoes irreversible shrinkage and compaction, as well as speedy rates of peat decomposition, resulting in a gradual but consistent rate of subsidence. Peat bulk density and carbon concentration increase with time after drainage due to physical processes such as consolidation, shrinkage, and compaction, which do not involve any loss of carbon. Sinking that takes place after the aforementioned secondary phase is likely to be caused by oxidation, which inevitably leads to the loss of carbon. Peat soils consist of stored organic carbon (10%) and water (90%). A peatland that has not been disturbed retains 90% of its weight and 300% of its volume in water (Grzywna, 2017). When water is drained out of the peat soil, the carbon present in it is exposed to aerobic conditions, causing the peat to decompose and CO_2 to be released into the atmosphere. As a peatland loses water, its volume decreases. Water drainage causes peat deposits to subside, resulting in the compaction and reduction of organic materials. The process continues as long as the drainage system is in place and continues until all the peat above the drainage level is depleted. The peat formations undergo drying and shrinking as the water typically trapped in the pores of the peat is drained out. As peat dries, it tends to become hydrophobic, making it difficult to regain its original moisture levels (Holden et al., 2006). In low-lying areas, the soil surface may sink below river or sea levels, leading to increased frequency and duration of floods. Peatland sinking has caused drainage issues, intrusion of salt in coastal peatlands can lead to the eventual depleting of fertile land.

2.5 Peat Carbon Loss (CO_2 Emissions)

Soil CO_2 emissions or soil respiration is one of the sources that contributes to global warming. It is between 50 and 75 Gt C of carbon is estimated to be released globally from soil each year, which accounts for 20-40% of the total annual input of carbon dioxide into the atmosphere (Lankreijer et al., 2003). Soil respiration is the process by which soil organisms produce carbon dioxide through respiration. This process involves the respiration of plant roots, microbes, soil fauna, and the rhizosphere. It is an important component of the carbon cycle between the atmosphere and terrestrial ecosystems, and can be used to study changes in ecosystem carbon storage or net fluxes to the atmosphere. It is the second largest flux of carbon cycling between the atmosphere and terrestrial ecosystems. There are two key components to soil respiration, i.e., autotrophic (Ra) and heterotrophic respiration (Rh) (Luo & Zhou, 2006). Autotrophic respiration refers to the metabolic respiration of live roots, as well as associated mycorrhiza and symbiotic nitrogen-fixing nodules. On the other hand, heterotrophic respiration is a result of microbial decomposition of root exudates found in the rhizosphere, as well as aboveground and belowground litter, and soil organic matter (Luo & Zhou, 2006). The heterotrophic contribution ranged from 10 to 95% in several studies, with an annual average of 54% and a peak of during the growing season, 40% of the total amount is attributable to this factor (Hanson et al., 2000). However, there was less information on soil heterotrophic respiration from drained tropical peatlands that were kept free of vegetation, particularly in Malaysia. This study tries to focus on CO_2 emissions from a bare drained peatland which is equals to heterotrophic soil respiration. One of the example concepts of carbon loss in the peat ecosystem is shown in Figure 2.2 which adapted from (Rixen et al., 2016). Net ecosystem carbon losses representing a negative net ecosystem production (NEP) (Hirano et al., 2007), CO_2

emissions from disturbed peat soils due to aerobic peat decomposition (Miettinen & Liew, 2010) and fires (Van Der Werf et al., 2008), carbon leaching, outgassing, and dissolve organic carbon (DOC) discharge into the ocean. The carbon uptake by the growing biomass results from the difference between soil emission and NEP. River outgassing is the difference between leaching and DOC discharge into the ocean.

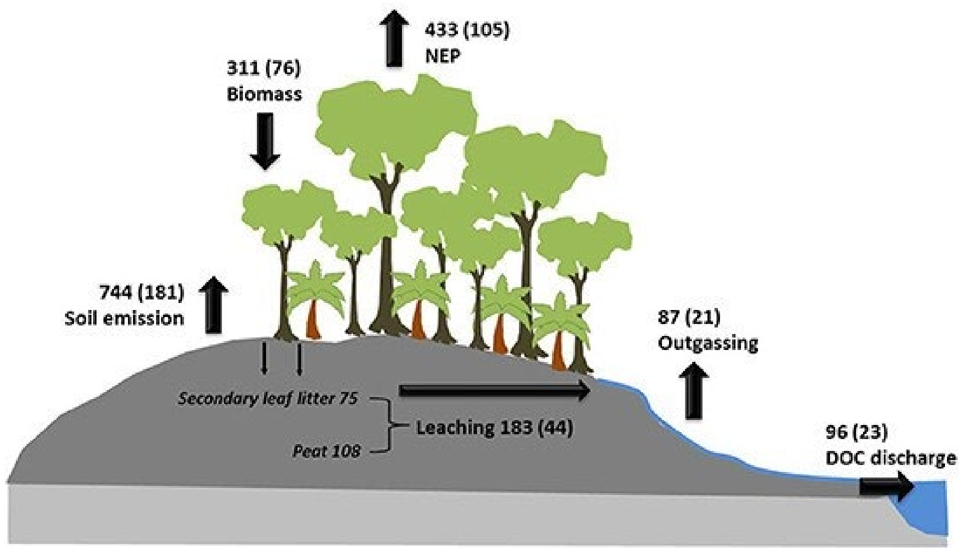

Figure 2.2 Carbon fluxes in disturbed peatland ecosystem. The numbers and the numbers in brackets are fluxes in g C m^{-2} yr^{-1} and Tg C yr^{-1}, respectively. Source: Rexin et al., (2016).

There are numerous methods for evaluating CO_2 fluxes from the peat soil to the atmosphere. Most common are the eddy covariance technique (Deshmukh et al., 2021; Hirano et al., 2007; Kiew et al., 2020), soil chamber measurements (Dariah et al., 2014; Hergoualc'h et al., 2017; Husnain et al., 2014; Kusumawati et al., 2021) and subsidence-based assessments (Hooijer et al., 2012; Wösten et al., 1997). An investigation was conducted to measure the CO_2 emissions from a logged-over, vegetation-free peat area using all three of these methods. The aim was to report CO_2 emissions from a bare drained peatland that was developed for oil palm plantation. This information is needed to determine the CO_2 emission contributed by microbial activity during peat decomposition, which refers to soil heterotrophic respiration.

2.5.1 The Eddy Covariance Technique

The eddy covariance is a micrometeorology-based method that is currently popular to directly measure the gases flux (i.e., CO_2, CH_4, N_2O, *etc.*), water vapour, energy, momentum and heat between the ecosystem and the atmosphere. It is commonly used to study connections between vegetation and the atmosphere over crops, forests, and natural vegetation. In 1951, Swinbank was the first to report on the eddy covariance principles. The increased trend of utilization of eddy covariance has led to a greater understanding of the major biotic and abiotic mechanisms governing net ecosystem exchange rates (NEE) of CO_2 between ecosystems and the atmosphere, resulting in increased knowledge of temporally and spatially integrated NEE (Bowling et al., 2001; Goulden et al., 1996; Loescher et al., 2006).

Continuous observation of carbon flux exchange between the ecosystem and atmosphere is possible using eddy covariance. Flux data is collected on an hourly scale using a sampling frequency of either 10 Hz or 20 Hz. For the indirect computation of ecosystem vegetation productivity, there are some well-established formulas. Eddy covariance has grown in popularity in recent years due to ongoing developments in computer data gathering, processing power, and sensors, mainly the invention and upgrading of ultrasonic wind speed sensors and high efficiency of CO_2 analysers. However, the method's use is hampered by its high hardware needs and cost. Even said, eddy covariance has yet to be widely deployed due to the logistical and financial challenges (Hill et al., 2017) and further research is desirable in tropical peatlands.

The process of eddy covariance involves computing the covariance between vertical wind velocity fluctuations and fluctuations in the physical quantity being measured, which ultimately yields the turbulence flux. It can also detect carbon, water, and heat flux in plant communities and the atmosphere directly. Minor changes in air mass and energy flux can be observed on multiple time scales (hour, day, season, and year) under present technical conditions. Compared to other flux measurement methods, the eddy covariance approach offers a valuable practical benefit by providing direct measurements of fluxes on an hourly or half-hourly basis, integrated over a designated area of interest. This method also enables continuous measurements throughout the year, capturing data during both daytime and night-time periods. This approach can measure a 100 to 2000 meters spatial range.

The fundamental concept behind measuring eddy flux involves quantifying the movement and speed of molecules traveling in both upward and downward directions over a period of time. One way to mathematically describe vertical flux is by calculating the covariance between measurements of vertical velocity, both upward and downward movements, and the concentration of the substance being studied (Burba, 2013). Turbulent fluctuations happen rapidly, and even minute changes in concentration, density, or temperature require precise and speedy measurement, such studies necessitate highly complex instrumentation and proper experiment planning. The method relies on the prevalence of the turbulent transport and involves intricate computations that rely heavily on several assumptions. When applying the eddy covariance method, modern sensor sets, and software that handles processing takes care of most of the issues. Errors brought on by failing to meet theoretical assumptions and system faults can be reduced or eliminated with the help of appropriate station design, careful planning and execution of experiments, and accurate data processing methods.

The eddy flux (F) can be calculated as the average of the air density ($\boldsymbol{\rho}$d), vertical wind speed (w), and the dry mole fraction (s) of the gas being measured (Burba,

2013) as stated in Equation 2.1. The mixing ratio is commonly referred to as the dry mole fraction.

$$\boldsymbol{F} \approx \overline{\boldsymbol{\rho d}}\ \overline{\boldsymbol{W'S'}} \qquad \text{Equation 2.1}$$

In the conventional eddy covariance technique, two key assumptions are made. First, it is assumed that air density variations are negligible. Second, for horizontally homogenous terrain, the mean vertical flow is considered to be insignificant, resulting in no flow divergences or conversions. Other main presumptions in the eddy covariance approach include: (i) The measurements taken at a specific point are considered to represent the characteristics of the surrounding area upwind of the point; (ii) It is assumed that the measurements are conducted within the boundary of interest and the layer with a constant flux; (iii) Assuming that the fetch and footprint are adequate, the flux is measured from the region of interest; (iv) The flux is considered entirely turbulent; (v) Assuming a flat and uniform terrain; (vi) The oscillations in air density are insignificant; (vii) There are no or negligible flow divergences and convergences; (viii) The instruments have the ability to detect even the slightest variations with a high level of frequency; (ix) The installation structure and the equipment themselves do not significantly alter mean air flow and turbulence at the measurement spot. The degree to which some of these assumptions are correct is determined by the selection of the site and design of the experiment. This will be mostly determined by weather and atmospheric conditions.

Eddy covariance measurements may encounter interruptions or errors due to various factors such as assumptions made during the process, physical phenomena, instrument malfunctions, or specifics of the particular setup being used. Consequently, a variety of possible flux errors exist, but they may be avoided, reduced, or rectified. Factors such as instrument time response, sensor separation, tube attenuation, path and volume averaging, sensor response mismatch, digital sampling, low and high pass filtering are all examples of frequency response errors. The speed of instruments may not be sufficient to record all the swift alterations caused by eddy transport, resulting in time response errors. The error of path averaging arises due to the fact that the sensor path is not a single point measurement, but instead involves integration over a certain distance. Consequently, it is possible that certain variations caused by eddy transport may be smoothed out. On the other hand, sensor separation errors can occur when there is a physical gap between the areas where wind speed and concentration are measured, leading to the calculation of covariance for quantities that were not simultaneously measured. Sensor response mismatch, filtering, and digital sampling can also lead to mistakes in frequency response. In addition, various sources of errors, such as spikes and noise in the measurements, unlevelled anemometer, wind angle of attack, sensor time delay (especially important in closed-path analysers with long intake tubes), sonic heat flux errors, the Webb-Pearman-Leuning density terms (WPL), spectroscopic effects and band-broadening effects (for LASER-based measurements) are all common sources of errors.

All fluxes may be affected by spikes and noise, although typically the flux should not be altered by more than 15%. Proper instrument selection and maintenance, along with the implementation of a spike removal procedure and data processing software filtering, can help minimize the impact of these errors. An unlevelled sonic anemometer can affect all fluxes since the vertical wind speed is contaminated by a horizontal component. Inaccuracy levels of 25% or more are possible, but can be easily minimized by utilizing a stable tower and ensuring the anemometer is level during station setup. Coordinate rotation is a processing technique that can be employed to correct for any remaining errors. Frequency response errors impact all fluxes and can range from 5% (in open-path devices) to 50% (in lengthy tube closed-path or slower instruments). Using fast instrumentation and appropriate experimental setup can help to partially mitigate these errors. Frequency response corrections can be utilized in data processing software to make further adjustments.

Sonic heat errors reduce sensible heat flow by around ten percent on average, and they can be corrected using a simple correction for sonic heat flux. Gas and water fluxes can be affected by density fluctuations when sensors measure fast density instead of fast-dry mole fraction. The errors in magnitude and direction can vary greatly, with potential differences of 300% of modest flow during winter or only a few percent during summer. Reducing or avoiding these errors can be achieved via utilising Webb-Pearman-Leuning density (WPL) terms or by using equipment that produce fast dry mole fraction. Fast concentrations and fluxes may be affected by spectroscopic effects in modern laser-based technologies. However, the scope is mostly unique to the technology that has received little research in eddy covariance should be approached with care, as they require careful consideration. The measurement of gas fluxes using the NDIR method can be affected by band-broadening errors, which can vary greatly depending on the type of sensor employed. It is normally ranging between 0% and 5%, the error can be corrected through the instrument's software or manufacturer-provided specifications. Krypton hygrometer readings are affected by oxygen in the path, although only by around 10%, involves implementing an oxygen adjustment.

Missing data can have an impact on all flux measurements, especially those that are integrated over long periods of time. However, this impact can be mitigated by selecting the appropriate instrument for the site conditions and implementing a regular