Future Challenges of Cultivating Oil Palm in Peat*

MATHEWS J

IOI Research Centre, 2 Km Gemencheh Batang Melaka Road, 73200 Gemencheh, Negri Sembilan Darul Khusus, Malaysia

South East Asia has the highest pool of tropical peat land mass. Planting of oil palm in peat is a subject of controversy. Most issues were triggered as the result of each cycle of anthropogenic induced environmental fire resulting in haze calamities, which in turn was directly related to the prolonged drought brought about by the El Niño phenomenon. Laws and regulations were reviewed, amended and implemented as new calamities arose. From the sustainability point of view, more stringent auditable approaches were taken from time to time. Studies conducted in West and Central Kalimantan indicated fire hotspots in peat during El Niño which was related to the frequency of rainfall, number of rain days and Oceanic Niño Index (ONI). An early warning system through the monitoring of ONI and precautionary measures can be taken to delay or reduce fire incidences in peat. High CO_2 emission is expected if groundwater table management is poor in peat, leading to higher annual subsidence of peat. A possible carbon tax for carbon emission may be expected for crude palm oil produced from peat. The subsidence of peat leads to the concept of drainability assessment for the existing oil palm plantation in peat before replanting and is expected to cease replanting by allowing to keep a peat buffer equivalent to cultivation of 40 years. The plantation may have to convert the 40 years peat buffer land to paludiculture. In view of conserving peat companies with large scale oil palm planted in peat is expected to manage peatland in landscape manner in the future.

***Keywords**: Peatland, peat fire, peat drainability, peat subsidence.*

It was estimated that there are 44 million hectares of tropical peatland globally (11% of total peatland), out of which 24.7 million (56%) is located in South East Asia. More than 20 million hectares of peatland is located in Indonesia followed by Malaysia and the rest of south east Asian countries. In South East Asia, Indonesia has the largest estimated peat volume of 1,138 Giga (G) m^3 (about 65%) followed by Malaysia 181 Gm^3 (10%) and the balance 25 per cent peat volume is distributed in the rest of the south east Asian countries, including Papua New Guinea (Page *et al*., 2011). The commercial planting of oil palm in virgin and deep peat in Malaysia could have been initiated in the 1960s, as cited in the studies on the complexities of micronutrients in peat by Ng *et al*. (1974) and Cheong and Ng (1977). The improvised water management techniques and planting methods have been implemented since the 1980s to achieve good yield on peat (Gurmit *et al.*, 1986; Tayeb *et al.*, 1997). Acceleration of the planting of oil palm in peat in South East Asia began in the 1990s. Since then, about 1.06 million hectares of peatland have been converted for oil palm cultivation in Malaysia. While in Indonesia about 2.0 million hectares of peatland have been cultivated with

* Reproduced from the 15th ISP National Seminar 2022 Book, “Addressing Challenges in Plantation Management”.

oil palm (Miettinen *et al*., 2016). The total coverage of peatland under oil palm cultivation in these south east Asian countries is about 3.1 million hectares. Some of the oil palm cultivation in peat are the second or third cycle of oil palm cultivation.

From the environmental point of view, controversies were triggered due to the large-scale land clearing in peat. Oil palm is not the only crop planted in peat, paper and pulp industry too cleared peatland for planting *Acacia* (Hooijer *et al.*, 2012a; Paramananthan, 2016b). After each environmental calamity, especially the fire that led to haze during the El Niño years, pressure has been built on the oil palm plantations and now are under constant scrutiny by governmental and non-governmental organisations. Substantial work has been carried out on peat since the 1997 El Niño cycle. Page *et al.* (2002) estimated the carbon storage of peat and the high amount of carbon emitted as greenhouse gas (GHG) into the atmosphere as the result of peat fire in 1997. The annual oxidation and shrinkage of organic matter results in annual subsidence which is a phenomenon brought about by draining water in peat and is directly related to the emission of GHG (Wösten *et al.*, 1997; Hooijer *et al.*, 2010; Hooijer *et al.*, 2012b). Soil respiration related to greenhouse gas emission was conducted or reviewed by Melling *et al*. (2005), Hooijer *et al*. (2010) and Carlson *et al.* (2015). As the result of continuous draining of water and subsidence of peat, a situation may arise, where the water level of peatland could reach the drainage base, after which the drainage of water by natural gravity may not be possible. The consequence expected will be prolonged flooding through incursion of tidal water or river water, leading to uncultivatable land conditions for oil palm in the future. This gave rise to the concept of drainability assessment (Wösten *et al*., 2006). Prior to the replanting of the existing stands of oil palm on peat growers are bound by the Roundtable on Sustainable Palm Oil (RSPO) to measure the number of years available for peat cultivation and to cease cultivation at least 40 years prior to reaching the undrainable conditions. The buffer peat equivalent to 40 years is expected to undergo rehabilitation through paludiculture (RSPO Principle and Criteria, 2013; RSPO Principle and Criteria, 2018; Parish *et al*., 2019a; Parish *et al*., 2019b; Mathews *et al.,* 2021).

Concerns and pressures are being developed at the international level on the respective governments with regard to the extension of oil palm cultivation on peat especially when the global situation is vulnerable to catastrophic environmental related climatic changes situation. Based on the situation, the governments from time to time developed and changed legal benchmarks. Some of the legal points developed were on the depth of peat and type of underlying mineral soil to allow cultivation and restoration of cultivated peatland through water management to avoid fire-related environmental calamities (Parish *et al.*, 2019a). With pressure especially from non-governmental organisations many of the large plantation companies had volunteered not to invest in new oil palm plantings in peatland through multistakeholder platforms like RSPO. Since 15 November 2018, “no new planting in peat” has become part of the principle and criteria for RSPO oil palm growers who became members in the organisation voluntarily. Such pledges by the RSPO stakeholders is encouraging for the time being, but many non-members are currently opening land for oil palm cultivation in peat. These newly emerging plantation companies will face obstacles to participate in the common multistakeholder platform as many lack information on high conservation value forest (HCVF) and high carbon stock (HCS) studies. The supply chain and traceability of palm oil produced from peatland is being monitored by the non-governmental organisations (NGOs) and multi-national traders and global consumers. Even to sell the peatland planted with oil palm by a non-RSPO member to RSPO members, the remediation and compensation process (RaCP) can be an issue and discussions are likely to be active in future in the multistakeholder consultation RSPO (RSPO Principle and Criteria 2018). The objective of the present paper is to bring to light the global challenges of cultivating oil palm in peat. Practical operational management and its monitoring in future may be expected to be tougher than the smooth operations conducted in the late 1980s and early 1990s. More challenges can be expected in the future and perhaps climate change could be one of the major factors that could change the cultivation practices in peat.

PEAT AND ITS USE FOR OIL PALM

Definition

Globally, as per USDA (United States Department of Agriculture) (1998) and FAO *et al.* (Food and Agriculture Organisation) (1998) classification of the tropical peat comes under the definition of histosols, which are organic soils saturated with water 30 days or more per normal year, with cumulative organic layer(s) comprising more than half of the upper 80 cm or 100 cm of soil surface with fibric/ hemic/sapric material of bulk density below 0.1g/cm^3 and containing 12 to 18 per cent or more organic carbon depending on mineral clay fraction. Paramananthan (2016a) explained that organic soil material is saturated with water for a long period. After excluding the live roots, the organic soils have organic carbon content (by weight) as follows:

a. Eighteen per cent or more if mineral fraction contains 60 per cent or more clay,
b. Twelve per cent or more if mineral fractions contain no clay, and
c. Organic carbon between 12 and 18 per cent if mineral content is between zero to 60 per cent.

Paramananthan (2010; 2016a) further explains aspects of organic soils with reference to bedrock as follows:

a. Depth to the bedrock between 50 cm to 100 cm and total thickness of organic soil layers taken cumulatively is equal to or more than half the depth to bed rock, or
b. The depth of bedrock less than 50 cm and total thickness of the organic soil layers taken cumulatively is more than half of the depth to bedrock.

Malaysian peat soil is further defined as organic soil with organic content cumulated in a thickness more than 50 cm within the depth of top one metre of the soil profile and contains organic matter of more than 65 per cent determined through loss of ignition or organic carbon of more than 35 per cent. The organic matter with loss of ignition between 35 to 65 per cent is considered as muck (Dachnowski -Stokes, 1930, 1935; Leamy & Panton, 1966; Paramananthan, 2016a; Parish *et al.*, 2019a). The Agricultural Ministry of Indonesia Regulation.14/ Permentan/ pl.110/2/2009 and Government Regulation PP 57/2016 definition of peat is similar to the Malaysian definition (Parish *et al.*, 2019a).

CULTIVATION OF OIL PALM ON PEAT

Laws and regulations for oil palm cultivation on peat

Parish *et al*. (2019a) had elaborated the laws and regulations of peat in Indonesia. The occurrence of catastrophic climate calamities, especially the fire related haze prompted the respective governments to change the law on cultivation on peat from time to time. The declaration of governing laws and regulations are more robust in Indonesia as compared to Malaysia. Indonesian Presidential Decree No.32/1990 prohibits the use of peatlands for oil palm cultivation, if the peat depth or thickness is more than 3 m. The existing plantation licences pending application on peat soils with a depth greater than 3 m, the licences are likely to be revoked under this provision. An interim forest moratorium was announced on 20 May 2011, under which central, province, and local governments are not allowed to issue new permits on primary forests and peatlands that are located in conservation areas, protected forest and production forests. The forest moratorium was further extended till 2019 and is now considered as permanent law. The decree was further reinforced through PP71/ 2014 and PP57/2016. Regulation PP71/2014, later amended to PP57/2016 which stipulates the ban on all new land clearing and canal constructions in peatland. Land developed by converting forest to agricultural cultivation on peat has to standardise the water table to 40 cm from ground level. The ground water table has to be maintained, monitored and reported to relevant local and central authorities. It is also illegal to burn peatland prior to development and the law is applicable for all private companies and communities. Further to sub regulation PP14/2017, the government expected the owners to declare the peatland inventory and determination of peat ecosystem functions. PP15/2017 orders the procedure for measuring peat groundwater levels at designated monitoring points. PP16/2017 provides the technical guidelines for functions recovery of peat ecosystem. In 2019, the plantation houses were expected to maintain fire free hotspots within the 5 km radius of the property. Fire prevention supporting and monitoring systems were to be placed in the plantation premises and to help the local communities with such support system. The Ministry of Agriculture Decree No. 14/2009 states that peatland overlying acid sulphates soils and quartz sand may not be developed for crop cultivation.

In Malaysia, the Ministry of Natural Resources and Environment developed a national action plan for peatlands in 2011 with the objective of conserving biodiversity, climate regulation and to support human welfare (Ministry of Natural Resources and Environment, 2011). On 28 November 2019, the Ministry of Primary Industries and Commodities announced sustainable cultivation and the ban of conversion of forest reserves areas for oil palm cultivation. The policies also included the stopping of planting oil palm in peat land areas and strengthening regulations for existing oil palm cultivation in peat (https://www.mpic.gov.my/mpi/en/info-siaran-media/media-release-2019/icon-fa-newspaper-o-icon-media-release-28-november-2019).

Studies by STRAPEAT-UNIMAS-NREB (2004) of Sarawak on land development for plantations provide the following guidelines on aspects to be incorporated in the environmental impact assessment (EIA):

a. Establishing the geomorphological, topography features with peat depth of the project area,

b. Examining the drainability of the project area for agricultural development and avoidance of undrainable deep peat from development,
c. Identification of all the natural drainage in the project area and its significance in establishing habitat for supporting aquatic life, saline intrusion, flood control, waterway access etc.,
d. Inventory of plants and animals of scientific and conservation importance and estimation of above ground biomass,
e. Mapping the present land use, including those on Native Customary Right (NCR) land and neighbouring plantations with crop specification and water management needs,
f. Demarcating water catchment area, and
g. Determining potential land ownership conflicts.

Once the EIA is approved by State or Federal Environmental Ministry, as needed, the recommendations given in the report become regulations and the agricultural developer is dutybound to follow-up the implementation holistically. With the current climate change, more issues on drought related negative consequences are expected and eventually more laws may be developed in order to prevent such catastrophic incidences in nature.

Changes in guidelines on planting (since the inception of Principles and Criteria in RSPO)

Chronologically, the subject of peat in RSPO is changing to a tougher stand since the inception and adoption of principle and criteria document in 2007 as shown in *Table 1*.

When RSPO principles and criteria was launched in November 2007, it allowed the planting of oil palm on peat. In Principle 4, Criterion 4.3, in existing oil palm plantings on peat, the water table maintenance at a mean of 60 cm (50-75 cm) was a requirement. At the same time in Principle 7, and Criterion 7.4 a guidance indicated that the planting on extensive areas of peat soils and other fragile soils should be avoided, although in 2007 the terms “extensive areas” were not well defined.

In 2013, the Principle 4, Criterion 4.3, Indicator 4.3.4 repeated the monitoring and minimisation of subsidence in peat soils in existing oil palm planted in peat with a specific guidance, where the field water table was to be maintained at an average of 50 cm (between 40-60 cm) below ground surface and measured with groundwater piezometer readings in the field. But for collection drain, an average of 60 cm (between 50-70 cm) below ground surface was to be maintained in the water collection drains. The additional Indicator 4.3.5 in Criterion 4.3 was on drainability assessments prior to replanting on peat to determine the long-term viability of the necessary drainage for oil palm growing. In 2013 the qualitative assessment was expected to be carried out by the frequency and the number of days of flood in the peat fields. Though drainability assessment identified areas unsuitable for oil palm replanting, plans should be in place for appropriate rehabilitation or alternative use of such areas. If the assessment indicates high risk of serious flooding and/or salt water intrusion within two crop cycles, growers and planters should consider ceasing replanting and implementing rehabilitation. As a guidance document, plantations on peat is to be managed at least to the standard set out in the ‘RSPO Manual on Best Management Practices

TABLE 1
SUMMARY OF SEQUENCE OF DEVELOPMENT OF PEATLAND CRITERIA AND INDICATORS IN RSPO

Year and source of data	*Changes and adoption of RSPO Principle and Criteria*
2007[1/]	Principle 4. Criterion 4.3, the indicator calls for the need of minimising subsidence of peat soils through an effective and documented water management programme. As guidance for criterion 4.3 for existing plantings on peat, the water table should be maintained at a mean of 60 cm (within a range of 50-75 cm) below ground surface through a network of appropriate water control structures e.g. weirs, sandbags, etc. in fields, and water gates at the discharge points of main drains. In Principle 7 and Criterion 7.4 mentioned the extensive planting on steep terrain, and/or on marginal and fragile soils, to be avoided. As a guidance it indicated that the planting on extensive areas of peat soils and other fragile soils should be avoided.
2013[2/]	In Principle 4, Criterion 4.3, indicator 4.3.4 subsidence of peat soils shall be minimised and monitored. A documented water and ground cover management programme shall be in place. As "specific guidance" for 4.3.4: of existing plantings on peat, the water table should be maintained at an average of 50 cm (between 40 - 60 cm) below ground surface measured with groundwater piezometer readings, or an average of 60 cm (between 50 - 70 cm) below ground surface as measured in water collection drains, through a network of appropriate water control structures e.g. weirs, sandbags, etc. in fields, and water gates at the discharge points of main drains. 4.3.5 Drainability assessments shall be required prior to replanting on peat to determine the long-term viability of the necessary drainage for oil palm growing. For 4.3.5: Where drainability assessments have identified areas unsuitable for oil palm replanting, plans should be in place for appropriate rehabilitation or alternative use of such areas. If the assessment indicates high risk of serious flooding and/or salt water intrusion within two crop cycles, growers and planters should consider ceasing replanting and implementing rehabilitation. Guidance: Plantations on peat should be managed at least to the standard set out in the 'RSPO Manual on Best Management Practices (BMPs) for existing oil palm cultivation on peat', June 2012 (especially water management, fire avoidance, fertiliser use, subsidence and vegetation cover).
2018[3/]	Principle 7. Criterion 7.7 No new planting on peat, regardless of depth after 15 November 2018 and all peatlands are managed responsibly. 7.7.1 (C) There is no new planting on peat regardless of depth after 15 November 2018 in existing and new development areas. 7.7.2 Areas of peat within the managed areas are inventoried, documented and reported (effective from 15 November 2018) to RSPO Secretariat. 7.7.3 (C) Subsidence of peat is monitored, documented and minimised. 7.7.5 (C) For plantations planted on peat, drainability assessments are conducted following the RSPO Drainability Assessment Procedure, or other RSPO recognised methods, at least five years prior to replanting. The assessment result is used to set the timeframe for future replanting, as well as for phasing out of oil palm cultivation at least 40 years, or two cycles, whichever is greater, before reaching the natural gravity drainability limit for peat. When oil palm is phased out, it is replaced with crops suitable for a higher water table (paludiculture) or rehabilitated with natural vegetation.

contd.

TABLE 1 (CONTD.)
SUMMARY OF SEQUENCE OF DEVELOPMENT OF PEATLAND CRITERIA AND INDICATORS IN RSPO

Year and source of data	*Changes and adoption of RSPO Principle and Criteria*
7.7.6 (C)	All existing plantings on peat are managed according to the 'RSPO Manual on Best Management Practices (BMPs) for existing oil palm cultivation on peat', version 2 (2018) and associated audit guidance.
	7.7.7 (C) All areas of unplanted and set-aside peatlands in the managed area (regardless of depth) are protected as "peatland conservation areas"; new drainage, road building and power lines by the unit of certification on peat soils is prohibited; peatlands are managed in accordance with the 'RSPO BMPs for Management and Rehabilitation of Natural Vegetation Associated with Oil Palm Cultivation on Peat', version 2 (2018) and associated audit guidance.
	7.12 Land clearing does not cause deforestation or damage any area required to protect or enhance High Conservation Values (HCVs) or High Carbon Stock (HCS) forest. HCVs and HCS forests in the managed area are identified and protected or enhanced.
	7.12.4 (C) Where HCVs, HCS forests after 15 November 2018, peatland and other conservation areas have been identified, they are protected and/ or enhanced. An integrated management plan to protect and/or enhance HCVs, HCS forests, peatland and other conservation areas is developed, implemented and adapted where necessary, and contains monitoring requirements. The integrated management plan is reviewed at least once every five years. The integrated management plan is developed in consultation with relevant stakeholders and includes the directly managed area and any relevant wider landscape level considerations (where these are identified).
	7.12.8 (C) Where there has been land clearing without prior HCV assessment since November 2005, or without prior HCV-HCSA assessment since 15 November 2018, the Remediation and Compensation Procedure (RaCP) applies.

[1/] RSPO Principles and Criteria for the Production of Sustainable Palm Oil 2007
[2/] RSPO Principles and Criteria for the Production of Sustainable Palm Oil 2013
[3/] RSPO Principles and Criteria for the Production of Sustainable Palm Oil 2018

(BMPs) for existing oil palm cultivation on peat', (June 2012) (especially water management, fire avoidance, fertiliser use, subsidence and vegetation cover).

In 2018 the strictness of guidelines and rules on peat was further emphasised in Principle 7, Criterion 7.7, Indicator 7.7.1 (C) which ruled against new planting on peat. A reporting system to be in place for areas of peat within the managed areas which are inventoried, documented and reported (effective from 15 November 2018) to RSPO Secretariat (Indicator 7.7.2). Indicator 7.7.5 (C) introduced a stronger stringent approach on drainability to measure quantitatively prior to replanting. The assessment result is used to set the timeframe for future replanting, as well as for phasing out of oil palm cultivation at least 40 years, or two cycles, whichever is greater, before reaching the natural gravity drainability limit for peat. When oil palm is phased out, it is replaced with crops suitable for a higher water table (paludiculture) or rehabilitated with natural vegetation. All existing plantings on peat are to be managed according to the 'RSPO Manual on Best Management Practices (BMPs) for existing oil palm cultivation on peat' (Parish *et al.*, 2019a) and associated audit guidance [Indicator 7.7.6 (C)]. Apart from it, Indicator 7.7.7 (C) expect all areas of unplanted and set-aside peatlands in the managed area (regardless of depth) are protected as "peatland conservation areas". New drainage, road building and power lines by the unit of certification on peat soils is prohibited; peatlands are managed in accordance with the 'RSPO BMPs for Management and Rehabilitation of Peatlands' (Parish *et al.*, 2019b), version 2 and related audit guidance.

Land development without high conservation value forest (HCVF) and high carbon stock (HCS) will have to undergo remediation and compensation process (RaCP). Surely peatland comes under HCVF and HCS categories and definitely peatland will have high carbon stock without taking into consideration the upper storied carbon stock of vegetation. The remediation likely to be is the rehabilitation or conservation of another piece of land equivalent to HCVF or HCS of developed land or compensation through a monetary payment for the land.

Peat-fire and climate

For the last decade climate related fire has become a global concern. This was evident through the devastating fire events in Indonesia in 2015, Australia 2019/2020, California in 2020 (Mathews & Ardiyanto, 2016; Paramananthan, 2016b; Filkov *et al.*, 2020; Goss *et al.*, 2020). It is time to recognise that the global fire incidences are becoming more severe and causing extreme damage to the atmosphere, environment and on human health through fire related haze within a country and transboundary countries. The recent fire trends were caused as the result of anthropogenically induced climatic change resulting in increased dry or hot days that prolongs the fire (Filkov *et al.*, 2020). Fire incidences in Indonesia were not exceptional and mostly anthropogenically generated although a few incidences could be by biophysical means. The fire incidences were observed during prolonged drought and obviously the incidence is prominent and prolonged during the El Niño period. In 1997 about 730,000 hectares of peatland burnt in Central Kalimantan and it was estimated that 0.19 to 0.23 gigatonnes (Gt) of carbon could have been released from peat and 0.05 Gt of carbon by burning the upper storied vegetation of peat (Page *et al.*, 2002).

A case study made in relation to rainfall, rain days, the total number of hotspots and number of hotspots in peat and the 3 months running average of sea surface temperatures [Oceanic Niño Index (ONI)] with hotspots in West and Central Kalimantan is shown in *Table 2*. The trend curves indicate that the higher the rainfall and the number of rain days the lower will be the number of hotspots both in West and Central Kalimantan provinces in Indonesia. A similar trend rainfall and number of rain days was observed in total peat hotspots. The hotspots in West and Central Kalimantan were related to ONI, which is the 3 monthly running average of the equatorial Pacific Ocean sea surface temperature (SST) anomalies measured at Niño 3.4 region (5^{O}N-5^{O}S, 120^{O}W-170^{O}W). When there is a rise in ONI, there will be a rise in hotspots in West and Central Kalimantan and was related to cubical and fourth degree of polynomial trends (IOI Internal Report, 2022).

The rise in ONI can be an early warning system to mitigate work on the fire prevention in land. The burning conducted during dry months is on mineral soils for slash and burn farming system (Paramananthan, 2016b). Any burning except in rice fields is prohibited in

TABLE 2
RELATIONSHIP OF RAINFALL (MM), RAIN DAYS HOTSPOTS AND ONI AT NINO 3.4

X	*Y*	*Modelling*	R^2
		West Kalimantan	
Rainfall (mm)	Total number of hotspots	$y = 0.000000000001x^6 - 0.0000000025x^5 + 0.000002x^4 - 0.0007x^3 + 0.13x^2 - 10.68x + 361.11$	0.87
Rain days	Total number of hotspots	$y = -0.003x^5 + 0.24x^4 - 6.53x^3 + 84.00x^2 - 507.52x + 1197.10$	0.87
Rainfall (mm)	Total number of hotspots in peat	$y = 0.00000000000033x^6 - 0.00000000065x^5 + 0.0000005x^4 - 0.00018x^3 + 0.034x^2 - 2.92x + 100.32$	0.88
Rain days	Total number of hotspots in peat	$y = -0.00086x^5 + 0.063x^4 - 1.74x^3 + 22.61x^2 - 138.38x + 329.97$	0.89
Annual 3 monthly running average Niño 3.4 sst (°C)	Annual total number of hotspots	$y = 757.84x^4 - 917.66x^3 - 310.11x^2 + 834.62x + 533.84$	0.59
Annual 3 monthly running average Niño 3.4 sst (°C)	Annual total number of hotspots in peat	$y = 203.53x^4 - 263.18x^3 - 58.817x^2 + 242.55x + 140.66$	0.62
		Central Kalimantan	
Rainfall (mm)	Total number of hotspots	$y = -0.000000000092x^5 + 0.00000017x^4 - 0.00011x^3 + 0.037x^2 - 5.5x + 314.46$	0.97
Rain days	Total number of hotspots	$y = -0.0006x^5 + 0.043x^4 - 1.2503x^3 + 18.508x^2 - 143.16x + 483.43$	0.98
Rainfall (mm)	Total number of hotspots in peat	$y = 0.000000000000050x^6 - 0.00000000011x^5 + 0.000000096x^4 - 0.000044x^3 + 0.011x^2 - 1.36x + 69.33$	0.96
Rain days	Total number of hotspots in peat	$y = -0.0005x^5 + 0.0318x^4 - 0.7713x^3 + 8.9276x^2 - 51.18x + 128.29$	0.92
Annual 3 monthly running average Niño 3.4 sst (°C)	Annual total number of hotspots	$y = 166.83x^3 + 202.8x^2 + 108.92x + 368.75$	0.45
Annual 3 monthly running average Niño 3.4 sst (°C)	Annual total number of hotspots in peat	$y = -7.1572x^3 + 113.64x^2 + 116.88x + 63.083$	0.81

Malaysia. Therefore this applies to Indonesia. However, in most cases the peat fire that is blown over occurs by wind from mineral soil to neighbouring peatland. Once the fire is caught in peat, it smoulders beneath the peat and will be difficult to extinguish, unless there is enough water to flood the peat. Preparation to reduce or to avoid fire incidences is a challenge for the plantation and the surrounding as the farmers use traditional agricultural practices of shift in cultivation through slash and burn system. Regular social consultation with village farmers and plantation communities has to be intensified and fire prevention or control programmes have to be in place both within and surrounding of the plantation of 5 km radius.

There are other anthropogenic factors that can create fire. Hunting is another factor, where the xerophytic vegetation of the spodosols is set on fire. With partial burning of vegetation, the newly flourishing leaves of the partially burnt xerophytic plants attracts deer and they fall prey to hunters in the communities. The fire created for the hunting can spread to peat as well. The other possibility is fishing by the community folks along the banks of the peatland river and throwing burning cigarette butts on the land thereby starting a fire. Throwing burning cigarette butts on dry grassland creates fire hotspots. Land grab by the transmigratory community on government forest reserve or peat reserves creates higher incidence of fire hotspots during El Niño. As the water level in peat are generally low the burning activities will progress. Fire prevention in peat is a great challenge. If fire catches in peat planting of oil palm, the water level in the peat has to be raised. Pumping the river water during drought and raising the water level in peat by the river is necessary as larger quantity of water is needed to stop the smouldering fire under the peat completely. Pumping small amount of water on the surface of peat will not help in controlling fire in deep peat. When early warning system through ONI is available, the water level in peat cultivation has to be systematically blocked and controlled through water management. Such action may not completely prevent peat fire, however it can delay the onset of fire in peat. Naturally occurring rain is the best way to put out fire in peat although theoretical suggestions were made to construct tube well and release water from an aquifer depth (Paramananthan, 2016b). Further work is needed on the quantity of water needed, the costs and pump machines to be used. The overall system is yet to be tested commercially on a large scale in peat cultivation.

Peat subsidence and water management

Peat subsidence through decomposition of the organic matter is an inevitable phenomenon in oil palm cultivated in peatland. Subsidence of peat layer is the major factor for the study of drainability assessment of peat currently being cultivated with oil palm. Gurmit *et al.* (1986) had described the advancement and management practices of oil palm cultivation, where importance of water management of peat in oil palm cultivation had been emphasised by installing water gates and weirs at strategic locations of the main and collection drains. Wösten *et al.* (1997) in their study at Western Johore Integrated Agricultural Development Project (IADP) on ombrogenous peat had proven that the analyses of peat subsidence in the initial years of measurement from 1974 was about 4.6 cm per year and subsequent measurements from 1988 was 2 cm per year. This subsidence was related to the groundwater management and they came to the conclusion that with higher water table in peat, the subsidence can be reduced. Tie (2004) indicated a subsidence of 60 cm with water table of 75 cm to 105 cm in the first two years after opening of land for oil palm cultivation and in the subsequent years 6 cm of subsidence per annum. He also mentioned that there are continual records of subsidence at 2.5 cm per year in the subsequent years. Othman (2009) from his study on peat at Sessang station in Sarawak for 9 years indicated a subsidence of about 29 cm in the first year due to drainage and compaction of peat during land preparation. In the second year, the subsidence reduced to 17 cm and in the subsequent years the rate of subsidence was 5 cm to 6 cm from (years 3 to 9). Thereafter, the subsidence rate was further reduced to 2 cm to 4 cm per year due to proper water management practices. Hooijer *et al.* (2012a) in their study stated that the conversion of tropical peatlands to crop cultivation results in land subsidence and was considered as substitute measurement for the carbon dioxide emissions to the atmosphere. Their studies in *Acacia* and oil palm plantations in Indonesia mentioned that in the first year of draining water in peat resulted in 75 cm of subsidence and in the subsequent 4 years average subsidence rate was 16.75 cm per year. The same study cites that with a water table of 70 cm in the drains the average subsidence after the first 5 years was stabilised at 5 cm per year again indicating the importance of water management in oil palm cultivation as a vital management tool to reduce the subsidence of peat (Hooijer *et al.*, 2012a; Hooijer *et al.*, 2012b). The leaning of palms is the result of peat subsidence and poor water management and eventually the palms die affecting the yields of the fields due to low palm stand. Maintenance of water table at a height of 40 cm to 50 cm above ground level will reduce and delay the leaning phenomenon and maintain high yields. Traditionally, the drains were constructed in peat on a grid system for water management. Lately, in well-managed peat plantations the system has been improved by contour-based system (Parish *et al.*, 2019a). During El Niño when the water level in the surrounding river subsides, the water from the peatland will be forced to move from the higher to lower topographical terrain due to gravity even when the water in the drains are controlled by some infra structures. Efficient water management with reduced subsidence is an important aspect to consider in the daily operations of the peatland.

Drainability assessment prior to replanting in existing oil palm planted in peat and paludiculture

The continuous draining of water in peatland by natural gravity through canals and drains will result in the subsidence of peat and the quantum of subsidence varies depending on the draining and management of groundwater (Gurmit *et al.*, 1986; Wösten *et al.*, 1997; Tie, 2004; Mathews & Clarence, 2004; Hooijer *et al.*, 2012a; Hooijer *et al.*, 2012b; Paramananthan, 2016a; Parish *et al.*, 2019a; Mathews *et al.*, 2021). Progressively, a situation may arise where the water level of peatland may reach the drainage base. Once it reaches drainage base further drainage by natural gravity in peat becomes impossible (Wösten *et al.*, 1997; Tie, 2004; Hooijer *et al.*, 2012a; RSPO Drainability Assessment Procedure 2019). When the peat thickness diminishes by continuous drainage, the depth to the drainage base of the land will reach to same or lower than the water level of the nearest waterbody. When peat subsidence to such an extent happens, the water in the land cannot be drained further by natural gravity and this paves the way for the intrusion of tidal sea and river flood water into the cultivated peatland. The consequence of such an effect will be prolonged flooding, leading to an uncultivatable condition of the land for oil palm in future (Wösten *et al*., 1997; Tie, 2004; Parish *et al*., 2019a). Before permanent intrusion of water happens, the growers should consider ceasing replanting oil palm and initiate rehabilitation through paludiculture (Latin Palus = swamp) to keep the peatlands wet at all time. The type of plants or crop suitable for paludiculture in tropical peat are *Metroxylon sagu* (Sago), *Dyera polyphylla* (Swamp Jelutong), *Aquilaria beccariana* (Grahau), *Melaleuca cajuputi* (Gelam), *Shorea* species (Illipe), etc. (Joosten *et al*., 2012; Parish *et al*., 2019b).

Greenhouse gas (GHG) accounting

The draining of water in peat with subsequent subsidence and the maintenance of groundwater table play a role in annual carbon emission. The draining of water exposes the upper layer of peat leading to aerobic processes, which causes faster decomposition of organic matter (Wösten *et al*., 1997; Melling *et al*., 2005; Hooijer *et al*., 2010; Hooijer *et al*., 2012). Wösten *et al*. (1997) estimated that an average subsidence rate of 2 cm results in reduction of peat volume by 200 m^3 per hectare per year with the bulk density of 0.1 g/cm^3, and 60 per cent subsidence due to oxidation leads to 12 tonnes of decomposed peat per hectare per year with carbon emission of 7.2 or CO_2 emission of 26.5 tonnes per hectare per year. Hooijer *et al*. (2010), developed the relationship between groundwater table level in peat and CO_2 emission as, CO_2 emission (tonnes) per hectare = 91 x groundwater table level (in meters). The linear regression line indicates that for every 10 cm level of groundwater table in peat the CO_2 emission is equivalent to 9.1 tonnes CO_2 per hectare per year. Hooijer *et al*. (2012) estimated a carbon loss (after the first 5 years of cultivation due to subsidence) was about 178 tonnes CO_2 per hectare per year and for the subsequent years the average emission was reduced to 73 tonnes of CO_2 per hectare per year; and for 25 years would average 100 tonnes of CO_2 emission per hectare per year at the groundwater table level of 70 cm. Review evaluation by Carlson *et al*. (2015) have shown a positive relation between the maintenance of groundwater table and soil respiration (total and heterotrophic) in peat. The net carbon loss *via* subsidence with the groundwater table depth of 70 cm is about 20 tonnes carbon per hectare per year which was closer to the findings of Hooijer *et al*. (2010). The GHG emission from peat would become essential to plantations as they need to measure the groundwater levels regularly on a biweekly to monthly basis and subsidence annually to calculate the annual CO_2 emissions for the individual company.

In addition to carbon emission due to subsidence and groundwater table, there is CO_2 emission due to total soil respiration out of which 80 per cent is heterotrophic soil respiration. Melling *et al*. (2005) indicated seasonal carbon flux due to climate, soil moisture and bulk density. However, such carbon flux or soil respiration in oil palm cultivated field was dominantly influenced by the higher percentage of soil water filled pore space (WFPS). In their study, not only does oil palm or sago cultivation emit heterotrophic CO_2 but also forest peat, which is 7.7 kg per m^2 per year, which is expected to be assimilated by the forest vegetation itself. Carlson *et al*. (2015) estimated total soil respiration to be about 20 tonnes CO_2, out of which the heterotrophic soil respiration is about 17 tonnes CO_2 per hectare per year.

European Union (EU) had initiated ambitious objectives in Climate Action of Paris Agreement 2015 to reduce 55 per cent of greenhouse gas from 1990 levels in 2030 and by 2050 to be carbon neutral in all sectors of the economy including agriculture (Climate Action, Paris Agreement 2015). In any agricultural crop, during cultivation practices, the CO_2 emission is unavoidable (Dumortier & Elobeid, 2020; Madden *et al.*, 2022). Companies cultivating oil palm on peat will have to include CO_2 emissions as the result of annual emission of carbon due to subsidence and groundwater table. For every 1,000 hectares of peatland cultivated with oil palm at 50 cm of groundwater table, the CO_2 emission is about 45,500 tonnes per year. Mathews and Ardiyanto (2015) estimated that the emission is about 416 kg CO_2 per tonne crude palm oil (CPO) for oil palm field operations in mineral soils. If processing of fresh fruit bunch (FFB) is carried out without the capture of the emitted methane gas, the estimated CO_2 emission was 1,131 kg per tonne CPO. Once peat cultivation is included, the additional CO_2 emission as the result of maintaining groundwater table at 50 cm will be 9,100 kg of CO_2 per tonne CPO (calculated at production of 5 tonnes of CPO per hectare at 25 tonnes FFB with oil extraction rate of 20%). Such high emission of CO_2 in peat through groundwater management and subsidence will have to be compensated when the crop is harvested when they may have to pay a possible carbon tax during trading CPO in future.

Relationship between FFB production and water deficit of oil palm on peat

The yield of oil palm FFB performance in peat is dependent on water management, the level of subsidence of peat and the leaning of the palms, which is an indication of the extent of subsidence of peat. With good management practices good yields are expected in peat planting. The relationship between FFB production and peat moisture has been reported by Mathews (2019) as shown in *Figure 1*.

The FFB production on peat showed a quadratic expression with an inverted parabolic

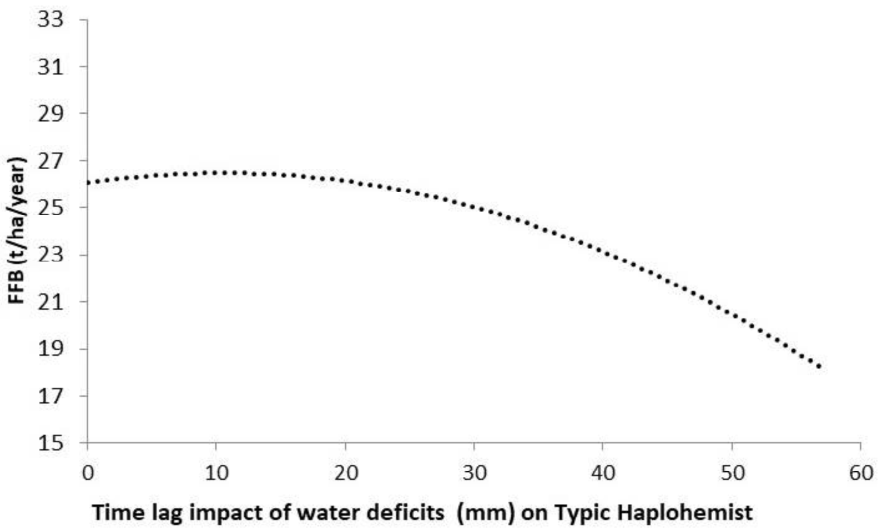

Figure 1 Relationship between FFB production and impact of water deficit on yield

curve in relation to moisture. This indicates that good water management through well-maintained water level in peat is essential to achieve high yields. Droughts and low maintenance of groundwater affects the depressive effect on yields of palms planted in peat. Climate change is a reality in South East Asia. Extreme prolonged droughts by El Niño followed by La Niña floods create difficulty in water management of the cultivated peatland. Yields will be affected under both situations, the drought reduces the yield, while the good water level management under controlled conditions during La Niña improves the yield, although harvesting can be affected by periodic floods.

Peat protection on landscape basis

Landscape approach of protecting peatland has been initiated by some plantation houses. There is a multistakeholder participation by plantation houses along with local communities, governmental and non-governmental organisations. Although the clearing and planting of oil palm on peat appeared to be an easy job, the rehabilitation of degraded peatland is an enormous task requiring high manpower for the restoration programmes. Many such projects are costly and expenditure may partly be taken up by the plantation houses without any immediate returns and some may also be funded by international organisations. The cost incurred in such projects, is part of the expenditure and probably some rebates in taxation could be expected. Such large projects, if owned by plantation houses may provide some carbon storage in their land and provide credits to negate the current carbon emission in the rest of the oil palm cultivation. The protection of landscape includes, paludiculture, planting of natural trees grown in peat, rewetting, corridor development for the movements of animal, fire prevention plans and activities that enhance biodiversity in the area. In the current scenario, a more novel approach and work would be expected from plantation personnel to manage the peat plantation.

CONCLUSIONS

The existing oil palm planted in peatlands will have stricter and tougher operational monitoring and maintenance. Water management by maintaining the lowest subsidence of peat per year by maximising the groundwater table will be the tedious operational work. The CO_2 emission in peat cultivation depends on the groundwater table monitoring and the data developed through monitoring will have to be used for annual greenhouse gas emission of the plantation company and may become part of the carbon taxation in carbon trading of CPO. The yields in oil palm plantation are also dependent on the optimal groundwater management. Fire prevention in drought seasons will be the most uphill task for the plantation, this needs to be implemented through social and environmental programmes by an early warning system through monitoring of ONI. Peat conservation and protection in a landscape basis is the next demanding task for managing it.

ACKNOWLEDGEMENT

The author wishes to thank IOI Group for giving permission to publish this paper. Author is thankful to the Plantation Director for having been supportive throughout the work on peat.

REFERENCES

CARLSON, K. M., GOODMAN, L. K. and MAY-TOBIN, C. C. 2015. Modelling relationships between water table depth and peat soil carbon loss in South East Asian plantations. *Environmental Research Letters* **10** (7): 0744006.

CHEONG, S. P. and NG, S. K. 1977. Major nutrient requirements of oil palms on deep acid peat in Malaysia. In: *Proceedings of Clamatrops Conference on Classification and Management of Tropical Soils* (Joseph, K. T., ed.). Kuala Lumpur: Malaysian Society of Soil Science. 525-533.

CLIMATE ACTION PARIS AGREEMENT. 2015. https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_en.

DACHNOWSKI-STOKES, A.P. 1930. Report to the sub commission for peat soils of International Society of Soil Science. In: *Proceedings and papers of the Second International Congress of Soil Science, Commission VI, Application of Soil Science to Agricultural Technology* (Kostiakov, A. N. and Dokturovsky, V. S., eds.). Leningard, Moscow, USSR. 209-211.

DACHNOWSKI-STOKES, A.P. 1935. Essentials of a general system of classifying organic soils sub commission VIa peat soils. In: *Transactions of Third International Congress of Soil Science, Vol.1, Commission Papers* (Crowther, E., Cutler, D.W., Heintze, S., Jacks, G.. V., Richardson, H.L., Schofield R.K., Scott Blair, G.W. and Thornton, H.G, eds.). Oxford: England. 416-418.

DUMOIRTIER, J. and ELOBEID, A. 2020. Effects of a carbon tax in United States on agricultural markets and carbon emissions from land use change. Science Direct, Land Use Policy Elsevier

FAO/ISRIC/ISSS. 1998. World reference base for soil resources. World Soil Resource Report #84 FAO, Rome. pp 88.

FILKOV, A. I., NGO, T., MATTHEWS, S., TELFER, S. and PENMAN, T. D. 2020. Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. Retrospective analysis and current trends. *Journal of Safety Science Resilience* 1: 45-56.

GOSS, M., SWAIN, D. L., ABATZOGLOU, J. T. SARHADI, A., KOLDEN, C. A. WILLIAMS, A. P. and DIFFENBAUGH, N. S. 2020. Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environmental Research Letters* 15: 1-14.

GURMIT, S. 1983. Micronutrient studies on oil palm on peat. In: *Proceedings of Seminar on Fertilisers in Malaysian Agriculture*. Selangor: The Malaysian Society of Soil Science and University Pertanian Malaysia.

GURMIT, S., TAN, Y. P., PADMAN, C. V. R. and LEE, W. F. 1986. Experiences on the cultivation and management of oil palm in deep peat in United Plantation Berhad. In: *Proceedings of Second International Soil Management Workshop-Classification and Utilisation of Peatland*. Hat Yai, Thailand. 143-157.

HOOIJER, A., PAGE, S., CANADELL, J. G., SILVIUS, M., KWADIJK, J., WÖSTEN, J. H. M. and JAUHAIINIEN, J. 2010. Current and future CO_2 emissions from drained peatlands in Southeast Asia. *Biogeosciences* 7: 1505-1514.

HOOIJER, A., PAGE S.E., JAUHAIINIEN J., LEE W.A., LU, X.X., IDRIS, A and ANSHARI, G. 2012a. Subsidence and carbon loss in drained tropical peatlands. *Biogeosciences* 9:1-19.

HOOIJER, A., TRIADI, B., KARYANTO, O., PAGE, S., VAN DER VAT, M. and ERKENS, G. 2012b. Subsidence in drained coastal peatlands in SE Asia: Implications for sustainability. Extended abstract 176 of Congress, 14th International Peat Congress, Stockholm, Sweden.

IOI INTERNAL REPORT. 2022. Relationship of rainfall pattern and fire occurrence in West and Central Kalimantan paper writing in progress.

JOOSTEN, H., DOMMAIN, R., HABERI, A., PETERS, J., SILVIUS, M. and WITCHMANN, W. 2012. Peatlands- guidance for climate change mitigation through conservation and sustainable use. *Mitigation of Climate Change in Agriculture Series 5. Chapter 2, Implementation*.

LEAMY, M. L. and PANTON, W.P. 1966. Soil survey manual for Malayan conditions. Ministry of Agriculture and Cooperatives (Malaysia) Division of Agriculture, *Bulletin 119*.

MADDEN, S., RYAN, A. and WALSH, P. 2022. Exploratory study on modelling agricutural carbon emissions in Ireland, *Agriculture* 12: 34 1-12.

MATHEWS, J. 2019. Effect of soil water deficits on annual fresh fruit bunch production in Central Kalimantan. *The Planter* **95** (1121): 551-567.

MATHEWS, J. and CLARENCE, P. J. 2004. Some observations on premature frond desiccation of oil palm trees planted in very deep peat. *The Planter* **80** (936): 143-156.

MATHEWS, J. and ARDIYANTO, A. 2016. Impact of forest fire induced haze on oil extraction(OER) in Central Kalimantan Province. *Journal of Oil Palm, Environment and Health* 7: 28-33.

MATHEWS, J., MOHANARAJ, SIKAB, A. M., CHIA, Y. Z., AGUS, T.S. and WANORHESSAM, O. 2021. RSPO Tier 1 drainability assessment in deep peat of Kinabatangan River basin-A case study. *The Planter* **97** (1142): 293-313.

MELLING, L., HATANO, R. and GOH, K. J. 2005. Soil CO_2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. *Tellus* 57B 1-11.

MELLING, L., LAU, J.U., GOH, K. J., HARTONO, R. and OSAKI, M. 2006. Soils of Loagan Bunut National Park, Sarawak, Malaysia. Final Report, Peat Swamp Forests Project MAL/99/G31, UNDP, GEF, Department of Agriculture, Sarawak, Malaysia.

MIETTINEN, J., SHI, C. and LIEW, S. C. 2016. 2015 Land cover map of Southeast Asia at 250 m spatial resolution. *Remote Sensing Letters* **7** (7): 701-710.

MINISTRY OF NATURAL RESOURCES AND ENVIRONMENT, MALAYSIA. 2011. *National Action Plan for Peatlands.* ISBN:987-967-0250-00-7.

MINISTRY OF PRIMARY INDUSTRIES AND COMMODITIES, MALAYSIA. 2019. https://www.mpic.gov.my/mpi/en/info-siaran-media/media-release-2019/icon-fa-newspaper-o-icon-media-release-28-november-2019.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION. 2022. National Centers for Environment information. El Niño Southern Oscillation (ENSO). https://www.ncdc.noaa.gov/teleconnections/enso/sst#oni assessed on 15 January 2022.

NG, S. K. and TAN, Y. P. 1974. Nutritional complexes of oil palms planted soil in Malaysia I. Foliar symptoms, nutrient composition and yield. *Oléagineux* 29:1-14.

NG, S. K., TAN, Y. P., CHAN, E. and CHEONG, S. P. 1974. Nutritional complexes of oil palms planted on peat soil in Malaysia II. Preliminary results of copper sulphate treatments. *Oléagineux* 29: 445-456.

OTHMAN, H. 2009. Experiences in peat development for oil palm planting in the MPOB Research Station at Sessang, Sarawak. *Oil Palm Bulletin* 58, May 2009, 1-13.

PAGE, S. E., SIEGERT, F., RIELEY, J. O., BOEHM, H. D. V., JAYA, A. and LIMIN, S. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. *Letters to Nature* **420** (6911):, 61-65.

PAGE, S. E., RIELEY, J. O. and BANKS, C. J. 2011. Global and regional importance of the tropical peatland carbon pool. *Global Change Biology* **17** (2): 798-818.

PARAMANANTHAN, S. 2002. Training course notes on Soil Survey and Management of Tropical Soils, conducted by Param Agricultural Soil Surveys (M) Sdn Bhd. 13th -17th May 2002, Felda Trolak Country Resort, Perak, Malaysia.

PARAMANANTHAN, S. 2010. Malaysian Soil Taxonomy Revised Second Edition Param Agricultural Soil Surveys (M) Sdn Bhd, Malaysia

PARAMANATHAN, S. 2016a. *Organic Soils of Malaysia, Their Characteristics, Mapping, Classification and Management of Oil Palm Cultivation*. Kelana Jaya, Malaysia: Malaysian Palm Oil Council.

PARAMANANTHAN, S. 2016b. Minimising the Haze. *The Planter* **92** (1085): 523-541.

PARISH, F., MATHEWS, J., LEW, S. Y., FAIZUDDIN, M. Z. and LO, J. 2019a. *RSPO manual on BMPs for existing Oil Palm Cultivation on Peat.* Volume 1, Second Edition, RSPO, Kuala Lumpur.

PARISH, F., LEW, S. .Y, FAIZUDDIN, M. Z. and GIESEN, W. 2109b. *RSPO Manual on Best Management Practices (BMPs) for Management and Rehabilitation of Peatlands.* Volume 2, Second Edition, RSPO, Kuala Lumpur.

RSPO WORKSHOP OF PEATLAND WORKING GROUP. 2018. Field visit to Woodman Plantation, Miri, Sarawak

ROUNDTABLE ON SUSTAINABLE PALM OIL (RSPO). 2007. RSPO Principles and Criteria for the Production of Sustainable Palm Oil. Kuala Lumpur.

ROUNDTABLE ON SUSTAINABLE PALM OIL (RSPO). 2013. RSPO Principles and Criteria for the Production of Sustainable Palm Oil. Kuala Lumpur.

ROUNDTABLE ON SUSTAINABLE PALM OIL (RSPO). 2018. RSPO Principles and Criteria for the Production of Sustainable Palm Oil. Kuala Lumpur.

ROUNDTABLE ON SUSTAINABLE PALM OIL (RSPO). 2019. Drainability Assessment Procedure, Drainability Assessment Procedure for Replanting of Existing Oil Palms in Peatlands. November 2019, Kuala Lumpur.

STRAPEAT-UNIMAS-NREB. 2004. Handbook of Environmental Impact Assessment (EIA) of development on peatlands. University Malaysia Sarawak, Kota Samarahan, Sarawak, November 2004.

TAYEB, D. M., HAMDAN, A. B. TARMIZI, M. A. and ROSLAN, A. 1997. Recent progress on research and development on peat for oil palm. *PORIM Bulletin* 34: 11-34.

TIE, Y. L. 2004. Long-term drainability of and water management in peat soil areas. *The Planter* **80** (940): 423-439.

UNITED STATES DEPARTMENT OF AGRICULTURE NATURAL RESOURCES

CONSERVATION SERVICES. 1998. *Keys to Soil Taxonomy* by soil survey staff. Eighth edition, pp 12.

WÖSTEN, J. H. M., ISMAIL, A. B. and VAN WIJIK, A. L. M. 1997. Peat subsidence and its practical implications: a case study in Malaysia. *Geoderma* 78: 25-36.

WÖSTEN, H., HOOIJER, A., SIDERIUS, C., RAIS, D. S., IDRIS, A. and RIELEY, J. 2006. Tropical peatland water management modelling of the Air Hitam Laut catchment in Indonesia. *International Journal River Basin Management* **4** (4): 233-244.