BEST MANAGEMENT PRACTICES FOR OIL PALM CULTIVATION ON PEAT: GROUND WATER-TABLE MAINTENANCE IN RELATION TO PEAT SUBSIDENCE AND ESTIMATION OF CO_2 EMISSIONS AT SESSANG, SARAWAK

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ABSTRACT

The study on peat subsidence was carried out in an area of shallow and deep peat in MPOB Research Station in Sessang, Sarawak. Upon completion of the latest phase of peat development for oil palm planting in 2001, water management was improved to maintain the ground water-table at 30 to 50 cm over the whole plantation. Data on peat subsidence and oil palm yields were collected from 10 blocks of oil palm of different ages planted on peat of different depths ranging from shallow to deep peat. A regression equation was established with subsidence data as a dependent variable, while ground water-table and time with quadratic effects were independent variables. Two separate equations were developed for the different depths of peat. The study shows that the subsidence rate was very much related to the age of peat development, i.e. *the number of years after oil palm had been planted. The subsidence rate over the years declined and stabilised after 15 years of peat development. A relationship between bulk density of the peat and age of peat development was also established. The CO_2 emission was estimated using the method based on depth of ground water-table. From the current study, it was found that maintaining high ground water-table was better for oil palm agronomics, while at the same time, it reduced the decomposition and mineralisation rates of peat, and hence prevented excessive CO_2 emission.*

Keywords: oil palm, peat, subsidence, decomposition, consolidation.

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INTRODUCTION

The practice of managing oil palm revolves around ways to ensure the sustainability of the oil palm planting. In the past, studies were carried out which focused on activities that increased yield, without factoring in practices related to carbon balance.

From a study carried out in West Johor, DID and LAWOO (1996) established subsidence rate (SR) and average water depth to be important parameters for CO_2 emission. Based on another study, the Department of Irrigation and Drainage Sarawak (2001) deduced that SR for peat in Sarawak should be monitored. However, the estimation of CO_2 emission based on SR criteria might lead to an overestimation because of the loose nature of peat in Sarawak, causing it to subside more unless a consolidation process had been carried out. Otherwise, the oxidation process would contribute to a higher CO_2 emission which might be lumped together with the emission due to subsidence alone. SR depends very much on the type of peat material, depth of the ground water-table and rainfall factors. The objective of this article is to establish SR from the data collected at MPOB Research Station in Sessang, Sarawak, and provide an estimate of CO_2

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emission relating to SR and ground water-table management.

MATERIALS AND METHODS

The study was carried out at MPOB Research Station located at Sessang, Sarawak, which has an area totalling 1000 ha of peatland. The area was previously a secondary mixed peat swamp forest. Initially, the peat depths ranged from 100 to 400 cm consisting of undecomposed plant biomass (fibric soil material), while the nature of the mineral subsoil below the peat layer was non-sulphidic clay. Based on the Sarawak Soil Classification (Tie, 1982), the area was classified as Epai and Anderson Series for peat depth of 100 to 150 cm (shallow peat) and more than 150 cm (deep peat), respectively (*Table 1*). Preliminary work to establish and set up the plantation in Sessang began in 1991. The standard land clearing method was adopted (Mohd Tayeb, 2005). Field development and maintenance work were carried out using the best management practices. Mechanical compaction of the harvesting paths and planting rows was carried out during land preparation to provide better accessibility through increased soil bulk density (Mohd Tayeb, 2005). The drainage system consisted of field drains established for every four planting rows, giving a drain intensity of 340 m ha^{-1}. Oil palm seedlings were planted using the 'hole-in-hole' planting technique (Mohd Tayeb, 2005). At a later stage, a technique of unidirectional slanting of the palms was introduced to improve management and productivity (Hasnol *et al.*, 2007).

An intensive study on peat subsidence was carried out in 2001, and water management for the whole plantation was improved by maintaining ground water-table in the field between 35 and 45 cm below the surface. The study covered 10 blocks of oil palm of different ages planted on peat of different depths. The youngest palm was two years, while the oldest palm was nine years.

Water-table Management

Hydrological and engineering aspects of the drainage system have been presented by the Department of Irrigation and Drainage Sarawak (2001) in a manual on water management guidelines for agricultural development in lowland peat swamps. Peat drains were designed to flush out water during heavy rainfall and to maintain ground water-table at a level as high as the palms could possibly withstand at all times. Mean rainfall data (1990-2007) at MPOB Research Station at Sessang are shown in *Figure 1*. The ground water-table fluctuated depending on the amount of rainfall; the lower the fluctuation, the lower was the rate of peat subsidence. A low rate of subsidence could be achieved by managing the fluctuation between high and low ground water-tables in the field drain as close as possible between 30 and 40 cm. In order to do this, the water level in the collection drains was maintained between 40 and 50 cm by using a series of water gates made of sand bags and wooden planks along the collection drains. These movable sand bags and adjustable wooden planks were used to control the water flow to maintain the water level at the required level. Water from the collection drains flowed into the main drain (canal), where a concrete structure was located to control the flow from the plantation and the nearby river.

Data Collection

Ground water-table data were collected at several points in the fields within the study blocks

TABLE 1. SITE CHARACTERISTICS

Description/detail	1	2	3
Soil series	Epai	Anderson	Anderson
Peat depth (cm)	100 – 150	350 – 400	300 – 350
Date of planting	February 1994	November 1995	July 1997
Planting material	MPOB's DxP	Four commercial DxP planting materials	MPOB's DxP
Land preparation	Soil compaction	Several compaction methods	Soil compaction
Planting technique	Hole-in-hole	Hole-in-hole Unidirectional	Normal hole
Planting density	160 palms ha^{-1}	160 palms ha^{-1}	160 palms ha^{-1}
Field drain intensity	Every 4 planting rows	Every 4 planting rows	Every 4 planting rows Every 8 planting rows

Source: Hasnol *et al*. (2009).

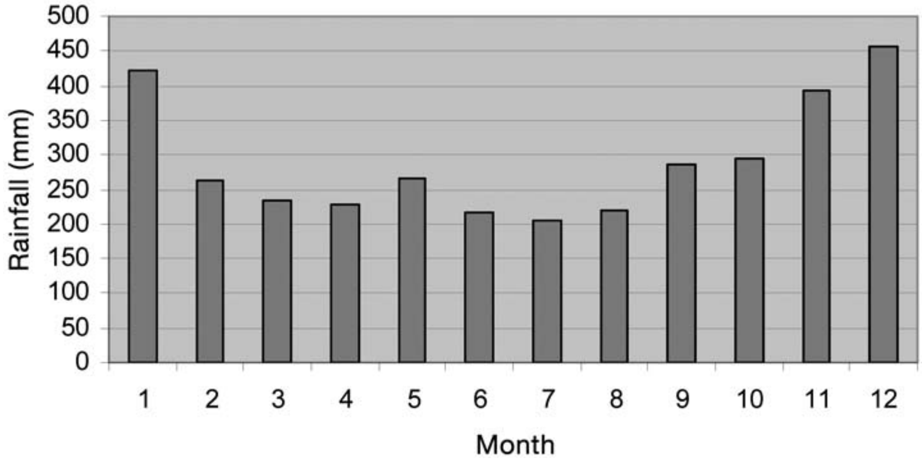


Figure 1. Mean rainfall (1990-2007) at MPOB Research Station at Sessang, Sarawak.

using the lysimeter method, and means of monthly data were calculated. Peat subsidence was measured at several points in the fields within the study blocks using subsidence poles. The changes in peat characteristics such as peat depth, degree of peat decomposition and bulk density were monitored and recorded. Independent observations on water-table in relation to palm physical conditions were also carried out at Tradewinds Plantations.

Fresh fruit bunch (FFB) yield data were obtained by carrying out palm-by-palm recording of bunch number and weight, and monthly yield data were summarised to give yearly figures. The data were kept and managed by a relational database for agronomy data systems (READA). The initial chemical properties of peat in the area under study were analysed.

TABLE 2. SUMMARY OF INITIAL SOIL CHEMICAL PROPERTIES OF PEAT AT MPOB RESEARCH STATION IN SESSANG, SARAWAK (peat sampled at 0-45 cm depth)

Property	Shallow peat	Deep peat
pH (H_2O)	3.54	3.35
Organic carbon (%)	24.50	24.86
Nitrogen (%)	1.21	2.98
C/N ratio	20.3	8.3
Extractable phosphorus (mg kg^{-1})	73.8	42.9
Exchangeable cations (cmol kg^{-1})		
Potassium	1.23	0.86
Calcium	7.00	4.05
Magnesium	4.45	3.65
Total exchangeable bases (TEB)	12.68	8.57
Aluminum (mg kg^{-1})	1.35	0.53
Manganese (mg kg^{-1})	24.5	21.4
Iron (mg kg^{-1})	108.8	75.2

Source: Hasnol *et al*. (2009).

RESULTS AND DISCUSSION

Chemical Properties and Carbon Content of Peat

Assessing the percentage of organic carbon in peat is crucial for agricultural purposes, particularly for calculating the C:N ratio of the material and carbon emission from peat oxidation. The initial soil chemical properties of peat in the study area are presented in *Table 2*. Except for nitrogen (N), the peat soils had very low nutrient content, especially potassium (K) and micronutrients. The total N was relatively high but its availability for plant uptake was assumed to be low due to high C:N ratio. Under natural conditions, peat is very acidic (as in this case), and this is a serious limiting factor for optimum growth for many crops.

At the early stage of development for both the shallow and deep peat, their soil pH and organic carbon content were relatively similar. The carbon content of peat samples collected down to 45 cm depth was 25%. However, at an adjacent site in MARDI Peat Station, Zulkefli *et al*. (2007) reported a carbon content of 49% for a peat sample collected at 30 cm depth (*Table 3*).

Data from various sources show that the organic carbon content of peat can vary from 12% to 60%. This wide range reflects the difference in the kind of organic materials, the stage of decomposition and probably the analytical method used. Kanapathy (1976) in his research on peat soils in Malaysia reported values ranging from 58% at the surface to 25% in the subsoil. Studies by Tie (1982) in Sarawak showed a range of 20% to 38%, indicating a higher

TABLE 3. BULK DENSITY, pH, CARBON AND NITROGEN CONTENTS OF PEAT# AT SESSANG, SARAWAK

Parameter	Shallow to moderately deep* 0-45 cm	Deep* 0-45 cm	Deep ** 0-30 cm
Bulk density (g cm^{-3})	0.14	0.09	0.10
pH (H_2O)	3.5	3.4	3.7
Organic carbon (%)	24.5	24.86	48.8
Nitrogen (%)	1.21	2.98	1.61
C: N ratio	20.3	8.3	30.3

Note: #samples taken at early stage of peat development.
Source: *Hasnol *et al*. (2009).
**Zulkefli *et al*. (2007).

TABLE 4. EFFECT OF LAND DEVELOPMENT FOR OIL PALM PLANTING ON PEAT PROPERTIES (0-30 cm depth) AT MPOB RESEARCH STATION SESSANG, SARAWAK

Peat category	Peat depth (cm)		Soil bulk density (g cm^{-3})	
	Initial[1]	Current[2]	Initial[1]	Current[2]
Shallow peat	135.0 ± 1.3	63.3 ± 1.3	0.14 ± 0.03	0.26 ± 0.04
Deep peat	362.1 ± 2.5	277.7 ± 2.1	0.09 ± 0.01	0.16 ± 0.03

Note: [1] Drained peat.
[2] 10 years after development.
Source: Hasnol *et al*. (2009).

content of organic carbon in the surface horizons of deep peat than in shallow peat. Ekono (1981) in his review of peat as a source of energy indicated organic carbon values of 48%-50% in slightly decomposed (fibric) peat, 53%-54% in moderately decomposed (mesic) peat and 58%-60% in highly decomposed (sapric) peat. Carbon contents between 45 and 90 kg C m^{-3} had been published for various peat deposits in Southeast Asia (Hooijer *et al*., 2009). The relationship between subsidence rate and CO_2 emission applied in an assessment done by Wösten and Ritzema (2001) assumed a carbon content of 60 kg m^{-3}. Further research is therefore needed to study the carbon content of various peat types at different peat development stages and different water-table regimes.

Peat Depth and Bulk Density

Bulk density measurements are of practical importance in interpreting soil analytical data, particularly those indicating fertility levels. Analytical values for organic soils must be recalculated on a weight per volume basis, using bulk density as a correction factor. Peat depth and soil bulk density are very important properties that influence the management practices of oil palm on peat. The thickness of the peat layer has been used in the classification of peat soils as well as in assessing agronomic suitability for oil palm planting. The loose and soft ground conditions associated with low soil bulk density present anchorage problems to the palms, resulting in poor growth and crop yields, and are also a constraint to accessibility. Low soil bulk density is among those peat properties that need amelioration for successful cultivation of tree crops such as oil palm according to Mohd Tayeb (2005). He reported that good soil compaction increased soil bulk density up to 0.23 g cm^{-3}, giving positive effects on palm growth, yield production and field accessibility.

The effects of land development and reclamation for oil palm planting on the peat properties at MPOB Research Station in Sessang are summarised in *Table 4*. The data were recorded from samples taken at two different depths of the peat, *i.e.* shallow to moderately deep, and deep peats developed from 1995 to 2001 for oil palm planting. Lowering the ground water-table by draining the area resulted in peat subsidence, which consequently decreased peat depth as well as increased the soil bulk density. Over the period of 10 years development, the initial peat depth without compaction had reduced from 135.0 to 63.3 cm and from 362.1 to 277.7 cm for shallow and deep peat, respectively. In deep peat, total subsidence over the 10-year period was slightly higher amounting to 84.4 cm compared to 71.1 cm for shallow peat. The subsidence rate was lower because peat consolidation, which caused initial subsidence, was not carried out. The initial soil bulk density of drained peat was low at an average of 0.14 and 0.09 g cm^{-3} for shallow and deep peat, respectively. Mechanical soil compaction and peat decomposition over the 10 years of development increased the soil bulk density to 0.26 and 0.16 g cm^{-3} for shallow and deep peat, respectively.

In the early years of peat development, the peat was fibric in form with a bulk density of less than 0.1 g cm^{-3}; it then developed to sapric with a bulk density of more than 0.2 g cm^{-3} after years of development. Based on the data of samples from 0 to 45 cm depth in MPOB Sessang Station, an equation was developed to estimate the increase in bulk density of the peat planted with oil palm over the years.

Bulk density = 0.0532+0.0149*Yr - 0.0002*Yr^2
where Yr = year after development
R^2 = 0.96

Figure 2 shows that bulk density increased from less than 0.1 g cm^{-3} to over 0.20 g cm^{-3} after 15 years of development.

Ground Water-table, Subsidence Rate and CO_2 Emission

The peat areas in Malaysia, especially in Sarawak, receive high rainfall, and this prevents irreversible drying of the peat during the dry months if the ground water-table is maintained at a higher level. There has been some dispute with regard to drainage depth in oil palm plantations. Hooijer *et al*. (2009) used an average drainage depth of well over 0.95 m for oil palm plantations. Such a low ground water-table would be detrimental to peat; peat drying was observed in Tradewinds Plantation in areas where the water-table over the years was kept at more than 60 cm from the surface, resulting from induced oxidation of the peat profile. The effect would be more pronounced during the dry months. In this study, sustainable high oil palm yield could be achieved by maintaining the ground water-table between 30 and 50 cm starting from the first year of planting, when the water level in the collection drains was maintained between 40 and 60 cm. This best management practice can reduce CO_2 emission, avoid peat drying and subsequently prevent premature desiccation of oil palm leaves due to moisture stress. As a result, Tradewinds Plantation has since adopted this high water-table management practice.

Subsidence of peat contributed by consolidation of loose-form peat in Sarawak his anticipated to be high because most of the peat is fibric. The consolidation process takes several years, proceeding at a declining rate, if the peat is left under natural conditions. In this study, managing a higher ground water-table (WT) would be able to reduce the subsidence rate depending on the peat depth. Subsidence of the shallow peat on average was 2.5 cm yr^{-1}, and this can be described as follows:

SR = 7.033 – 0.491 Yr + 0.004 Yr^2 + 0.027 WT
where SR = subsidence (cm); Yr = year after development; WT = ground water-table(cm); n= 56; R^2 = 0.635

Subsidence of the moderately deep peat on average was 3.0 cm yr^{-1}, described as follows:

SR = 10.605 – 0.899 Yr + 0.018 Yr^2 + 0.026 WT
where SR = subsidence (cm); Yr = year after development; WT = ground water-table(cm); n = 47; R^2 = 0.604

Subsidence of the deep peat on average was 4.3 cm yr^{-1}, described as follows:

SR = 7.05 – 0.691 yr + 0.008 yr^2 + 0.049 WT
where SR = subsidence (cm); Yr= year after development; WT=ground water-table(cm); n=147; R^2 = 0.626.

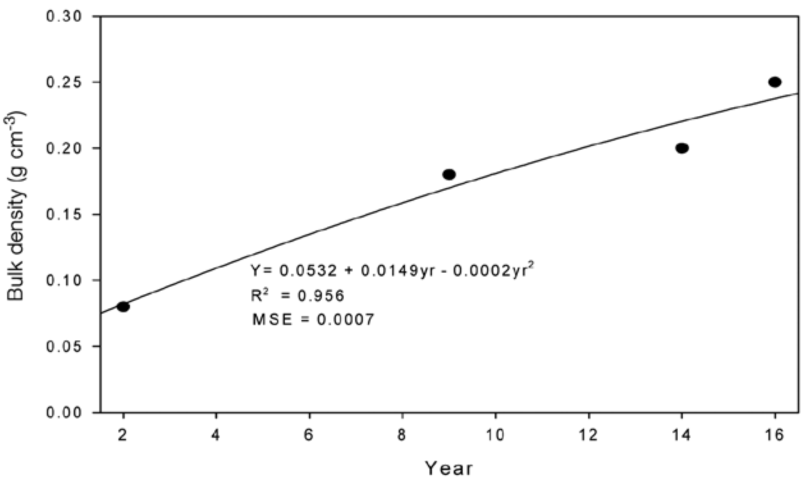


Figure 2. Change in bulk density over years of peat development in Sessang, Sarawak.

The estimation of CO_2 emission was based on the peat carbon content and bulk density to discount the contribution of compaction from the total subsidence rate (Wösten *et al.*, 1997; Wösten and Ritzema, 2001). The assessment was lacking in an adequate number of observations; thus, only a linear relation between drainage depth and CO_2 emission was established through the available data, whereas the actual relation is known to be non-linear. Carbon emission was dependent on peat decomposition rate which was a small factor that contributed to peat subsidence. Peat subsidence mainly due to compaction did not emit CO_2 and depended on initial bulk density. Kool *et al*. (2006) reported that the peat dome of Kalimantan subsided in the range of 2.2 to 4.0 m in six years due to compaction. Subsidence due to oxidation was in the range of 2 to 47 cm in six years. This range was very wide; therefore, the amount of CO_2 emitted from decomposition of per centimetre depth of peat was reported to be about 1.3 kg m^{-2} (DID Sarawak, 2001). As CO_2 emission was also a function of heterotrophic soil respiration, more studies are warranted. In temperate peat, although temperature affects microbial activities, ground water-table has been found to explain the variability in CO_2 effluxes significantly (Ojanen *et al*., 2010). In the tropics, variations in temperature were not the main concern, but CO_2 effluxes would be very much dependent on ground water-table.

The estimation of CO_2 emission based on water-table was developed by Hooijer *et al*. (2009):

$$CO_2 \text{ emission } (\text{t ha}^{-1} \text{ yr}^{-1}) = 0.91 \times \text{Water-table (WT) depth (m)}$$

Tables 5 to *9* show the average ground water-table of planting blocks of different peat depths, and estimates of CO_2 emission based on Hooijer's equation. On average, carbon emissions were estimated at 37 to 40 t ha^{-1} yr^{-1} for deep peat and at 30 to 34 t ha^{-1} yr^{-1} for shallow to moderately deep peat. These estimates are significantly lower than the carbon emission of 86 t ha^{-1} yr^{-1} estimated by Hooijer *et al.* (2009) because of the high subsidence rate due to the low water-table of 95 cm used in their estimation. In comparison, based on the average bulk density of 0.17 g cm^{-3} and the fraction of oxidised carbon of 40%, a peat subsidence rate of between 2 and 4 cm yr^{-1} would be emitting CO_2 amounting to between 32 and 63 t ha^{-1} yr^{-1}. Melling

TABLE 5. WATER-TABLE, SUBSIDENCE RATE, BULK DENSITY AND ESTIMATION OF CARBON DIOXIDE (CO_2) EMISSION ON DEEP PEAT (2 to 9 years of peat development*)

Planting block	Year	2001	2002	2003	2004	2005	2006	2007	2008	
17A, 18A	**Year after development**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Mean**
*Average of 2 blocks	Water-table (cm)	46.58	41.60	41.18	44.19	43.83	39.25	38.41	36.27	40.68
	Subsidence (cm)	8.10	7.70	5.70	5.85	5.85	4.55	2.90	2.85	5.06
	Bulk density (g cm^{-3})	0.08	0.10	0.11	0.12	0.14	0.15	0.16	0.17	0.13
	CO_2 emission (t ha^{-1})	42.39	37.86	37.47	40.21	39.89	35.72	34.95	33.00	37.01

TABLE 6. WATER-TABLE, SUBSIDENCE RATE, BULK DENSITY AND ESTIMATION OF CARBON DIOXIDE (CO_2) EMISSION ON DEEP PEAT (4 to 9 years of peat development*)

Planting block	Year	2001	2002	2003	2004	2005	2006	2007	2008	
15B (3 points), 16A (3 points), 15A (2 points), 16B (2 points)	**Year after development**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Mean**
*Average of 4 blocks (10 points)	• Water-table (cm)	37.27	40.17	38.73	40.34	46.49	50.34	47.95	46.65	43.49
	• Subsidence (cm)	5.31	5.69	5.99	5.10	5.50	2.90	3.16	3.19	4.61
	• Bulk density (g cm^{-3})	0.11	0.12	0.14	0.15	0.16	0.17	0.18	0.19	0.15
	• CO_2 emission (t ha^{-1})	33.91	36.55	35.24	36.71	42.30	45.80	43.63	42.45	39.58

TABLE 7. WATER-TABLE, SUBSIDENCE RATE, BULK DENSITY AND ESTIMATION OF CARBON DIOXIDE (CO_2) EMISSION ON DEEP PEAT (6 to 13 years of peat development*)

Planting block	Year	2001	2002	2003	2004	2005	2006	2007	2008	
12A, 12B, 13A, 13B, 14A and 14B	**Year after development**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**Mean**
*Average of 6 blocks	Water-table (cm)	-	47.91	43.78	46.28	49.54	51.85	48.42	46.21	47.71
	Subsidence (cm)	5.23	4.93	5.15	4.40	3.00	1.93	1.83	1.83	3.54
	Bulk density (g cm^{-3})	0.11	0.12	0.14	0.15	0.16	0.17	0.18	0.19	0.15
	CO_2 emission (t ha^{-1})	N.A	43.60	39.84	42.11	45.08	47.18	44.06	42.05	43.42

TABLE 8. WATER-TABLE, SUBSIDENCE RATE, BULK DENSITY AND ESTIMATION OF CARBON DIOXIDE (CO_2) EMISSION ON MODERATELY DEEP PEAT (9 to 16 years of peat development*)

Planting block	Year	2001	2002	2003	2004	2005	2006	2007	2008	
7A and 10A1	**Year after development**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**Mean**
*Average of 2 blocks	Water-table (cm)	36.13	35.26	31.92	32.50	33.50	34.25	30.83	31.51	33.24
	Subsidence (cm)	4.05	3.90	4.15	4.55	2.75	1.75	0.60	0.40	2.77
	Bulk density (g cm^{-3})	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.24	0.21
	CO_2 emission (t ha^{-1})	32.87	32.09	29.05	29.58	30.49	31.16	28.05	28.67	29.87

TABLE 9. WATER-TABLE, SUBSIDENCE RATE AND ESTIMATION OF CARBON DIOXIDE (CO_2) EMISSION ON SHALLOW PEAT (9 to 16 years of peat development*)

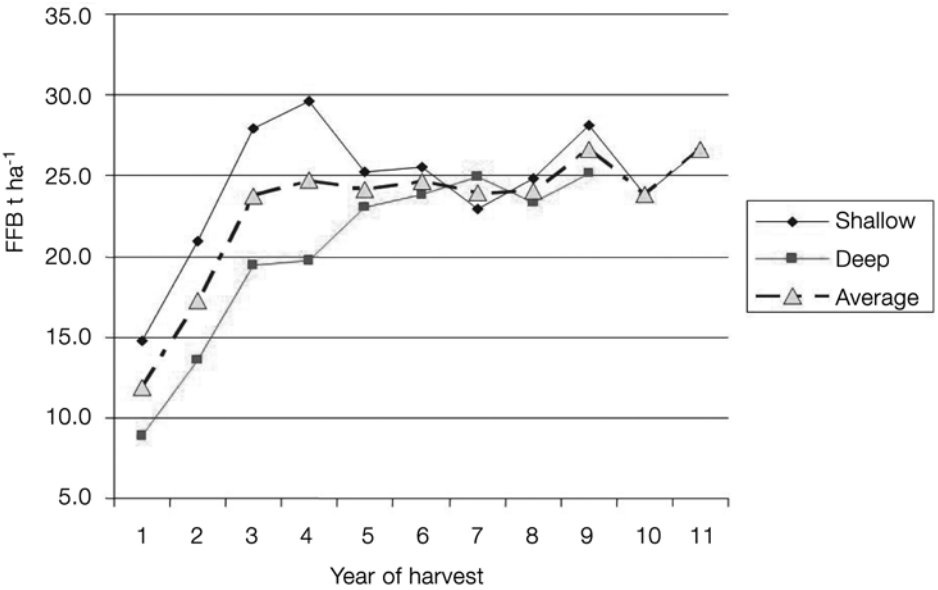
Planting block	Year	2001	2002	2003	2004	2005	2006	2007	2008	
6A2, 6B1, 8A2, 8B1 and 9A2	**Year after development**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**Mean**
*Average of 5 blocks	Water-table (cm)	38.22	39.03	36.29	37.78	39.61	36.86	34.96	36.35	37.39
	Subsidence (cm)	3.88	3.26	3.40	3.02	2.22	1.28	1.08	0.88	2.38
	Bulk density (g cm^{-3})	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.24	0.21
	CO_2 emission (t ha^{-1})	34.78	35.52	33.03	34.38	36.05	33.54	31.82	33.08	33.92

et al. (2005) measured monthly soil greenhouse gas (GHG) flux from tropical peatland of Sarawak. On an annual basis, they calculated that the soil CO_2 flux in a forest ecosystem and an oil palm plantation was 49 and 35 t CO_2 ha^{-1} yr^{-1}, respectively. From the current study, maintaining a high ground water-table was found to be better for oil palm agronomics and, at the same time, it will reduce the decomposition and mineralization rates of peat and, hence, prevent excessive CO_2 emission.

FFB Yield Performance

Earlier attempts to plant oil palm on peat had been less successful with the palms showing mediocre growth and yield performance. Much of this was due to a lack of understanding on how best to develop and manage this problematic soil. The adoption of the results obtained through time has resulted in better performance of oil palm (Mohd Tayeb, 2005).

Data on FFB yield of oil palm planted on peat at MPOB Research Station in Sessang are summarised in *Figure 3*. High ground water-table of 35 to 45 cm will prolong decomposition of peat and reduce CO_2 emission, and oil palm will produce high yield even with the application of less amount of fertiliser nitrogen. High FFB yields were obtained during the early years of production, recording 15 t ha^{-1} in the first year and then increasing to nearly



Source: Hasnol *et al*. (2009).

Figure 3. Fresh fruit bunches (FFB) yields of oil palm planted on peat with water-table maintained at 35 to 45 cm in MPOB Research Station in Sessang, Sarawak.

30 t ha^{-1} in the fourth year of harvesting. However, the FFB yield declined after the palms became fully mature at eight years after planting with yields ranging from 21 to 28 t ha^{-1}. High incidences of leaning palms and inter-palm competition due to high planting density could have influenced the FFB yield potential over that period.

CONCLUSION

The most promising mitigation measure to control peat subsidence is by practising optimal ground water-table management. This best management practice of maintaining a higher water-table is to avoid peat fires, reduce CO_2 emission, avoid peat drying and subsequently to prevent oil palm leaves from drying due to moisture stress. It is recommended that for oil palm cultivation, the water-level in the collection drains is best maintained between 40 and 50 cm, starting from the time of field preparation for planting. Further studies are needed to quantify CO_2 emission from peatland, in which, other than bulk density, the fraction of oxidised carbon in the dry matter of peat has to be determined for different stages of peat development.

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REFERENCES

DEPARTMENT OF IRRIGATION AND DRAINAGE (DID) SARAWAK (2001). *Water Management Guidelines for Agriculture Development in Lowland Peat Swamps of Sarawak, Manual.* 116 pp.

DID and LAWOO (1996). *Western Johor Integrated Agriculture Development Project*. Management Study, Malaysia and The Netherlands.

EKONO (1981). *Report on Energy Use of Peat.* Contribution to U.N. Conference on New and Renewable Sources of Energy, Nairobi.

HASNOL OTHMAN; AHMAD TARMIZI MOHAMMED and KHAIRUMAN HASHIM (2007). Uni-slant: unidirectional slanting-hole planting technique for oil palm on deep peat. *MPOB Information Series No. 359*. June 2007. MPOB, Bangi. 4 pp.

HASNOL OTHMAN; FARAWAHIDA MOHAMAD DARUS and AHMAD TARMIZI MOHAMMED (2009). Experience on peat development for oil palm planting in the MPOB Research Station in Sessang, Sarawak. *Oil Palm Bulletin No. 58*: 1-13.

HOOIJER, A; PAGE, S; CANADELL, J G; SILVIUS, M; KWADIJK1, J ; WÖSTEN, H and JAUHIAINEN, J (2009). Current and future CO_2 emissions from drained peatlands in Southeast Asia. *Biogeosciences Discuss., 6*: 7207-7230.

KANAPATHY, K (1976). Fertilizer requirement on peat soils. *Malaysian Agricultural J., 50*: 292-307.

KOOL, D M; BUURMAN, P and HOEKMAN, D H (2006). Oxidation and compaction of a collapsed peat dome in Central Kalimantan. *Geoderma, 137 (1-2)*: 217-225.

MOHD TAYEB, D (2005). *Technologies for Planting Oil Palm on Peat.* MPOB, Bangi. 83 pp.

MELLING, L; HATANO, R and KAH, J G (2005). Soil CO_2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. *Tellus, 57B*: 1-11.

OJANEN, P; MINKKINEN, K; ALM, J and PENTTILA (2010). Soil-atmosphere CO_2, CH_4 and N_2O fluxes in boreal forestry-drained peatlands. *Forest Ecology and Management, 24*: 109-123.

TIE, Y L (1982). Soil classification in Sarawak. *Technical Paper No. 6*. Department of Agriculture, Sarawak. 86 pp.

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

WÖSTEN, J H M and RITZEMA, H P (2001). Land and water management options for peatland development in Sarawak, Malaysia. *Int. Peat J., 11*: 59-66.

ZULKEFLI, M; ISMAIL, A B and JAMALUDIN, D (2007). Soil CO_2 flux from tropical peatland under different land clearing techniques. *Impact on Land Clearing on Peat Ecosystems. A Case Study at MARDI Peat Research Station, Sessang Sarawak* (Ismail, A B; Ong, H K; Mohamad Hanif, M J and Umi Kalsom, M S eds.). MARDI. p. 99-108.