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GREENHOUSE GAS EXCHANGE OF TROPICAL PEATLANDS – A REVIEW*

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ABSTRACT

This article presents data on greenhouse gas (GHG) exchange of tropical peat soils with emphasis on changes in emissions of gases during and following the conversion of native tropical peatlands to plantations of oil palm and other crops. The relevant GHGs are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Establishment of plantations on peat requires drainage, which, even if controlled, results in peat aeration and subsidence. Subsidence is mainly due to natural consolidation, often augmented by mechanical compaction, and is manifested as increased bulk density. Aeration causes carbon to be released as CO_2. Methods for distinguishing and quantifying these processes are discussed. Exchanges of CH_4 and N_2O are also changed by plantation development and are influenced by management practices but the quantities involved are small and in some cases peat soils even act as a sink and not a source, of these gases. There are seasonal changes in the GHG fluxes related to both water table depth and rainfall, and emissions of CH_4 and N_2O can be promoted by nitrogen application. GHG exchange of reclaimed peat is dominated by CO_2 despite the higher global warming potential of CH_4 and N_2O. Methods for estimating CO_2 fluxes are reviewed and their shortcomings are examined. The importance of adequately distinguishing between emission sources, e.g. *root and microbial respiration when evaluating carbon fluxes at the surface of peat soils is emphasised.*

Keywords: peat soil, greenhouse gas exchange, oil palm, subsidence, water table depth.

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INTRODUCTION

Peat soils form when the rate of carbon (C) deposition from vegetation exceeds the rate of carbon loss due to microbial decomposition and leaching. This situation is a consequence of the anaerobic conditions present in the peat swamp. Worldwide, peatlands serve as huge repositories of stored organic C and those in the tropics are major reserves. Associated conditions contributing to peat formation are high rainfall and low pH. Unlike temperate and boreal peats, the predominant vegetation on tropical peatland is forest, which itself constitutes a large C store.

Greenhouse gases (GHGs) are atmospheric constituents or contaminants held responsible for global warming and on-going climate change. The major GHG is carbon dioxide (CO_2), much of which is generated by man's activities. Soils are an important source of CO_2, which is released both during microbial decomposition of organic remains and by respiration of below-ground plant tissues and soil fauna. Most mineral soils contain low amounts of organic C and the CO_2 emitted is generally regarded as part of a balanced recycling process resulting from decomposition of plant litter and animal waste. By contrast, the C content of peat soil can often exceed 50% and is vulnerable to loss by the oxidation that is initiated following drainage. This loss of organic C contributes to peat subsidence; other causes being predominantly drainage-induced consolidation, mechanical compaction and, to a lesser extent, shrinkage due to drying. In the oil palm plantation, mechanical

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compaction is generally imposed prior to planting to increase the bulk density of the peat, which aids the movement of machines and the establishment of newly planted palms. Both C loss and subsidence are continuous processes but tend to diminish gradually over time.

Two other GHGs of importance in agricultural and natural ecosystems are methane (CH_4) and nitrous oxide (N_2O). Compared with CO_2, both are appreciably more effective in promoting global temperature rise, as indicated by their global warming potential (GWP) which is *c*. 25 and 298 times that of CO_2, respectively (IPCC, 2007). However, despite this, the GHG exchange of reclaimed peatland in terms of GWP remains dominated by CO_2 release.

In this article, we examine the data on the GHG exchange between peat soils and the atmosphere, and the effects on this exchange arising from land conversion and management practices. Some priorities for further research are identified.

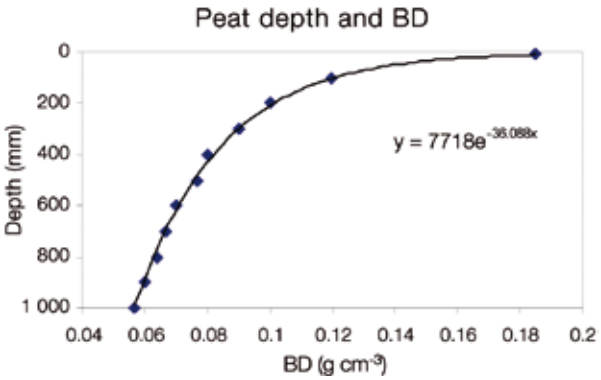

Figure 1. Relationship between peat depth and bulk density (BD) derived from data of Salmah et al. *(1992).*

PHYSICAL ASPECTS

Subsidence

Subsidence is the most obvious consequence of draining peatland, and is an important parameter for the long-term assessment of C loss. However, rates vary and are likely to be affected by several factors, such as the depth of the peat, the depth of drainage, peat structure, initial bulk density and time. Data are still quite limited and some of the relationships observed previously [*e.g.* Welch and Mohd Adnan (1989); Henson *et al.* (2002); Hasnol (2004); Hasnol *et al*. (2009)] are in need of confirmation by further studies.

Subsidence is best measured using vertically-installed high density polyethylene pipes, the bases of which need to be firmly embedded into the underlying mineral soil. At the same time, peat depth, type and structure can be recorded. Initially upon drainage, monthly readings should be taken, but after the first two years following drainage, when the rate of subsidence has slowed down (*e.g*. Hasnol *et al*., 2009), annual readings will probably prove sufficient. The number and location of the subsidence pegs will be determined to a large extent by the topography and area of the site. Measurement of subsidence is rendered difficult by the often irregular micro-topography (presence of hummocks and hollows) of the peat surface (Melling and Hatano, 2002).

Bulk Density

Bulk density (BD) measurements theoretically allow for the settling or compaction of peat that takes place after drainage, either under its own weight or as a result of mechanical pressure aimed at increasing BD to facilitate the movement of labour and equipment and to promote better establishment of newly planted palms. Undisturbed peat has a BD of around 0.10-0.15 g cm^{-3}, which can increase to 0.20 g cm^{-3} after mechanical compaction. Generally samples are taken only from the top 30 cm or so of the peat profile, but as shown in *Figure 1*, BD changes with depth (Salmah *et al*., 1992; Kool *et al*., 2006), so near-surface samples are not necessarily representative of the whole peat profile. There may also be spatial variation. Thus, BD has to be carefully assessed.

CO_2 EMISSION

CO_2 is normally emitted from all types of soil as part of the process of C recycling, whereby organic matter originating largely from plant debris, is broken down in the presence of water and oxygen by soil micro-organisms. This microbial oxidation is augmented by the CO_2 released in the respiration of plant roots, other below-ground plant parts and soil fauna. The combined efflux is usually referred to as soil respiration. Microbial oxidation is inhibited by anaerobic conditions resulting in organic matter build up to form peat. When peat soils are aerated the oxidation processes initiated result in an increased release of CO_2. This augments other processes in contributing to peat subsidence.

There are two main methods available for measuring peat C loss and thus CO_2 emission. One is a long-term approach based on soil measurements made over several years, referred to here as the stock change method, while the other involves short-term direct measurements of gas flux that allow quite rapid assessment. A combination of the two methods is often the best.

TABLE 1. EXAMPLES OF PEAT SUBSIDENCE AND THE FRACTION OF SUBSIDENCE DUE TO PEAT OXIDATION

Reference	Location	Number of years recorded	Mean subsidence rate (cm yr^{-1})	Fraction of subsidence due to oxidation
Kyuma *et al*. (1992)	Johor	-	2.5	72[1]
Murayama and Zahari (1996)	Selangor	-	3.0	52[2]
Wösten *et al.* (1997)	Johor	9	2.0	60[3]
Henson *et al.* (2002)	Perak	17	7.3	51[2]
	Johor	20	7.9	55[2]
		13	8.9	37[2]
Hasnol (2004)	Sarawak	10	7.0	56[2]
Kool *et al.* (2006)	Kalimantan	6	55.8	7.4[1]

Note: [1]calculated from comparison of different sites.
[2]Calculated using the equation of Murayama *et al*. (1992).
[3]Estimated using the POXAPS model.

Carbon Stock Change

The loss of C as CO_2 from peat can be calculated if the change in total C in an area over time is known. This is derived as:

$$[(V \times BD \times \%C)_{t1}] - [(V \times BD \times \%C)_{t2}]$$

where V is peat volume (m^3),
BD is mean bulk density (g cm^{-3}),
%C is mean percentage of C in the peat, and
$_{t1}$ and $_{t2}$ refer to the time of the initial and final measurements respectively.

The C content of peat can be obtained using standard laboratory techniques and normally ranges from 35% to 60% on a dry weight basis. A change in volume will be reflected as a change in peat depth due to subsidence. Mean BD should be used, since as already noted the BD can change with depth (Salmah *et al*., 1992; Kool *et al*., 2006) and surface samples will hence be unrepresentative. If mean values are not available, equations developed by Salmah *et al.* (*loc. cit*.) can be used as was done by Wösten *et al*. (1997).

An alternative approach is to derive C and thus CO_2 flux as the product of BD × %C × OxF, where OxF is the fraction of peat subsidence due to C loss by microbial oxidation. Kyuma *et al*. (1992) calculated OxF from comparative measurements of instantaneous CO_2 flux made in peat forest and bare peat sites assuming 40% of the flux from the former originated as root respiration and that %C was 50%. The value for OxF arrived at was nearly 72%. Murayama *et al*. (1992) developed an empirical equation that can be used to predict subsidence due to C loss from measurements of CO_2 flux, BD and C content. The percentage of subsidence due to oxidation can then be calculated knowing the total subsidence. This approach has since been applied to a number of sites (*Table 1*). Wösten *et al*. (1997), using the POXAPS model, arrived at an OxF value of 60%.

A notable exception to the generally high OxF values in *Table 1* is the very small contribution of C loss due to subsidence measured by Kool *et al*. (2006). However, C loss was not directly measured in that study but was inferred from ash and electrical conductivity (EC) measurements. There was a large range in the estimated flux depending on the underlying assumptions. The large contribution to subsidence in this study due to physical compaction may have its origins in the 'loose' structure of the peat domes and in drainage of water-filled 'vacant layers'.

The oxidation fraction is very likely to change as peat settles, being low initially (when most of the subsidence is due to consolidation) and then gradually increasing. However, this suggestion needs to be confirmed. Less contentious is the fact that the rate of subsidence decreases over time (Wösten *et al.,* 1997; Lim, 2005; 2007; Hasnol *et al*., 2009).

Assessing changes in the C stock of peat soils is necessarily a long-term procedure that involves measuring subsidence and changes in C content and BD over several years. Much care is therefore required to ensure valid data. The advantages of the C stock change method are that it gives a time-averaged rate of loss that automatically takes into account daily and seasonal variations in hydrology and climate, while (and just as important), it measures only the C loss from the peat substrate and does not include root respiratory losses.

Some examples of annual rates of C emission calculated from carbon stock change and other methods are given in *Table 2*.

TABLE 2. CO_2 EMISSION FROM PEAT SOILS FOLLOWING DRAINAGE

Reference	Location	Number of years recorded	Mean rate of emission (t CO_2 ha^{-1} yr^{-1})	Notes
a) C emission calculated from carbon stock change				
Wösten *et al.* (1997)	Johor	9	26.4	From 28 to 37 years after draining. Mixed cropping.
Henson *et al.* (2002)	Perak	17	65.3	Oil palm fields.
	Johor	20	60.9	
		13	46.9	
		9	58.7	
Hasnol (2004)	Sarawak	10	89.8	%C and OxF taken as 50%.
b) C emission calculated from gaseous flux measurments[1]				
Kyuma *et al.* (1992)	Johor	-	77.0	Bare fields.
Murayama and Zahari (1996)	Selangor	-	22.4	
Taylor and Ali (2001)	Sumatra	-	87.0	Drained, cleared, cropped land *c.* 4 years after clearing.
Inubushi *et al.* (2003)	Kalimantan	-	56.5	Abandoned rice fields.
Zulkefli *et al.* (2003)	Sarawak	-	25.5	Eight months after felling and burning.
Jauhiainen *et al.* (2004)	Kalimantan	-	19.3	Drained, cleared, cropped land *c.* 7 years after clearing.
Melling *et al.* (2004; 2005a)	Sarawak	-	56.5	Oil palm plantation, 4-5 years after planting.
Agus (2007)	Indonesia	-	27.0 to 39.3	Annual crops with water table at 30 cm.
Melling *et al.* (2007a)	Sarawak	-	33.6	Oil palm plantation, 4-5 years after planting. Data exclude root respiration.
Setyanto and Susilawati (2008)	Indonesia	-	36.5	Oil palm plantations, means of two daily sampling times and four ages of crop.
c) C emission calculated from ash and EC measurments				
Kool *et al.* (2006)	Kalimantan	6	75.1	EC measurements. Median estimate.

Note: [1]a more detailed and extensive listing is provided by Hooijer *et al.* (2006).

Gas Flux Measurements

An alternative to measuring long-term changes in total organic C is to directly monitor gas exchanges taking place between the soil surface and the atmosphere. This can be done in several ways, the most common being to trap gas released from the soil surface in inverted containers. Gas samples are then either collected in syringes for later laboratory analysis or, in the case of CO_2, may be diverted through portable infra-red gas analysers connected to the chambers, a method that allows concentration changes to be measured *in situ*. Another technique for CO_2 is to use absorbents such as KOH and soda lime that trap the gas. Using this method the containers can be left in place for a whole day and so effectively take into account diurnal variations in temperature and other factors. Otherwise, the use of chambers involves problems of representative sampling, not only in time (as sampling periods are generally brief) but also in space, as both the areas of soil and volume of gases sampled are small.

Chamber methods lend themselves to site and treatment comparisons and measure fluxes directly at the soil surface. There are currently several commercially produced chambers, the most elaborate of which can be set to automatically sample a number of adjacent locations over time. When using closed chambers care has to be taken to avoid distortion of natural flux rates due to failure to maintain normal atmospheric pressure within the chamber. Excess pressure will inhibit flux while insufficient pressure may promote it.

An alternative to using closed chambers for CO_2 is to use open-path sensors capable of detecting rapid changes in CO_2 concentrations above the soil surface. The currently most favoured technique is that of eddy correlation but, as with other micrometeorological methods, this requires large, uniform and generally flat sites and the equipment is expensive to install and to operate. Open path

sensors do not inherently discriminate between different sources of a gas nor do they sample a clearly defined area. Their main advantage is in providing continuous, long-term results on a landscape scale that permit correlations between fluxes and atmospheric conditions to be closely investigated.

An important consideration with CO_2 chamber studies is the source of the gas being measured. This normally originates from two main sources: microbial respiration (MR) associated with decomposition of soil organic matter, and respiration of below-ground living tissues, mainly plant roots. The latter represents recycling of some of the C fixed in photosynthesis. MR represents decay of soil organic matter, which if not replenished, leads to its decline. Measurements of total efflux do not distinguish between these and failure to do so can result in erroneous conclusions regarding the significance of the flux. A way to resolve this problem is to compare undisturbed soil containing roots with root-free soil. To obtain the latter, a fallow field can be used (*e.g*. Kyuma *et al*., 1992; Murayama and Zahari, 1996) or roots can be either physically separated from the soil (Henson, 1994; Lamade *et al*., 1996), or excised *in situ* by inserting an open ended chamber into the soil, with the severed roots then being allowed time to die and decay before measurements commence (Melling *et al*., 2007a). The latter method involves the least disturbance but there will be some uncertainty as to whether root decay is complete when measurements of gas flux are subsequently made. Unfortunately, while CO_2 flux from peat soils has been the subject of several studies (*Table 2*), there have been few attempts to isolate MR and to determine the relative contributions of microbial and root respiration. Apart from the studies of Kuyuma *et al.* (1992) and Murayama and Zahari (1996), which used bare plots, and Melling *et al*. (2007a) that measured areas after root excision, the remaining flux studies are likely to have included significant contributions from root respiration. The relative contribution of roots to the total flux would be expected to differ between peat and mineral soils, and the few measurements made in oil palm plantations (*Table 3*) tend to bear this out.

Much interest has centred on the effect of peat development (*i.e.* clearing of forest, drainage, planting) on CO_2 flux. Comparisons between forested and deforested sites have yielded mixed results (*Table 4*). In five of the nine cases examined,

TABLE 3. SOIL CO_2 EMISSION IN OIL PALM PLANTATIONS PARTITIONED BETWEEN ROOT AND MICROBIAL RESPIRATION

Study	Location	Soil	Palm age (year)	Root respiration (RR)	Microbial respiration (MR)	MR/RR
				t CO_2 ha^{-1} yr^{-1}		
Henson (1994)	Selangor	Coastal clay	9	16.2	13.1	0.81
Lamade *et al*. (1996)	Benin	Ferralsol	20	39.6	17.5[1]	0.44
Melling *et al*. (2005a; 2007a)	Sarawak	Deep peat	4 to 5	22.9[1]	33.6	1.47

Note: [1]calculated by difference.

TABLE 4. TOTAL SOIL CO_2 EMISSION FROM FORESTED AND DEFORESTED PEAT SOILS[1]

Study	Location	CO_2 emission(t ha^{-1} yr^{-1})		Notes	
		Forested	Deforested	Forested	Deforested
Kyuma *et al*. (1992)	Johor	42.2	77.0	Partly drained.	Bare soil.
Murayama and Zahari (1996)	Selangor	38.9	54.4	Primary forest.	Planted with oil palm.
Abdul Hadi *et al*. (2001)[2]	Kalimantan	45.0	74.0	Logged, undrained.	Rice-soyabean.
Inubushi *et al.* (2003)	Kalimantan	44.0	56.5	Logged.	Abandoned rice fields.
Jauhiainen *et al*. (2004)	Kalimantan	40.0	19.3	Logged.	Mixed cropped land *c*. 7 years after clearing.
Furukawa *et al.* (2005)[2]	Sumatra	86.0	64.0	Drained.	Planted with cassava.
Melling *et al.* (2005a)	Sarawak	78.1	56.5	Partly drained.	Planted with oil palm.
Ali *et al*. (2006)[2]	Sumatra	36.0	62.0	Logged.	Recently burnt and cleared.
Setyanto and Susilawati (2008)	Indonesia	34.8	27.06	'Natural' peat forest – mean of 2 samplings.	Newly cleared peat forest – mean of 2 samplings.

Note: [1]carbon fluxes were measured using the chamber method. [2]Quoted by Hooijer *et al*. (2006).

CO_2 emission was greater in deforested sites. Again, there is the need to take account of the lack of discrimination in measurements between microbial and root respiration and also the varied nature, especially the drainage conditions, of the sites sampled.

Dissolved Organic Carbon

Dissolved organic carbon (DOC) provides another route whereby C may be lost from the ecosystem. DOC enters waterways and can later be liberated by microbial activity from the water as CO_2. Increasing losses of C as DOC have been observed in temperate peatlands and are thought to be an indirect consequence of increased atmospheric CO_2 levels (New Scientist, 2004), thus providing a formidable example of positive feedback. The importance of this pathway for tropical peatlands has yet to be established. Hanafi *et al*. (2007) found little difference in DOC levels in aqueous extracts of peat samples taken from forest, sago and oil palm sites, although their degree of humification, as shown by sodium pyrophosphate solubility, varied quite markedly.

Correlation of CO_2 Flux with Other Factors

Murayama and Zahari (1996) found CO_2 flux to be significantly and positively related to peat soil pH and to ash content, hence, the use of the latter by Kool *et al.* (2006) as an indicator of C loss. Thus, liming of peat may accelerate its decomposition. Maintaining a high water table would generally reduce both oxidation and subsidence.

CH_4 AND N_2O FLUXES

Exchanges of CH_4 and N_2O between the soil and atmosphere are normally determined by collecting gas samples from closed chambers followed by analysis using gas chromatography. Unlike CO_2, CH_4 and N_2O are not generally recycled and their origins are of less importance when evaluating their impact on global warming.

CH_4

While the possibility of CH_4 being aerobically generated by higher plant tissues has recently been raised (Keppler *et al*., 2006; Wang *et al*., 2007), it is generally regarded as a product of anaerobic metabolism and of microbial origin. As such, its emission might be expected to decrease in drained, compared with undrained, peat. Indeed, studies have shown that drained peat often acts as a sink, rather than a source, of CH_4. This serves to offset the emission of CO_2, although because of the very small amounts of CH_4 involved, the effects are small. *Table 5* gives data on CH_4 fluxes in terms of CO_2 equivalents. There are some large differences between the results from different studies, pointing to the need for further investigations.

In addition to measuring soil surface fluxes of CH_4, the production of the gas below the soil surface has also been examined (Inubushi *et al.*, 1998; Melling *et al*., 2005b). Substantially larger quantities of CH_4 are often present in deep, less aerobic peat layers than nearer the surface. It may, therefore, be worthwhile to ascertain whether methane is released when peat is disturbed by such activities as land clearing, stump removal, construction of drains and levelling. Another possible source of CH_4, yet to be quantified, is from the water in drainage canals.

Fertiliser application can also affect CH_4 flux. Melling *et al.* (2006) examined the effects of two urea applications on CH_4 flux from peat under oil palm. Applying urea resulted in a positive CH_4 flux on both occasions in contrast to the negative flux (uptake) found in the months preceding application. This effect is thought to be due to an increase in soil NH_4^+ inhibiting CH_4 oxidation during its conversion to NO_3^-. It is suggested that by splitting the application of urea, total CH_4 emission should be reduced.

TABLE 5. CH_4-CO_2eq. EXCHANGES BETWEEN PEAT SOILS AND THE ATMOSPHERE[1]

Study	Location	CH_4 flux (kg CO_2eq ha^{-1} yr^{-1})		Notes	
		Forested	Deforested	Forested	Deforested
Inubushi *et al.* (1998)	Sarawak	0.275	0.344	Logged	Planted with sago.
Inubushi *et al.* (2003)	Kalimantan	0.400	0.633	Logged	Abandoned rice fields.
Jauhiainen *et al*. (2004)	Kalimantan	325.0	30.0	Logged	Mixed cropped land c. 7 years after clearing.
Melling *et al.* (2005b)	Sarawak	6.11	-5.11	Partly drained	Planted with oil palm.
		-	59.9	-	Planted with sago.

Note: [1]a positive flux indicates emission to air; a negative flux, uptake by soil. CO_2eq. was calculated assuming a GWP for CH_4 of 25 (IPCC, 2007).

TABLE 6. N_2O-CO_2eq. FLUXES BETWEEN PEAT SOILS AND THE ATMOSPHERE[1]

Study	Location	N_2O flux (kg CO_2eq ha^{-1} yr^{-1})		Notes	
		Forested	Deforested	Forested	Deforested
Inubushi *et al.* (2003)	Kalimantan	-239	-173	Logged.	Abandoned rice fields.
Melling *et al.* (2007b)	Sarawak	344	554	Partly drained.	Planted with oil palm.
		-	1571	-	Planted with sago.
Couwenberg *et al.* (2009)	Southeast Asia	1609	328	Drained and undrained agro-forest.	Drained, abandoned, unfertilised.

Note: [1]a positive flux indicates emission to air; a negative flux, uptake by soil. CO_2eq was calculated assuming a GWP of 298 (IPCC, 2007).

N_2O

The N_2O production is similarly promoted by poorly drained soil and like CH_4, any reduction arising from drainage risks being offset by increases due to the use of nitrogen fertilisers. As shown in *Table 6* measurements of N_2O flux are sparse and contradictory. Inubushi *et al*. (2003) found that both peat forest and peat cleared for agriculture and later abandoned, acted as N_2O sinks while Melling *et al*. (2007b) and Couwenberg *et al.* (2009) report the opposite. In both the latter studies nitrogen fertiliser application to oil palm resulted in increased N_2O emissions. Emissions from fertilised and drained agricultural land reported by Couwenberg *et al.* (2009) range from 3.3 to over 120 t CO_2eq. ha^{-1} yr^{-1}. In view of its high GWP, this considerable variation in rates of N_2O emission warrants further study.

CONCLUSIONS AND RECOMMENDATIONS

From the relatively sparse data presented it is evident that much remains to be done to quantify GHG emissions from tropical peat soils as well as the effect of developing tropical peatlands for agriculture on such emissions. In particular there is a need to resolve the following:

- the extent to which the processes of oxidation, consolidation, mechanical compaction and shrinkage contribute to peat subsidence. In particular we need to know the extent to which these components change over time, especially during the initial stages after drainage. If these components could be estimated more precisely, this would allow C loss to be much more easily determined;
- the relative contributions to the surface CO_2 flux by microbial oxidation, root respiration and other processes. This is needed to allow for meaningful comparisons to be made of C emissions and peat C loss at different sites with different vegetation cover;
- the extent and form by which subsidence, C loss and drainage depth are related. This is still a matter of conjecture, pointing to the need for more accurate and longer term studies; and
- the minimum drainage requirements needed for successful oil palm cultivation and ways of achieving these so as to reduce subsidence and peat oxidation. Knowing this, plantations could be managed with the aim of both extending peat life and minimising impacts on global warming.

Regarding the last point, it seems that there is likely to be an optimum depth of water table for maximising fresh fruit bunch yield of oil palm as found by Gurmit (2004) and Lim (2005). However, controlling the water table is not easy, especially in high rainfall areas such as are found in Sarawak.

From the measurements made thus far it seems that despite their high GWP, the contributions of CH_4 and N_2O to total GHG fluxes are small (Melling *et al*., 2004). However, there have been relatively few measurements and the variability of the data has been high. More effort is thus required to obtain more comprehensive and reliable information.

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