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Soil carbon dynamics under oil palm plantations

*Submitted for Doctorate of Philosophy
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Statement of the contribution of others

Nature of assistance	Contributors	Relevant section
Intellectual support	Dr Paul Nelson	Supervisor and co-author of all papers
	Dr Michael Bird	Supervisor and co-author of papers 1 and 2
	Dr Chris Wurster	Co-author paper 1
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- Goodrick, I., Nelson, P.N., Banabas, M., Wurster, C.M., and Bird, M.I. (2015) [Soil carbon balance following conversion of grassland to oil palm](#). *GCB Bioenergy*, 7 (2). pp. 263-272.

During the course of my candidature I contributed to several papers that were related to the work of the thesis but are not part of it:

- Nelson, P.N., Huth, M.I., Banabas, M., Webb, M.J., and Goodrick, I. (2016) [Ciclos de carbono y nitrógeno en plantaciones de palma de aceite: claves para la productividad y la sostenibilidad / Carbon and nitrogen cycling in oil palm plantations: the keys to yield and sustainability](#). *Revista Palmas*, 37 (1). pp. 214-224.
- Nelson, P.N., Banabas, M., Goodrick, I., Webb, M.J., Huth, N.I., and O'Grady, D. (2015) [Soil sampling in oil palm plantations: a practical design that accounts for lateral variability at the tree scale](#). *Plant and Soil*, 394 (1-2). pp. 421-429.
- Nelson, P.N., Webb, M.J., Banabas, M., Nake, S., Goodrick, I., Gordon, J., O'Grady, D., and Dubos, B. (2014) [Methods to account for tree-scale variability in soil- and plant-related parameters in oil palm plantations](#). *Plant and Soil*, 374 (1-2). pp. 459-471.
- Nelson, P.N., Banabas, M., Nake, S., Goodrick, I., Webb, M.J., and Gabriel, E. (2014) [Soil fertility changes following conversion of grassland to oil palm](#). *Soil Research*, 52 (7). pp. 698-705.

During the course of my candidature I also contributed to several other research projects on carbon cycling in tropical ecosystems, leading to the publications below.

- Goodrick, I., Connor, S., Bird, M.I., and Nelson, P.N. (2016) [Emission of CO₂ from tropical riparian forest soil is controlled by soil temperature, soil water content and depth to water table](#). *Soil Research*, 54 (3). pp. 311-320.
- Saiz, G., Wynn, J.G., Wurster, C.M., Goodrick, I., Nelson, P.N., and Bird, M.I. (2015) [Pyrogenic carbon from tropical savanna burning: production and stable isotope composition](#). *Biogeosciences*, 12. pp. 1849-1863.
- Saiz, G., Goodrick, I., Wurster, C.M., Zimmermann, M., Nelson, P.N., and Bird, M.I. (2014) [Charcoal re-combustion efficiency in tropical savannas](#). *Geoderma*, 219-220. pp. 40-45.
- Wurster, C.M., Lloyd, J., Goodrick, I., Saiz, G., and Bird, M.I. (2012) [Quantifying the abundance and stable isotope composition of pyrogenic carbon using](#)

[*hydrogen pyrolysis*](#). Rapid Communications in Mass Spectrometry, 26 (23). pp. 2690-2696

- Zimmermann, M., Bird, M.I., Wurster, C., Saiz, G., Goodrick, I., Barta, J., Capek, P., Santruckova, H. and Smernik, R. (2012) [*Rapid degradation of pyrogenic carbon*](#). Global Change Biology, 18 (11). pp. 3306-3316.

Abstract

Oil palm crops are expanding rapidly in the tropics, with implications for the global carbon cycle. Understanding the carbon dynamics of oil palm is important for maximising organic matter content of soils and minimising greenhouse gas emissions of plantations. In a series of laboratory and field experiments the nature of the oil palm carbon cycle is described for a group of plantations in Papua New Guinea.

In this work, oil palm soil organic carbon (SOC) stocks were found to be highly stable and SOC stocks and input/output fluxes were highly spatially variable. Where oil palm was planted on former grassland, unplanted areas of grassland and oil palm had average SOC stocks of 10.7 and 12.0 kg m⁻² respectively to a depth of 1.5 m. In the 0–0.05 m depth interval, 0.79 kg m⁻² of SOC was gained from oil palm inputs over 25 years and approximately the same amount of the original grass-derived SOC was lost. For the whole soil profile (0–1.5 m), 3.4 kg m⁻² of SOC was gained from oil palm inputs, with no significant losses of grass-derived SOC. The grass-derived SOC stocks were more resistant to mineralisation than reported in other studies. Black carbon produced in grassfires could partially but not fully account for the persistence of the original SOC stocks. Oil palm-derived SOC accumulated more slowly where soil nitrogen contents were high. Forest soils in the same region had smaller carbon stocks than the grasslands. In the majority of cases, conversion of grassland to oil palm plantations in this region resulted in net sequestration of soil organic carbon.

Tree-scale spatial distribution of soil carbon inputs and outputs in a mature oil palm plantation were spatially correlated at the tree scale (r^2 0.605), with a slope of 1:1. However, outputs were higher than inputs at all locations, with a mean overall output of 7.25 and input of 3.01 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Frond-, root- and groundcover-related inputs constituted 60, 36 and 4% of estimated inputs, respectively so frond inputs mainly controlled the spatial variability. The spatial correlation of carbon inputs and outputs suggests that mineralisation rate is controlled by the amount rather than nature or input depth of the additions. A spatially uniform net carbon loss was attributed to errors in root-related input estimates.

The laboratory study confirmed that carbon turnover for oil palm soils was slow, 6% of the soil carbon was mineralised over the first year of incubation. Fourier transform infrared spectroscopy revealed that fractions described in literature as resistant to decay contained more lignin or other aromatic carbon forms than labile fractions. Biochemical recalcitrance and physico-chemical protection controlled turnover rates of intermediate stability organic carbon and protection appeared to be related to interactions between organic matter and poorly crystalline Al and Fe oxides.

These findings help in understanding of the pathways and rates of carbon cycling in oil palm systems.

Table of Contents

1. Introduction	1
1.1 Literature review	1
1.2 Terms and scope of research.....	6
1.3 Current situation and research gaps	6
1.4 Importance of the proposed research.....	7
1.5 Research questions	8
1.6 Research objectives.....	8
2. Soil carbon balance following conversion of grassland to oil palm.....	9
2.1 Introduction	9
2.2 Materials and Methods.....	11
2.3 Results.....	15
2.4 Discussion	24
2.5 Summary	27
3. Tree-scale spatial variability of soil carbon cycling in a mature oil palm plantation.....	29
3.1 Introduction	29
3.2 Methods	31
3.3 Results.....	35
3.4 Discussion	42
3.5 Conclusions	47
3.6 Summary	47
4. Mineralisation of soil organic carbon in two Andisols under oil palm: an incubation study into controlling factors	48
4.1 Introduction	48
4.2 Methods	50
4.3 Results.....	54
4.4 Discussion	62
4.5 Summary	64
5. Conclusions	66
6. References.....	68

Tables

Table 1: Reported CO ₂ emission rates from oil palm plantation soils.....	4
Table 2: Soil organic carbon (SOC) stocks to 1.5 m depth. Asterisks indicate sites used in chronosequence study (CS).....	16
Table 3: Black carbon stocks in grassland and oil palm soil at Site 1. Asterisk indicates sample not measured. 'OP BZ' is between zones area in oil palm block and 'OP FP' is frond pile area.....	17
Table 4: Soil CO ₂ emission rates by season and zones of plantation.	40
Table 5: Calculated rates of carbon inputs to soil.....	41
Table 6: Correlation analysis between CO ₂ emission rates and measured variables. n=35.....	41
Table 7: Comparison of CO ₂ emission rates calculated in other studies on mineral soils.	43
Table 8: Soil properties at the start of the incubation.....	52
Table 9: Correlation matrix (Pearson coefficients) of measured parameters. Significant correlations (p<0.05) are bold and underlined.	55

Figures

Figure 1: Study area, showing locations of sampling sites, overlying a) aerial photos taken in 1953 (light grey areas are grassland and dark grey areas are forest) and b) vegetation cover in 2011 (map produced by EOWORLD for the World Bank).	12
Figure 2: Mean soil organic carbon content for each vegetation type and oil palm management zones at all 16 sites.	17
Figure 3: Mean and standard deviation (error bars) of soil bulk density for all vegetation types and zones across all 16 sites. There were no significant differences between vegetation types.....	18
Figure 4: Change in soil organic carbon (SOC) stocks since oil palm planting (ie. SOC stock under oil palm minus SOC stock under adjacent grassland). The regression of change in SOC stock with time since planting was not statistically significant (r=0.61, p=0.25).....	19
Figure 5: Isotopic composition of soil organic carbon ($\delta^{13}\text{C}$) for all 16 sites. Asterixes show the sites used in the chronosequence study.	21
Figure 6: Proportion of SOC derived from grassland and oil palm inputs (left) and total SOC stocks derived from each input (right) as a function of time from planting, for three depth intervals: 0-0.05 (top), 0-0.2 (middle) and	

0-1.5 m (bottom). Points are data and lines are fitted curves (Equation 3), shown only where r^2 was >0.3 . Site 7 was excluded from the regressions for the 0-1.5m depths due to its anomalous $\delta^{13}\text{C}$ values at depth (see Figure 4).....	22
Figure 7: Relationship between soil nitrogen content and rate of SOC accumulation from oil palm for 0 - 0.05m depth interval. The Y-axis values are calculated as the modeled SOC derived from oil palm minus the measured SOC derived from oil palm for each site. Positive values indicate the modeled proportion of SOC from oil palm was lower than the measured proportion of SOC from oil palm. A linear regression ($y=46.52-18.34*x$, $r^2=0.59$) was performed.....	23
Figure 8: Rainfall at the study site. Monthly rainfall is shown for the whole of 2012 (left-hand panel) and daily rainfall is shown for the week of sampling (in May and November) and preceding week (right-hand panel).....	33
Figure 9: Root density (dry weight to 2m depth), showing mean (n=4) and standard error. The palm trunk is at the centre of the left side of the trapezoid, frond pile is in the lower area, harvest path is in the upper area, and the white dots are the measurement locations.....	36
Figure 10: Soil volumetric water content (0-0.12 m depth), showing mean (n=16) and standard error. The palm trunk is at the centre of the left side of the trapezoid, frond pile is in the lower area, harvest path is in the upper area, and the white dots are the measurement locations.....	37
Figure 11: Soil CO ₂ emission, showing mean (n=16) and standard error. The palm trunk is at the centre of the left side of the trapezoid, frond pile is in the lower area, harvest path is in the upper area, and the white dots are the measurement locations.	38
Figure 12: Effect of the number of measurement points on the mean calculated CO ₂ emission rate, expressed as deviation from the value calculated using all measurement points, for the whole grid, between zones area, frond piles and weeded circles.	38
Figure 13: Average soil CO ₂ emission (hollow data points) and soil temperature at 0-0.12 m depth (black data points) over the course of a day in May (n=6, 2 points from each zone) repeated every half hour. Error bars are the standard deviation from the mean.	39
Figure 14: Relationship between carbon inputs to soil and outputs from soil, at each point of the sampling grid. Black data points and solid black line indicate carbon inputs, including fronds, root turnover and ground cover. Hollow data points and dashed line indicate carbon inputs including fronds, root turnover, root maintenance, root growth and ground covers. Dotted line shows a 1:1 relationship.....	40
Figure 15: Mean turnover rate of carbon (\pm SE) in the soils over the course of the incubation, with power functions fitted.	57

Figure 16: Mean soil carbon content (\pm SE) at the start and end of the incubation.	
	58
Figure 17: Relationship between carbon turnover rate and the pre-incubation ratio of potassium permanganate-oxidisable carbon (POC) to total carbon (TC), at two times during the incubation.	59
Figure 18: Relationship between carbon turnover rate and the pre-incubation ratio of acid oxalate-extractable Al (Alox) to total carbon (TC), at two times during the incubation.	60
Figure 19: Relationship between mean carbon turnover rate and temperature sensitivity of mineralisation (Q10) at days 379 and 812 of the incubation, with error bars showing the SE of turnover rate. Closed symbols are 0-5 cm depth, open symbols are 15-20 cm depth, circles are from between zones (BZ) and triangles are from frond pile (FP). Dashed line shows the overall linear regression.	61
Figure 20: FTIR spectra of pre-incubation soils (0-5 cm depth, mean of 4 replicates).....	62

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1. Introduction

Organic matter is an important determinant of soil quality. Soil organic matter content has been shown to exert control over nutrient holding capacity, water potential, pH, and soil structure (Reeves 1997). Interest in soil organic matter has increased as the role of soil carbon cycling in global carbon fluxes became an important question. Understanding the pathways and rates of carbon fluxes in various ecosystems and agricultural systems is now important for predicting how changes to ecosystems will change global carbon cycling.

Oil palm is an important food crop, particularly in south-east Asia where it is a major export commodity for a number of nations. Oil palm crops cover more than 16 million ha and the area is expanding at a rate of around 400 000 ha yr⁻¹ (FAOSTAT, 2013). Interest in oil palm carbon cycling was propelled in particular by the association between oil palm and greenhouse gas emissions from tropical forest clearing, important because these forests are recognized as the stores of 36–60% of ecosystem carbon (Dixon & Solomon, 1994; Butler & Koh, 2009). This means the growth of oil palm production has important implications for global carbon cycles and interest in greenhouse gas budgets for oil palm plantations (Gibbs *et al.*, 2008; Ziegler *et al.*, 2012). Greenhouse gas budgets for palm oil production so far have had to use incomplete information on carbon fluxes in plantations. This encouraged more research into carbon fluxes in oil palm plantations.

1.1 Literature review

The literature on carbon cycling in oil palm plantations can be categorised by the routes of carbon movement they investigate. The main categories are; total carbon budgets for oil palm systems, the emission of CO₂ from soils, changes in soil carbon stocks, characterisations of soil related to organic matter such as microbial activity and carbon budgeting for the lifecycle of palm oil production.

General oil palm research and carbon budgets

There is a range of general soil carbon research and carbon budgets for oil palm systems. General research of soil carbon in oil palm systems typically investigates relationships between organic matter and soil fertility. Additional work on the greenhouse gas implications of oil palm plantations required information of soil carbon stocks. Published greenhouse gas budgets for oil palm began appearing in the last 10 years. One complete greenhouse gas balance evaluated the total carbon balance of oil palm production on various land types

(Germer and Sauerborn 2006). In that study above-ground carbon storage change was interpreted from a number of studies of biomass of oil palm and other vegetation types, however below-ground changes were derived from general studies of carbon cycling neither specific to tropical soils or agroforestry. Another carbon budget of oil palm, this time comparing the biofuel potential of oil palm to other crop types was also able to give specific information of aboveground carbon changes in plantations but only able to estimate below-ground changes from general methodologies (Gibbs *et al.* 2008). The methodology used by both these budgets is derived from the IPCC Good Practice Guidance methodology (IPCC 2006). This methodology is a general system for estimating soil carbon changes but is lacking evidence from tropical soils and agroforestry, making it useful for estimating carbon changes in cropping but inexact for oil palm plantations. More recently, Chase and Henson (2010) modelled carbon flow through oil palm production and attempted to calculate the rate of carbon flow along each pathway. That study noted an important lack of information on changes in soil carbon during land use change and through the life of the plantation. The conclusions of these carbon budget papers for oil palm plantations illustrate the limits of understanding of soil carbon cycling.

Carbon dioxide emissions

The earliest investigation of CO₂ emissions from oil palm soils was a study from Benin (Lamade *et al.* 1996). Emissions were measured in the field and from root-free soils in the laboratory, to determine emission rates and the contribution of roots to total soil emissions. The study recognised the wide spatial variability in palm plantations, created by management practices, where emissions are high in the areas near to the palm trunks and piled fronds and low in other areas. The sampling methodology used by Lamade *et al.* (1996) accounted for zones of different CO₂ emissions in plantations but equipment limitations prevented many replicates. An estimate of total emissions was made and the contributions of roots was calculated at 20-80% for frond piles and 75% for areas other than frond piles and palm trunks. Although all zones of the plantation were included in the study to illustrate spatial variability, the methodology did not attempt to quantify the areas of these zones in order to allow the calculation of the total plantation CO₂ emission rate.

Two similar studies aiming to compare land use types in Indonesia calculated emissions from oil palm from 3 and 21 observations respectively (Ishizuka *et al.* 2002, Ishizuka *et al.* 2005). These studies were unable to assess variation in space or time, but provided a value for emissions in plantations at a particular point in time and space. The previously mentioned studies dealt with mineral soils, but emissions from peat soils in Malaysia have also been investigated (Melling *et al.* 2005). That study was a comparison of four-year-old oil palm

plantations with other forest types, which measured oil palm soil CO₂ emissions and made comparisons to forests on peat soils. In addition, the study identified that soil water-filled pore space and bulk density were the strongest predictors of emission rates. However, the factors identified as predictors of emission rates are likely specific to peat soils, and emissions from mineral soil are probably controlled by different mechanisms.

A study in a Malaysian oil palm plantation on mineral soils focussed on spatial variability compared to that in forest soils (Adachi *et al.* 2006). Soil carbon was found to drive spatial variability, followed by microbial carbon. However, the study was limited by its lack of replicates, as only 16 measured points were used. Fine root biomass was also identified as being related to emission rates, but much more weakly than for other forest types. In another study of Malaysian plantations on mineral soils, CO₂ emission was one of the characteristics measured on a chronosequence of seven plantations (Smith *et al.* 2012). The study aimed to investigate temporal changes in carbon movements, and found emissions from soil increased with plantation age. The emissions were measured on a nine-point grid replicated three times, and an average emission rate was calculated for the range of plantations. Emissions from an oil palm plantation have been measured by eddy covariance, which calculates gas flux from the landscape to the atmosphere, rather than directly from the soil surface, as measured in the previously mentioned studies (Fowler *et al.* 2011). This method gave a calculation of CO₂ emissions far greater than all other studies (1200 mg C m⁻² h⁻¹), and likely gives an inaccurate estimation of emission rate due to diurnal variability in mixing of gases in the atmosphere. The authors noted that the emissions were measured during the day, when CO₂ that has accumulated over-night due to temperature inversion is released, overestimating the average rate.

Reported CO₂ emission rates from oil palm plantation soils vary widely. The methodologies used differed, with a range in sampling methods that affects the ability to capture the spatial variability of CO₂ emissions. The equipment used to measure emission rates also varied; portable infrared analysers were used in the most recent studies and static chambers with laboratory analysis of samples was used in earlier studies (Melling *et al.* 2005 and Ishizuka *et al.* 2002, 2005).

Table 1: Reported CO₂ emission rates from oil palm plantation soils

Publication	Soil type/location /notes	n	Emission in reported units	Standard Deviation (mg CO ₂ m ⁻² h ⁻¹)	mg CO ₂ m ⁻² h ⁻¹
Lamade <i>et al.</i> 1996	Ferralsol/Benin		3.2 to 10 μmol CO ₂ m ⁻² s ⁻¹	-	506 to 1584
Ishizuka <i>et al.</i> 2002	Indonesia	3	57 mg CO ₂ m ⁻² h ⁻¹	13	57
Ishizuka <i>et al.</i> 2005	Udults/Entisol/Ultisol/Indonesia	14 & 21	1.88 to 3.12 g C m ⁻² d ⁻¹	73-185	287 to 477
Melling <i>et al.</i> 2005	Peat/Malaysia	36	46 to 335 mg C m ⁻² h ⁻¹	-	167 to 1228
Adachi <i>et al.</i> 2006	Malaysia	16	966 mg CO ₂ m ⁻² h ⁻¹	577.7	966
Smith <i>et al.</i> 2012	Malaysia	189	679.2 mg CO ₂ m ⁻² h ⁻¹	462.6	679.2

Soil carbon stocks

A number of studies have reported soil carbon stocks and described trends in soil carbon stocks under oil palm plantations. In studies looking at a range of changing soil carbon content in a chronosequence of plantations, soil carbon was found to not change over the life of a plantation (Smith *et al.* 2012 and Khasanah *et al.* 2015). This conclusion was based on carbon content variation across the chronosequence of plantations. The author speculated that although no change was detected over the life of the plantations, the initial conversion to oil palm from the former land use should result in a change in carbon stocks. However the findings of this study did not consider changes to spatial variability of soil carbon stocks under oil palm. Sampling was limited to a nine-point grid at each plantation, without regard for large differences in soil carbon which occur at that scale (Haron *et al.* 1998). In a Brazilian experiment comparing oil palm plantations to forest or pasture land uses, oil palm plantations were found to have higher soil carbon stocks than forest, though less than pasture (Frazao *et al.* 2012). The Brazilian study sought to account for spatial variability by adopting a sampling method accounting for differences between frond piles and other zones and the distance from trees.

In an earlier study of soil carbon and its relationship to microbial carbon, large increases in soil carbon stocks were seen over one plantation life cycle (Haron *et al.* 1998). But as the focus

of the study was the relationship between carbon content and microbial carbon, no calculation of change in carbon stock was made. In that paper the large spatial variability in the plantation was identified, and sampling was carried out according to the three identifiable zones of the plantation. Another study focussing on spatial variability in oil palm soils did not report total carbon stocks, but gave clues to changes in carbon stocks as spatial variation is developed as the plantations age (Law *et al.* 2009). This study demonstrated that large differences exist between frond piles, weeded circles and the between zones, which was attributed to different rates of organic matter application to these zones. Changes to soil carbon stocks over time were investigated in a model of carbon cycling in a plantation on a deep peat soil in Malaysia (Melling *et al.* 2007). Soil carbon changes were estimated from measurements of other sections of the carbon cycle and calculated to increase slightly over time. This result was surprising for a peat soil plantation, as plantations established on peat soils are usually expected to result in massive carbon export from mineralisation of organic matter.

Characterisation of soil organic matter in oil palm plantations

Important information about soil organic matter can be gained from characterisation of its various forms. There are many methods for characterising soil organic matter, some of which have been used in studies of oil palm systems.

Microbial carbon and its relationship to total soil carbon was measured in a Malaysian plantation (Haron *et al.* 1998). This characteristic describes the status of microbes important for processing of organic matter and other nutrients. The study found a relationship between soil carbon contents and microbial carbon contents. However it did not relate the quality of soil organic matter to its associated microbial carbon, apart from noting that the soil of the frond piles, though high in organic matter content, were unexpectedly low in microbial carbon. A more recent study also investigated this characteristic (Smith *et al.* 2012) and found a similar result.

Measuring the relative proportions of different soil carbon components is a useful method of characterising soil carbon. Fractions of soil carbon have physical and chemical properties depending on factors such as age and stability. By separating unique carbon fractions based on chemical or physical properties, it is possible to understand the characteristics of the soil carbon stock. The nature of soil carbon can also be assessed through experiments investigating its behaviour under incubation. The process of microbial mineralisation under incubation can vary depending on the nature of the carbon stock. Incubation experiments of tropical and young volcanic soils have shown that soil mineralogy did not have a significant effect on CO₂ release as a proportion of total carbon (Motavalli *et al.* 1994). In that study a volcanic soil was

compared to tropical smectitic, kaolinitic and oxidic soils and found to have higher carbon in the bulk fraction, soluble fraction, and low specific gravity fraction. The high carbon content of the volcanic soil was attributed to allophanic minerals, which have strong potential for containing organic matter. In these soils up to 16% of total carbon was mineralised after an incubation of 341 days. In another study of a high carbon volcanic soil, active aluminium and iron contributed to the carbon holding potential of volcanic soils (Hiradate *et al.* 2004). For the same soils, low specific gravity fractions accounted for large parts of soil carbon stocks; the majority of carbon was found in particles with a specific gravity less than 1.8 (g cm^{-3}). A fractionation and incubation experiment on volcanic ash soils found the low specific gravity fraction had the highest soil carbon content (Phiri *et al.* 2001) and low and medium density fractions were associated with soil phosphorus levels. It is likely that soil carbon under oil palm plantations has similar characteristics, although fractionation or incubation experiments have not been done.

1.2 Terms and scope of research

This research project deals with below-ground carbon cycling in oil palm plantations. The research sites were on volcanic mineral soils in oil palm plantations of Papua New Guinea. The experiments aimed to characterise movements of carbon into, around and out of soil via all major pathways. The timeframe of the carbon cycle was restricted by the research period but where possible the conclusions aimed to be representative of the full oil palm plantation lifecycle. Above-ground carbon stocks and partitioning are better understood so this project did not include them.

1.3 Current situation and research gaps

There is a deficiency of literature describing carbon cycling and using carbon cycle information for greenhouse gas budgeting in oil palm plantations. The literature describing carbon cycling can be divided into groups based on the steps in the carbon cycle they investigate.

There are significant gaps in our knowledge about inputs of carbon to soils in oil palm plantations. These existing papers evaluate carbon inputs to soil, usually as a part of a larger study of carbon cycling (Smith *et al.* 2012, Chase and Henson 2010). This aspect of the cycle is relevant to total soil carbon, because of the assumption that changes in total soil carbon are related to changes in organic matter inputs (Frazao *et al.* 2012). Carbon inputs have been evaluated but not well replicated and there is disagreement in the findings (Frazao *et al.* 2012, Smith *et al.* 2012). Research gaps exist for quantifying this step of the carbon cycle using

methodology that is more precise and representative of longer time scales. Determining rates of carbon inputs to soil carbon in oil palm systems will be useful for understanding carbon cycles of other land use types, as there is little information of carbon inputs under other forest types.

There are significant gaps in our knowledge of carbon exports from oil palm soils, which occurs primarily as CO₂ emission. While spatial variability of CO₂ emissions in oil palm plantations is appreciated (Law *et al.* 2009), all previous estimates of emission rates are based on insufficient replicates or methodologies that do not thoroughly account for spatial or temporal variability. In addition, no studies have included the emissions from frond pile areas of plantations. Neither has any adequate attempt been made to examine temporal variability, except for one study with few replicates (Lamade *et al.* 1996). Therefore a research gap exists for a thorough measurement of emission rates at the plantation scale, including frond piles and covering all sources of variability. This research topic can be extended to compare spatial variability in carbon emission rates and carbon input rates.

The process of incorporation and transformation of oil palm plantation organic matter into soils is not well understood, except for some information of microbial carbon dynamics (Haron and Brooks 1998). Studies of similar processes in comparable environments are also lacking; characterisation of soil carbon in tropical and agroforestry environments is scarce compared to temperate and more globally significant crops. There is a large gap of information in this area; some of the areas yet to be investigated are: turnover rates of soil carbon under oil palm, characterisation of soil carbon under oil palm and the factors influencing recalcitrance of soil carbon.

1.4 Importance of the proposed research

The proposed research is important for understanding the carbon cycle of oil palm plantations and similar systems. Oil palm plantations are globally significant, accounting for large areas of land use change in the tropics. The information will be used in two main areas: to inform people interested in soil carbon from a soil fertility perspective, and people interested in soil carbon from a greenhouse gas emission perspective. The research will be of value in informing actions to improve of soil quality through increasing soil organic matter. Understanding the nature of soil carbon in oil palm situations and how it differs from soil carbon in other environments can guide actions to maintain and improve soil quality. Soil carbon cycling in oil palm environments is unique compared to well-studied temperate farming systems therefore more information from oil palm systems on tropical soils is important. The information generated will also be of use to quantify greenhouse gas emissions from oil palm

plantations. Calculation of greenhouse gas budgets for oil palm needs accurate information about soil carbon cycling, which is missing from existing budgets.

1.5 Research questions

The research questions are:

- Are soils under oil palm plantations sources or sinks or sources of CO₂?
- What is the rate of emission of carbon from oil palm soils and what factors control this emission rate?
- How does the chemistry of oil palm soil carbon relate to its cycling properties?

1.6 Research objectives

The questions raised in this research project are answered in more than one step, the relevant objectives are as follows:

1 (i) quantify soil carbon stocks in a chronosequence of oil palm plantations established on grassland;

(ii) quantify the rate of accumulation of soil carbon from oil palm inputs and the rate of disappearance of the grass-derived soil carbon; and

(iii) identify whether soil in oil palm plantations established on tropical grasslands are a source or sink of atmospheric carbon dioxide.

2 (i) Accurately calculate soil CO₂ emissions in a mature oil palm plantation using a methodology that accounts for spatial variability and includes emissions from the frond pile;

(ii) determine the extent to which spatial variability in CO₂ emission is determined by carbon inputs (via roots and pruned fronds), soil moisture and soil temperature.

3 (i) Determine the turnover rate of soil carbon under laboratory conditions;

(ii) determine the nature of soil carbon by physical and chemical classification;

(iii) relate the nature of soil carbon to its recalcitrance.

2. Soil carbon balance following conversion of grassland to oil palm

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2.1 Introduction

Oil palm is a major food crop and its rapid spread has important implications for the global carbon cycle (Lamade & Bouillet 2005; Gibbs *et al.* 2008; Ziegler *et al.* 2012). Oil palm crops cover more than 16 million ha and the area is expanding at a rate of around 400,000 ha per year (FAOSTAT 2013). The crop has been linked with deforestation in tropical regions; important because these forests are recognized as the stores of 36-60% of ecosystem carbon (Butler *et al.* 2009, Dixon *et al.* 1994). The threat of large greenhouse gas emissions from forest conversion to oil palm has been documented, for example in Kalimantan (Carlson *et al.* 2012). From the perspectives of carbon cycling and biodiversity it is desirable that further expansion occurs on non-forested areas rather than forested areas (Germer & Sauerborn 2008; Koh & Wilcove 2008; Corley 2009; Sayer *et al.* 2012). Therefore, there is a clear need for more research into carbon implications of converting different vegetation types (Lamade & Bouillet 2005; Sheil *et al.* 2009; Bessou *et al.* 2012a; Ziegler *et al.* 2012). Further research on SOC dynamics in oil palm crops, especially on different soil types and previous vegetation covers, is necessary for several reasons. The scale of expansion of oil palm crops means that any change to SOC stocks due to oil palm cultivation will have far reaching consequences. Greenhouse gas budgets have been produced for palm oil production systems but they are based on limited information on SOC stocks (Syahrudin 2005; Germer & Sauerborn 2008; Gibbs *et al.* 2008; Reijnders *et al.* 2008; Wicke *et al.* 2008; Chase & Henson 2010; Bessou *et al.* 2012b). While modelling studies suggest that carbon may be sequestered when oil palm is planted on some vegetation types, such as anthropogenic grasslands, this has not been substantiated by empirical research.

Many studies have shown that the SOC stocks of tropical soils decline when they are brought into cultivation (Detwiler *et al.* 1986; van Noordwijk *et al.* 1997; Ogle *et al.* 2005; Don *et al.* 2011; Ziegler *et al.* 2012), but that may not necessarily be the case with oil palm. There have been few studies on the fate of SOC stocks after conversion to oil palm. Haron & Brooks (1998) measured an increase of SOC content with plantation age in their study area, where the previous land cover had been secondary forest. Law & Balasundram (2009) also identified an overall increase in SOC content with plantation age, with SOC content increasing under frond piles and decreasing in harvest paths. Frazão *et al.* (2013) found stable total SOC stocks in oil palm soils compared to forest soils, and increasing spatial variability as SOC accumulated from root material inputs was concentrated around the trees. In the same study, SOC stocks were greater in pasture-land that had replaced forest than in the forest. Smith *et al.* (2012) investigated replanted oil palm plantations of different ages and found no effect of plantation age on SOC stocks. Similarly, Schroth *et al.* (2002) reported stable SOC stocks in peach palm (*Bactris gasipaes* (Kunth)) plantations over 7 years. There has been much research on deep peat soils, from which large amounts of carbon are released to the atmosphere following conversion to oil palm, due to lowering of the water table by installation of drains (Melling *et al.* 2007).

Where oil palm replaces grassland, the dynamics of SOC can be studied by exploiting the substantial difference in stable carbon isotope composition of inputs from the two vegetation types. Tropical grasses generate biomass and SOC inputs which are identifiable by a $\delta^{13}\text{C}$ value of around -12‰, whereas oil palm generates biomass and SOC inputs of around -29‰ $\delta^{13}\text{C}$ (Lamade *et al.* 2009). The $\delta^{13}\text{C}$ of SOC will reflect the history of inputs of grass- versus oil palm-derived carbon. This situation provides an opportunity to observe and quantify rate of loss of grass-derived carbon and the rate of accumulation of oil palm-derived carbon over time.

The aims of this study were to: 1) Measure soil carbon stocks in a chronosequence of oil palm plantations established on grassland, 2) quantify the rate of accumulation of SOC from oil palm inputs and the rate of disappearance of the grass-derived SOC, and 3) identify whether soil in oil palm plantations established on tropical grasslands is a source or sink of atmospheric carbon dioxide.

2.2 Materials and Methods

Study Area

Sixteen smallholder oil palm plantations were chosen for the study, all located around Popondetta, in Oro Province, Papua New Guinea, and all planted on grassland (Figure 1). The area has a humid tropical climate, annual rainfall is approximately 2380 mm, with a wet season in October-May and a dry season in June-September (average monthly rainfalls of 244 mm and 107 mm, respectively). The soils are Vitrands (Soil Survey Staff, 2010) formed in alluvially redeposited tephra, with mineralogy dominated by albite/anorthite and cristobalite, and amorphous material (glass) being a minor component. The grassland areas are maintained by regular burning and their distribution has been fairly stable over time, or at least the last few decades. Comparison of modern vegetation maps with aerial photographs taken in 1953 show similar distribution of grassland and forest (Figure 1). The age of the plantations ranged from one to 25 years and each plantation had adjacent grassland that was representative of the vegetation prior to planting. The planting densities of the plantations ranged from 115 to 150 palms per hectare. After $\delta^{13}\text{C}$ values were measured for each of the adjacent grassland areas, it was determined that 9 of the plantations were established on areas which had been grassland for a long enough period (probably centuries) for any isotope signature of previous forest cover to have been lost. These 9 sites were selected for the chronosequence analysis. Data from the other sites (where influence of previous forest cover was evident) are also presented to improve the inventory of information on SOC stocks in plantations established on former grassland soils.

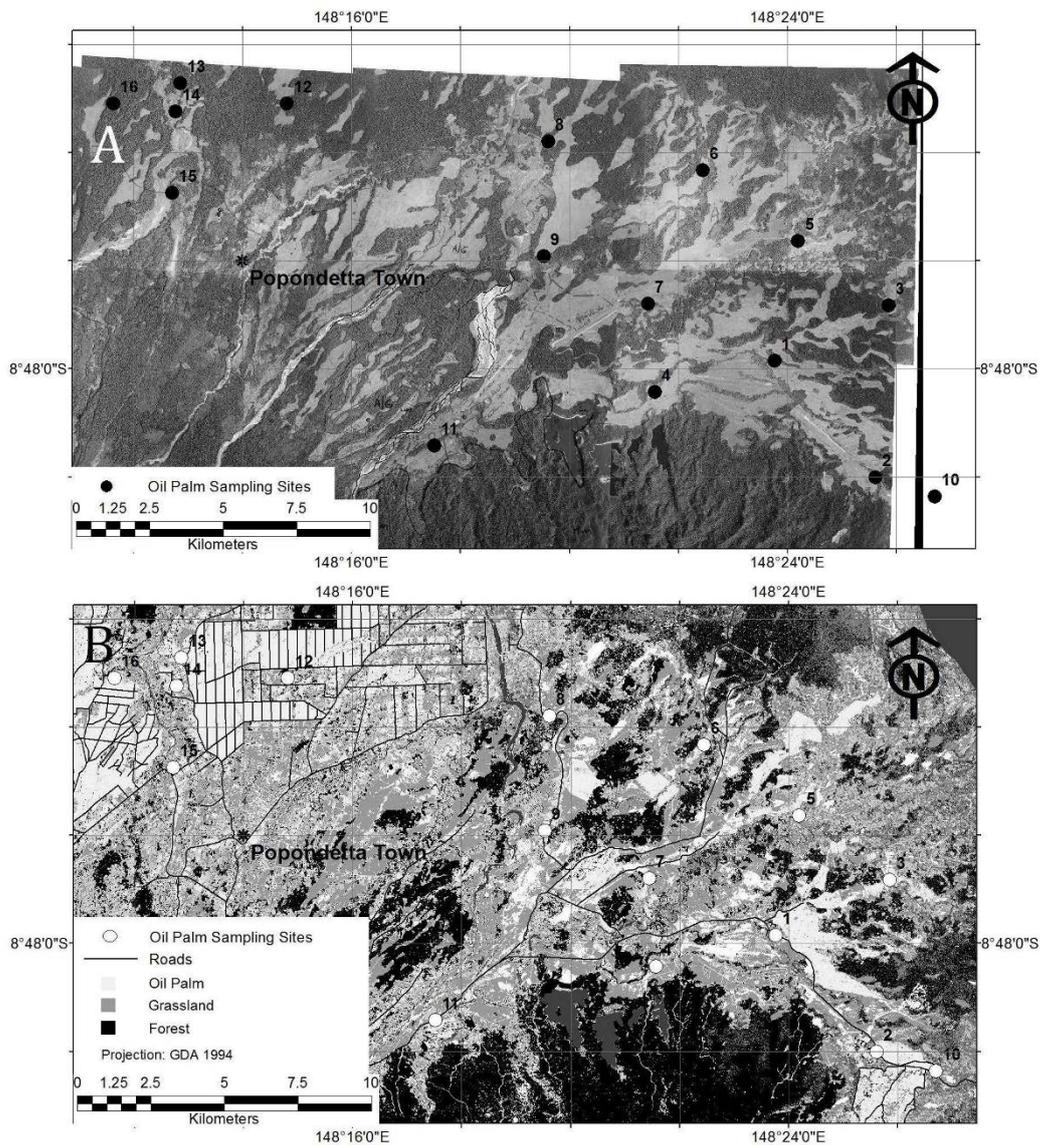


Figure 1: Study area, showing locations of sampling sites, overlying a) aerial photos taken in 1953 (light grey areas are grassland and dark grey areas are forest) and b) vegetation cover in 2011 (map produced by EOWORLD for the World Bank).

Soil Sampling and Analysis

At each of the 16 sites, soil was sampled in the oil palm plantation, adjacent grassland and nearby secondary forest, using steel rings of 52-mm diameter to 0.2-m depth, and an auger from 0.2 to 1.5 m depth. Litter on the soil surface was discarded until the point where organic matter was in pieces of less than one centimeter. No appropriate grassland or forest sites were available at site 10. The depth intervals sampled were 0 - 0.05, 0.05 - 0.1, 0.1 - 0.15, 0.15 - 0.2, 0.2 - 0.5, 0.5 - 1.0 and 1.0 - 1.5 m. The samples from the palm plantations were taken separately from three zones: the weeded circle (WC), frond pile (FP) and the remaining area,

designated ‘between zones’ (BZ) and the dimensions of these zones were measured (Nelson *et al.* in press). Samples were collected from 4 replicate sites for each vegetation type and then combined into composite samples, which were used for subsequent analyses. Samples were homogenized, sieved to <2 mm and air-dried prior to analysis. Bulk density was measured for each depth interval, with each site and vegetation type (and management zone for the oil palm sites) having 4 replicate locations for the 0-0.2 m depth intervals and one for the 0.2-1.5 m intervals. Soil total carbon content and $\delta^{13}\text{C}$ values were measured following combustion using a Costech elemental analyser coupled to a Delta-Vplus stable-isotope ratio mass spectrometer. The stable isotope results are reported as per mil (‰) deviations from the VPDB reference standard scale for $\delta^{13}\text{C}$ values. The precision (standard deviation) on internal standards was better than $\pm 0.2\text{‰}$ ($\delta^{13}\text{C}$ values), and $\pm 2\%$ of the value (abundance estimates). The soils contain no carbonate, so total carbon content was assumed to equal total organic carbon content.

For the 0-0.05 m depth interval, soil pH and electrical conductivity (1:5 soil:water), total nitrogen content, exchangeable Al, Ca, K, Mg and Na and effective cation exchange capacity (extraction with 0.01 M Ag thiourea) were measured (Rayment & Higginson 1992). The content and isotopic composition of black carbon in soil at one of the sites (Site 1) was determined by analysis before and after hydrogen pyrolysis (Wurster *et al.* 2012) using a commercially available hydrogen pyrolysis rig (Strata Technology Ltd., Middlesex, UK). The soil samples were loaded with a Mo catalyst using an aqueous/methanol solution of ammonium dioxodithiomolybdate $[(\text{NH}_4)_2\text{MoO}_2\text{S}_2]$. In order to give a nominal Mo load of 1% of organic carbon mass, the catalyst mass was ~5% of the sample mass for all samples. Dried, catalyst-loaded samples were placed in the reactor and pressurised with 15MPa of hydrogen with a sweep gas flow of 0.083Ls^{-1} , then heated. A temperature program previously optimized for *black carbon* quantification was used; samples were initially heated at 5°Cs^{-1} to 250°C , then at $0.133^\circ\text{Cs}^{-1}$ until a final temperature of 550°C , which was maintained for 120 s.

Data Analysis

First, the SOC stocks were calculated for each vegetation type at each site. For the oil palm sites, stocks under each zone (WC, FP and BZ) were determined and then a weighted average was calculated using the proportional area of each zone. Differences in SOC stocks between the oil palm site and the adjacent grassland were then calculated for each site. The fractions of SOC originating from the former grassland vegetation (f_{GL}) and the oil palm crop (f_{OP}) were calculated according to the formula described by Bernoux *et al.* (1998),

$$f_{\text{OP}} = \frac{(\delta_{\text{OPS}} - \delta_{\text{GLS}})}{(\delta_{\text{C3S}} - \delta_{\text{GLS}})} \quad \text{Equation 1}$$

and

$$f_{GL} = 1 - f_{OP} \quad \text{Equation 2}$$

where $\delta_{OS} = \delta^{13}\text{C}$ value of the soil samples taken from the oil palm plantation, weighted for aerial proportion of zones; $\delta_{GS} = \delta^{13}\text{C}$ value of the soil samples taken from the adjacent grassland; and $\delta_{C3S} = \delta^{13}\text{C}$ value of a nearby soil in which all SOC originates from C3 vegetation (with a unique value for each depth interval to account for observed increase in $\delta^{13}\text{C}$ values with depth). The stocks of SOC derived from each source were calculated by multiplying the total SOC stock by the fraction originating from either source. These calculations of stocks were carried out for the 0-0.05, 0-0.2 and 0-1.5 m layers.

Using SPSS 20, paired t-tests were carried out to compare; 1) SOC stocks between the oil palm plantations and original grassland, 2) the SOC stocks of forest and grassland sites, 3) the SOC $\delta^{13}\text{C}$ values of oil palm and grassland sites, 4) the SOC $\delta^{13}\text{C}$ values of forest and grassland sites. These four tests were carried out using data for the 0-0.05 and 0-1.5 m layers. To model changes over time, an 'exponential rise to maximum' function,

$$c = a(1 - e^{-bx}) \quad \text{Equation 3}$$

was fitted to the data using SigmaPlot 10.0. In the equation, c = the amount or proportion of SOC derived from oil palm or grass, x = years after planting of oil palm and a and b are fitted constants. Differences between actual and modeled values were compared to soil pH, electrical conductivity, nitrogen content, effective cation exchange capacity, and exchangeable Al, Ca, K, Mg and Na contents for the 0-0.05 m layer, using regression.

2.3 Results

Stocks of SOC were lowest under forest and highest under grassland and oil palm (Table 2). Across all 16 sites, SOC content ranged from 23.6 to 107.5 g kg⁻¹ at the surface and 0.0 to 4.2 g kg⁻¹ at depth (Figure 2). Differences between sites and vegetation types were confined to the top 0.5 m; deeper than this the concentrations were very low irrespective of site or vegetation. Bulk density ranged from 0.09 to 1.00 Mg m⁻³ at the surface and 0.72 to 1.47 Mg m⁻³ at depth (Figure 3). In the oil palm sites, bulk density near the surface was slightly lower under the frond pile than under the weeded circle or between zones areas. Over all sites, there were significant differences in SOC stocks (0-1.5 m depth) between grassland and forest (two-tailed p=0.040) but not between the grassland and oil palm (two-tailed p=0.294). When only the 9 chronosequence sites were considered, there was still no significant difference in SOC stocks (0-1.5 m depth) between the grassland and oil palm sites (two-tailed p=0.197). However, in all but one of the 9 sites, SOC stock was the same or higher under oil palm than grassland (Figure 4). The one unusual site (Site 1) had the least well-maintained oil palm stand and appeared to have low productivity. When it was removed from the comparison there was significantly higher SOC stock under oil palm than grassland (two-tailed p=0.010). Black carbon, measured at Site 1, comprised 6.5-15.7% of SOC, increasing with depth. It had $\delta^{13}\text{C}$ of -15.1 at 0-0.05m depth to -17.6 at 0.5-1 m depth, consistent with a grass-derived origin.

Table 2: Soil organic carbon (SOC) stocks to 1.5 m depth. Asterisks indicate sites used in chronosequence study (CS).

Site	Years after planting	Grassland SOC stock (kg m ⁻²)	Oil Palm SOC stock (kg m ⁻²)	Forest SOC stock (kg m ⁻²)
1*	25	16.8	11.9	5.1
2	10	14.0	12.9	9.7
3*	12	10.3	11.2	10.7
4*	6	15.7	20.4	10.3
5*	12	7.0	7.6	6.9
6*	11	9.6	11.8	7.9
7*	9	4.5	8.8	5.6
8*	25	11.5	14.0	9.3
9*	25	10.7	12.3	9.9
10	21		11.0	
11*	10	10.3	10.3	8.3
12	2	7.2	5.8	5.6
13	3	10.8	10.1	2.4
14	1	10.8	12.9	13.9
15	3	7.4	6.0	6.9
16	3	7.6	8.5	8.0
Mean (all sites)		10.3	11.0	8.0
Mean (CS)		10.7	12.0	8.2
Std. dev. (CS)		3.8	3.6	2.0

Table 3: Black carbon stocks in grassland and oil palm soil at Site 1. Asterisk indicates sample not measured. 'OP BZ' is between zones area in oil palm block and 'OP FP' is frond pile area.

Depth interval (m)	Total SOC (grassland) kg m^{-3}	Black Carbon (grassland) kg m^{-3}	Black Carbon proportion of total SOC (%)	Black Carbon $\delta^{13}\text{C}$ (grassland)	Black Carbon $\delta^{13}\text{C}$ (OP BZ)	Black Carbon $\delta^{13}\text{C}$ (OP FP)
0-0.05	45.1	2.9	6.5	-15.1	-15.5	-16.3
0.05-0.1	44.3	3.1	6.9	-14.7	-15.4	-15.2
0.1-0.15	40.7	3.0	7.5	-14.6	*	*
0.15-0.2	40.0	3.6	9.0	-13.7	-13.9	-14.9
0.2-0.5	20.2	1.7	8.2	-14.3	*	*
0.5-1	3.8	0.6	15.7	-17.6	-17	-17.3

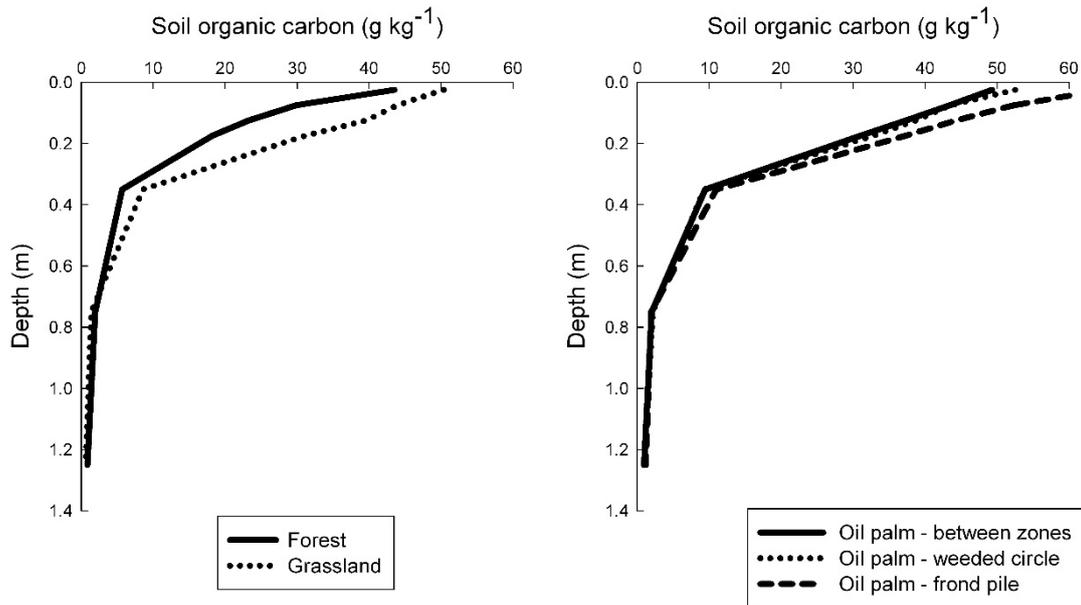


Figure 2: Mean soil organic carbon content for each vegetation type and oil palm management zones at all 16 sites.

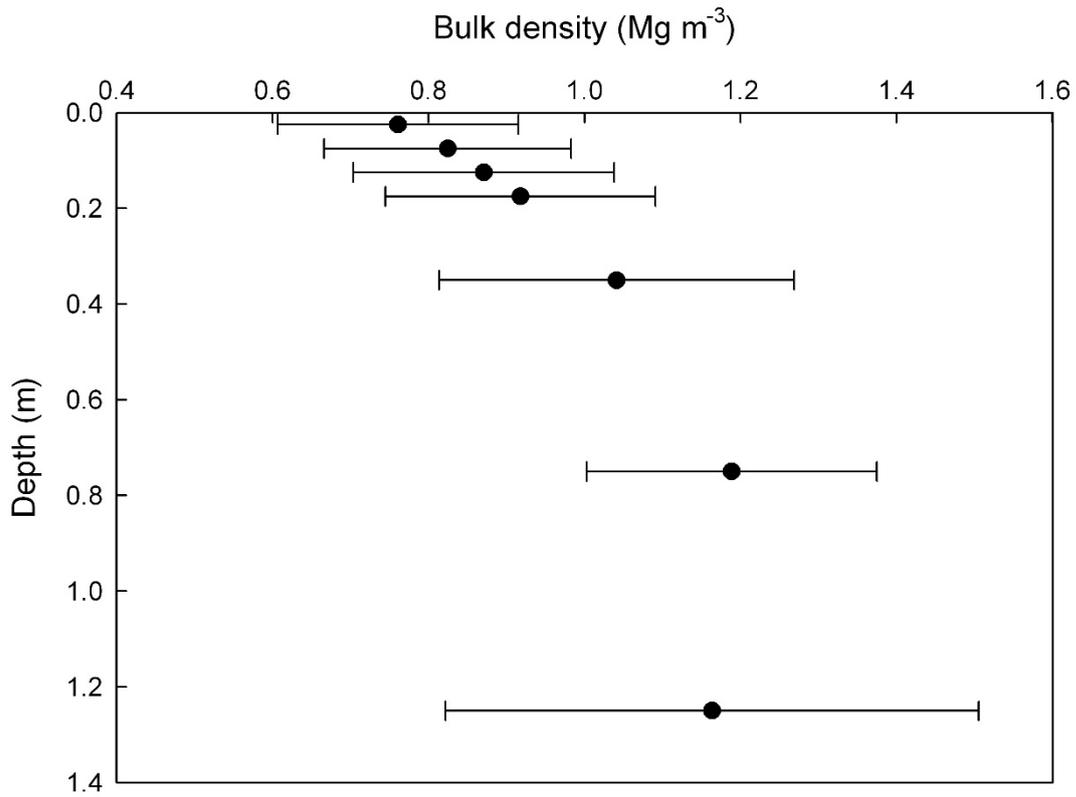


Figure 3: Mean and standard deviation (error bars) of soil bulk density for all vegetation types and zones across all 16 sites. There were no significant differences between vegetation types.

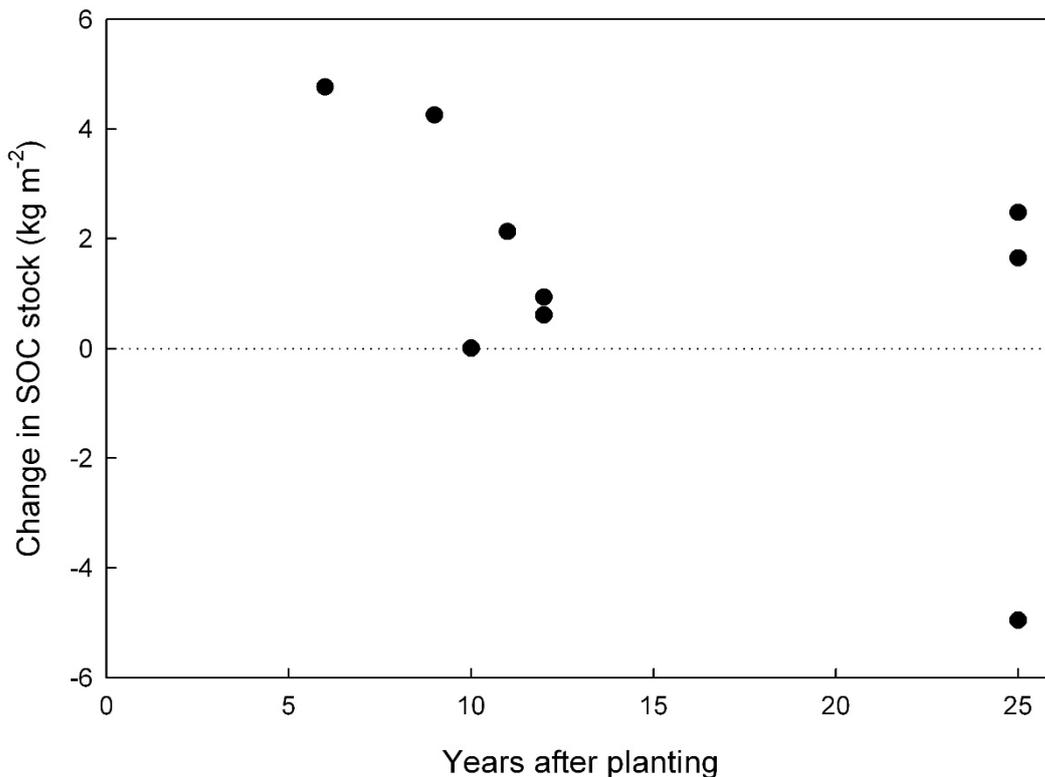


Figure 4: Change in soil organic carbon (SOC) stocks since oil palm planting (ie. SOC stock under oil palm minus SOC stock under adjacent grassland). The regression of change in SOC stock with time since planting was not statistically significant ($r=0.61$, $p=0.25$).

The grassland soils at sites 1, 3-9 and 11 had $\delta^{13}\text{C}$ values around -15% , suggesting the long-term presence of grassland prior to planting of oil palm (Figure 5). For that reason these sites were included in the chronosequence analysis. The grassland soils at sites 2, 12, 13, 14, 15, 16 had $\delta^{13}\text{C}$ values of -20% or less at some point in the profile. This suggests these sites were under forest recently enough for the isotopic composition of SOC to have been influenced C3 vegetation. For that reason these sites were excluded from the chronosequence analysis. For the chronosequence sites, $\delta^{13}\text{C}$ differed significantly between the grassland and oil palm soils and between the grassland and forest soils in paired t-tests ($p=0.003$ and $p=0.000$ respectively at $0-0.05\text{ m}$ and $p=0.038$ and $p=0.000$, respectively for $0-1.5\text{ m}$ depth).

Isotopic analysis of plant samples showed clear distinctions between oil palm and forest systems on the one hand and grassland on the other. Forest leaves had $\delta^{13}\text{C}$ of -31.8% (middle canopy) and -29.8% (upper canopy). Oil palm tissues had $\delta^{13}\text{C}$ of -30.6 to -30.4% (leaflets) and -28.8 to -28.1 (rachises and roots), and the legume cover crop *Pueraria phasedoides*

(Roxb.) Benth. had $\delta^{13}\text{C}$ of -30.4‰. The dominant grassland species had $\delta^{13}\text{C}$ of -13.9 ‰ (*Imperata cylindrica* (L.) P.Beauv.) and -13.2 ‰ (*Saccharum edule* Hassk.).

After 25 years of oil palm growth, the proportion of SOC derived from oil palm was 38% in the 0-0.05 m depth layer, 28% in the 0-0.2 m layer and 27% in the 0-1.5 m layer (Figure 6). The remainder of SOC was derived from grass inputs. The regressions for SOC stocks derived from each source against time were significant only for the oil palm inputs at 0-0.05 m and 0-0.2 m. After 25 years, oil palm inputs had contributed 2.1 kg m⁻² of SOC in the 0-0.2 depth interval and 3.4 kg m⁻² of SOC in the 0-1.5m depth interval. There was no significant decrease in grass-derived SOC stocks over the same period. Although there was a significant upward trend over all sites in the fraction of SOC derived from oil palm, some sites deviated substantially from the mean trajectory. Examination of correlations with soil chemical properties showed that, in the 0-0.5 m layer, these deviations were related to total nitrogen content (Figure 7). In soils with nitrogen contents >3.9 g kg⁻¹, the fraction of SOC derived from oil palm increased more slowly than the average, and at sites with soil nitrogen content ≤3.9 g kg⁻¹ it increased more rapidly.

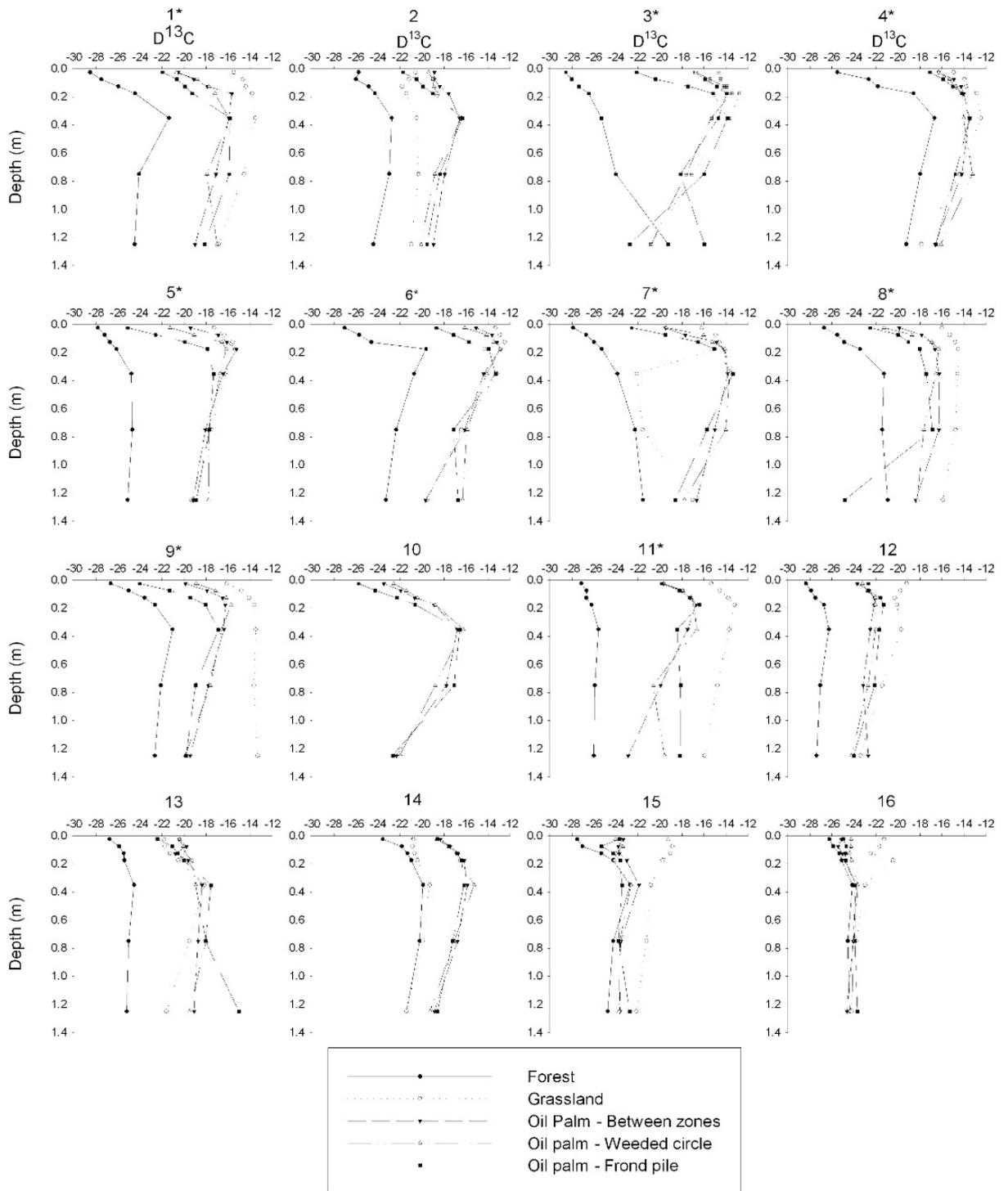


Figure 5: Isotopic composition of soil organic carbon ($\delta^{13}\text{C}$) for all 16 sites. Asterixes show the sites used in the chronosequence study.

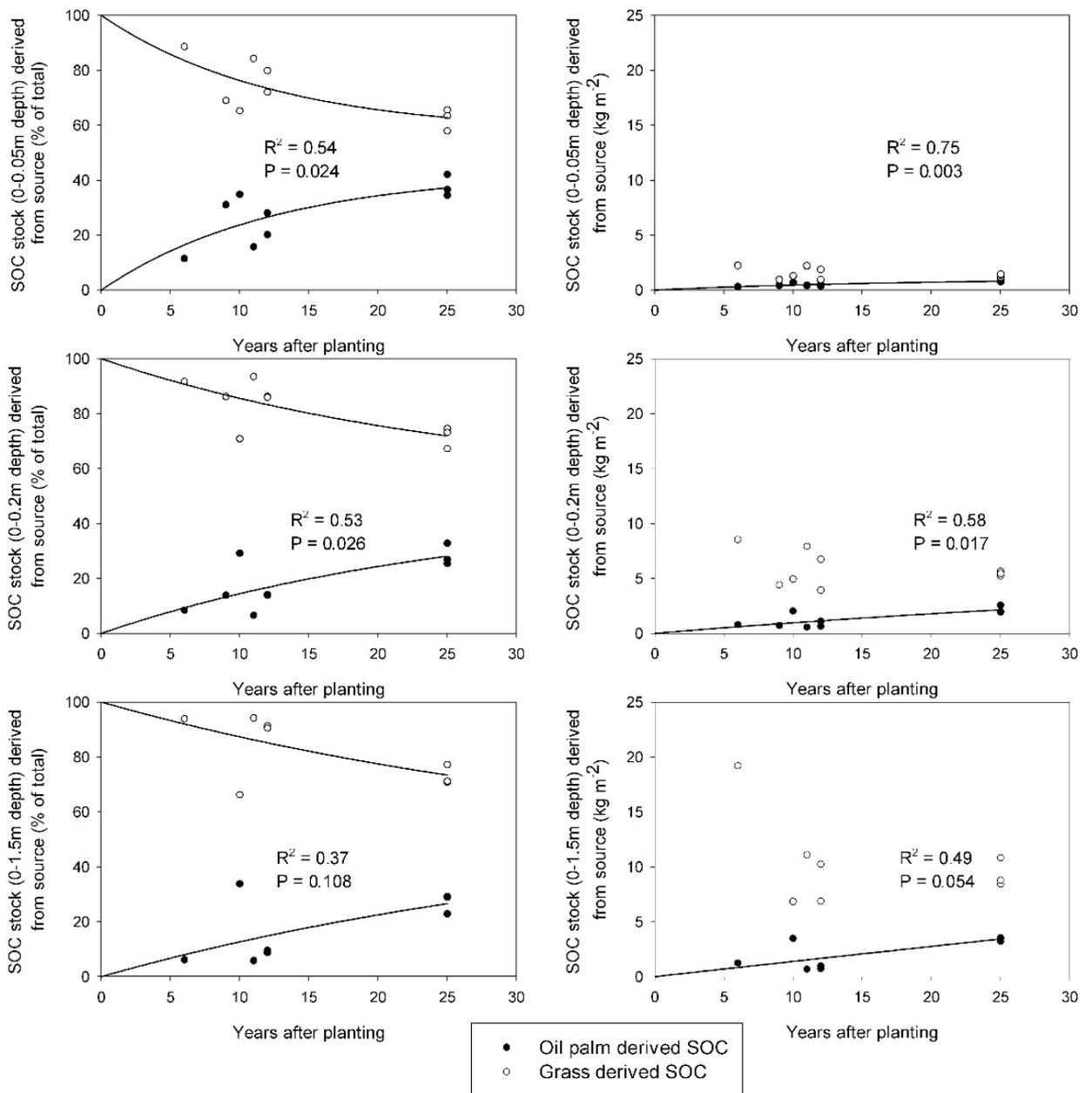


Figure 6: Proportion of SOC derived from grassland and oil palm inputs (left) and total SOC stocks derived from each input (right) as a function of time from planting, for three depth intervals: 0-0.05 (top), 0-0.2 (middle) and 0-1.5 m (bottom). Points are data and lines are fitted curves (Equation 3), shown only where r^2 was >0.3 . Site 7 was excluded from the regressions for the 0-1.5m depths due to its anomalous $\delta^{13}\text{C}$ values at depth (see Figure 4).

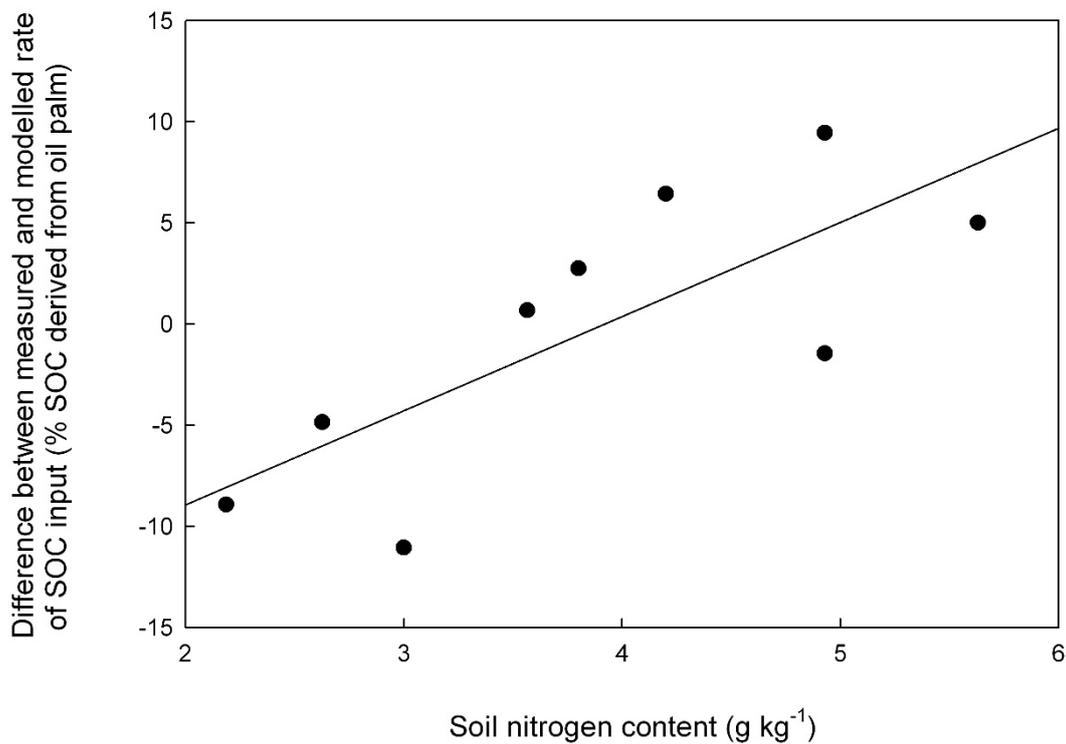


Figure 7: Relationship between soil nitrogen content and rate of SOC accumulation from oil palm for 0 - 0.05m depth interval. The Y-axis values are calculated as the modeled SOC derived from oil palm minus the measured SOC derived from oil palm for each site. Positive values indicate the modeled proportion of SOC from oil palm was lower than the measured proportion of SOC from oil palm. A linear regression ($y=46.52-18.34*x$, $r^2=0.59$) was performed.

2.4 Discussion

In 7 of the 9 chronosequence sites, SOC stocks were greater under oil palm than grassland, suggesting an increase in SOC stocks following conversion of grassland to oil palm. In one site there was no change and in one site there was a decrease. Our findings, of no overall significant change, but an upward trend, are similar to those of previous studies, although none of those studies examined changes following conversion of grassland to oil palm. Haron & Brooks (1998) and Law *et al.* (2009) found no significant increase under oil palm, Trouve *et al.* (1994), found no significant increase where forestry replaced tropical grasslands, and Smith *et al.* (2012) and Frazão *et al.* (2013) measured increases in SOC stocks under oil palm. A meta-analysis of tropical studies by Don *et al.* (2011) showed decreases in SOC stocks when forest was converted to grassland and increases when grassland was converted to forest. Changes in SOC stocks were expected because the conversion of grassland to oil palm involves a number of processes which will impact the carbon cycle of the soil. These include the change in vegetation from grassland species to oil palm and leguminous cover crops, application of fertilizers and cessation of the fires that are a regular feature of the grasslands. If we take into account the large difference in biomass carbon between grassland and oil palm (Ziegler *et al.* 2012), then it is clear that conversion from grassland to oil palm leads to net sequestration of carbon in the environment studied. Aside from the substantial economic and carbon balance benefits that may ensue from such plantings, they can also be an effective way of eliminating *Imperata cylindrica* (L.) P.Beauv. and thus facilitate the establishment of less vigorous crops such as cocoa (Jagoret *et al.* 2012).

The change in soil carbon stocks with time under oil palm did not show a clear trajectory as we had hypothesized when designing the experiment, despite choosing sites where oil palm had been planted on long-established grasslands with similar composition on similar soil types and climate. The considerable variation we encountered was presumably largely due to variations in soil properties. Nitrogen content in the surface layer went some way towards explaining variability in rate of carbon stock change, and soil properties deeper in the profile may also have been important. High soil nitrogen contents have been shown to reduce the stability of the labile carbon fraction (Neff *et al.* 2002), so similar mechanisms may have influenced SOC accumulation at our study sites. Nitrogen fertiliser had been applied in most of the studied oil palm plantations, but the application history of each particular site is unknown. Considerable spatial variation within the oil palm plantations also probably contributed error. The soil sampling method relied on representative sampling and accurate area measurement of management zones delineated by eye. The location of sampling points within management zones may not have been entirely representative (Nelson *et al.* in press).

Furthermore, visible boundaries between the zones at the time of sampling may not necessarily have corresponded well with carbon cycling processes in the underlying soil.

The SOC stocks of the grasslands (dominated by *Imperata* and *Saccharum*) are interesting, as the stocks of 107 Mg ha⁻¹ found here are higher than those published in other studies. The stocks identified for an *Imperata* grassland in Kalimantan were comparatively low, at 36.19 Mg ha⁻¹ to 0.04m depth (van der Kamp *et al.* 2009). However, a study of an *Imperata* grassland in Papua New Guinea by Hartemink (2004) showed SOC stocks of 85.7 Mg ha⁻¹ to only 0.15 m depth, which is comparable to the results of this study. Although this study focused on changes occurring when grassland is converted to oil palm, the comparison of grassland with forest was also interesting. We found higher stocks of SOC under grassland than forest. A similar result was found in van der Kamps (*et al.* 2009) study in Indonesia, in a region having similar climate to our study site, where SOC stocks were higher in grasslands than primary forests. The literature on the effects of conversion from one land use to the other is ambiguous. At a global scale, Guo & Gifford's (2002) meta-analysis showed that conversion of forest to pasture increased SOC, but in a meta-analysis of tropical studies, Don *et al.* (2011) found that SOC decreased upon conversion of forest to grassland and increased upon conversion of grassland to forest. Ziegler *et al.* (2012) concluded that the effects of many land use changes were ambiguous and more studies were needed.

Profiles of $\delta^{13}\text{C}$ with depth had characteristic forms. The soil under oil palm had depleted $\delta^{13}\text{C}$ relative to the original grassland, to at least 0.25 m depth at all chronosequence sites and to 1.5 m at four sites (Figure 5). The depletion generally became more pronounced, especially at depth, with time since planting to oil palm. The technique used to calculate rates of SOC inputs was based on this shift in $\delta^{13}\text{C}$ values. The depth profile of $\delta^{13}\text{C}$ generally showed an increase to 0.35 m and then decrease from 0.35 m to 1.5 m. While this depth profile was most pronounced under oil palm, it also occurred under forest and grassland, so it must be due to fractionation processes rather than site- or vegetation-specific factors. Enrichment to a depth of 0.35 m can be explained as the result of Rayleigh distillation (Wynn *et al.* 2005) but the depletion deeper in the profile is not as easy to explain. It may be due to selective stabilisation of ¹³C-depleted materials at depth due to particular mineralogy or other conditions, such as waterlogging, that occur there (Krull & Skjemstad 2003; Schmidt *et al.* 2011), or it may be due to inputs from C3 forest in the distant past.

For this research, the equation of Bernoux *et al.* (1998) for calculating SOC turnover was modified. The modification involved substituting the $\delta^{13}\text{C}$ value of vegetation inputs with the $\delta^{13}\text{C}$ value of soil in the study region whose SOC was purely derived from either C4 or C3

vegetation. It can be argued that this method is more robust than the original method because $\delta^{13}\text{C}$ of soils cannot be expected to reach that of the inputs, due to fractionation processes. The soils of this study, and many other soils, exhibit non-uniform $\delta^{13}\text{C}$ values with depth due to a number of fractionation processes. The method described by Bernoux *et al.* (1998) relies on a single $\delta^{13}\text{C}$ value for each of the two sources of carbon, and ignores isotopic fractionation that occurs when it is incorporated into SOC. This fractionation may be insignificant when investigating surface soils, but the method has limitations when applied to deeper soil horizons. The method presented here uses a measured $\delta^{13}\text{C}$ value at each depth of a soil at both ends of the range of possible SOC $\delta^{13}\text{C}$. In this way it is accounting for fractionation processes the organic matter undergoes at each depth.

Oil palm-derived organic matter was incorporated to 0.5 depth quite quickly. After conversion of grassland to oil palm, SOC stocks begin to reflect the $\delta^{13}\text{C}$ of the oil palm organic matter inputs after only a few years (Figure 5). Changes in $\delta^{13}\text{C}$ near the surface are easy to explain as most inputs are made close to the surface. However it was surprising that 1.3 kg m^{-2} of oil palm-derived SOC accumulated between the depths 0.2 and 1.5 m over 25 years, because SOC at these depths is usually assumed to be nearly exclusively made up of old and stable compounds rather than recent inputs (Bernoux *et al.* 1998). It might be that oil palm roots were responsible for introducing new carbon at these depths. Upon closer examination though, it appears that down to a depth of at least 0.2 or 0.5 m, incorporation of organic matter applied to the soil surface as pruned fronds was more important than inputs from roots. Relative contributions from pruned fronds and roots could be deduced from differences in $\delta^{13}\text{C}$ between the management zones. Although root biomass and activity is much greater under the weeded circle than under the frond pile (Nelson *et al.* 2006), $\delta^{13}\text{C}$ generally decreased more under the frond pile than under the weeded circle in the chronosequence sites (to 0.2 or 0.5 m depth, Figure 5). The only means by which frond-derived organic matter can be incorporated into the soil is by faunal activity, so fauna evidently play a major role in maintaining or increasing SOC stocks under oil palm.

The results of this study suggest more resistant original SOC stocks than have been found in other agricultural systems. In a study of sites where cropping and grazing had replaced native forest in Ethiopia, Lemenih *et al.* (2005) found that the original 0-0.1 m SOC stock decreased by more than 50% in the first 25 years. Organic matter inputs from the crops were not able to replace the losses of SOC from the original stock so the total stock declined. As a result, the $\delta^{13}\text{C}$ of this depth interval shifted 50% of the direction towards a SOC stock fully derived from the new agricultural crop. In another comparative study, where a C3 forest plantation replaced savannah in Congo, Trouve *et al.* (1994) showed that after 25 years, the top soil had almost

completely derived from the new tree crop organic inputs. This is very different to the findings here, where after 25 years, only 37% of the SOC stock had been replaced in the 0-0.05 m depth interval and the inputs from the oil palm crop were high enough to replace the losses from the pre-existing SOC stock.

One possible reason for the persistence of the original SOC stock in this study could be the presence of SOC in recalcitrant forms. Possible candidates are organo-mineral associations and highly aromatic materials produced during fires (Baldock & Nelson 2000; Schmidt *et al.* 2011; Schneider *et al.* 2011; Cusack *et al.* 2012). The black carbon contents we measured were persistent for 25 years but they accounted for a relatively small proportion of the total SOC (6.5-9.0% in the layers where changes were greatest; Table 3), so other resistant forms of carbon must be abundant within the SOC stocks in order to explain the slow rate of change. The method employed to measure black carbon is conservative in that it measures only highly condensed materials (Bird & Ascough 2010); less condensed but still recalcitrant materials may also have been present.

2.5 Summary

Oil palm (*Elaeis guineensis* Jacq.) crops are expanding rapidly in the tropics, with implications for the global carbon cycle. Little is currently known about soil organic carbon (SOC) dynamics following conversion to oil palm and virtually nothing for conversion of grassland. We measured changes in SOC stocks following conversion of tropical grassland to oil palm plantations in Papua New Guinea using a chronosequence of plantations planted over a 25-year period. We further used carbon isotopes to quantify the loss of grassland-derived and gain in oil palm-derived SOC over this period. The grassland and oil palm soils had average SOC stocks of 10.7 and 12.0 kg m⁻² respectively, across all the study sites, to a depth of 1.5 m. In the 0-0.05 m depth interval, 0.79 kg m⁻² of SOC was gained from oil palm inputs over 25 years and approximately the same amount of the original grass-derived SOC was lost. For the whole soil profile (0-1.5m), 3.4 kg m⁻² of SOC was gained from oil palm inputs with no significant losses of grass-derived SOC. The grass-derived SOC stocks were more resistant to decrease than SOC reported in other studies. Black carbon produced in grassfires could partially but not fully account for the persistence of the original SOC stocks. Oil palm-derived SOC accumulated more slowly where soil nitrogen contents were high. Forest soils in the same region had smaller carbon stocks than the grasslands. In the majority of cases, conversion of grassland to oil palm plantations in this region resulted in net sequestration of soil organic carbon.

3. Tree-scale spatial variability of soil carbon cycling in a mature oil palm plantation

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3.1 Introduction

Carbon is continually cycling through the earth's biosphere and atmosphere, primarily through the processes of photosynthesis and respiration. Around 98 billion tonnes of carbon move from soils to the atmosphere each year via respiration (Bond-Lamberty and Thomson 2010). This is the second largest movement of carbon to the atmosphere and is greater than fossil fuel emissions of CO₂ (Reichstein *et al.* 2003). For this reason, even small differences in soil carbon cycling affect atmospheric CO₂ concentrations, which in turn drive climate change. Carbon cycling research often focuses on increasing or decreasing soil carbon stocks. However, recent thinking suggests managing carbon flows rather than stocks is a more realistic route to climate change mitigation through soil management (Janzen 2015). Agricultural soils deserve particular attention as they are modified from their natural equilibrium. This is especially so in the humid tropics, where photosynthesis and respiration rates can be high and land use is rapidly changing.

Oil palm is an important and expanding crop in tropical regions, currently occupying more than 15 million hectares (FAOSTAT), with important implications for the carbon cycle (Lamade and Bouillet 2005; Gibbs *et al.* 2008; Sayer *et al.* 2012). Land use conversion causes the most significant perturbation to the carbon cycle and the pre-existing type of land and vegetation has an important influence (Bessou *et al.* 2013). Good field measurements are an essential requirement for improved modelling and life cycle assessment of oil palm cultivation (Bessou *et al.* 2013).

The CO₂ emitted from soil originates from a number of distinct sources, with fluxes from each source being controlled by a range of factors. The principal two sources are respiration by plant roots and respiration by heterotrophic organisms decomposing organic matter (Ryan and

Law 2005). In natural systems plant roots and heterotrophs are non-uniformly distributed and derive their metabolic substrate from a number of sources, creating much spatial and temporal variability in emission rates. The environmental factors controlling emission rates differ for each ecosystem but plant root activity, soil temperature, moisture content, organic matter content, pH and above-ground weather conditions have all been identified as controllers of spatial variability (Bowden *et al.* 1998, Ohashi *et al.* 2008, Luo and Zhou 2006, Ekblad *et al.* 2005). The distribution of some of these factors can be random or may occur in systematic patterns, particularly in human-modified ecosystems.

Heterotrophic and autotrophic respiration are intertwined processes, which makes it difficult to identify emissions from these separate sources in field studies. For example, distinguishing emissions of root-attached hyphae from those of free-living microbes dependent on root exudates is near impossible. However, traditional conceptual models of soil carbon cycles have focused on partitioning of substrate supply between autotrophic and heterotrophic respiration (Ryan and Law 2005). These partitioned respiration models usually do not incorporate total plant carbon allocation patterns or attempt to couple the canopy with below-ground processes, but to do so may facilitate greater understanding of soil carbon cycling (Ryan and Law 2005).

In established oil palm plantations much of the spatial variation in carbon inputs and outputs is systematic, related to plant architecture and management regime (Nelson *et al.* 2014). The tree-scale spatial variability in ground conditions is visible to the naked eye, as management practices create different 'zones' around each palm, with different attendant physical and chemical conditions above and below the ground. The frond pile, where pruned fronds are placed, is an area with high carbon inputs, rich in decomposing organic matter. The area immediately surrounding the palm trunk is kept clear of groundcover plants and is compacted by harvesting operations, but this zone also contains the majority of the palm roots. The remaining area is mostly covered with low growing groundcover plants, except for the harvest path, which is affected by vehicle or foot traffic. The resulting spatial variability in soil carbon contents is evident within the lifetime of one crop (Goodrick *et al.* 2015).

Carbon dioxide emission rates are known to differ between management zones in oil palm plantations. In a Benin plantation, emissions under moist conditions were twice as high in the frond piles as in the inter-row (Lamade *et al.* 1996). That study concluded that leaf pruning and planting patterns play a major role in determining the spatial distribution of CO₂ emissions. However, a 5-point sampling design was used, so the complete spatial pattern was not determined and therefore an overall plantation mean emission was not calculated. In a Malaysian plantation, soil carbon content was determined to be the primary cause of spatial variation in CO₂ emissions, followed by fine root biomass (Adachi *et al.* 2006). That was in

contrast to forests, where fine root biomass variation nearly completely accounted for emission variability (Adachi *et al.* 2006). The contribution of root density to spatial variation of soil respiration was determined to be weak for oil palm plantations on peat soils; linear correlations were highest for roots of 0.5 to 2.5mm diameter in 15-year-old plantations (R^2 of 0.28) (Dariah *et al.* 2013). Roots of other diameters or in younger plantations were shown to be even less well correlated with soil respiration rates (Dariah *et al.* 2013). The eddy covariance technique has also been used to measure emission rates in an oil palm plantation (Fowler *et al.* 2011). While this method is useful for determining large-scale net carbon movements, it does not help us understand small-scale soil processes.

In light of the previous work done, improvement in the measurement of soil CO₂ emissions in oil palm plantations is possible and this was our main objective. With good accuracy of CO₂ emissions we hypothesised that spatial variability in CO₂ emissions can be explained by spatial variability in carbon inputs. We exploited the systematic spatial variability of an oil palm plantation to test this hypothesis. Our aims were to 1) accurately calculate soil CO₂ emissions in a mature oil palm plantation, 2) determine the number of measurement points required to obtain a mean value with specified degree of precision, and 3) determine the extent to which spatial variability in CO₂ emission is determined by carbon inputs (via roots and pruned fronds), soil moisture and soil temperature.

3.2 Methods

Study Area

The study was carried out in Bebere plantation (5.61°S, 150.23 °E) in West New Britain Province, Papua New Guinea. It is a second generation oil palm plantation, with the second generation palms having been planted in alternate rows to the first. The palms were 20 years old at sampling and were planted in an equilateral triangular pattern at a density of 130 palms per hectare. Management of the plantation results in the creation of a bare area around the palm trunk (*weeded circle*) and a linear pile of pruned fronds in every second row (*frond pile*). The remaining areas were termed *between zones*, this area includes the space not occupied by the other two zones and is comparable to the zone described as *inter-row* or *avenue* in other publications. That area includes a harvest path on alternating rows with frond piles. The soil is an Andisol formed in recent tephra deposits (Bleeker 1983; Soil Survey Staff 2014). The climate is humid tropical, having average annual rainfall of approximately 3000 mm, with moderate seasonality, and mean annual temperature of approximately 26°C. Across the plantation, the soil (0-0.1 m depth) had mean pH (1:2 soil:water) of 5.8, total organic carbon content of 4.4 %, total nitrogen content of 0.31%, Olsen P content of 20 mg kg⁻¹, and

exchangeable potassium, magnesium and calcium contents 0.58, 0.71 and 6.9 cmol(+) kg⁻¹, respectively. Those values are the means of 27 composite samples taken in 2008, each made up of a sample from multiple locations, and each location having one sample from the weeded circle, one from the frond pile and two from the between zones area. The profile of total organic carbon content with depth, measured in one profile, was 3.7, 0.5, 0.6, 1.5 and 1.0 % at 0-0.1, 0.1-0.23, 0.23-0.42, 0.42-0.74 and 0.74-0.99 m depth, respectively. The lower two depth increments were buried A horizons. As the soil is acidic, no precipitation of CO₂ as carbonate occurs.

Field measurements methodology

Measurement of CO₂ emissions and other parameters for palms were made at 35 points on a trapezoid grid covering half of a 'palm unit', which is the repeating unit of the systematic spatial variation induced by management and palm geometry (Nelson *et al.* 2014). Four such grids were established, representing four separate palms, and each was sampled for root density and CO₂ emissions. At each point of the grid the management zone was noted. For the point theoretically directly under the trunk, CO₂ emission was measured directly adjacent to the trunk. Root density measurements were made to 2 m depth in April-August 2011 using push-tube corers, according to the methodology specified by Nelson *et al.* (2014) where the figures of interpolated root density are published.

For the soil CO₂ emission measurements, the four palm units selected were within 18 m of the palm units sampled for root density. Emissions were measured in two periods, during the wet season, on 21st -25th May 2012, and during the dry season, on 14th -19th Nov. 2012. There was no rainfall during the May measurement period but regular rainfall at night during the November period (Figure 8). Just prior to the May measurements, empty fruit bunches (EFB, a by-product from the palm oil mill) had been applied in the plantation. The 4 palm units selected for measurement had received little EFB, but because of its possible effect on emissions rates, 16 grid points under or near EFB were excluded from the data set; their values were interpolated from the surrounding 3 points. Between the two measurement events, some trees in the plantation were felled for research purposes. This affected the soil surface of two of the palm units selected for emission measurements. Therefore, two adjacent palm units were substituted for the November round of measurements. Emission was measured twice at each grid point, on separate days during the week. These two values were averaged to give a value for respiration for that week.

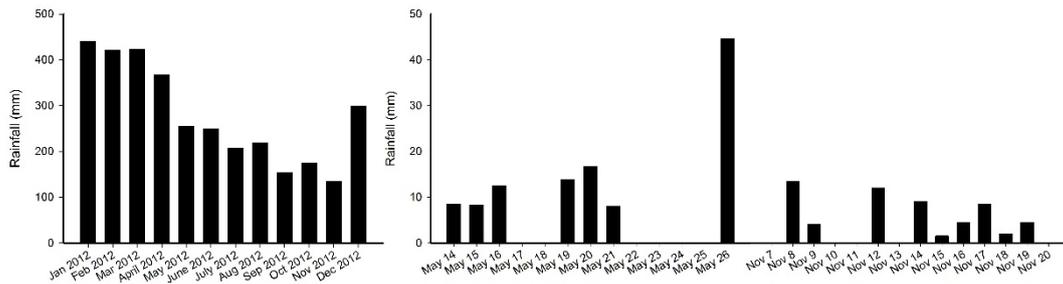


Figure 8: Rainfall at the study site. Monthly rainfall is shown for the whole of 2012 (left-hand panel) and daily rainfall is shown for the week of sampling (in May and November) and preceding week (right-hand panel).

All CO₂ emission measurements were made using a Licor portable infrared gas analyser (LI-8100, LI-COR, Lincoln, NE, USA). A 0.1-m diameter collar, on which the Licor chamber sat, was pushed into the soil surface to a depth of 20 mm. All observations with the Licor were made for 2.5 minutes. For points which fell in the frond pile zone and were covered with pruned fronds, a 0.2 x 0.2 m square was cut down through the decomposing fronds to the soil surface, the frond material from this area was placed in an airtight container fitted with a fan for mixing and an opening to accommodate the Licor chamber. The CO₂ emission from the frond pile litter was then measured while inside the container. After soil emission was measured for the point, the fronds were carefully returned to the soil surface until the second emission measuring campaign. Some frond pile locations did not require removal of the fronds because they were sufficiently few and decomposed to allow the collar to be pushed through to the soil surface. Soil temperature and soil volumetric water content (0-0.12 m) were also measured at each point, using a Campbell Scientific HydroSense probe.

In order to calculate the average emission over the whole trapezoid grid, it was divided into 48 triangles. The emission value for each triangle was calculated as the average of its three apical measurement points. The average emission rate of all 48 triangles in the trapezoid was then calculated. This calculation method prevented bias that would have occurred for edge versus non-edge points, if a simple average of the points themselves had been calculated. The emission rates specific to each zone in the plantation were calculated by averaging the emission rates of each sampling point in each zone. Maps of root density, CO₂ emission and soil moisture were produced in ArcMap 10.2 using natural neighbour interpolation from the point measurements.

The effectiveness of determining spatially averaged mean emission rates using fewer sampling points was tested by calculating the mean rate for the whole trapezoid, or each of the

management zones, using different numbers of points. First, the CO₂ emission measurements were randomly ordered, the mean emission rate from one point in each zone (3 points) was calculated for each hexagon and the average value of each trapezoid was calculated. This was repeated for each number of points used to calculate the emission rate, up to the full 35 points of the trapezoid. This procedure was also carried out for each individual zone, using the number of points which happened to be in each zone. The mean emission rates calculated in this way were then compared to the value calculated using all points.

Diurnal variability was investigated by making repeated measurements over a 15-hour period. These measurements were made in one of the palm units in both May and November. Two points from the weeded circle, two points from the frond pile and two points between zones were chosen. Each of these points was measured every thirty minutes between 4:30 am and 7:30 pm on 25/5/2012.

Calculation of carbon inputs and outputs

Soil carbon stocks under mature oil palm plantations on mineral soils have been shown to be near static (Ollagnier *et al.* 1978; Smith *et al.* 2012; Goodrick *et al.* 2015), so we assumed no change in soil carbon content at our study. The rate of root biomass accumulation of palms in plantations has been shown to stabilise to a very low rate by an age of 15 years (Ng *et al.* 1968; Henson and Dolmat 2003), so we assumed it to be zero. Seasonal variation in climate is very small in this location, with negligible variation in temperature and periods of water deficit being rare. Inputs of carbon occur continuously, as the plants are active year round; fronds are pruned at each harvest of fruit, which occurs approximately fortnightly, and roots maintain similar continual activity. In this system, carbon addition to the soil occurs through:

- Placement of pruned fronds on the frond pile,
- growth of oil palm roots and exudation of organic materials by them,
- photosynthate transported to the oil palm roots for maintenance respiration and growth respiration as defined by Amthor (1984),
- litterfall, and root growth, exudation and respiration from ground cover plants.

The carbon input rate from each source was calculated. The application rate of pruned fronds equals the rate of frond production, so records of frond production rate, dry mass and carbon content were taken from a fertiliser trial carried out on an adjacent plantation. In a mature plantation there is continual replacement of the root biomass (Corley and Tinker 2003) but we presume root biomass is relatively constant at maturity and root growth rate can be equated to root death rate. The rate of root growth (and death) was calculated from measured root density

and the annual rate of turnover, taken as 15% for large roots and 57% per year for small roots according to Henson and Dolmat (2003), based on observations by Dufrene (1989). Root maintenance and root growth respiration were calculated separately using the methods described by van Kraalingen *et al.* (1989) using measured root nitrogen and mineral contents. As most light is intercepted by the mature oil palm canopy, most of the net primary production (NPP) and carbon input to soil will be from the oil palms rather than groundcover plants (Huth *et al.* 2014). Groundcover NPP was estimated from observed groundcover canopy cover, daily average solar radiation observations from 2008 to 2013 from the *NASA Prediction of Worldwide Energy Resource (POWER)* records (NASA 2014), interception of 29% of total solar radiation (not consumed by the palm canopy) (Henson and Dolmat 2003), and a radiation use efficiency (dry matter production) of 1.3 g MJ⁻¹ (Huth *et al.* 2014).

The total carbon additions from the calculations above were then spatially allocated across the representative trapezoid grid according to measured distributions of pruned fronds and roots. Inputs delivered by roots (root turnover plus maintenance and growth respiration) were spatially allocated according to average root density at each point. The carbon inputs from root turnover were allocated separately according to large and small root densities. Root maintenance and growth respiration were allocated according to total root biomass, despite the likelihood that fine roots respire more than large roots (Desroches *et al.* 2002, Makita *et al.* 2012), because of a lack of published data about relative respiration of large and small roots. Allocation of input from fronds was calculated from the probability of the frond pile occurring at each point. Ground cover plants grew in the between zones and frond pile zones but not the weeded zone, so groundcover-derived inputs were spatially allocated accordingly. The carbon inputs from each source were summed to give the total carbon input at each point.

Using correlation analysis in SPSS, the CO₂ emissions from soil at each grid point were then correlated with; soil temperature, soil moisture, soil total root density, and calculated carbon inputs at the corresponding point. The spatial correlation was carried out with and without the root respiration (growth and maintenance) estimate, to test the significance of this parameter for the total budget.

3.3 Results

Soil CO₂ emissions were highest in the frond piles and lowest in the between zones area (Figure 11). Roots were concentrated beneath the palm trunk, with the density of roots at all other locations being very small in comparison (Figure 9). Soil moisture tended to be highest around the harvest path area and lowest near the trunk (Figure 10). The deviation of calculated overall mean emission rate from the rate calculated using all measured points reached values less than

5% when 24 or more points were included (Figure 12). Considering the management zones separately, the deviation reached less than 5% with more than 10 points for the between-zones area and 9 points for the weeded circle. The frond pile was most variable; any less than the maximum measured number of 13 points resulted in a deviation greater than 5%. . The emission rate of all zones combined appears to be well represented by the 35-point trapezoid, with the deviation being fairly low and constant with more than 25 points. Soil emission rates showed some diurnal variation. There was an increase from 7.5 to 9.3 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ between 7:30 am and 1:30 pm in May (Figure 13). The increase at 5:30 pm occurred after a period of rainfall.

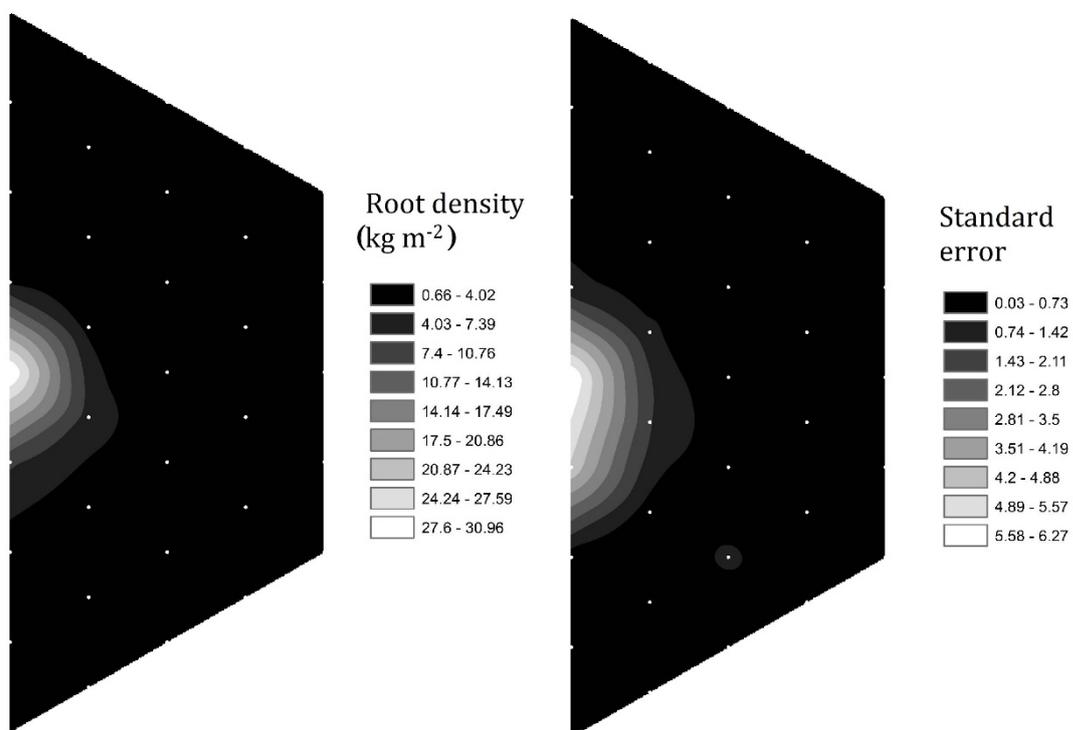


Figure 9: Root density (dry weight to 2m depth), showing mean (n=4) and standard error. The palm trunk is at the centre of the left side of the trapezoid, frond pile is in the lower area, harvest path is in the upper area, and the white dots are the measurement locations.

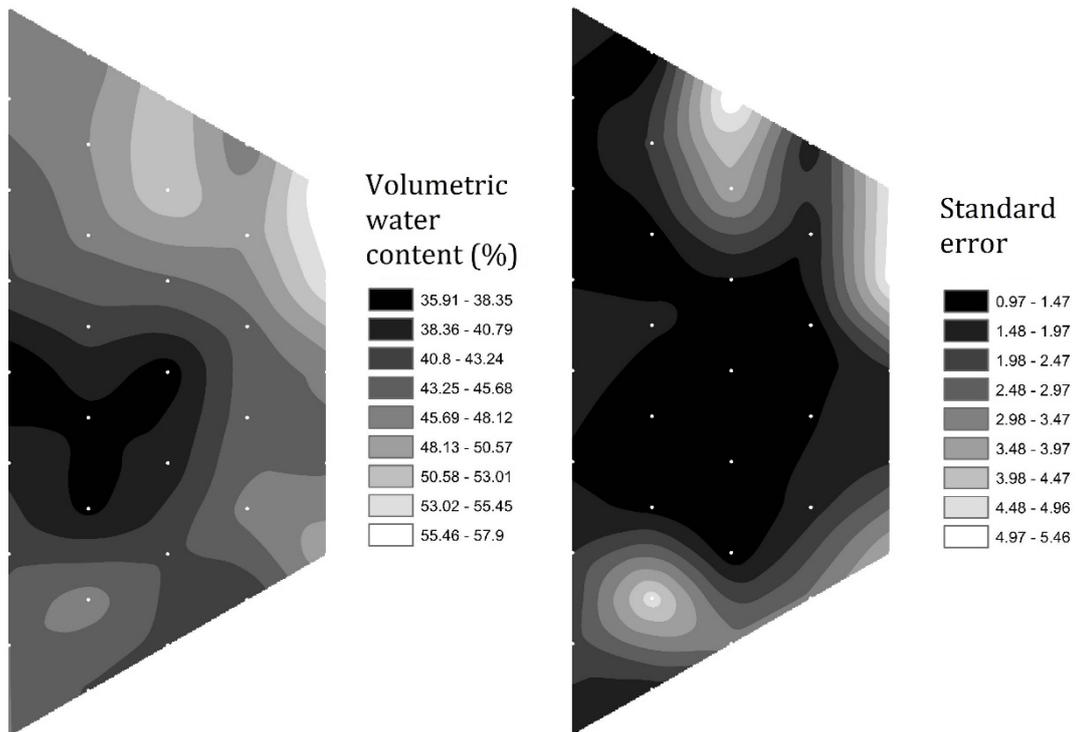


Figure 10: Soil volumetric water content (0-0.12 m depth), showing mean (n=16) and standard error. The palm trunk is at the centre of the left side of the trapezoid, frond pile is in the lower area, harvest path is in the upper area, and the white dots are the measurement locations.

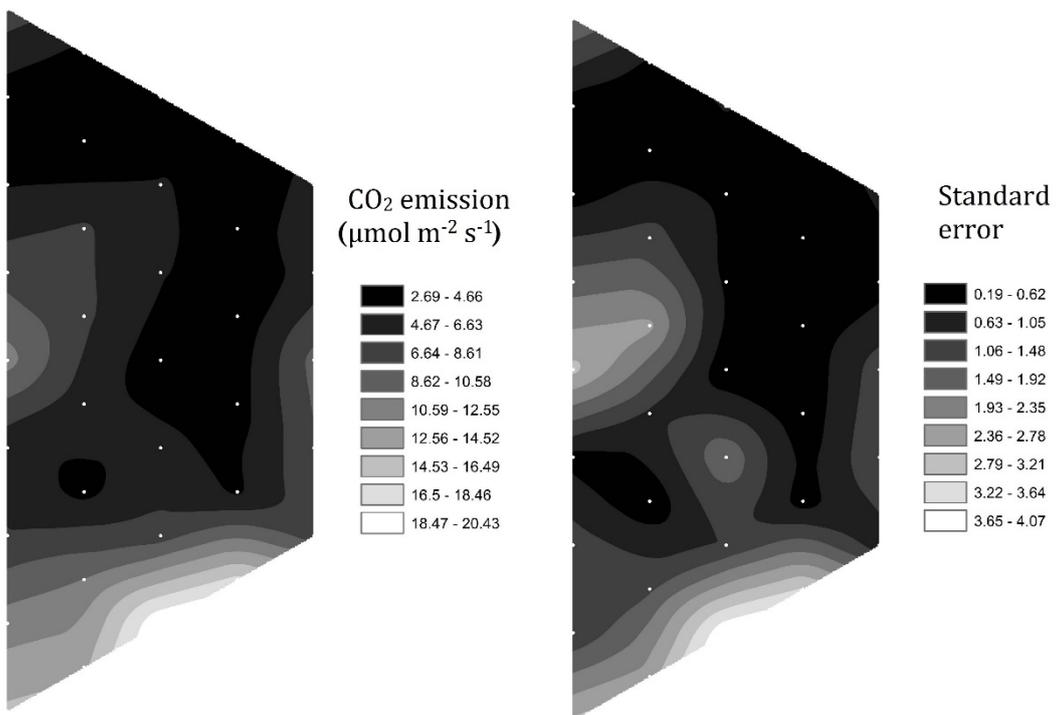


Figure 11: Soil CO₂ emission, showing mean (n=16) and standard error. The palm trunk is at the centre of the left side of the trapezoid, frond pile is in the lower area, harvest path is in the upper area, and the white dots are the measurement locations.

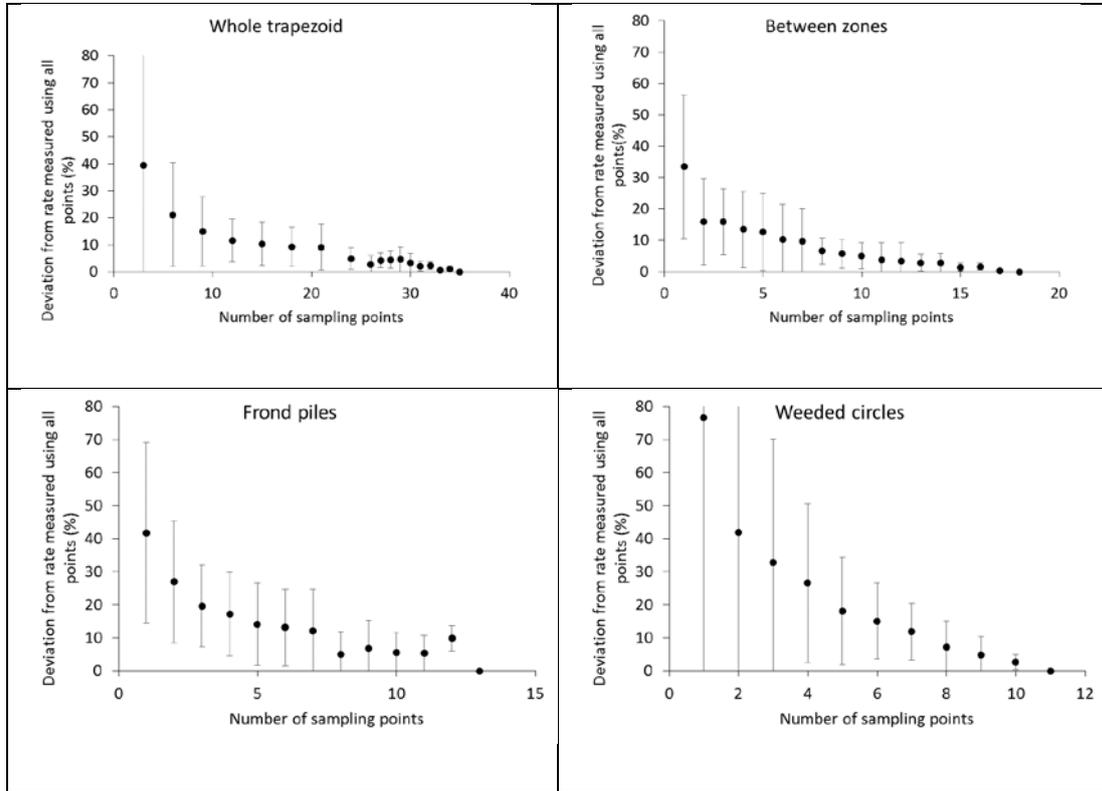


Figure 12: Effect of the number of measurement points on the mean calculated CO₂ emission rate, expressed as deviation from the value calculated using all measurement points, for the whole grid, between zones area, frond piles and weeded circles.

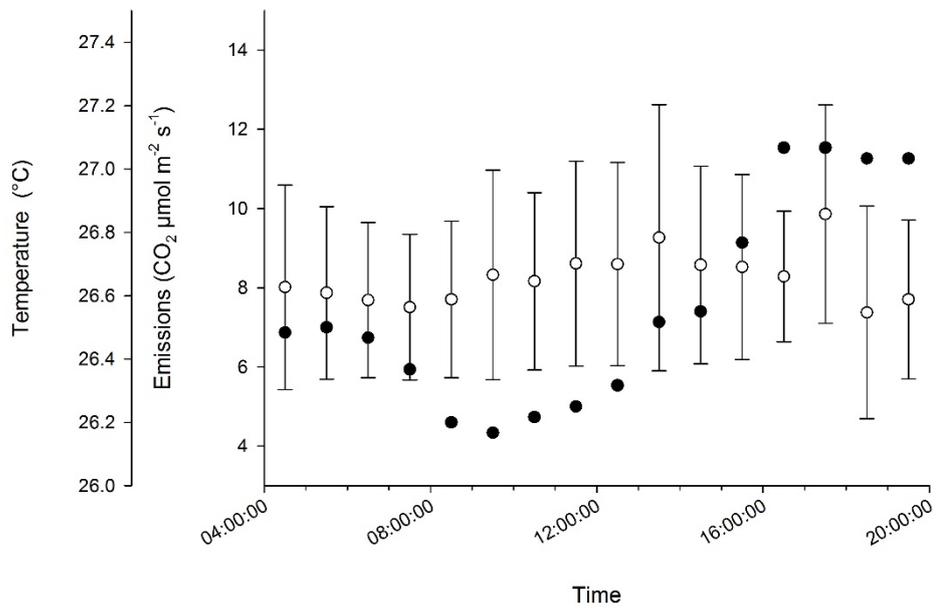


Figure 13: Average soil CO₂ emission (hollow data points) and soil temperature at 0-0.12 m depth (black data points) over the course of a day in May (n=6, 2 points from each zone) repeated every half hour. Error bars are the standard deviation from the mean.

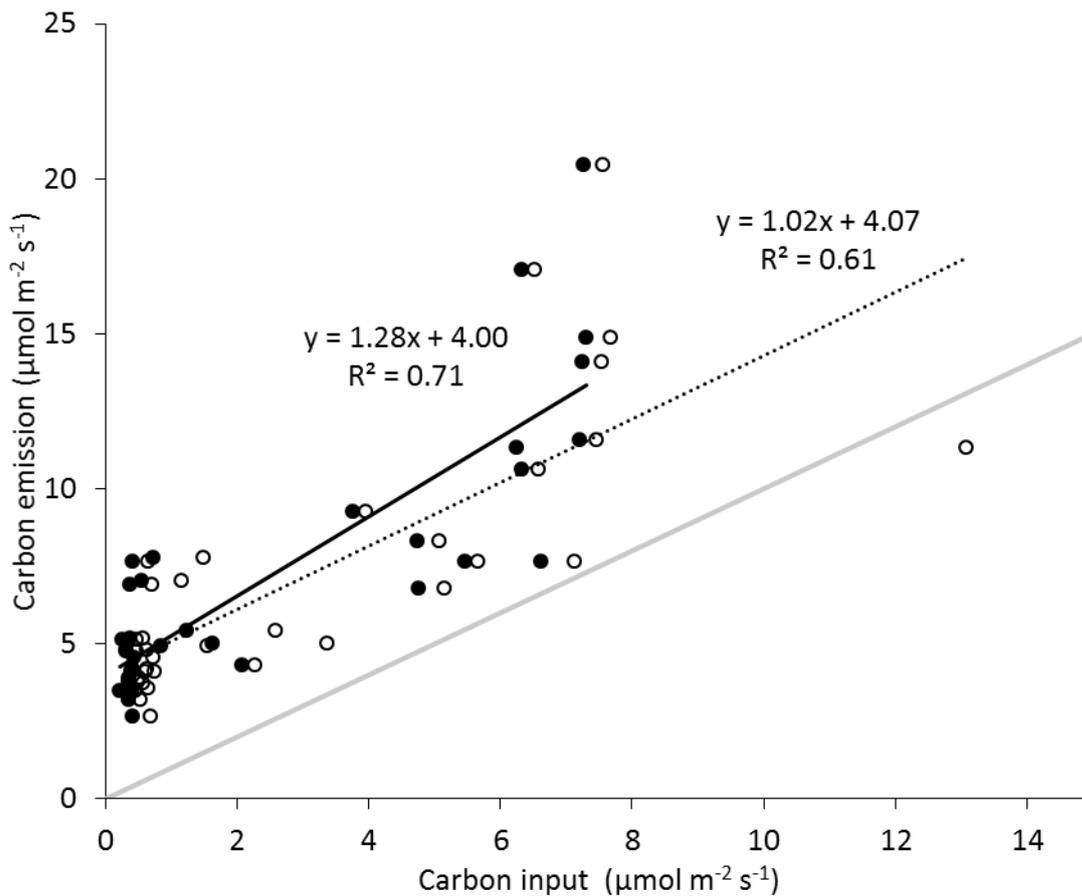


Figure 14: Relationship between carbon inputs to soil and outputs from soil, at each point of the sampling grid. Black data points and solid black line indicate carbon inputs, including fronds, root turnover and ground cover. Hollow data points and dashed line indicate carbon inputs including fronds, root turnover, root maintenance, root growth and ground covers. Dotted line shows a 1:1 relationship.

Table 4: Soil CO₂ emission rates by season and zones of plantation.

	CO ₂ emission rate (μmol m ⁻² s ⁻¹)	Standard error	N
All measurements	7.24	0.31	526
May	7.61	0.38	248
November	6.92	0.47	278
Weeded circle	6.18	0.52	152
Between zones	4.50	0.19	225
FronD pile	12.53	0.81	148

Table 5: Calculated rates of carbon inputs to soil.

Input source	Carbon addition rate ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$)
Pruned fronds	1.82
Root turnover	0.51
Root maintenance respiration	0.04
Root growth respiration	0.52
Groundcover NPP	0.14
Total	3.02

Table 6: Correlation analysis between CO₂ emission rates and measured variables. n=35.

Variable	Spearman's coefficient	p value
Total root density	0.354	0.037
Carbon inputs (excl. root respiration)	0.773	0.000
Carbon inputs (incl. root respiration)	0.803	0.000
Moisture	-0.207	0.233
Temperature	0.134	0.443

Emissions of CO₂ were three times greater in the frond piles than between-zones areas of the plantation and differed slightly between the two measurement periods (Table 4). Pruned fronds constituted the largest carbon input to the soil (Table 5). Root respiration (the sum of growth and maintenance respiration), accounted for 19% of total carbon inputs to soil. The correlation analysis of emissions with measured and calculated variables indicated that the calculated carbon inputs were the strongest predictor of emission rates (Table 6).

Relationship between carbon inputs to soil and outputs from soil, at each point of the sampling grid. Black data points and solid black line indicate carbon inputs, including fronds, root turnover and ground cover. Hollow data points and dashed line indicate carbon inputs including fronds, root turnover, root maintenance, root growth and ground covers.

Measured outputs of carbon from soil via respiration were greater than calculated inputs, with an intercept of $4.1 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (Figure 14). The data sets inclusive and exclusive of calculated root turnover and root growth are presented because these carbon fluxes are most dependant on assumptions. The slope of the input-output relationship was not significantly

different from a 1:1 relationship. The relationship was driven mostly by frond inputs of carbon, which account for 60% of the total. Frond inputs were also the most reliably quantified of the inputs. The points with high input rates were mostly in the frond piles, except for the point under the trunk, which had very high root-derived carbon inputs. Of the total carbon inputs, root inputs, including turnover, maintenance respiration and growth respiration, accounted for 36% and groundcover inputs for 4%. The calculation of root inputs is open to more error than the other components because of uncertainties in the assumptions of the calculation and uncertainties in the assumptions controlling the spatial allocation of the inputs.

3.4 Discussion

The calculated mean soil CO₂ emission rate in this study was at the upper end of those reported in the literature (Table 7). This may be due to the plantation of our study being highly productive; the environment received evenly distributed rainfall, had young soils and optimal temperatures for growth. In comparison, Ishizuka *et al.* (2002) attributed the very low rate they measured (Table 7), to the soils being compacted. Furthermore, our sampling methodology had greater spatial resolution than previous studies and therefore provides the most spatially representative result to date. All comparable studies used fewer measurement points and were thus less likely to have adequately accounted for spatial variability. The relationship between the number of sampling points per palm and the deviation of the resulting rate from the most thoroughly measured rate (Figure 12) indicated that fewer than 20 sampling points will give a deviation of 0.5 $\mu\text{mol m}^2 \text{s}^{-1}$ per palm, approximately 9% for our study site. The main cause of this error is the high spatial variability of emissions from the frond pile zones; the maximum sampling point density used may not have adequately represented the variability of this zone (Figure 12). Random error in soil CO₂ emission observations are known to increase with the magnitude of emissions (Cueva *et al.* 2015), so it follows that to account for the variability of the frond pile zone, a higher density of measurement points is needed. The relative uniformity of the between-zones area and weeded circles (Figure 12), meant that less points are required to adequately account for spatial variability of these zones than under the frond pile. Using a different sampling density in different zones means that the areas of the zones must be measured accurately in order to calculate an area-weighted average. An alternative approach to adequately account for spatial variability is to use the linear transect approach proposed by Nelson *et al.* (2015). It can provide similar or better representation of spatial variability than the grid approach used here, but it is much less time-consuming to set up and covers a larger area.

Table 7: Comparison of CO₂ emission rates calculated in other studies on mineral soils.

Publication	Soil type, location	<i>n</i>	Emission in reported units	Standard Deviation (mg CO ₂ m ⁻² h ⁻¹)	mg CO ₂ m ⁻² h ⁻¹
Lamade <i>et al.</i> 1996	Ferralsol, Benin	-	3.2 to 10 μmol CO ₂ m ⁻² s ⁻¹	-	506 to 1584
Ishizuka <i>et al.</i> 2002	Indonesia	3	57 mg CO ₂ m ⁻² h ⁻¹	13	57
Ishizuka <i>et al.</i> 2005	Udults/Entisol/Ultisol, Indonesia	14 & 21	1.88 to 3.12 g C m ⁻² d ⁻¹	73-185	287 to 477
Melling <i>et al.</i> 2005	Peat, Malaysia	36	46 to 335 mg C m ⁻² h ⁻¹	-	167 to 1228
Adachi <i>et al.</i> 2006	Malaysia	16	966 mg CO ₂ m ⁻² h ⁻¹	577.7	966
Smith <i>et al.</i> 2012	Malaysia	189	679.2 mg CO ₂ m ⁻² h ⁻¹	462.6	679.2
Mande <i>et al.</i> 2014	Ultisol, Malaysia	30	3.259 μmol CO ₂ m ⁻² s ⁻¹	355.3	516.3
This study	Volcanic, Papua New Guinea	526	7.24 μmol CO ₂ m ⁻² s ⁻¹	1162.4	1146.8

Our calculations were based on measurements from two week-long periods in one year, which may not have been long enough to represent the yearly average. However, our measurements were more temporally extensive than previous studies, with the exception of Melling *et al.* (2005), who made monthly measurements over the course of a year in peat soils. There was some temporal variability in CO₂ emissions, as speculated by others (eg. Smith *et al.* 2012). However, the similarity between the May and November emission rates (Table 4) indicates that seasonal variation was small at this site. There was also little difference in soil moisture between the two sampling periods. This is likely related to the rainfall events immediately preceding sampling and the reasonably even distribution of annual rainfall at this site (Figure 8) and the well-drained nature of the soil. There was some diurnal variability in soil CO₂ emission in this study (Figure 13). Noticeable increases in emissions during rainfall periods such as at the end of the diurnal observation period may be explained by a combination of improved conditions for biological activity and the purging of gases contained in empty pore spaces caused by infiltrating water (Rochette *et al.* 1991, Luo and Zhou 2006). More thorough sampling at night could probably determine the factor by which emissions decrease at night.

Soil CO₂ emissions and inputs were highly variable in space. Spatial variability in agricultural systems have been attributed to factors such as root density and soil compaction, which are systematically arranged in agricultural systems (Rochette *et al.* 1991), but our study is the first to spatially relate emissions to carbon inputs. The significant 1:1 relationship between carbon inputs and outputs indicates that emission rate was determined by carbon addition rate at each point, rather than the nature of the inputs or the depth at which they were added, or environmental conditions such as moisture and temperature (Figure 14). This conclusion corresponds with modelling studies using a range of carbon inputs in a range of environments (Yang and Janssen, 2000). However, there was a tendency for points dominated by frond pile-derived carbon to have higher-than-modelled outputs, which may indicate that carbon additions to the soil via fronds are more easily mineralised than additions via roots. Alternatively, it may reflect that carbon inputs via roots are underestimated. Soil moisture has been correlated with emission rates in another study with smaller sample size (Mande *et al.* 2014) but no relationship between CO₂ emission and soil moisture was found in our study.

The strong correlation between carbon emissions and inputs demonstrates that spatial variability is largely controlled by carbon inputs from frond pile material (Table 5). This is because most of the carbon input is via fronds and these inputs are concentrated into the small area of the frond piles. This concentration of inputs corresponds to the spatial distribution of soil carbon measured in other studies (Haron *et al.* 1998, Goodrick *et al.* 2015). The result is the creation of a zone where the mass of decomposing organic matter provides ample food for soil heterotrophs and high rates of CO₂ emission. This spatial congruence of residue inputs, high soil carbon content and high CO₂ emissions has been noted in previous studies of emissions from oil palm plantations (Lamade *et al.* 1996), although one recent study, by Smith *et al.* (2012), found otherwise. They found that respiration was most related to root density. However, that study employed a 9-point measurement grid with 10-m spacing, which mostly excluded frond piles. In temperate forests root carbon inputs have been shown to dominate soil emission rates (Hogburg *et al.* 2001). This difference between tropical and temperate systems is likely due to different ratios of root activity to NPP.

Although the relationship between carbon inputs and outputs was significant, there were also considerable deviations from this pattern, particularly at higher values (Figure 14). Some of the differences are likely to have been due to our allocation system for frond-derived carbon inputs. We allocated frond carbon inputs according to the probability of a frond pile occurring at that point in the sampling grid. However, even though the frond pile would always occur at two particular points, they could individually have different actual frond input rates. Estimated inputs at the point immediately adjacent to the trunk were high, due to the high root density

beneath the trunk. However, measured emissions from this point are lower than the predicted values; it appears as an outlier on Figure 14. This discrepancy may be due to differences in respiration between root types or preferential transport of soil-respired CO₂ along pathways close to the palm trunk rather than being emitted evenly from the soil surface. Maintenance respiration per unit of tree biomass (including roots) must decrease with age because tissues become divided into two sections differing in physiological functioning (van Kraalingen *et al.* 1989). From a study of the morphology of palm roots, Ruer (1967) proposed that larger and deeper roots are more important for anchorage than obtaining nutrients. Observations by Parthasarathy (1968) described oil palm trunks as having ‘callose and outgrowths of adjacent parenchyma cells which is proof of an internal deterioration of the trunk and therefore a decrease in activity’. The process of lignification and decreasing metabolic activity presumably also applies to the root mass directly under the tree, which like the trunk, has a mainly structural function. A largely structural root mass with low metabolic activity provides explanation for the outlier on the graph and would justify decreasing the allocated maintenance emission to that point. In addition, it is possible that roots distant from the trunk are more active, performing functions requiring relatively more energy, therefore receiving and respiring more (per unit root mass) of the carbon allocated belowground by the palms than roots closer to the trunk. The predictive power of the carbon input model would be strengthened if less carbon was allocated to roots with structural roles and low metabolic activity. In addition, the measurement of respiration rates and root density adjacent to the tree is prone to greater error than other zones of the plantation because of the high respiration rates and root densities encountered there. These errors may be compounded in our model of carbon inputs. More direct measurements of root respiration in oil palm systems are warranted, for example using in-situ chambers (Snell *et al.* 2015). Although our investigation showed little temporal variability in total emission rates, emissions originating from the different sources may have significant temporal variability. Emissions originating from frond materials would be temporally stable but root respiration rates are known to vary diurnally (Huck *et al.* 1962). Information of diurnal variation in root-related carbon transport in oil palms could improve our method of relating variability of carbon inputs and emissions.

Overall, the measured emission of carbon from soil via respiration was $4.1 \mu\text{mol m}^{-2} \text{s}^{-1}$ greater than the estimated inputs (intercept of Figure 14). In summary, possible explanations for this discrepancy are:

1. Error in estimation and positioning of some of the carbon inputs. Root-related carbon inputs are more likely to be the source of error than frond inputs, as calculation of the latter was comparably straightforward. The calculation of root

respiration is notoriously difficult to verify. Our measurements and estimates resulted in root respiration being 36% of soil CO₂ emission, which is within the range reported for crop systems in other studies (Raich and Tufekcioglu, 2000). Our root-related input estimates were also similar to those in two previous analyses of carbon cycling in oil palm plantations. Henson and Dolmat (2003) calculated that carbon delivered to soil by roots amounted to approximately 2.69 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for a plantation of comparable planting density, on peat soil, slightly less than our estimate of 3.02 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Lamade *et al.* (1996), who measured carbon allocation to oil palm roots in Benin using a completely different method, reported a higher value. They calculated a total carbon allocation to roots of 3.82 $\mu\text{mol m}^{-2} \text{s}^{-1}$, comprised of 0.94 $\mu\text{mol m}^{-2} \text{s}^{-1}$ in root turnover and 2.88 $\mu\text{mol m}^{-2} \text{s}^{-1}$ root respiration. Allocation of carbon to roots might be expected to be higher at our study site than theirs, due to better growing conditions at our site.

2. Overestimation of CO₂ emissions. Emissions were measured during two relatively short periods, and it is possible that they did not represent emissions over the course of a year. Small diurnal variation in emissions was identified, this should contribute error to the model.
3. Emissions from decreasing native soil carbon stocks. This is not likely as carbon stocks are shown to be stable or increasing for mineral soils under mature oil palm (Goodrick *et al.* 2015, Smith *et al.* 2012, Frazao *et al.* 2013). Ollagnier *et al.* (1978) showed that soil C content declined following deforestation but had more-or-less stabilised by 14 years of age. A similar trend could be expected following felling of the previous oil palm crop, with oil-palm derived carbon decomposing at least as quickly as forest-derived C.
4. Carbon inputs via sources unaccounted for by our methodology. Applications of EFB would partially contribute to the unaccounted CO₂ emissions, but inputs are intermittent and small. Some other source of carbon is possible, such as carbon fixation by chemoautotrophic bacteria or Archaea, such as nitrifiers, but the amounts are also likely to be small (Miltner *et al.* 2005), or legacy emissions from organic matter in soil horizons buried under more recently deposited volcanic material.
5. Emission of CO₂ from non-biological processes such as geothermal or volcanic CO₂ degassing (Rey 2014).
6. Inaccuracy in our measurements due to calculation of annual averages from two weeks of sampling.

3.5 Conclusions

Soil carbon inputs and losses were highly spatially variable at the tree scale in this oil palm plantation, due mostly to the positioning of pruned fronds, but also to heterogeneity in root distribution. Average emission of CO₂ from the soil across the repeating unit of the plantation was 7.24 μmol m⁻² s⁻¹. This is at the upper end of all estimates previously reported for oil palm, probably due to high NPP at this site, and our high-resolution measurement regime that accounted for frond piles. Measurement of carbon inputs and outputs at coarser spatial resolution than we employed is likely to produce inaccurate and low estimates of fluxes. Higher resolution sampling in the frond pile zone is likely to produce higher and more accurate estimates. A spatially uniform net carbon loss was attributed to errors in the flux estimates, with several possible sources of error. An underestimate of root-related inputs seems likely because of the many assumptions involved. However, our estimates of root-related inputs were similar to estimates made by others, using different approaches. Finally, the high spatial correlation between carbon inputs and outputs in this study suggests that mineralisation rate is controlled by the amount rather than nature or input depth of the additions.

3.6 Summary

Soil carbon fluxes are highly variable in space and time under tree crops such as oil palm, and attempts to model such fluxes must incorporate an understanding of this variability. In this work we measured soil CO₂ emission, root biomass and pruned frond deposition rates and calculated carbon fluxes into and out of the soil in a mature (20-yr old, second planting cycle) oil palm plantation in Papua New Guinea. Tree-scale spatial variability in CO₂ emission and root biomass was quantified by making measurements on a 35-point trapezoid grid covering the 38.5 m² repeating unit of the plantation (n=4 grids). In order to obtain an overall mean soil CO₂ emission rate within 5% of the most accurate estimate, 24 or more measurement points were required. Soil CO₂ emissions were spatially correlated with calculated carbon inputs (r² 0.605, slope of 1:1). However, outputs were higher than inputs at all locations, with a mean overall output of 7.24 and input of 3.02 μmol m⁻² s⁻¹. Frond-, root- and groundcover-related inputs constituted 60, 36 and 4% of estimated inputs, respectively. The spatial correlation of carbon inputs and outputs indicates that mineralisation rate is controlled mostly by the amount rather than nature or input depth of the additions. A spatially uniform net carbon loss was attributed to unknown fluxes or errors in calculated estimates, of which root-related inputs involved the most assumptions.

4. Mineralisation of soil organic carbon in two Andisols under oil palm: an incubation study into controlling factors

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4.1 Introduction

Soil carbon in the tropics is important for the global greenhouse gas balance, and also as a determinant of soil quality. Substantial decreases in soil carbon stocks have occurred and will continue to occur in the tropics, due to changes in land use, high initial stocks, and high potential rates of decomposition (Greenland *et al.* 1992; Don *et al.* 2011). One land use change that has come under particular scrutiny over recent years is the expansion of the oil palm industry, partly because its scale means there are potentially global carbon balance implications (Lamade and Bouillet 2005; Sayer *et al.* 2012). In addition to land use change, a warming climate is likely to increase the ratio of soil carbon mineralisation to inputs, thus decreasing soil carbon stocks (Greenland *et al.* 1992). Finally, changes in soil carbon stocks depend not only on land use and climate, but also on the nature of the soil itself. Soils of the tropics vary enormously, but volcanic ash soils are particularly important because of their relatively common occurrence in the tropics, high fertility and exploitation, and peculiar physical and chemical properties (Shoji *et al.* 1994).

To predict how stocks of carbon in any particular soil will be influenced by changes in land use, management or climate, carbon cycling models must be employed. Models must mimic the decrease in mineralisation rate that occurs after each addition of organic matter. They generally do so either by treating each cohort of added materials as one pool whose turnover rate decreases with time, or by treating the soil organic carbon as several discrete pools, each with a unique turnover rate, with carbon losses from each pool being apportioned to mineralisation and transfer to another pool (Smith 2006). Soil organic matter is a

heterogeneous mixture of materials along a continuum of mineralisability, often grouped as labile, intermediate and passive. Most of the soil carbon is generally thought of as being intermediate in mineralisability (Townsend *et al.* 1997).

The mineralisibility of organic matter can be quantified using various approaches. One approach is to measure the amount of mineralisation when the organic matter is exposed to chemical oxidants such as potassium permanganate. Another is to quantify molecules or structures known to differ in recalcitrance, for example using spectroscopic techniques. Alternatively, mineralisation rate can be determined directly in incubations. Doing so at a range of temperatures gives more information about the nature of the substrates (Kirschbaum 1994; Conant *et al.* 2011). Reaction kinetics show that mineralisation of recalcitrant substrates is more sensitive to temperature (requires higher activation energy and has higher Q_{10}) than mineralisation of labile substrates, and because recalcitrant substrates are abundant in soil, the balance between the two can influence overall temperature sensitivity of soil organic matter mineralisation (Davidson and Janssens 2006). However, temperature sensitivity does not necessarily increase with depth or decrease when labile substrates are added, so chemical recalcitrance alone does not explain observed variations in temperature sensitivity of soil organic matter decomposition (Pang *et al.* 2016). Temperature sensitivity is also important for predicting the changes to soil carbon stocks under warming climatic conditions (Kirschbaum 1994).

Soil carbon turnover rates of tropical soils cover a wide range. They have often been described as comparatively rapid (Ayanaba and Jenkinson 1990; Feller and Beare 1997) and high emission rates have been reported, for example, up to 15.5% of soil carbon emitted as gas over a year for high carbon content allophanic soil (Motavalli *et al.* 1994), and up to 9% emitted over 4 weeks in soil from the dry tropics (Chander *et al.* 1997). However, such high turnover rates may not be universal for tropical soils, and recent studies have found soil stocks under oil palm cultivation to be quite stable (Smith *et al.* 2012; Goodrick *et al.* 2015a). Poorly crystalline Al and Fe oxides and allophane, which are relatively common in tropical soils, especially soils formed in recent volcanic ash, are known to interact intimately with organic matter, increasing its stability against decomposition (Torn *et al.* 1997; Baldock and Skjemstad 2000; Mikutta *et al.* 2006). The total soil carbon stabilisation capacity of soils is related to the formation of organo-mineral complexes, with total mineral surface area and soil pH as the strongest determinants of total capacity (Beare *et al.* 2014). Furthermore, in oil palm plantations the amount, cycling and perhaps nature of soil carbon is particularly variable in space (Nelson *et al.* 2014b; Goodrick *et al.* 2015b). The high tree-scale spatial variability of respiration measured in the field (Goodrick *et al.* 2015b) may be due to root respiration, to

variability in environmental conditions (which are usually confounded in the field), or to variability in the nature of the soil organic matter.

The aim of this work was to determine the factors controlling the mineralisability of the intermediate-stability carbon fraction of surface soils from oil palm plantations on recent volcanic ash soils. We hypothesised that soil carbon turnover rate is related to the content of carbon (total and chemically labile) and organic matter-associated aluminium, iron and silicon, and the Q_{10} of respiration. We tested the hypotheses by sampling soils from two depths (0-5 and 15-20 cm) and a range of management regimes, incubating them at optimum temperature and moisture over a 32-month period with no input of fresh organic matter, and examining relationships between respiration and soil properties.

4.2 Methods

Soil samples were collected from smallholder oil palm plantations in the two major oil palm growing regions of Papua New Guinea, one at Kimbe and another at Popondetta. Average annual rainfall is approximately 3250 mm at Kimbe and 2380 mm at Popondetta. Both sites are on a coastal plain with humid tropical climate and volcanic ash soils (Bleeker, 1983). The Kimbe site, sampled on 18 May 2010, had been forest until being planted with oil palm in 1988. Its location is 5°37.2'S 150°9.7'E, its smallholder block number is 1613 and it was called Site 17 in the work of Nelson *et al.* (2014). The Kimbe soil is an Andisol developed in air-fall tephra consisting of predominantly amorphous material (glass) and plagioclase, with pumice layers and some allophane at depths below 0.2 m. The Popondetta site, sampled on 22 May 2010, had been grassland until being planted with oil palm in 1985. Its location is 8°47.9'S 148°23.8'E, its smallholder block number is 881111, and it was called Site 1 in the work of Nelson *et al.* (2014a) and Goodrick *et al.* (2015a). The Popondetta soil is a sandy Andisol formed in alluvially redeposited tephra, with mineralogy dominated by albite/anorthite and cristobalite, and amorphous material (glass) being a minor component.

At both sites, soil samples were collected from two depth intervals (0-5 cm and 15-20 cm) under the frond piles (FP, the area in alternate rows of the plantation where cut fronds are piled). At Popondetta, samples were also collected from the 'between zones' (BZ) area, which comprises most of the plantation area, and which is covered with herbaceous understory, with minimal weeding and no input of pruned fronds. There was a total 24 samples, which included 4 replicates of each management zone and depth. Each sample was collected adjacent to one palm, with the four replicate samples collected at separate palms in a representative part of the plantation. All replicate samples were kept separate for all subsequent manipulations and analyses, to obtain a representation of spatial variability in

the field. Frond pile samples were collected at both sites because the FP is the most active part of the plantations in terms of carbon cycling (Goodrick *et al.* 2015b). Under the FP, the soil surface was defined as the plane below which there were no more large (>2 cm) pieces of decomposing fronds. There was a great deal of humus and living roots above this plane. Samples were taken using steel rings (6 rings of 5-cm diameter and 5-cm length at each sampling point), placed in plastic bags and transported to Australia in field-moist condition. Roots greater than 1 mm in diameter and 20 mm in length were removed by hand. The initial soil properties are presented in Table 8. The Kimbe soils contained more organic matter, had much lower bulk density, and therefore had less mass of sample in the jars for incubation. Field capacity was determined by adding water to the top of a column of dry soil (insufficient to wet the whole column), allowing it to equilibrate, and then measuring the water content of the upper portion of wetted soil (Olmstead, 1937). Field capacity water content was 30% and 25% for the shallow and deep Popondetta soils and 155% and 66% for the shallow and deep Kimbe soils, respectively. During the incubation the samples were maintained at between 80% and 100% of field capacity by additions of Milli-Q (high purity) water at approximately fortnightly intervals. On 2 June 2010 the samples were divided into three portions, one third of each sample (treatment T0) was immediately air dried and stored dry, the other two treatment groups were incubated at 30°C for 341 days (T1) or 1062 days (T2). The incubated soils were contained in glass jars with lids unscrewed but resting on the jar to reduce drying but allow gas exchange. The Kimbe soils appeared visibly drier than the Popondetta soils during the incubation, probably because of their higher water holding capacity and lesser mass of soil which dried slightly quicker during the fortnight between wetting. The samples were designated 'Pop' for Popondetta, 'Kim' for Kimbe.

Table 8: Soil properties at the start of the incubation.

Soil	Soil field texture	pH	Total carbon content (%)	Bulk density (g cm ⁻³)	Dry mass of soil incubated (g)
Kimbe FP 0-5 cm	Clay loam	6.17	27.44	0.72	32
Kimbe FP 15-20 cm	Sandy clay	6.59	9.25	0.93	82
Popon. FP 0-5 cm	Loam	6.92	6.48	1.11	158
Popon. FP 15-20 cm	Sandy loam	5.95	4.74	1.15	173
Popon. BZ 0-5 cm	Loam	5.90	5.27	1.20	175
Popon. BZ 15-20 cm	Sandy loam	5.55	5.01	1.28	186

Soil CO₂ emission was measured with a Licor portable infrared gas analyser (LI-8100, LICOR, Lincoln, NE, USA), which was fitted to the lid of the glass jars via an airtight seal. All measurements were carried out at 25° within the incubator to prevent the sudden change in temperature affecting emission rates. A small fan was hung inside the jars to ensure adequate mixing and the emission rates were calculated accounting for the volume of airspace of the jars. Emission measurements were carried out over a 2.5 minute period at 54, 85, 341, 379 and 812 days of incubation. Respiration was not measured during the initial phase of the incubation so as to avoid the effect of labile forms of carbon and disturbance (Giardina and Ryan 2000). One day prior to emission measurements, soils were wetted to ensure they were at close to 100% of field capacity. Carbon turnover rate at each time of measurement was determined by dividing the emission rate of carbon (as CO₂) by the soil's total carbon content at the time.

Temperature sensitivity of mineralisation was measured at days 377-381 and 810-814 of incubation, by measuring emission rates at different incubation temperatures. Soils were pre-incubated at 5, 15, 25, 35 and 45°C for one day each, prior to the measurement of CO₂ emissions at each of these temperatures. This method ensured that the same suite of substrates and organisms was present during the assessment of temperature sensitivity,

unlike approaches in which a range of temperatures is established for the whole incubation. The relationship between temperature and respiration was modelled using equations given by Lloyd and Taylor (1994). The van't Hoff equation

$$R = \alpha e^{\beta T} \quad \text{Equation 1}$$

where R is the microbial respiration rate ($\text{mg CO}_2 \text{ g}^{-1} \text{ h}^{-1}$), T the soil temperature ($^{\circ}\text{C}$), and α and β are fitted coefficients, was fitted to the emission data. The temperature sensitivity of soil respiration can be expressed as the factor by which respiration rates increase under a 10°C rise in temperature (Q_{10}). The Q_{10} value for the whole curve was calculated using the equation

$$Q_{10} = e^{10\beta} \quad \text{Equation 2}$$

Total carbon (TC) content and stable isotope composition of the soils were measured by combustion with a Costech elemental analyser coupled to a Delta-V plus stable-isotope ratio mass spectrometer. The stable isotope results are reported as $\delta^{13}\text{C}$ values, being ‰ deviations from the Vienna Pee Dee Belemnite reference standard. The precision (SD) on internal standards for analysis was better than ± 0.2 ‰ ($\delta^{13}\text{C}$ values), and $\pm 2\%$ of the value (abundance values). Potassium permanganate-oxidisable carbon (POC) content of the T0 and T1 soils was measured with 0.033 M KMnO_4 , according to Rayment and Lyons (2011). Samples were centrifuged at 500 rpm rather than being left to stand for 5 minutes, to allow easier removal of the supernatant as the quantities of soil and reagent used were small. Absorbance was measured at 550 nm using a VWR spectrophotometer.

Diffuse reflectance Fourier transform infrared (FTIR) absorbance spectra of the pre-incubation 0-5 cm depth samples were measured using a Bruker Alpha R instrument according to the method of Baldock *et al.* (2013). For analysis, the dry and finely ground samples were packed in cups and the surface was scraped smooth and level with the cup edge. No other sample preparation was performed. Absorbance in the $1600\text{-}1740 \text{ cm}^{-1}$ region was attributed to carbonyl and carboxyl groups and absorbance at 1081 cm^{-1} was attributed to C-O-C groups. Thus the ratio of one to the other (B/C) was taken as an indication of relative carbonyl plus carboxyl content of the organic matter (Ellerbrock and Gerke 2004).

Acid oxalate-extractible Al, Fe and Si contents (Al_{ox} , Fe_{ox} and Si_{ox}) of the pre-incubated soils were measured by ICP-AES analysis of extracts prepared according to Rayment and Lyons (2011). The acid oxalate reagent extracts Al, Fe and Si from poorly crystalline minerals and organic matter.

The effects of location (including site and management zone) on measured parameters were tested using ANOVA and the more conservative Levene's test of equality of error variances. Relationships between parameters were examined using Pearson's correlation and linear regression.

4.3 Results

Mineralisation rates and turnover rates were high and variable early in the incubation and decreased to low and less variable levels by the end. Mean mineralisation rate at day 54 ranged from 0.2 $\mu\text{g C kg}^{-1}\text{ soil s}^{-1}$ for Popondetta BZ 15-20 cm to 14.0 $\mu\text{g C kg}^{-1}\text{ soil s}^{-1}$ Kimbe FP 0-5 cm soil. At day 812 it ranged from 0.033 to 0.482 $\mu\text{g C kg}^{-1}\text{ soil s}^{-1}$ for the same soils. The turnover rate of carbon followed a similar pattern over time, ranging from 0.177-1.578 a^{-1} at day 54 to 0.029-0.073 a^{-1} at day 812 (Figure 15). The magnitude of the decrease in TC content with time was related to the initial TC content of the samples, the Kimbe FP soils had the highest TC and largest decreases (Figure 16). POC content was closely related to TC content, with $r=0.94$ at T0 (Table 9). POC decreased from T0 to T1, but the values were very variable and the p value of the decrease was 0.088. Isotopic composition of soil carbon reflected the land use history of the sites, with $\delta^{13}\text{C}$ being higher in the Popondetta soils and increasing with depth in those soils (Table 10). There was no significant change in isotopic composition over the course of the incubation.

Table 9: Correlation matrix (Pearson coefficients) of measured parameters. Significant correlations ($p < 0.05$) are bold and underlined.

	TC ₀	POC ₀	Al	Fe	Si	POC/C	Al/C	Fe/C	Si/C	R ₅₄	R ₃₇₉	R ₈₁₂	TO ₅₄	TO ₃₇₉	TO ₈₁₂	Q10 ₃₇₉	
TC ₀																	
POC ₀	<u>0.94</u>																
Al	-0.33	-0.25															
Fe	-0.27	-0.22	<u>0.91</u>														
Si	-0.08	0.03	<u>0.91</u>	<u>0.85</u>													
POC/C	<u>0.64</u>	<u>0.83</u>	0.09	0.09	0.36												
Al/C	<u>-0.74</u>	<u>-0.69</u>	<u>0.50</u>	0.38	0.30	<u>-0.50</u>											
Fe/C	<u>-0.76</u>	<u>-0.72</u>	<u>0.42</u>	0.40	0.23	<u>-0.54</u>	<u>0.95</u>										
Si/C	<u>-0.43</u>	-0.36	<u>0.80</u>	<u>0.69</u>	<u>0.80</u>	-0.09	<u>0.76</u>	<u>0.70</u>									
R ₅₄	<u>0.97</u>	<u>0.89</u>	<u>-0.47</u>	-0.34	-0.16	<u>0.54</u>	<u>-0.68</u>	<u>-0.70</u>	<u>-0.46</u>								
R ₃₇₉	<u>0.86</u>	<u>0.90</u>	-0.18	-0.05	0.15	<u>0.75</u>	<u>-0.66</u>	<u>-0.69</u>	-0.34	<u>0.84</u>							
R ₈₁₂	<u>0.81</u>	<u>0.88</u>	-0.10	-0.10	0.14	<u>0.75</u>	<u>-0.58</u>	<u>-0.62</u>	-0.27	<u>0.73</u>	<u>0.72</u>						
TO ₅₄	<u>0.88</u>	<u>0.84</u>	-0.41	-0.20	-0.04	<u>0.62</u>	<u>-0.68</u>	<u>-0.67</u>	-0.38	<u>0.93</u>	<u>0.83</u>	<u>0.71</u>					
TO ₃₇₉	0.26	0.37	0.18	0.17	0.30	<u>0.44</u>	-0.15	-0.21	-0.03	0.20	<u>0.62</u>	0.29	0.19				
TO ₈₁₂	0.13	0.26	0.26	0.21	0.31	0.42	-0.08	-0.07	0.10	0.07	0.17	0.58	0.15	0.25			
Q10 ₃₇₉	-0.13	-0.10	-0.06	-0.03	-0.15	0.06	0.00	0.03	-0.15	-0.15	-0.24	-0.15	-0.08	-0.15	-0.04		
Q10 ₈₁₂	-0.13	-0.08	0.09	0.08	0.07	0.08	-0.02	0.04	0.04	-0.13	-0.09	-0.14	-0.08	-0.02	-0.16	<u>0.47</u>	

TC, total carbon content; POC, permanganate-oxidisable carbon content; R, respiration rate; TO, turnover rate. Superscripts designate time of measurement (days of incubation).

There was a significant effect ($p < 0.05$) of location (including site and management zone), depth and their interaction on TC and POC content (day 54 and 379), mineralisation rate (day 54, 379 and 812) and turnover rate (day 54). Turnover rate on day 379 was significantly affected by location only, and turnover rate on day 812 was not significantly affected by either factor. The Q_{10} of mineralisation at day 379 and 812 was not significantly ($p = 0.05$) affected by location or depth. Pairwise comparisons of the mineralisation rates showed that the Kimbe FP soils differed from both Popondetta soils but the Popondetta soils were not significantly different from each other.

Mineralisation rates and turnover rates were correlated with several soil parameters (Table 9). Mineralisation rate was positively correlated with TC content, POC content and the ratio of POC-to-TC, at all times during the incubation. It was negatively correlated with the ratio of Al_{ox} - and Fe_{ox} -to-TC. At day 379 it was also negatively correlated with Al_{ox} and the ratio of Si_{ox} -to-TC. Turnover rate was of course highly positively correlated with mineralisation rate at the time of measurement. At day 54, turnover rate was positively correlated with TC content, POC content and the ratio of POC-to-TC (Table 9, Figure 17), and negatively correlated with the ratio of Al_{ox} - and Fe_{ox} -to-TC (Table 9, Figure 18). The correlation with POC-to-TC was still evident at 379 days, but none of the correlations were significant at 812 days. Turnover rate was not significantly correlated with Q_{10} at individual times of measurement (Table 9), but the two parameters were weakly negatively correlated over the two times of measurement (Figure 19). Mean Q_{10} increased with incubation time in all cases, but the change was not significant ($p = 0.5$). There were also no consistent trends in Q_{10} with depth (Figure 19).

The FTIR spectra of the Kimbe soils exhibited peaks at the range of 1430, 1190 and 560 cm^{-1} that were not present in the Popondetta soils (Figure 20). The Popondetta FTIR spectra were similar for both between zones and frond pile soils and peaks at 670 and 1310 cm^{-1} were present that did not appear for the Kimbe soils. The ratio of absorbance in the 1600-1740 cm^{-1} region

to absorbance at 1081 cm^{-1} , an indication of relative carbonyl and carboxyl content, was 0.985 for the Kimbe FP, 0.922 for Popondetta BZ and 0.897 for Popondetta BZ.

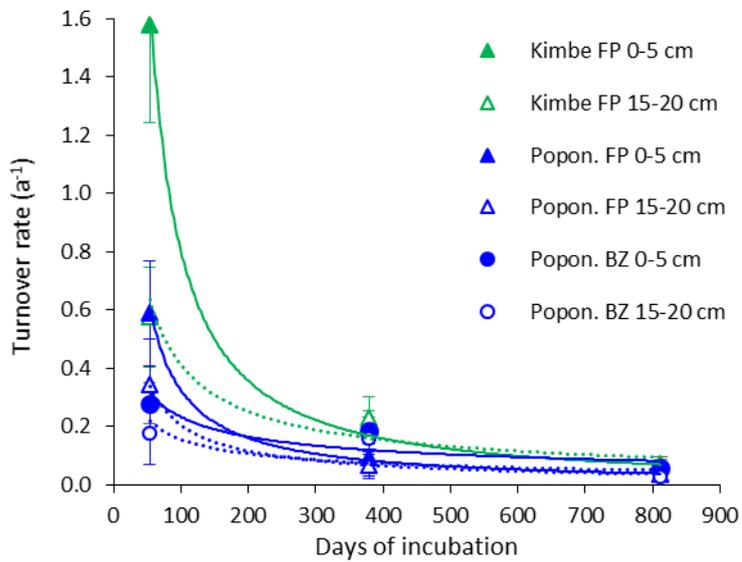


Figure 15: Mean turnover rate of carbon ($\pm\text{SE}$) in the soils over the course of the incubation, with power functions fitted.

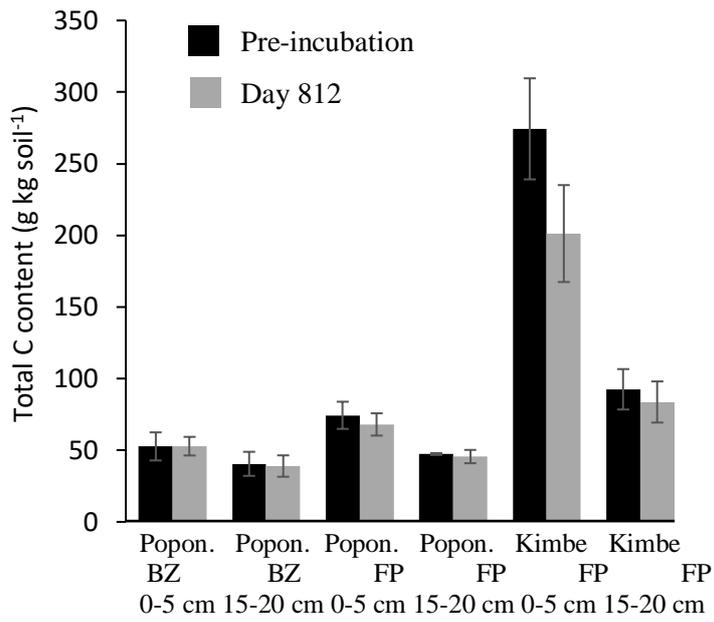


Figure 16: Mean soil carbon content (\pm SE) at the start and end of the incubation.

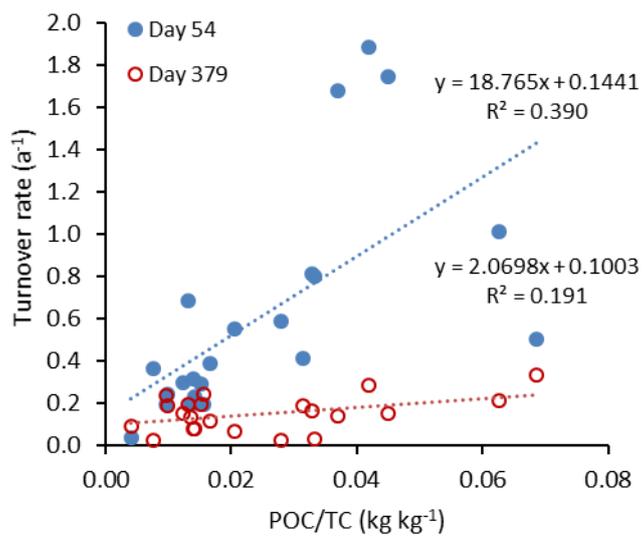


Figure 17: Relationship between carbon turnover rate and the pre-incubation ratio of potassium permanganate-oxidisable carbon (POC) to total carbon (TC), at two times during the incubation.

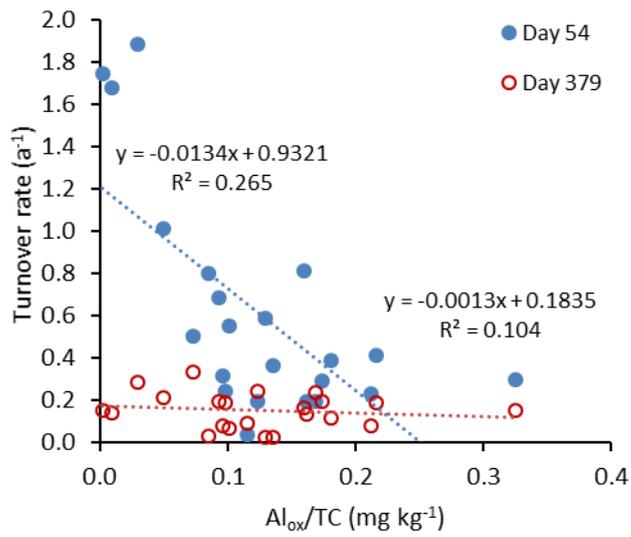


Figure 18: Relationship between carbon turnover rate and the pre-incubation ratio of acid oxalate-extractable Al (Alox) to total carbon (TC), at two times during the incubation.

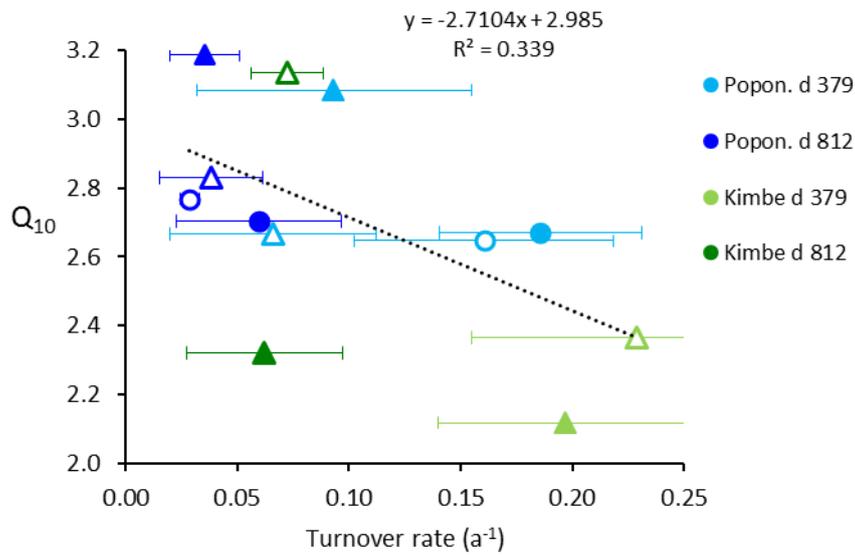


Figure 19: Relationship between mean carbon turnover rate and temperature sensitivity of mineralisation (Q_{10}) at days 379 and 812 of the incubation, with error bars showing the SE of turnover rate. Closed symbols are 0-5 cm depth, open symbols are 15-20 cm depth, circles are from between zones (BZ) and triangles are from frond pile (FP). Dashed line shows the overall linear regression.

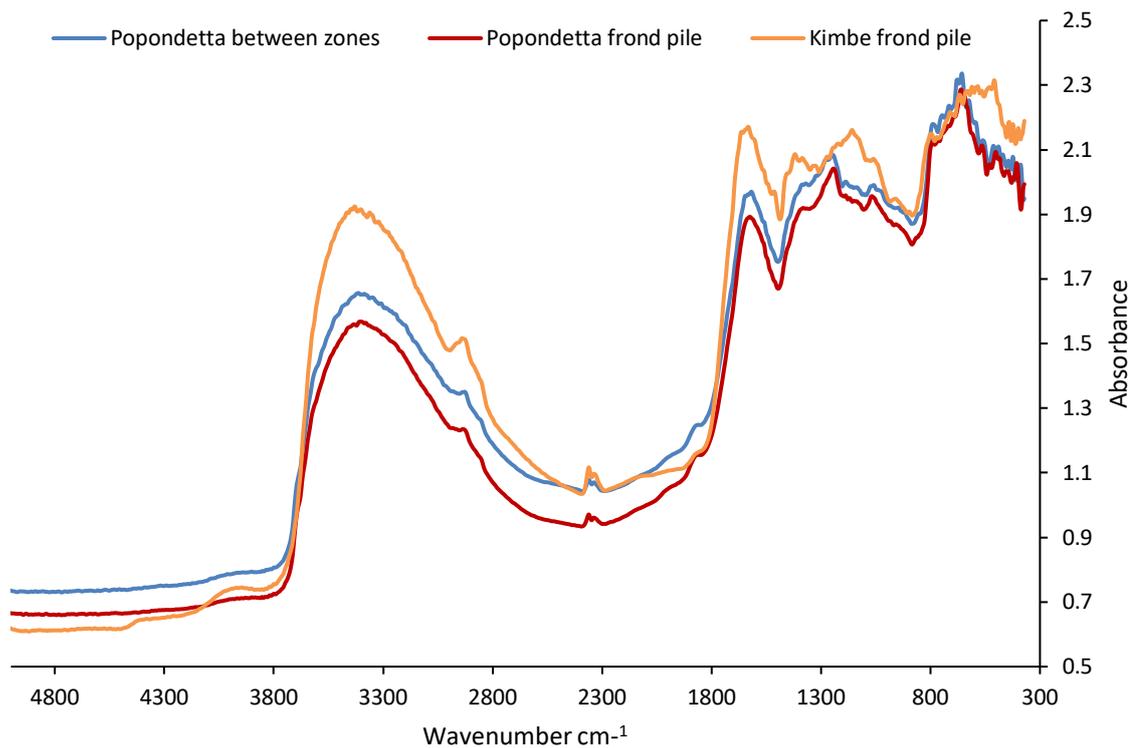


Figure 20: FTIR spectra of pre-incubation soils (0-5 cm depth, mean of 4 replicates)

4.4 Discussion

We hypothesised that poorly crystalline Al and Fe oxide contents are related to turnover rates, these relationships between described for other volcanic soils with large organic matter stocks (Hiradate *et al.* 2004). In a study on temperate soils, poorly crystalline Fe and Al was argued to control protection of carbon through ligand exchange reactions in acidic soils and interactions with polyvalent cations in near neutral soils (Kaiser *et al.* 2012). The relationship between mineralisation rates and poorly crystalline Al and Fe in our study suggest that the presence of Al and Fe reduce turnover rates of labile carbon forms. Such an effect may be due to interactions between organic matter and poorly-crystalline Fe hydroxides such as ferrihydrite. Ferrihydrite influenced turnover of soil organic matter over 400k year timescales in a chronosequence study, accounting for more than 40% of variation in organic C content (Torn *et al.* 1997). Our results indicate that, as well as controlling C mineralisation over long timescales, Al and Fe are active in controlling C mineralisation of labile carbon forms, on the time scale of one to a few years. These results correspond with those of Krull *et al.* (2003) who showed that organo-mineral interactions protect labile as well as recalcitrant materials. Later in the incubation, when comparatively recalcitrant forms remained, either the ratio of C

to Fe and Al was lowered to the extent where all of the organic matter was protected by association with Fe and Al, or some other mechanism of protection was operating, such as biochemical recalcitrance.

We hypothesised that carbon turnover is related to POC. Carbon content, and particularly readily-oxidisable forms of carbon are known to be important determinants of potential soil respiration (Wang *et al.* 2003). Since POC was closely related to total carbon content for our soils, it is unsurprising that total and POC were the best determinants of respiration and turnover rates both early and late in the incubation. Although total carbon and POC were closely related, the proportion of total carbon that was permanganate-oxidisable was predictive of turnover rates early in the incubation (Figure 17). We might have expected that for the soils with more potential mineral protection, the deep Popondetta soils for example, the proportion of chemically oxidisable carbon would be reduced. The moderate negative correlation between POC and Al and Fe are evidence that protection from soil mineralogy is controlling the chemical availability of carbon present in the soils.

The FTIR results from the incubated soils generally indicate the presence of readily oxidisable carbon forms in Kimbe soils; peaks in the 1190 cm⁻¹ region indicate polysaccharides and stretching peaks from OH (Grube *et al.* 2006) and peaks around 1430 cm⁻¹ can indicate carboxylate (Silverstein *et al.* 2005). Carbonyl and carboxyl content for Kimbe soils was also indicated as higher than both Popondetta soils by their 1600-1740 cm⁻¹ absorbance ratio. Popondetta soils were largely similar to Kimbe soils but the peak at 670 cm⁻¹ is likely representative of a recalcitrant form of carbon (Steinbeiss 2009). The characteristics of the carbon forms revealed by FTIR correspond with turnover rates during the incubation; turnover rates were considerably higher for the Kimbe soils, whose spectra indicated more accessible carbon forms.

The Popondetta soils contained organic matter derived from two distinct sources in their history, each with characteristic $\delta^{13}\text{C}$. The older inputs were expected to be subject to protection by organo-mineral associations. Over the course of the incubation, as labile carbon forms became preferentially removed, changes in $\delta^{13}\text{C}$ may have been expected, but were not apparent. This suggests that historic and recent carbon inputs were subject to similar protection mechanisms and behaved similarly during the incubation.

There was no significant relationship between Q10 values and soil properties, and only a slight negative relationship between Q10 and turnover rate when the day 379 and day 812 data were combined (Figure 19). Several factors influence temperature sensitivity of mineralisation in different ways. Q10 increases with increasing substrate recalcitrance in substrate-limited

systems, like most soils (Davidson and Janssens 2006; Pang *et al.* 2016). However, Q10 decreases with increasing physical protection (Gillabel *et al.* 2010). In the case of our experiment, it appears chemical recalcitrance and physical protection varied together, and their effects on turnover rates were similar, so their opposing effects on Q10 cancelled each other out.

All measured parameters were variable across the samples in the study, representative of differences between the two sites and spatial variability at the scale of metres to tens of metres. The main determinants of turnover rates, differences in carbon contents and respiration rates, are produced by organic matter input rates, which are highest in surface layers under frond piles (Goodrick *et al.* 2015a). The variability within these zones is also apparent, especially under the frond piles (Figure 15). Spatial variability in the other controlling factors of turnover rates, Al and Fe concentrations is evident, variability increased with concentration across the zones, so it is likely that control exerted by these mechanisms becomes more variable in zones where it is more influential.

In conclusion, biochemical recalcitrance and physico-chemical protection both controlled the turnover rates of intermediate-stability organic carbon in the Andisols examined. Physico-chemical protection appeared to be related largely to interactions between organic matter and poorly crystalline Al and Fe oxides.

4.5 Summary

Understanding the factors controlling stability against mineralisation of soil organic matter is important for predicting changes in carbon stocks under changed environment or management. Soil carbon dynamics in oil palm plantations are little studied and have some characteristics that are unusual compared to other agricultural soils, such as high management-induced spatial variability and warm moist conditions. The aim of this work was to determine the factors controlling the mineralisability of the intermediate-stability carbon fraction of volcanic ash surface soils (0-5 and 15-20 cm depth) from oil palm plantations in Papua New Guinea. Soils with carbon contents of 2.2 - 35.2 %, from areas with low and high organic matter inputs, were incubated for up to 812 days and soil respiration was measured periodically. Mean carbon turnover rates were 0.18-1.58, 0.07-0.23 and 0.03-0.07 a⁻¹ at days 54, 379 and 812, respectively. Turnover rate was initially (day 54) correlated with pre-incubation total carbon content ($r=0.88$), the ratio of permanganate-oxidisable-to-total carbon ($r=0.62$) and the ratio of oxalate-extractable Al- and Fe-to-total carbon ($r= -0.51$ and -0.54 , respectively), but the correlations decreased with time, being insignificant at day 812. In the soils that had changed from C4 grassland 25 years previously, turnover rate was negatively correlated with $\delta^{13}C$,

which increased with depth, but $\delta^{13}\text{C}$ did not change significantly over the course of the incubation. Temperature sensitivity of mineralisation varied little, despite large differences in soil properties and changes in mineralisation rate. This suggested that turnover rates were affected to similar extents by biochemical recalcitrance and physical protection, as these two factors influence temperature sensitivity in opposing directions. Physico-chemicalal protection of organic matter appeared largely related to interaction with poorly crystalline Al and Fe oxides.

5. Conclusions

This body of work aimed at characterising the soil carbon cycle under oil palm plantations. The average soil carbon stock under oil palm plantations established on grassland was 12 kg m^{-2} , higher than stocks on adjacent unchanged grassland. Oil palm plantations accumulated soil carbon at a rate of 3.4 kg m^{-2} per year over a 25-year period (to 1.5 m depth). The export of carbon via soil respiration was $7.2 \mu\text{mol CO}_2 \text{ m}^{-2}$ per second, and was spatially variable throughout the plantation. Because soil carbon stocks increased over time, mineralisation of carbon from soil must be marginally less than the total carbon inputs to soil. This is unique for productive agricultural systems, which generally do not accumulate soil carbon.

Soil carbon stability

Soil carbon in oil palm plantations on volcanic ash soils was highly stable as indicated by field and the laboratory incubation studies. The high carbon stock under oil palm plantations compared to the original grassland was due to increased inputs from the new oil palm source and an original grass-derived carbon stock resistant to decay. The input of organic matter from oil palm sources occurred throughout the life of the plantation without significant losses of existing grass-derived soil carbon. The laboratory experiment confirmed the resistance of oil palm soil carbon: only 6% of the soil carbon was mineralised over the first year of incubation. Although the soils were rich in carbon forms associated with lability and expected to have short turnover times, the carbon was very stable compared with similar incubation experiments with other soil and crop types.

Explanations for stability

The soil carbon was stable for several reasons. The chronosequence identified that black carbon produced in grassfires could partially account for the persistence of the original soil carbon stocks. Additionally, soil carbon was also resistant in areas where previous land use was not regularly burnt grassland. Aromatic molecules were more prominent in fractions traditionally associated with recalcitrance. Some carbon forms such as cellulose were less prominent in the resistant fractions than the most labile fraction. Aluminium and iron were found to be active in controlling carbon mineralisation of labile carbon forms, on the time scale of one to a few years. At time scales longer than this, protection by aluminium and iron appears to be near complete or some other mechanism of protection is operating.

Expected turnover times for all the carbon fractions are very different to observed carbon turnover rates, which suggests that oil palm soil carbon dynamics are not well represented by multiple pool models of oil palm soils.

Spatial variability

Soil carbon stocks and movement pathways are highly spatially variable in oil palm plantations and this variability had not been properly addressed in previous studies. High tree-scale variability in plantations makes it difficult to quantify soil carbon stocks and CO₂ emissions. Spatial variability of CO₂ emissions was related to variability of carbon inputs, regardless of their source, suggesting that the nature of carbon inputs was not related to the likelihood of its mineralisation. However, although spatial distribution of soil carbon inputs and losses in a mature oil palm plantation were spatially correlated at the tree scale (r^2 0.605), with a slope of 1:1, outputs were higher than inputs at all locations, with a mean overall output of 7.25 and input of 3.01 $\mu\text{mol m}^{-2} \text{s}^{-1}$. This suggests that either root carbon input to soil was underestimated by our methodology (and most previous attempts to estimate root respiration in the literature) or significant amounts of carbon is entering the soil carbon cycle via unknown routes. The finding that emission is controlled by organic matter input amount rather than nature was not disproven by further experimentation of mineralisation of soil carbon, in the incubated soils, soils derived from frond and root organic matter inputs did not differ in turnover times from the soils in areas with no frond inputs.

Carbon stock accumulation potential

The results indicate that soils of oil palm plantations planted on grasslands are carbon sinks; conversion of grasslands to oil palm results in net sequestration of carbon and soil carbon stocks produced by oil palm plantations have potential to remain for longer than carbon stocks of other ecosystem types, even for similar soil types.

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