Agriculture, Ecosystems and Environment 211 (2015) 195–206

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

# Carbon neutral? No change in mineral soil carbon stock under oil palm plantations derived from forest or non-forest in Indonesia

Ni'matul Khasanah[a,b,*], Meine van Noordwijk[a,b], Harti Ningsih[a], Subekti Rahayu[a]

[a] World Agroforestry Centre (ICRAF), Southeast Asia Regional Programme, Bogor, Indonesia
[b] Plant Production Systems, Department of Plant Sciences, Wageningen University, Wageningen, The Netherlands

ARTICLE INFO

*Article history:*
Received 26 July 2014
Received in revised form 9 June 2015
Accepted 11 June 2015
Available online 6 July 2015

*Keywords:*
Biofuel
Carbon footprint
*Elaeis guineensis*
Life cycle analysis
Soil carbon sequestration
Sustainable palm oil

ABSTRACT

Sustainability criteria for palm oil production guide new planting toward non-forest land cover on mineral soil, avoiding carbon debts caused by forest and peat conversion. Effects on soil carbon stock (soil $C_{stock}$) of land use change trajectories from forest and non-forest to oil palm on mineral soils include initial decline and subsequent recovery, however modeling efforts and life-cycle accounting are constrained by lack of comprehensive data sets; only few case studies underpin current debate. We analyzed soil $C_{stock}$ (Mg ha$^{-1}$), soil bulk density (BD, g cm$^{-3}$) and soil organic carbon concentration ($C_{org}$, %) from 155 plots in 20 oil palm plantations across the major production areas of Indonesia, identifying trends during a production cycle on 6 plantations with sufficient spread in plot age. Plots were sampled in four management zones: weeded circle (WC), interrow (IR), frond stacks (FS), and harvest paths (HP); three depth intervals 0–5, 5–15 and 15–30 cm were sampled in each zone. Compared to the initial condition, increases in $C_{org}$ (16.2%) and reduction in BD (8.9%) in the FS zone, was compensated by decrease in $C_{org}$ (21.4%) and increase in BD (6.6%) in the HP zone, with intermediate results elsewhere. For a weighted average of the four management zones and after correction for equal mineral soil basis, the net temporal trend in soil $C_{stock}$ in the top 30 cm of soil across all data was not significantly different from zero in both forest- and non-forest-derived oil palm plantations. Individual plantations experienced net decline, net increase or U-shaped trajectories. The 2% difference in mean soil $C_{stock}$ in forest and non-forest derived oil palm plantations was statistically significant ($p < 0.05$). Unless soil management changes strongly from current practice, it is appropriate for C footprint calculations to assume soil $C_{stock}$ neutrality on mineral soils used for oil palm cultivation.



## 1. Introduction

Current use of palm oil from Southeast Asia as biofuel is far from carbon neutral (Reijnders and Huijbregts, 2008; Sheil et al., 2009; Agus et al., 2013). It is part of the 12–15% of total anthropogenic carbon emissions due to deforestation (Houghton et al., 2010; van der Werf et al., 2009). Current use of peat soils causes $CO_2$ emissions that far exceed the amount sequestered in harvested products (Hooijer et al., 2010; Couwenberg et al., 2010; Hergoualc'h and Verchot, 2011). Carbon debts due to conversion can continue to increase on peat soils at a rate exceeding the reductions of fossil energy release that palm oil products can substitute for, causing (near) infinite 'pay-back' times (van Noordwijk et al., 2014b). On mineral soils, an initial carbon debt to the atmosphere can be recovered by subsequent biomass development and harvestable yields if these offset fossil fuel use. Current understanding is that palm oil can be both the best and the worst known source of biofuel from a global C balance perspective, having the widest 'management swing potential' (Davis et al., 2013).

Oil palm expansion is a prominent cause of tropical deforestation and associated C emissions in many landscapes in Southeast Asia, although total oil palm area is yet to cover 5% of Indonesia and deforestation rates have been at least 1% per year for the past 20 years (van Noordwijk et al., 2014a). Due to consumer pressure and environmental concerns of major stakeholders in the palm oil value

* Corresponding author at: World Agroforestry Centre (ICRAF), Southeast Asia Regional Programme, JL. CIFOR, Situgede, Sindang Barang, PO Box 161, Bogor 16115, Indonesia. Fax: +62 251 8625416.
*E-mail addresses:* n.khasanah@cgiar.org (N. Khasanah), m.vannoordwijk@cgiar.org (M. van Noordwijk), h.ningsih1@gmail.com (H. Ningsih), s.rahayu@cgiar.org (S. Rahayu).

http://dx.doi.org/10.1016/j.agee.2015.06.009

chain, oil palm is being weaned from new forest conversion and use of peat soils under voluntary agreements of the Roundtable on Sustainable Palm Oil (http://www.rspo.org/; Tan et al., 2009; Laurance et al., 2010). Converting low vegetation $C_{stock}$ on mineral soils is seen as the future of sustainable palm oil, but its effects on soil carbon stock (soil $C_{stock}$) have not been sufficiently quantified. The literature is based on isolated case studies and unconstrained modeling exercises at best (Adachi et al., 2011; Nair et al., 2011).

A number of authors reported that conversion to oil palm plantations on mineral soils can lead to a net gain of soil $C_{stock}$ (Germer and Sauerborn, 2008; Verhoeven and Setter, 2010; Flynn et al., 2011; Hassan et al., 2011; Patthanaissaranukool and Polprasert, 2011; Siangjaeo et al., 2011). Others, however, reported a net loss (Kotowska et al., 2015) or estimated loss to be 10% of the forest soil $C_{stock}$ (Busch et al., 2015). Empirical data of both initial $C_{org}$ and trends over time during a production cycle of oil palm are needed to verify the claims that soil $C_{stock}$ will increase and to validate or improve the models used. Replicated trials with randomly assigned treatments carried through the relevant time scale (at least one rotation of 25 years) do not exist, and thus attention is needed to possible differences in soil type, texture and bulk density (BD) where survey data are used. A specific challenge is that with change in BD soil samples taken to constant depth may involve different layers of soil (Ellert and Bettany, 1995; Post and Kwon, 2000; Lee et al., 2009). Evidence relevant to the issue of net increase or decrease of soil organic carbon concentration ($C_{org}$) during an oil palm production cycle can come from observed spatial patterns, from processes that are understood in a quantitative sense, or a combination of the two.

Current national accounting systems of greenhouse gas rely largely on global or nationally derived 'default' data on relative effects of land use on soil $C_{stock}$. As part of the 2nd IPCC review, Paustian et al. (1997) summarized known effects of land use change on $C_{org}$ across climatic zones and soil types. Subsequent literature led to some refinement. Don et al. (2011) in a global meta-analysis of 385 studies on land-use change in the tropics found that the highest $C_{org}$ losses were caused by conversion of primary forest into cropland (25%) and perennial crops (30%), but forest conversion into grassland also reduced soil $C_{stock}$ by 12%. If this would be a simple additive system, one might thus expect conversion of grasslands to perennial crops to lead to a decrease of $C_{org}$ by about 18%, but a meta-analysis cannot compensate for sampling bias of the case studies that are reported in the literature. Another recent meta-analysis (Powers et al., 2011) focused on 'paired plot' literature and found little consistency in $C_{org}$ change, with both 'forest to grassland' and 'grassland to forest' conversions leading to statistically significant $C_{org}$ gain; this may raise doubts on the selection bias in the results that are published. Both reviews confirm that complete data sets that combine measurements of BD and $C_{org}$ are scarce, and that spatial extrapolation is affected by unbalanced representation of tropical soil types. Given the current importance of having unbiased results underpinning global carbon accounting standards, the net change in soil $C_{stock}$ of conversion to oil palm mineral soils needs to be understood across the range of production conditions.

The world's main palm oil production areas are Sumatra and the Indonesian and Malaysian parts of Borneo, peninsular Malaysia and southern Thailand.[1] As oil palm is restricted to areas with minimum temperatures of 18 °C and does not respond well to climates with more than one dry month (Corley and Tinker, 2003), the primary expansion has been within an area of relatively homogeneous climate. Specifically for Sumatra, van Noordwijk et al. (1997) found effects similar to those of Don et al. (2011), except for lower $C_{org}$ losses in conversion to cropland, potentially because permanently cropped upland soils are relatively scarce in Sumatra where intensification of shifting cultivation has generally moved toward permanent tree crops (van Noordwijk et al., 2008). Imperata grasslands and areas formerly used for shifting cultivation may not have substantially lower $C_{org}$ than forests (Santoso et al., 1997). Soil $C_{stock}$ in tree plantations were reported to be 0–40% less than stocks in swidden cultivation, with the largest losses found in mechanically-established oil palm plantations (Bruun et al., 2009). The above-mentioned studies show that the effect of land use change on the trend of $C_{org}$ remains unclear from studies of existing spatial patterns.

More process-oriented studies suggest that we can expect a decline of $C_{org}$ inherited from preceding vegetation and a gradual build-up of $C_{org}$ from the vegetation that replaces it. Based on carbon isotope differences between sugarcane residue and forest soil C pools, Sitompul et al. (2000) quantified the annual loss of forest $C_{org}$ after conversion to sugarcane. The annual loss of forest $C_{org}$ was 8.2% per year (± 2.8% per year) for an ultisol (*Grossarenic Kandiudult*) in Sumatra, with differentiation between density fractions: 14–19% per year for macro-organic matter varying in degree of association with soil particles and hence in density, and lower rates for fine material associated with clay and silt. Similar initial decay rates can be expected for oil palm plantations, possibly reduced by microclimate modification and absence of soil tillage in oil palm, compared to sugarcane stands. As specified in the Century model (Sitompul et al., 2000) and confirmed in a Sumatra-wide data set (van Noordwijk et al., 1997), variation in soil clay and silt content is likely to influence the amount of $C_{org}$ protected from decomposers by physical association with soil particles, leading to different $C_{org}$ decomposition rates for the soil as a whole.

In further applying this conceptual model of breakdown and build-up, we expect that the decay of $C_{org}$ inherited from preceding forest, grassland or other vegetation, is balanced by two types of organic inputs: aboveground litter, which can be readily quantified from the known leaf production (minus any biomass removals), and (fine) root turnover which is poorly quantified as yet. The spatial organization of oil palm plantations, where aboveground litter is typically accumulated in 'frond stacks' in between palms, differentiates the relative contributions of above- and below-ground inputs, allowing some separation of the terms of the $C_{org}$ change equation. Four different management zones are normally recognized: weeded circle (WC), frond stacks (FS), interrow (IR) and harvest paths (HP) (Corley and Tinker 2003; Law et al., 2009). Between plantations there is variation in the degree to which aboveground litter is stacked (to facilitate access to the plots) or spread out (to protect the soil), leaving only the HP and WC free of litter.

Specific questions for the current analysis of this data set are:

1) Are there statistically significant positive or negative trends within oil palm plots in BD and $C_{org}$ with age of oil palm for the four management zones in oil palm on mineral soil?
2) How does a correction for equal-soil-mineral basis of comparisons influence the estimated changes in soil $C_{stock}$?
3) Does the average soil $C_{stock}$, weighted over the four management zones, increase or decrease with age of oil palm plots and is the change influenced by having forest or non-forest as recent land use history?
4) Is variation between plantations in the shift from a negative to a positive trend of soil $C_{stock}$ with time and hence in time-averaged $C_{stock}$ attributable to known management practices?

[1] The FAO stat data for 2012 (http://faostat3.fao.org) indicate a global production of $52.9 \times 10^6$ metric ton (valued at 21.6 109 USD), with 50.9%, 35.5%, 3.4% and 1.6% for Indonesia, Malaysia, Thailand and other Asia/Pacific countries, respectively. The remaining 9% of global production comes from W. Africa (3.8%) and Latin/Central America (4.8%).

## 2. Materials and methods

### 2.1. Demand-led research, confidentiality arrangements

As the renewable energy directive of the EU ('EU RED'; European Comission, 2010) implies a need for comprehensive data on the C footprint of palm oil if this is to be exported to Europe and used for biofuel, the Indonesian Palm Oil Commission asked the World Agroforestry Centre to lead a study that would provide an initial database for comparisons and build capacity of the private sector to apply established methods. The study was implemented together with 20 plantations, recruited on a voluntary basis among all major oil palm producing companies in Indonesia. While confidentiality on the identity of participants was the basis for participation in a data collection of commercial importance in a politically sensitive arena, the data set as a whole represents an opportunity to analyze the temporal trends of $C_{org}$ (%), BD ($g\,cm^{-3}$) and soil $C_{stock}$ ($Mg\,C\,ha^{-1}$) in the four different management zones. Aboveground $C_{stock}$ not only from of the same plantations, but also from other 5 plantations in peat soil is described in a parallel manuscript.

### 2.2. Study design and plantation selection

This study focused on the analysis of the temporal changes of BD, $C_{org}$, and soil $C_{stock}$, in mineral soil in a total of 155 plots within 20 selected landscapes or plantations (Fig. 1 and Table 1). Selection of the 20 landscapes or plantations and 155 plots was based on stratifiers we derived at national level to sample landscape or plantation and at landscape level to sample soil at various age of oil palm.

At the national level, we had three stratifiers: (1) landscape or plantation history (derived from forest versus non-forest (other vegetation or from preceding oil palm), (2) soil type (mineral soils versus peat), and (3) the prevalence of oil palm in the surrounding area, assessed at provincial level, as areas of high oil palm prevalence are likely to represent a longer history of the crop, potentially selected for the most suitable climatic conditions, and may have the best knowledge and processing infrastructure. Climatic aspects are confounded with the other characteristics of this distinction, but the primary climatic distinction within the oil palm zone of Indonesia, in climatic zones A and B but not C as described by Aldrian and Susanto (2003), is in the frequency and strength of dry periods, which affects fruit rather than vegetative production. *A priori* expectations of effects of this climatic variation on soil $C_{stock}$ are thus limited.

At the landscape or plantation level, we distinguished between what in the commonly used terminology is termed the 'nucleus', a core plantation managed by a company, the 'plasma' or plantations initially managed by a company during establishment until the early production stage and then transferred to a farmer as the owner of the land (Santoso, 2010), and independents smallholder plantations (IFC, 2013). We thus used three additional strata: (1) plantation management (nucleus, plasma, independent smallholders), (2) soil type (mineral soils versus peat), and (3) age during the crops' life cycle.

Factorial combinations across the three criteria at the national level led to 12 (=3 × 2 × 2) clusters. In this paper, we analyzed the focused study mentioned in mineral soil only (cluster 4, 5, 6, 10, 11 and 12 in Fig. 1). Table 1 presents number of plot among stratifiers in mineral soil. From the 155 plots sampled, 112 plots (72%) and 43 plots (28%) were derived from forest and non forest respectively; 108 plots (70%), 29 plots (19%) and 18 plots (12%) were under nucleus, plasma and smallholder management, respectively; 53 plots (34%), 64 plots (41%), 38 plots (25%) were in between 0 and 8, 9–16 and 17–25 age of oil palm, respectively.

### 2.3. Plantation landscapes description

Based on the intra- and inter-annual variation in rainfall and the statistical correlation of rainfall with sea surface temperatures in the Pacific and Indian Ocean, Aldrian and Susanto (2003) recognized three climatic regions in Indonesia. Oil palm is currently grown in the two wettest of these regions, with a center of gravity in region B that is located in northwest Indonesia and stretches from northern Sumatra to north western Kalimantan.

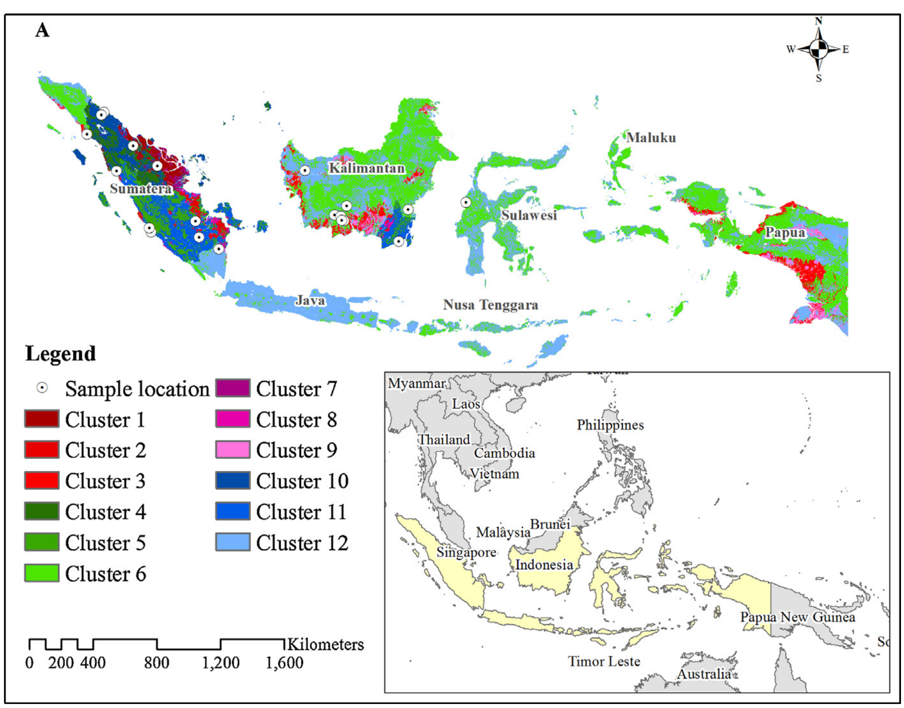


**Fig. 1.** Spatial distribution of 20 oil palm landscapes or plantations selected for inclusion in this study. The color definition refers to cluster definition in Table 1.

**Table 1**
Study design with the actual number of plots sampled across plot age, management style, preceding vegetation, and oil palm prevalence in the surrounding area that assessed at provincial level. Clusters 1–3 and 7–9 are peat soil equivalents of 4–6 and 10–12, respectively and excluded from the table as the paper focused on mineral soil.

| Plantation parameters | | Cluster | Number of land scapes | N = nucleus, P = plasma, I = independent | Number of sampled plots per age category (year) | | | |
|---|---|---|---|---|---|---|---|---|
| Preceding land cover | Prevalence of oil palm (% of area in province) | | | | 0–8 | 9–16 | 17–25 | Total |
| Forest | 5–15% | 4 | 3 | N | 2 | 5 | 10 | 17 |
| | | | | P | – | 2 | 2 | 4 |
| | | | | I | – | – | – | – |
| | 1–5% | 5 | 3 | N | 6 | 8 | 7 | 21 |
| | | | | P | 1 | 2 | – | 3 |
| | | | | I | 2 | 1 | – | 3 |
| | <1% | 6 | 9 | N | 16 | 20 | 7 | 43 |
| | | | | P | 4 | 4 | 1 | 9 |
| | | | | I | 10 | 2 | – | 12 |
| Non forest | 5–15% | 10 | 2 | N | 4 | 5 | 2 | 11 |
| | | | | P | – | – | – | – |
| | | | | I | – | – | – | – |
| | 1–5% | 11 | 3 | N | 2 | 8 | 6 | 16 |
| | | | | P | 4 | 6 | 3 | 13 |
| | | | | I | 2 | 1 | – | 3 |
| | <1% | 12 | – | – | – | – | – | – |
| Total | | | 20 | – | 53 | 64 | 38 | 155 |

While mean annual rainfall (2600 mm year$^{-1}$) and the number of months with rainfall over 200 mm is 7 months is similar between regions A and B (Fig. 2), the pattern of interannual variability differs. However, the average mean annual rainfall of those regions is not statistically significant ($p < 0.05$).

Region B has a tendency to a bimodal pattern without months of less than 100 mm rainfall on average, combined with low sensitivity to El Nino patterns of interannual variability in the Pacific and modest response to the Indian Ocean dipole (Niedermeyer et al., 2014) have created a climate in northern Sumatra that is eminently suitable for oil palm. Region A is located in southern Indonesia and stretches from south Sumatra to Timor, southern Kalimantan, Sulawesi and part of Papua. Its unimodal rainfall has a relatively dry period between May to September that in interaction with interannual variability can reduce oil palm yields, depending on the degree of water buffering by the soil. The highest 'oil palm prevalence' at provincial level (5–15%) coincided with climate region B for this study, while the data for 'oil palm prevalence' below 5% where derived from climate region A.

With regards to soil type, the dominant soil in the 155 sampled plots was classified as Ultisols (55%) and Inceptisols (19%), respectively. Other soil types encountered less frequently were Spodosols, Oxisols and Entisols. Across these soil types, variation in soil texture and pH account for differences in $C_{org}$ that can exceed the effects of land cover (forest, non-forest categories) (van Noordwijk et al., 1997). Soil organic carbon reference (soil $C_{org\_ref}$) was then used to take into account the variation of soil types (Section 2.4.3).

### 2.4. Sampling design and calculation of soil carbon stock

#### 2.4.1. Soil carbon stock measurement

This study represents what is considered to be, by the plantations, "good practice" management of oil palm plantation related to management of soil organic input. Typical "good practice" management of soil organic input is the plantation area normally distinguished into four different management zones: weeded circle (WC), frond stacks (FS), interrow (IR) and harvest paths (HP) (Fig. 3B). WC zone is around palm trunk and occupy only 12% of total area. It is normally free of understorey for fertilizer application. During plantation establishment, legume cover crop is typically planted and the cover crop is allowed to grow only in IR zone (46% of total area) once the oil palm reach mature stage (> 3 years). Recycling management of yield residue such as empty fruit bunches (EFB) is sometime also applied in the IR zone. Pruned frond is managed and piled in each alternate row (FS zone, it is about 30% of total area) with the harvest path of oil palm (12% of total area) kept free of litter. Soil sampling in each plot considered this organic input management zones, and recorded the site-specific variations in spatial extent of the zones.

Soil $C_{stock}$ in each plot was estimated by measuring BD and analyzing $C_{org}$ (Hairiah et al., 2011) at 0–30 cm soil depth with intervals of 0–5 cm, 5–15 cm and 15–30 cm. The sampling was focused on the first 30 cm, besides the default for soil depth for soil $C_{stock}$ measurement provided by IPCC (2006) is 30 cm, it is also as

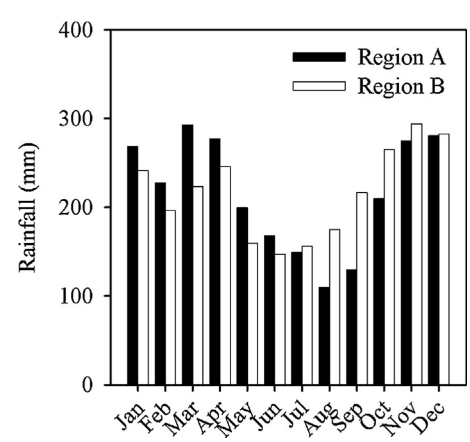


**Fig. 2.** Mean monthly rainfall of all plantations presented based on climate regions A and B as derived by Aldrian and Susanto (2003).

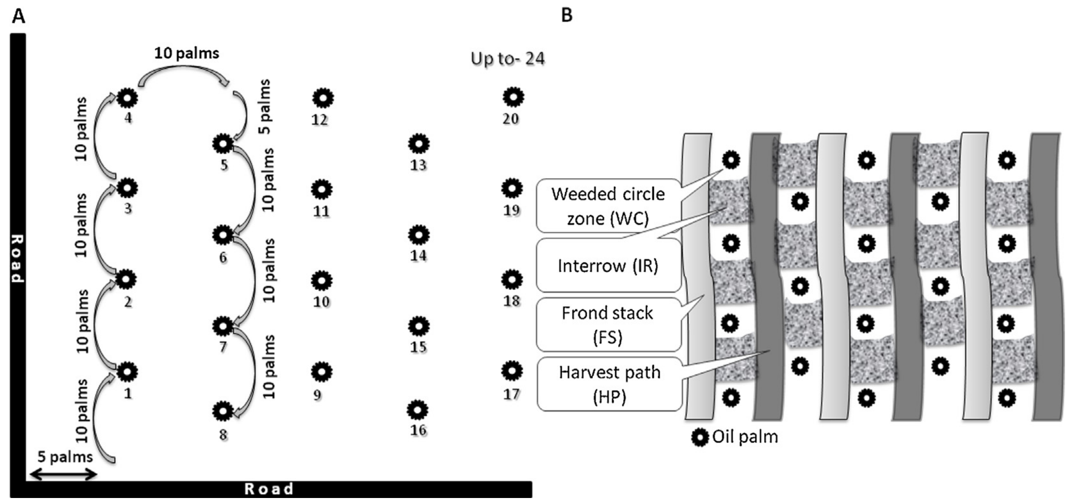


**Fig. 3.** (A) Scheme of selected palms where soil at four different management zone to be measured in each plot. (B) Sampling measurement scheme of soil representing four spatial zones: weeded circle (WC) or fertilizer application zone; interrow (IR)/grass/empty fruit bunch (EFB) application zone; frond stacks (FS) zone; and harvest paths (HP) zone).

the greatest proportion of the total root mass is confined to the top 30 cm of the soil surface (Ravindranath and Ostwald, 2008).

The BD was measured by taking samples using a 0.2 × 0.2 m sample frame around palm numbers 1, 3, 6, 9, 12, 15, 18, 21 in Fig. 3A in four different management zones (Fig. 3B). Hence the total sample per plot is 96 samples (8 palms × 4 management zones × 3 soil layers) or more than 10,000 samples from the whole landscapes or plantations. Selected palms (1–24) in Fig. 3A in each plot followed the standardized selection scheme used in establishing leaf sampling units (LSU) for fertilizer recommendation (some of the details varied between plantation companies). Within these 24 trees, 8 palms were chosen to represent spatial distribution of the palm in each plot. The soil samples were oven-dried at 80°C in laboratory to determine the total dry weight.

The soil's $C_{org}$ was analyzed by taking soil samples at the same position as BD measurement and composite from 8 trees. The composited soil samples were air-dried and sieved, ground to pass though a 2 mm sieve in laboratory prior to analysis using the Walkley and Black method. This method requires a correction factor for incomplete oxidation of organic C (McCarty et al., 2010; Schulte, 1995); we used a correction factor of 1.32 (Nelson and Sommers, 1996).

The soil $C_{stock}$ was then calculated as follow:

$$\text{soilC}_{\text{stock}_i} = \frac{\text{BD}_i D_i C_i}{100} \quad (1)$$

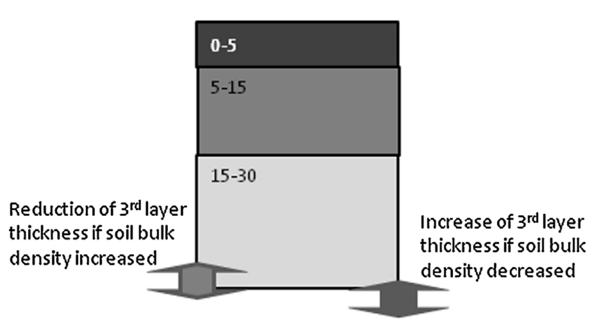


**Fig. 4.** Diagram of the three soil layers and the type of correction needed to adjust for increase or decrease of soil bulk density.

$$\text{BD}_i = \frac{W_i}{V_i} \quad (2)$$

where soil $C_{stock\_i}$ is soil carbon stock at depth $i$ (g cm$^2$), $BD_i$ is soil bulk density at depth $i$ (g cm$^{-3}$) = total dry weight of soil ($W_i$) divided by soil volume ($V_i$), $D_i$ is soil thickness at depth $i$ (cm), and $C_i$ is soil organic carbon at depth $i$ (%).

Soil $C_{stock}$ at each sampling point was then up-scaled into per unit area of estimation (Mg C ha$^{-1}$) that was measured taking into account the area of each management zone per ha (weighted average).

*2.4.2. Correction of soil carbon stock for equal mineral soil basis*

Soil $C_{stock}$ that is quantified from BD, $C_{org}$ and soil depth is often over-estimated or under-estimated because of increasing BD due to minimum tillage (Badalikova, 2010) or decreasing BD due to large organic inputs. In the four different management zones of oil palm plantations (Fig. 3B), the harvest path zone is a zone where BD increases and the interrow and frond stack zones are zones where it potentially decreases. Hence, correction is needed to ensure equal soil masses are compared for each different zone (Lee et al., 2009). We used the correction proposed by Ellert and Bettany (1995) to express results on an equal soil mass. Fig. 4 clarifies its rationale.

The derivation of the equation for correcting carbon stock estimates is as follows. Let the mineral soil and $C_{org}$ content of a volume of soil that is sampled in three layers at time $t$ be described by:

$$\text{Min}_t = \sum_{i=1}^{3} S_i \times \text{BD}_{t,i} \times \left(\frac{100 - C_{t,i}}{100}\right), \text{for each management zone} \quad (3)$$

$$\text{Cstock}_t = \sum_{i=1}^{3} S_i \times \text{BD}_{t,i} \times \frac{C_{t,i}}{100}, \text{for each management zone} \quad (4)$$

where $\text{Min}_t$ = initial (for $t = 0$) or final (for $t = T$) mineral soil content between soil surface and depth $i$, g cm$^{-2}$; $\text{Cstock}_t$ = initial (for $t = 0$) or final (for $t = T$) soil carbon stock between soil surface and depth $i$, g cm$^{-2}$; $S_i$ = soil thickness of depth $i$, cm; $\text{BD}_{t,i}$ = soil bulk density of depth $i$ at $t=0$ or at $t=T$, g cm$^{-3}$; $C_{t,i}$ = soil organic carbon concentration of depth $i$ at $t=0$ or at $t=T$ zone $i$, %.

The correction factor (CF, %) to be added to $Cstock_{T(\text{uncorrected})}$ is (for an example where three soil layers were sampled):

$$CF = \frac{(Min_0 - Min_T) \times C_{0,3}/100 - C_{0,3}}{(Min_0 - Min_T) \times C_{0,3}/100 - C_{0,3} + Cstock_{t,3}} \quad (5)$$

$$Cstock_{\text{corrected}} = Cstock_{T(\text{uncorrected})} \times (1 + CF) \quad (6)$$

### 2.4.3. Estimation of texture-specific reference of soil carbon stock

To normalize the effect of soil texture on $C_{org}$ of different soil classification, we calculated soil carbon stock reference (soil $C_{stock\_ref}$) based on BD reference ($BD_{ref}$) (Wosten et al. (1998) and soil organic carbon reference ($C_{org\_ref}$) (van Noordwijk et al., 1997).

$BD_{ref}$ indicated maximum or reference of bulk density and can be used to see the status of soil compaction, which is ratio of measured bulk density and bulk density reference ($BD/BD_{ref}$). A value of the $BD/BD_{ref}$ ratio bigger than 1 indicate compaction of soil. $C_{org\_ref}$ is a reference $C_{org}$ level representative of forest soil. The ratio of $C_{org}$ and $C_{org\_ref}$ can be used as an indicator for $C_{org}$ sustainability. A value of the $C_{org}/C_{org\_ref}$ ratio above 1 indicates soil $C_{stock}$ improvement relative to forest soil conditions.

The estimation of $C_{org\_ref}$ used an equation developed by van Noordwijk et al., 1997 and subsequently refined (van Noordwijk, pers. comm.):

$$C_{ref(\text{adjusted})} = (1.489 \times Z_{sample})^{-0.528} \times \exp(1.333 + 0.00994 \times Clay + 0.00699 \times Silt - 0.156 \times pH_{KCl} + 0.000427 \times elevation) \quad (7)$$

The estimation of $BD_{ref}$ used an equation developed by Wosten et al. (1998) (cited in Suprayogo et al., 2003):

For clay + silt contents less than 50% and top soil

$$BD_{ref} = \left(-1.984 + 0.01841 \times OM + 0.032 + 0.00003576 \times (Clay + Silt)^2 + \frac{67.5}{MPS} + 0.424 \times Ln(MPS)\right)^{-1} \quad (8)$$

For clay + silt content less than 50% and sub soil

$$BD_{ref} = \left(-1.984 + 0.01841 \times OM + 0.00003576 \times (Clay + Silt)^2 + \frac{67.5}{MPS} + 0.424 \times Ln(MPS)\right)^{-1} \quad (9)$$

For clay + silt more than 50%:

$$BD_{ref} = (0.603 + 0.003975 \times Clay + 0.00207 \times OM^2 + 0.01781 \times Ln(OM))^{-1} \quad (10)$$

where clay = percentage of clay, silt = percentage of silt, OM = percentage of organic matter, BD = soil bulk density, g cm$^{-3}$, MPS = mean particle size of sand (default 290 μm).

### 2.4.4. Estimation of time-averaged soil carbon stock

Time-averaged $C_{stock}$ of oil palm plantation represents the soil $C_{stock}$ of an oil palm plantation over a life cycle (typically 25 years). The time-averaged $C_{stock}$ of oil palm plantations was estimated by developing an allometric equation of soil $C_{stock}$ (Mg C ha$^{-1}$), 0–30 cm soil depth of plantation as a function of palm age (year). The soil $C_{stock}$ of plantation is average value of four management zones taking into account area of each management zone (weighted average).

### 2.5. simple model of soil carbon stock

To understand the decrease and increase of soil $C_{stock}$ over time, a simple model was developed based on Sitompul et al. (2000). In the absent of soil organic input, the changes of soil $C_{stock}$ as follow:

$$Cstock_t = Cstock_{s_t} + Cstock_{m_t} + Cstock_{l_t} \quad (11)$$

$$Cstock_{s_t} = a(1 - k_s)^t \quad (12)$$

$$Cstock_{m_t} = b(1 - k_m)^t \quad (13)$$

$$Cstock_{l_t} = c(1 - k_l)^t \quad (14)$$

where $Cstock_t$ is total soil $C_{stock}$ at time $t$; $Cstock_{s_t}$, $Cstock_{m_t}$, and $Cstock_{l_t}$ are soil $C_{stock}$ of slow (or heavy), medium and fast (or light) pools, respectively at time $t$; $a$, $b$ and $c$ are initial soil $C_{stock}$ of slow (25 Mg C ha$^{-1}$), medium (15 Mg C ha$^{-1}$) and fast (15 Mg C ha$^{-1}$) pools, respectively; $k_s$, $k_m$ and $k_l$ are decomposition rate of slow (0.142 per year), medium (0.185 per year) and fast (0.194 per year) pools, respectively.

The same calculation was then applied to the present of oil palm organic inputs. The amount of oil palm organic inputs is around 4.6 Mg ha$^{-1}$ yr$^{-1}$ and to increase over time to 10.9 Mg ha$^{-1}$ yr$^{-1}$, by year 8 and it is distributed to slow (20%), medium (30%) and light (50%) pool, respectively.

### 2.6. Statistical data analysis

All soil BD, $C_{org}$ and $C_{stock}$ data were analyzed for single effect of the factors: plantation management (nucleus, plasma, and independent), soil classification (ultisols, inceptisols and others), landscape or plantation history (derived from forest or non forest), management zones (weeded circle, interrow, frond stacks and harvest paths) and age of oil palm using SYSTAT 11. The analysis refers to 5% probability levels.

## 3. Results

### 3.1. Trends in soil bulk density (BD) and soil organic carbon ($C_{org}$) with age of oil palm per management zone

Fig. 5A and B shows the BD and $C_{org}$ at various ages of oil palm and management zones in the top 30 cm of soil. Some measured plots under nucleus management and derived from forest had low BD and high $C_{org}$. These plots in fact had a layer of mature peat but of insufficient depth to be classified as peat soils. Overall, BD did not reveal any significant differences among types of plantation management, initial land cover, management zones and age of plantation ($p < 0.05$). By contrast, there were significant differences in $C_{org}$ among types of plantation management, initial land cover, soil classification and management zones ($p < 0.05$) (Table 3).

Over a plantation life cycle, the BD increased by 6.6% (due to soil compaction) in the harvest path zone and decreased by 8.9% in the frond stack zone compared to the initial condition. However, these trends could not be statistically distinguished from a no-effect null-hypothesis. The opposite trend was found in $C_{org}$ over a life cycle, the $C_{org}$ significantly increased by 16.2% in the frond stack zone and decreased by 21.4% in the harvest path zone.

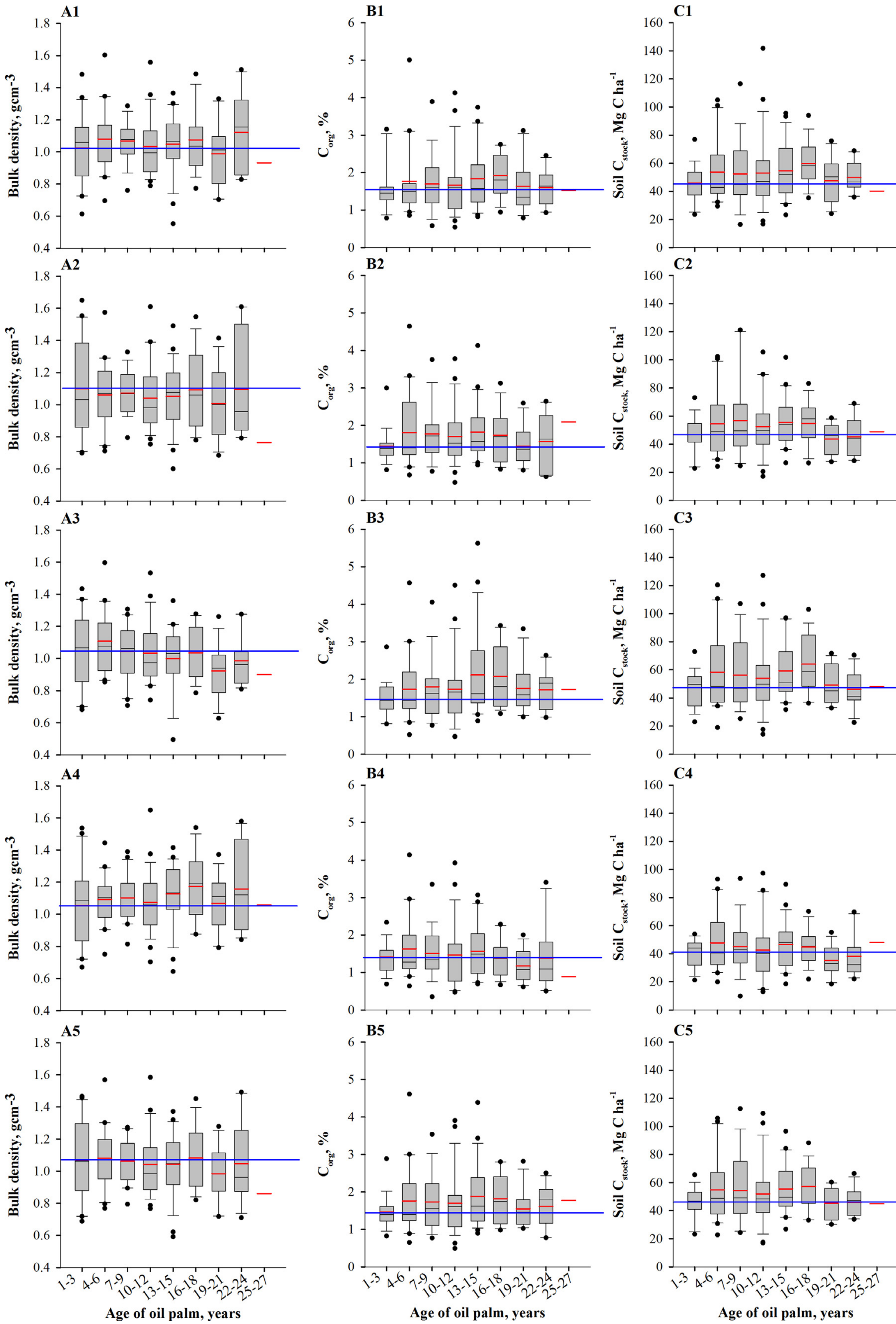


**Fig. 5.** Soil bulk density (g cm$^{-3}$) (A), soil organic carbon (%) (B), and corrected soil $C_{stock}$ (Mg C ha$^{-1}$) at 0–30 cm depth at different oil palm ages and management zones. 1 = weeded circle (WC) zone, 2 = interrow zone (IR), 3 = frond stack (FS) zone, 4 = harvest path zone, and 5 for weighted average over four zones. Black and red line within the box marks the median and the mean. Blue line is a line at the mean of the first box (years 1–3), it can be easy to recognize weather the mean of the last box (year 25) increase or decrease compared to the first box. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 2**
Calculation of the correction factor for four management zones.

| Time | Zone | Soil thickness | Soil depth | BD ($g\,cm^{-3}$) | Soil $C_{org}$ (%) | Mineral parts ($g\,cm^{-2}$) | Organic part ($g\,cm^{-2}$) | Correction factor 3-layer (%) | Correction factor 1-layer (%) |
|---|---|---|---|---|---|---|---|---|---|
| Initial (year 0) | – | 5 | 0–5 | 0.94 | 2.52 | 4.59 | 0.12 | – | – |
| | – | 10 | 5–15 | 1.13 | 1.74 | 11.15 | 0.20 | | |
| | – | 15 | 15–30 | 1.21 | 1.12 | 17.91 | 0.20 | | |
| | – | Total | | | | 33.65 | 0.52 | | |
| Year 25 | Weeded circle | 5 | 0–5 | 0.88 | 2.99 | 4.25 | 0.13 | −0.8 | −1.21 |
| | | 10 | 5–15 | 1.14 | 1.79 | 11.21 | 0.20 | | |
| | | 15 | 15–30 | 1.25 | 1.11 | 18.57 | 0.21 | | |
| | | Total | | | | 34.04 | 0.54 | | |
| | Inter row | 5 | 0–5 | 0.83 | 3.13 | 4.02 | 0.13 | 2.6 | 3.51 |
| | | 10 | 5–15 | 1.09 | 1.75 | 10.73 | 0.19 | | |
| | | 15 | 15–30 | 1.19 | 1.07 | 17.70 | 0.19 | | |
| | | Total | | | | 32.45 | 0.51 | | |
| | Frond stack | 5 | 0–5 | 0.72 | 3.57 | 3.49 | 0.13 | 6.1 | 8.86 |
| | | 10 | 5–15 | 1.03 | 1.91 | 10.10 | 0.20 | | |
| | | 15 | 15–30 | 1.15 | 1.17 | 17.02 | 0.20 | | |
| | | Total | | | | 30.61 | 0.53 | | |
| | Harvest path | 5 | 0–5 | 1.02 | 2.01 | 5.00 | 0.10 | −6.5 | −7.21 |
| | | 10 | 5–15 | 1.19 | 1.39 | 11.75 | 0.17 | | |
| | | 15 | 15–30 | 1.29 | 0.86 | 19.23 | 0.17 | | |
| | | Total | | | | 35.98 | 0.43 | | |

### *3.2. Soil carbon stock before and after correction*

Table 2 presents calculation of the correction factor for four management zones. In a zone where the soil became compacted (harvest path zone) and decreased in $C_{org}$, the estimated soil $C_{stock}$ should be decreased by 6.5% and in a zone that increased in $C_{org}$ and decreased the soil BD (frond stack zone) the estimated soil $C_{stock}$ should be increased by 6.1%. Within this dataset, BD of the frond stack zone decreases (loose) and $C_{org}$ of the frond stack zone increases with age of oil palm. While, BD of the harvest path zone increases (compacted) and $C_{org}$ of the harvest path zone decreases with age of oil palm. These opposite trends make level of overall trend of soil $C_{stock}$ of oil palm plantation. This is reflected from the no significant different of weighted average of soil $C_{stock}$ among age of plantation ($p < 0.05$) (Fig. 5C). The correction factors do not substantially change the conclusion that there is no significant net change in soil $C_{stock}$ over an oil palm production cycle (Fig. 6A and B).

### *3.3. Time-averaged of carbon stock of a plantation*

The soil $C_{stock}$ in the top 30 cm soil depth was differ significantly among types of plantation/company management, initial land covers, soil types or management zones ($p < 0.05$). The soil $C_{stock}$ did not differ significantly with the age of the oil palm plantations ($p < 0.05$). This allowed us to estimate the time-averaged $C_{stock}$ of an oil palm plantation over a life cycle (25 years) based on the mean value of the weighted average of four management zones over the entire set of measurement points. The highest time-averaged $C_{stock}$ for the first 30 cm soil depth over a plantation life cycle was independent plantation, followed by nucleus and plasma plantation (Table 3).

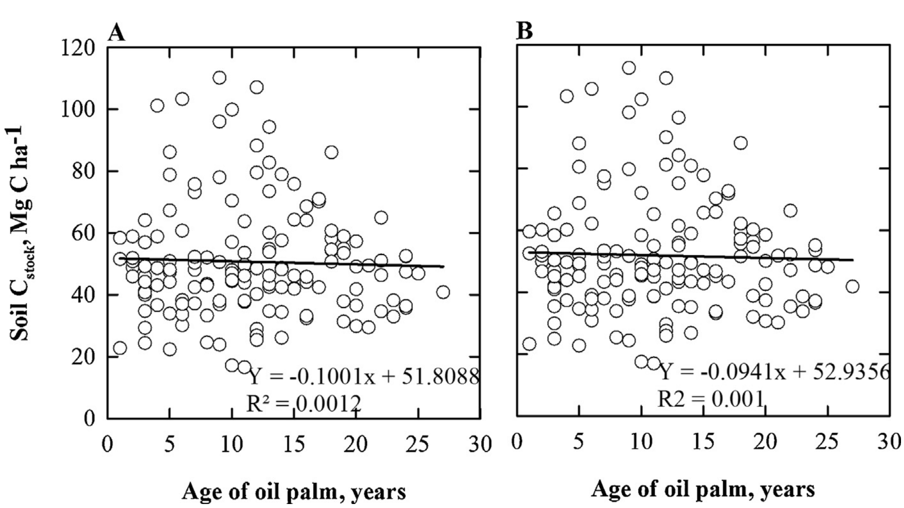


**Fig. 6.** Weighted average of soil $C_{stock}$ of mineral soil at 0–30 cm depth at different oil palm ages, before (A) and after (B) corrections for sampling depth based on changes in soil bulk density.

**Table 3**
Soil carbon stock of mineral soil in the top 30 cm of soil at different plantation/company managements, soil types, initial land covers, soil depths and management zones.

| Factors | | Bulk density ($g\,cm^{-3}$)[a] | Soil $C_{org}$ (%)[a] | Time-averaged stock ($Mg\,C\,ha^{-1}$)[a] |
|---|---|---|---|---|
| Plantation/company management | Nucleus | 1.04 ± 0.20 | 1.72 ± 0.75 | 51.60 ± 17.14 |
| | Plasma | 1.07 ± 0.21 | 1.60 ± 0.81 | 50.00 ± 22.02 |
| | Independent | 1.08 ± 0.17 | 1.76 ± 0.63 | 56.13 ± 20.42 |
| Soil type | Inceptisol | 1.02 ± 0.15 | 1.58 ± 0.80 | 45.53 ± 16.93 |
| | Ultisol | 1.07 ± 0.21 | 1.69 ± 0.55 | 53.45 ± 15.20 |
| | Others | 1.03 ± 0.22 | 1.91 ± 1.08 | 56.04 ± 27.04 |
| Initial land cover | Forest | 1.05 ± 0.22 | 1.72 ± 0.70 | 53.63 ± 15.98 |
| | Other than forest | 1.05 ± 0.16 | 1.63 ± 0.78 | 49.86 ± 20.94 |
| Depth | 0–5 cm | 0.88 ± 0.19 | 2.92 ± 1.37 | |
| | 5–15 cm | 1.11 ± 0.18 | 1.87 ± 0.88 | |
| | 15–30 cm | 1.07 ± 0.23 | 1.14 ± 0.54 | |
| Management zone | 1 (Weeded circle) | 1.05 ± 0.19 | 1.71 ± 0.77 | 52.12 ± 20.80 |
| | 2 (Interrow) | 1.06 ± 0.23 | 1.69 ± 0.75 | 51.99 ± 19.47 |
| | 3 (Frond stack) | 1.03 ± 0.19 | 1.80 ± 0.87 | 54.77 ± 21.72 |
| | 4 (Harvest path) | 1.10 ± 0.20 | 1.46 ± 0.70 | 43.08 ± 17.28 |
| Time-averaged carbon stock for depth 0–30 cm | | | | 51.85 ± 18.95 |

[a] Mean ± standard deviation.

Further analysis of the weighted average of soil $C_{stock}$ of forest and non-forest derived plantation, excluding the plantation that was already in the 2nd or 3rd cycle for the second category gave an interesting result as the net temporal trend of soil $C_{stock}$ in both forest and non-forest derived oil palm plantations was slightly negative (Fig. 7A). The lowest 8 points all belong to the non-forest category, the means for forest and non forest, 53.63 ± 15.98 and 49.86 ± 20.94 $Mg\,C\,ha^{-1}$ were significantly different in a *t*-test ($p < 0.05$). However, soil $C_{stock}$/soil $C_{stock\_ref}$ value is bigger than 1 with only some plot having values smaller than 1 (Fig. 7B). This also indicates that current practices of maintaining soil organic input from fronds, cover crops, and empty fruit bunches (where applied) sustain the soil $C_{stock}$.

### 3.4. Differences between plantations

For the six plantations with sufficient data over the life cycle of oil palm (Fig. 8A) a mixed set of temporal response curves was obtained. These varied from the concave pattern of initial decline followed by recovery, to essentially linear and convex ones that peaked at ages of 15–20 years. Within these six plantations we did not have sufficient degrees of freedom to associate differences in temporal pattern to plot history or other factors.

## 4. Discussion

The research was designed to answer four questions that jointly allow recommendations on how to treat oil palm in national C accounting schemes and footprint calculations, depending on land use change history. In response to the first question regarding the trend of BD and $C_{org}$ with age of oil palm for the four management zones, our data confirmed differentiation between the management zones within a plot. This implies that comparisons over time are not to be trusted unless the spatial sampling scheme acknowledges such differences in trends and compensates for them by appropriate weighting of sample locations. Over a plantation life cycle, $C_{org}$ in the weeded circle, interrow, and frond stack increased by 5.6%, 5% and 16.2%, respectively. The increments in $C_{org}$ in the circle must have been largely derived from root material (Frazão et al., 2013; Lamade et al., 1996) as the circle is maintained free of aboveground plant material. By contrast, the large input of pruned fronds led to an increase in $C_{org}$ beneath the frond stack. Significant yet small changes in $C_{org}$ between management zones were also reported by Fairhurst (1996) and Haron et al. (1998). As part of this exploration of the differentiation between zones corrections for comparisons at equal mineral soil mass (question 2) are indeed important. Without them, the differences would appear to be more pronounced, as lower BD and higher $C_{org}$ concentration per unit soil dry weight tend to correlate. Of methodological interest is that a correction could also have been applied if the 0–30 cm soil layer had been sampled as a single layer,

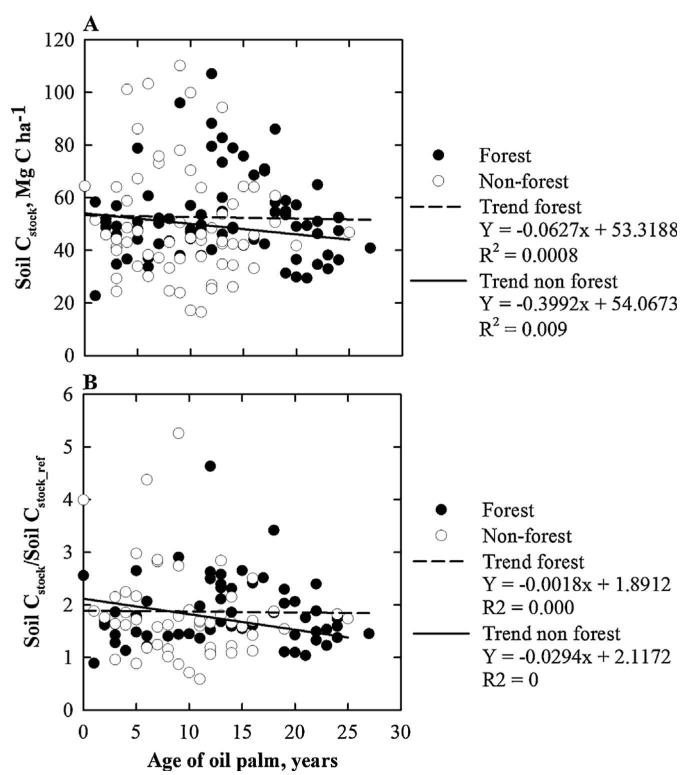


**Fig. 7.** Soil carbon stock at 0–30 cm depth of forest-derived plantation and non-forest derived plantation at different oil palm ages (A) and ratio of soil carbon stock and soil carbon stock reference (B). Data at year 0 are coming from forest and non forest land cover before conversion into oil palm.

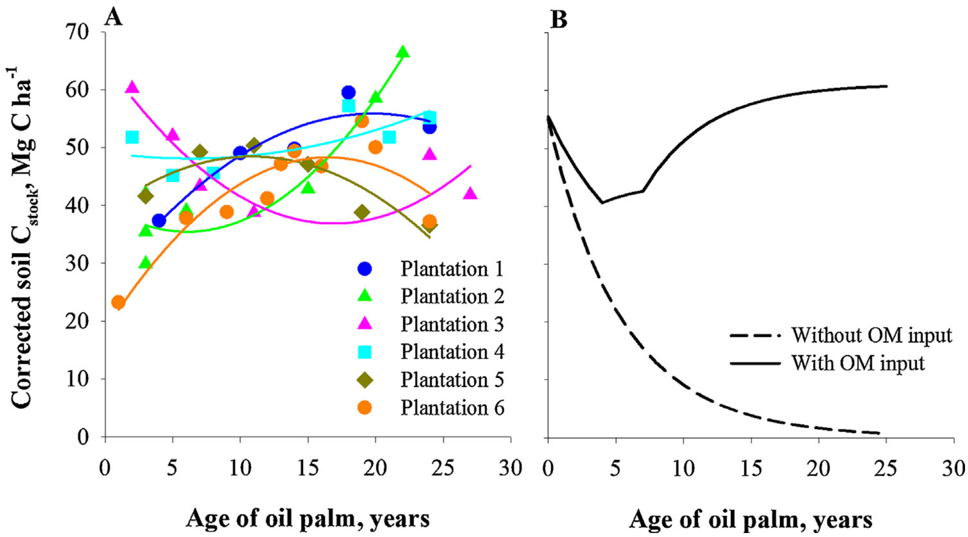


**Fig. 8.** (A) Non linear soil $C_{stock}$ trends in six plantations with sufficient age differentiation; (B) expected soil $C_{stock}$ for a simple model (based on Sitompul et al., 2000) of decline of inherited soil $C_{stock}$ and buildup of new soil $C_{stock}$ based on oil palm above- and below-ground residues.

as some C sampling protocols suggest. If we compare the correction factors for 1-layer (0–30) or 3-layers (0–5, 5–15 and 15–30 cm depth intervals), however, the correction factors would be more extreme if a single layer had been sampled. The 3-layer scheme gives a smaller correction factor because the $C_{org}$ of the deepest layer (which is used for the soil $C_{stock}$ correction) is known with greater precision.

In relation to our third question, increase or decrease of soil $C_{stock}$ with age of oil palm, we found evidence for a net decrease in the early part of the cycle, but not for the cycle as a whole. Several studies (Guo and Gifford, 2002; Schroth et al., 2002; Don et al., 2011; de Blécourt et al., 2013) reported that conversion of forest into agricultural systems, rubber or oil palm plantations leads to decreases in $C_{org}$ in the surface 30 cm of soil, but most of these studies assessed the early parts of the tree crop's life cycle. The reduced inputs of organic matter in agricultural systems or oil palm plantations can, according to some authors, lead to a soil $C_{stock}$ that is threefold less than under natural forest (Lamade and Bouillet 2005; Schroth et al., 2002). Our results, however, show that the zone-averaged soil $C_{stock}$ in the top 30 cm soil depth did not change significantly with time or age of plantation in either forest or non-forest derived plantations. This lack of net effect can be understood as a balance between initial decline of the soil C inherited from preceding vegetation, and build-up of oil palm-derived soil C. The time-averaged soil $C_{stock}$ was $51.85 \pm 18.95$ Mg C ha$^{-1}$. This indicates that good management practice that includes retention of organic inputs from fronds, cover crops, and even yield residue can in balance sustain the soil $C_{stock}$ as also indicated by soil $C_{stock}$/soil $C_{stock\_ref}$ value that is bigger than 1. However, use of EFB is mostly seen as form of waste disposal to oil palm fields near the mill, rather than as recycling to all plots (Bakar et al., 2011).

Aboveground $C_{stock}$ in the same plantations was estimated and the time-averaged aboveground $C_{stock}$ varied around 40 Mg C ha$^{-1}$ (Khasanah et al., 2012) and so the soil $C_{stock}$ to aboveground $C_{stock}$ ratio was around 1.25:1. The time-averaged soil $C_{stock}$ was relatively close to the 50.37–55.38 Mg C ha$^{-1}$ in the top 30 cm of soil measured in temperate forests by Dar and Sundarapandian (2013). Compared with the aboveground C losses due to land conversion, belowground C losses are small (Sommer et al., 2000). Our findings that soil $C_{stock}$ do not change significantly with the age of plantation, and that no net soil C emissions were detected may be used to improve the life cycle C accounting of biodiesel derived from palm oil.

Regarding the fourth question, variation in the trend of soil $C_{stock}$ between plantations, our plantation level data (Fig. 8A) suggest that there is variation between plantations in temporal pattern that may be further explored. As comparison, a simplified model based on Sitompul et al. (2000) is presented in Fig. 8B. A wide range of alternative model results can be obtained by varying initial allocation over the pools, e.g., related to soil texture, variations in decay rates for the pools, e.g., related to soil texture or soil water regime linked to drainage, and management of the palms that may influence the above- and belowground litter inputs and/or the temporal pattern of these inputs. Within a plausible parameter range both net increase and net decrease of soil $C_{stock}$ over a life-cycle is feasible.

A recent summary of soil $C_{stock}$ dynamics on agricultural soils described a 'soil C transition curve', with initial decline followed by recovery. Where net recovery has occurred under mainstream agricultural practice, it has generally been associated with an increase of organic inputs, above and/or belowground, and reduction of soil tillage (van Noordwijk et al., 2015). It seems to be plausible that a similar dynamic occurs within each oil palm life cycle, and that both net increases and net decreases are possible outcomes, depending on details of site and management. The real 'proof of the pudding' of sustainability assessments is the long-term persistence of productivity. The plantations that were part of this survey that were in their 2$^{nd}$ or 3$^{rd}$ oil palm cycle were not clearly differentiated from the other data. The primary soil-related issue for such plantations appears to be the increased prevalence of the *Ganoderma* fungus (Corley and Tinker, 2003) rather than net loss of $C_{org}$. A more detailed specific sampling of these plantations may in future test hypotheses that relate changes in both *Ganoderma* and $C_{org}$ to mycorrhiza development, beyond what our current data set could assert.

Overall, our data support conclusions of 'no net effect' for the response of soil carbon to well-managed oil palm plantations, compared to either a forest or a non-forest land use history. This conclusion is dependent on current management practices, and may need to be revised if practices change (e.g., by removal of fronds as source of biofuel). Carbon footprint calculations and national C accounting schemes can use a no-change assumption, while further exploration of the balance between decay and buildup of soil carbon may explain some of the apparent differences found between plantations.

## 5. Conclusions

The weighted average of corrected soil $C_{stock}$ in the top 30 cm across the four management zones from plantations with "good practice" management (as currently practiced in Indonesia) did, on average, not change significantly over the plantation cycle. These results imply that current retention in the field of organic plant residues and pruned fronds can recover from the initial loss and maintain soil $C_{stock}$ when assessed over a production cycle. Thus, there was no detectable net carbon emission from soil at a scale relevant for national C accounting. Increments that are supposed to accrue for oil palm established in non-forest backgrounds were not evident. With current soil management practices it is appropriate for life-cycle assessments to assume that soil $C_{stock}$ on mineral soils neither increase nor decrease due to oil palm cultivation.

## Acknowledgements

Underlying research was funded by the Dutch Government through the "Carbon Footprint of Oil Palm Production in Indonesia" project. NORAD and the CGIAR Forests, Trees and Agroforestry research program supported the preparation and publication of the manuscript. We thank Dr. Rosediana Soeharto (Indonesia Palm Oil Committee/IPOC) for linking us to oil palm companies and organizing the survey and the 25 oil palm plantations for participating the study. Andree Ekadinata, Elissa Dwiyanti and Sonya Dewi contributed to the design and implementation of the stratification scheme. We received valuable inputs from Jean Pierre Caliman (PT. Smart, Tbk), Mukesh Sharma (PT. Asian Agri, Tbk), Ken Giller (Plant Production Systems, Department of Plant Sciences, Wageningen University), participants of the REDD-ALERT write-shop in Samosir island, North Sumatra and anonymous reviewers.

## References


Adachi, M., Ito, A., Ishida, A., Kadir, W.R., Ladpala, P., Yamagata, Y., 2011. Carbon budget of tropical forests in Southeast Asia and the effects of deforestation: an approach using a process-based model and field measurements. Biogeosciences 8 (9), 2635–2647.

Agus, F., Henson, I.E., Sahardjo, B.H., Harris, N., van Noordwijk, M., Killeen, T.J., 2013. Review of emission factors for assessment of $CO_2$ emission from land use change to oil palm in Southeast Asia. In: Killeen, T.J., Goon, J. (Eds.), Reports from the Technical Panels of the Second Greenhouse Gas Working Group of the Roundtable for Sustainable Palm Oil (RSPO). RSPO, Kuala Lumpur, pp. 7–27. http://www.rspo.org/file/GHGWG2/3_review_of_emission_factors_Agus_et_al.pdf.

Aldrian, E., Susanto, R., 2003. Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature. Int. J. Climatol. 23, 1435–1452.

Badalikova, B., 2010. Influence of soil tillage on soil compaction. In: Dedousis, A.P., Bartzanas, T. (Eds.), Soil Engineering. Springer, pp. 19–30.

Bakar, R.A., Darus, S.Z., Kulaseharan, S., Jamaluddin, N., 2011. Effects of ten year application of empty fruit bunches in an oil palm plantation on soil chemical properties. Nutr. Cycl. Agroecosyst. 89 (3), 341–349.

Bruun, T.B., De Neergaard, A., Lawrence, D., Ziegler, A.D., 2009. Environmental consequences of the demise in swidden cultivation in Southeast Asia: carbon storage and soil quality. Hum. Ecol. 37 (3), 375–388.

Busch, J., Ferretti-Gallon, K., Engelmann, J., Wright, M., Austin, K.G., Stolle, F., Baccini, A., 2015. Reductions in emissions from deforestation from Indonesia's moratorium on new oil palm, timber, and logging concessions. Proc. Natl. Acad. Sci. U. S. A. 112, 1328–1333.

Corley, R.H.V., Tinker, B., 2003. The Oil Palm, fourth ed. Blackwell Science, Oxford.

Couwenberg, J., Dommain, R., Joosten, H., 2010. Greenhouse gas fluxes from tropical peatlands in South-East Asia. Glob. Change Biol. 16, 1715–1732.

Dar, J.A., Sundarapandian, A., 2013. Soil organic carbon stock assessment in two temperate forest types of western Himalaya of Jammu and Kashmir, India. For. Res. 3, 1.

de Blécourt, M., Brumme, R., Xu, J., Corre, M.D., Veldkamp, E., 2013. Soil stocks decrease following conversion of secondary forests to rubber (*Hevea brasiliensis*) plantations. PLoS ONE 8 (7), e69357. doi:http://dx.doi.org/10.1371/journal.pone.0069357.

Davis, S.C., Boddey, R.M., Alves, B.J.R., Cowie, A., Davies, C., George, B., Ogle, S.M., Smith, P., van Noordwijk, M., van Wijk, M., 2013. Management swing potential for bioenergy crops. Glob. Change Biol. Bioenergy 5, 623–638.

Don, A., Schumacher, J., Freibauer, A., 2011. Impact of tropical land-use change on soil organic carbon stocks—a meta-analysis. Glob. Change Biol. 17, 1658–1670.

Ellert, B.H., Bettany, J.R., 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75, 529–538.

European Comission, 2010. Guidelines for the calculation of land carbon stocks for the purpose of Annex V of Directive 2009/28/EC. Off. J. Eur. Union .

Fairhurst, T., 1996. Management of Nutrients for Efficient Use in Smallholder Oil Palm Plantations. Department of Biological Sciences, Wye College, University of London.

Flynn, H.C., Milà i Canals, L., Keller, E., King, H., Sim, S., Hastings, A., Wang, S., Smith, P., 2011. Quantifying global greenhouse gas emissions from land use change for crop production. Glob. Change Biol. 18 (5), 1622–1635.

Frazão, L.A., Paustian, K., Pellegrino Cerri, C.E., Cerri, C.C., 2013. Soil carbon stocks and changes after oil palm introduction in the Brazilian Amazon. Glob. Change Biol. Bioenergy 5, 384–390.

Germer, J., Sauerborn, J., 2008. Estimation of the impact of oil palm plantation establishment on greenhouse gas balance. Environ. Dev. Sustain. 10 (6), 697–716.

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Glob. Change Biol. 8, 345–360.

Hairiah, K., Dewi, S., Agus, F., Velarde, S.J., Ekadinata, A., Rahayu, S., van Noordwijk, M., 2011. Measuring Stocks Across Land Use Systems: A Manual. World Agroforestry Centre—ICRAF, SEA Regional Office, Bogor, Indonesia p. 154.

Haron, K., Brookes, P.C., Anderson, J.M., Zakaria, Z.Z., 1998. Microbial biomass and soil organic matter dynamics in oil palm (*Elaeis guineensis* jacq.) plantations, West Malaysia. Soil Biol. Biochem. 30 (5), 547–552.

Hassan, M.N.A., Jaramillo, P., Griffin, W.M., 2011. Life cycle GHG emissions from Malaysian oil palm bioenergy development: the impact on transportation sector's energy security. Energy Policy 39, 2615–2625.

Hergoualc'h, K., Verchot, L.V., 2011. Stocks and fluxes of carbon associated with land use change in Southeast Asian tropical peatlands: a review. Glob. Biogeochem. Cycl. 25 (2) GB2001.

Hooijer, A., Page, S., Canadell, J.G., Silvius, M., Kwadijk, J., Wosten, H., Jauhiainen, J., 2010. Current and future $CO_2$ emissions from drained peatlands in Southeast Asia. Biogeosciences 7, 1505–1514.

Houghton, R.A., Greenglass, N., Baccini, A., Cattaneo, A., Goetz, S., Kellndorfer, J., Laporte, N., Walker, W., 2010. The role of science in reducing emissions from deforestation and forest degradation (REDD). Carbon Manag. 1, 253–259.

IFC, 2013. Diagnostic Study on Indonesian Oil Palm Smallholders: Developing a Better Understanding of Their Performance and Potential. International Finance Corporation, Washington.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Japan.

Khasanah, N., van Noordwijk, M., Ekadinata, A., Dewi, S., Rahayu, S., Ningsih, H., Setiawan, A., Dwiyanti, E., Octaviani, R., 2012. The carbon footprint of Indonesian palm oil production. Technical Brief No 25: Palm Oil Series. World Agroforestry Centre—ICRAF, SEA Regional Office, Bogor, Indonesia p. 10.

Kotowska, M.M., Leuschner, C., Triadiati, T., Meriem, S., Hertel, D., 2015. Quantifying above- and below-ground biomass carbon loss with forest conversion in tropical lowlands of Sumatra (Indonesia). Glob. Change Biol. doi: 10.1111/gcb.12979 (accepted).

Lamade, E., Bouillet, J.P., 2005. Carbon storage and global change: the role of oil palm. Ol. Corps Gras Lipides 12, 154–160.

Lamade, E., Djegui, N., Leterme, P., 1996. Estimation of carbon allocation to the roots from soil respiration measurements of oil palm. Plant Soil 181 (2), 329–339.

Laurance, W.F., Koh, L.P., Butler, R., Sodhi, N.S., Bradshaw, C.J.A., Neidel, J.D., Consunji, H., Vega, J.M., 2010. Improving the performance of the roundtable on sustainable palm oil for nature conservation. Conserv. Biol. 24, 377–381.

Law, M.C., Balasundram, S.K., Husni, M.H.A., Ahmed, O.H., Harun, M.H., 2009. Spatial variability of soil organic carbon in oil palm. Int. J. Soil Sci. 4 (4), 93–103.

Lee, J., Hopmans, J.W., Rolston, D.E., Baer, S.G., Six, J., 2009. Determining soil carbon stock changes: simple bulk density corrections fail. Agric. Ecosyst. Environ. 134 (3), 251–256.

McCarty, G.W., Reeves, J.B., Yost, R., Doraiswamy, P.C., Doumbia, M., 2010. Evaluation of methods for measuring soil organic carbon in West African soils. Afr. J. Agric. Res. 5 (16), 2169–2177.

Nair, P.K.R., Saha, S.K., Nair, V.D., Haile, S.G., 2011. Potential for greenhouse gas emissions from soil carbon stock following biofuel cultivation on degraded lands. Land Degrad. Dev. 22 (4), 395–409.

Nelson, D.W., Sommers, L.E., et al., 1996. Total carbon, organic carbon, and organic matter. In: Sparks, D.L. (Ed.), Methods of Soil Analysis. Part 3. Chemical Methods. SSSA Book Series No. 5. SSSA and ASA, Madison, WI, pp. 961–1010.

Niedermeyer, E.M., Sessions, A.L., Feakins, S.J., Mohtadid, M., 2014. Hydroclimate of the western Indo-Pacific warm pool during the past 24,000 years. Proc. Natl. Acad. Sci. U. S. A. 111, 9402–9406.

Patthanaissaranukool, W., Polprasert, C., 2011. Carbon mobilization in oil palm plantation and milling based on a carbon-balanced model—a case study in Thailand. Environ. Asia 4, 17–26.

Paustian, K., Andrén, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., Woomer, P.L., 1997. Agricultural soils as a sink to mitigate $CO_2$ emissions. Soil Use Manag. 13, 230–244.

Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land-use change: processes and potential. Glob. Change Biol. 6 (3), 317–327.

Powers, J., Corre, M., Twine, T.E., Veldkamp, E., 2011. Geographic bias of field observations of soil carbon stocks with tropical land-use changes precludes spatial extrapolation. Proc. Natl. Acad. Sci. U. S. A. 108, 6318–6322.

Ravindranath, N.H., Ostwald, M., 2008. Carbon Inventory Methods Handbook for Greenhouse Gas Inventory, Carbon Mitigation and Round-wood Production Projects. Springer, Dordrecht, pp. 165–166.
Reijnders, L., Huijbregts, M.A.J., 2008. Palm oil and the emission of carbon-based greenhouse gases. J. Clean. Prod. 16 (4), 477–482.
Santoso, A., 2010. Plasma and its accounting implications. Palm Oil Plantation: Industry Landscape, Regulatory and Financial Overview. PricewaterhouseCoopers, Indonesia.
Santoso, D., Adiningsih, S., Mutert, E., Fairhurst, T., Van Noordwijk, M., 1997. Site improvement and soil fertility management for reclamation of Imperata grasslands by smallholder agroforestry. Agrofor. Syst. 36, 181–202.
Schroth, G., D'Angelo, S.A., Teixeira, W.G., Haag, D., Lieberei, R., 2002. Conversion of secondary forest into agroforestry and monoculture plantations in Amazonia: consequences for biomass, litter and soil carbon stocks after 7 years. For. Ecol. Manag. 163, 131–150.
Schulte, E.E., 1995. Recommended soil organic matter tests. Recommended soil testing procedures for the northeastern United States. Northeast Reg. Bull. 493, 47–56.
Sheil, D., Casson, A., Meijaard, E., van Noordwijk, M., Gaskell, J., Sunderland-Groves, J., Wertz, K., Kanninen, M., 2009. The Impacts and Opportunities of Oil Palm in Southeast Asia. Center for International Forestry Research (CIFOR), Bogor, Indonesia p. 67.
Siangjaeo, S., Gheewala, S.H., Unnanon, K., Chidthaisong, A., 2011. Implications of land use change on the life cycle greenhouse gas emissions from palm biodiesel production in Thailand. Energy Sustain. Dev. 15 (1), 1–7.
Sitompul, S.M., Hairiah, K., Cadisch, G., Van Noordwijk, M., 2000. Dynamics of density fractions of macro-organic matter after forest conversion to sugarcane and woodlots, accounted for in a modified Century model. Neth. J. Agric. Sci. 48, 61–73.
Sommer, R., Denich, M., Vlek, P.L.G., 2000. Carbon storage and root penetration in deep soils under small-farmer land-use systems in the Eastern Amazon region, Brazil. Plant Soil 219, 231–241.
Suprayogo, D., Widianto, C.G., van Noordwijk, M., 2003. A pedotransfer resource database (PtfRDB) for tropical soils: test with the water balance of WaNuLCAS. In: Post, D. (Ed.), MODSIM Proceedings, Townsville, Australia, July 2003.
Tan, K.T., Lee, K.T., Mohamed, A.R., Bhatia, S., 2009. Palm oil: addressing issues and towards sustainable development. Renew. Sustain. Energy Rev. 13, 420–427.
van der Werf, G.R., Morton, D.C., DeFries, R.S., Olivier, J.G.J., Kasibhatla, P.S., Jackson, R.B., Collatz, G.J., Randerson, J.T., 2009. CO emissions from forest loss. Nat. Geosci. 2, 737–738.
van Noordwijk, M., Mulyoutami, E., Sakuntaladewi, N., Agus, F., 2008. Swiddens in Transition: Shifted Perceptions on Shifting Cultivators in Indonesia. World Agroforestry Centre—ICRAF, SEA Regional Office, Bogor, Indonesia p. 48.
van Noordwijk, M., Woomer, P., Cerri, C., Bernoux, M., Nugroho, K., 1997. Soil carbon in the humid tropical forest zone. Geoderma 79, 187–225.
van Noordwijk, M., Agus, F., Dewi, S., Purnomo, H., 2014a. Reducing emissions from land use in Indonesia: motivation, policy instruments and expected funding streams. Mitig. Adapt. Strateg. Glob. Change 19, 677–692.
van Noordwijk, M., Matthews, R.B., Agus, F., Farmer, J., Verchot, L., Hergoualc'h, K., Persch, S., Tata, H.L., Lusiana, B., Widayati, A., Dewi, S., 2014b. Mud, muddle and models in the knowledge value-chain to action on tropical peatland issues. Mitig. Adapt. Strateg. Glob. Change 19, 863–885.
van Noordwijk, M., Goverse, T., Ballabio, C., Banwart, S., Bhattacharyya, T., Goldhaber, M., Nikolaidis, N., Noellemeyer, E., Zhao, Y., 2015. Soil carbon transition curves: reversal of land degradation through management of soil organic matter for multiple benefits. In: Banwart, S.A., Noellemeyer, E., Milne, E. (Eds.), Soil Carbon: Science, Management and Policy for Multiple Benefits. CAB International, Harpenden (UK), pp. 26–46.
Verhoeven, J.T.A., Setter, T.L., 2010. Agricultural use of wetlands: opportunities and limitations. Ann. Bot. 105 (1), 155–163.
Wosten, J.H.M., Lilly, A., Nemes, A., Le Bas, C., 1998. Using existing soil data to derive hydraulic parameters for simulation models in environmental studies and in land use planning. Report 156. SC-DLO, Wageningen (The Netherlands) 106 pp.