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A REVIEW OF MODELS FOR ASSESSING CARBON STOCKS AND CARBON SEQUESTRATION IN OIL PALM PLANTATIONS

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ABSTRACT

Reliable estimates of the carbon present in stands of oil palm, both in the palms themselves and in other biomass components of oil palm plantations, are crucial for assessing the net greenhouse gas (GHG) balance and carbon footprint of palm oil production. Carbon sequestered during the growth of the oil palm crop generally represents the largest item of the oil palm GHG budget, being second in magnitude only to land use change (LUC) or, for crops grown on peat soil, to microbial peat oxidation. In this article, alternative models available for assessing carbon stocks and carbon sequestration in oil palm plantations are examined taking into account factors such as palm age, planting density and soil type. Both linear and non-linear models are discussed and the crop and plantation components contributing to them are reviewed, as is the methodology used, which may involve destructive or non-destructive techniques, or a combination of both. Guidance is given for selecting the most appropriate model.

Keywords: oil palm biomass, growth models, carbon stock, plantation components.

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INTRODUCTION

Estimating carbon sequestration by the oil palm crop and by other components of oil palm plantations is a major step towards determining the greenhouse gas (GHG) balance of palm oil production. Such estimates, normally carried out annually and ideally throughout the life of the crop, form a crucial part of palm oil GHG accounting but one that has proved to be the most controversial and difficult to assess by the producer. This is partly due to the substantial amount of work involved in making the necessary measurements and in determining the most appropriate methods for doing this. This article reviews the methodology available and provides guidelines for selecting the most appropriate model from a variety of alternatives.

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The grower has the choice of carrying out his own measurements or using existing models that have been identified as providing realistic estimates for a particular plantation or estate. A reliable model is one that gives good correspondence between *in situ* measurements and model output. Measurements on the standing crop are highly desirable if not essential for assessing selected models but once this has been done and a model has been verified it can be used to generate missing data as well as to extrapolate results to give a full accounting of growth throughout the life of a crop.

Available models can be classified according to the following attributes:

- models giving palm and plantation biomass as a function of palm or plantation age; and
- models relating palm or plantation biomass to some easily measured attribute such as trunk height.

Methods used may involve destructive or non-destructive measurements and may differ in their scope and degree of detail. Thus, *e.g.* only the palms themselves may be assessed and other plantation components ignored or all components may be included. In the case of the palms, many studies consider above-ground biomass only and ignore roots and other below-ground components.

CONSTRUCTING OIL PALM GROWTH CURVES FROM POOLED DATA

There are numerous examples in the literature of oil palm biomass assessments for palms of different ages but the majority of such data have generally been poorly replicated and both the age range covered and the measurements made have generally been incomplete. To overcome or at least minimise these deficiencies, data obtained from some 34 sources relating biomass to palm age were pooled as shown in *Figure 1*. This procedure revealed a non-linear trend in biomass versus palm age with increases in biomass with age gradually diminishing over time. One problem with this approach has been the paucity of data for old palms (*i.e.* those above 20 or so years in the field).

For comparative purposes, *Figure 1* also includes data produced by a 'vigorous growth' version of the Oil Palm Production Simulator (OPRODSIM) growth simulation model (Henson, 2005). OPRODSIM is a physiologically based mechanistic model that simulates basic growth processes resulting in biomass values for the main oil palm components such as roots, fronds and trunk. It can be seen that the data generated by OPRODSIM yield a non-linear curve located approximately mid way between the extreme values given by the assorted data obtained in the field.

Some examples where data produced by the OPRODSIM model closely match those obtained by field measurements can be found in Henson (2009c) and others are shown in *Figure 2*. Both the total standing oil palm biomass and the biomass of individual palm components (fronds and trunk) are well simulated in these cases.

A comparison was also made between the oil palm above-ground standing biomass curve obtained using OPRODSIM and a similar curve produced by Germer and Sauerborn (2008) based on the latter's review of the literature covering 51 plantings and 12 studies. As shown in *Figure 3*, both curves resulted in a very similar time-averaged standing biomass present over 30 years of 63.62 and 66.77 t ha^{-1} yr^{-1}; equivalent respectively to 28.63 and 30.0 t carbon (C) ha^{-1} yr^{-1} assuming a 45% C content.

Possible Causes of Non-linear Biomass Accumulation

Non-linear growth patterns such as those involving declines in standing biomass towards the end of the life of a plantation (*e.g. Figure 1*), are simulated by the OPRODSIM model (*Figure 2*), and can be accounted for by several processes. These include the belated shedding of frond bases (which are otherwise left attached to the trunk for several years after bunch harvest and frond pruning

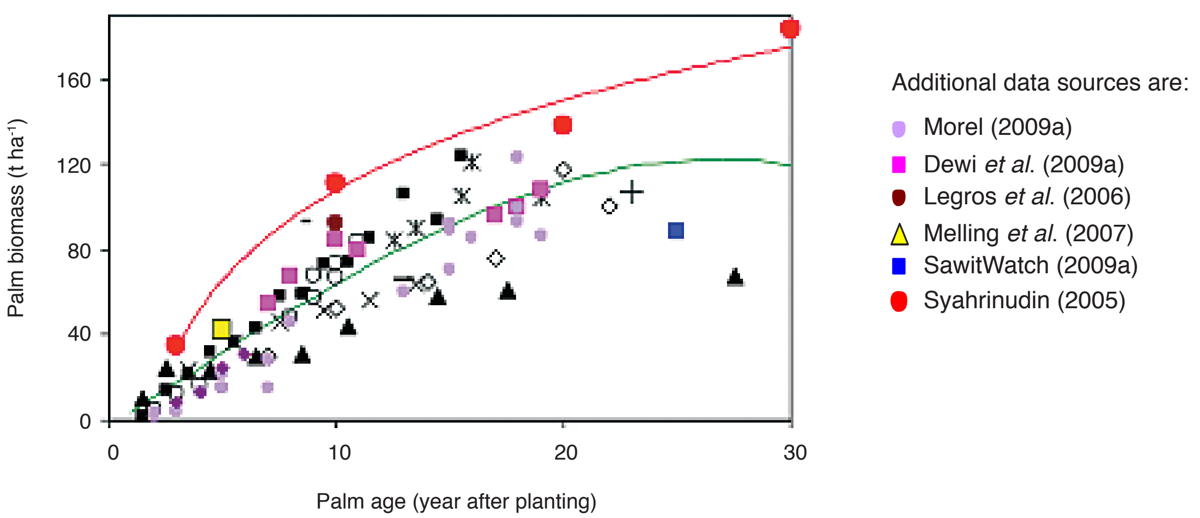

Figure 1. Standing biomass of oil palm stands of different ages.

Note: Data represented by black and white symbols are reproduced from Henson (1999; 2009d). Other data, represented by coloured symbols, were obtained from newer sources listed below. All measurements include roots or an allowance for roots but exclude minor biomass components such as frond bases left on the trunk after pruning, male inflorescences still attached to the palm, and developing fruit bunches. Where necessary, data were adjusted for differences in planting density using a standard density of 148 palms ha^{-1}. The majority of data were obtained by destructive measurements. The green curve was produced using the 'vigorous' growth option of the Oil Palm Production Simulator (OPRODSIM) model (Henson, 2005). The figure is modified from Henson (2009a).

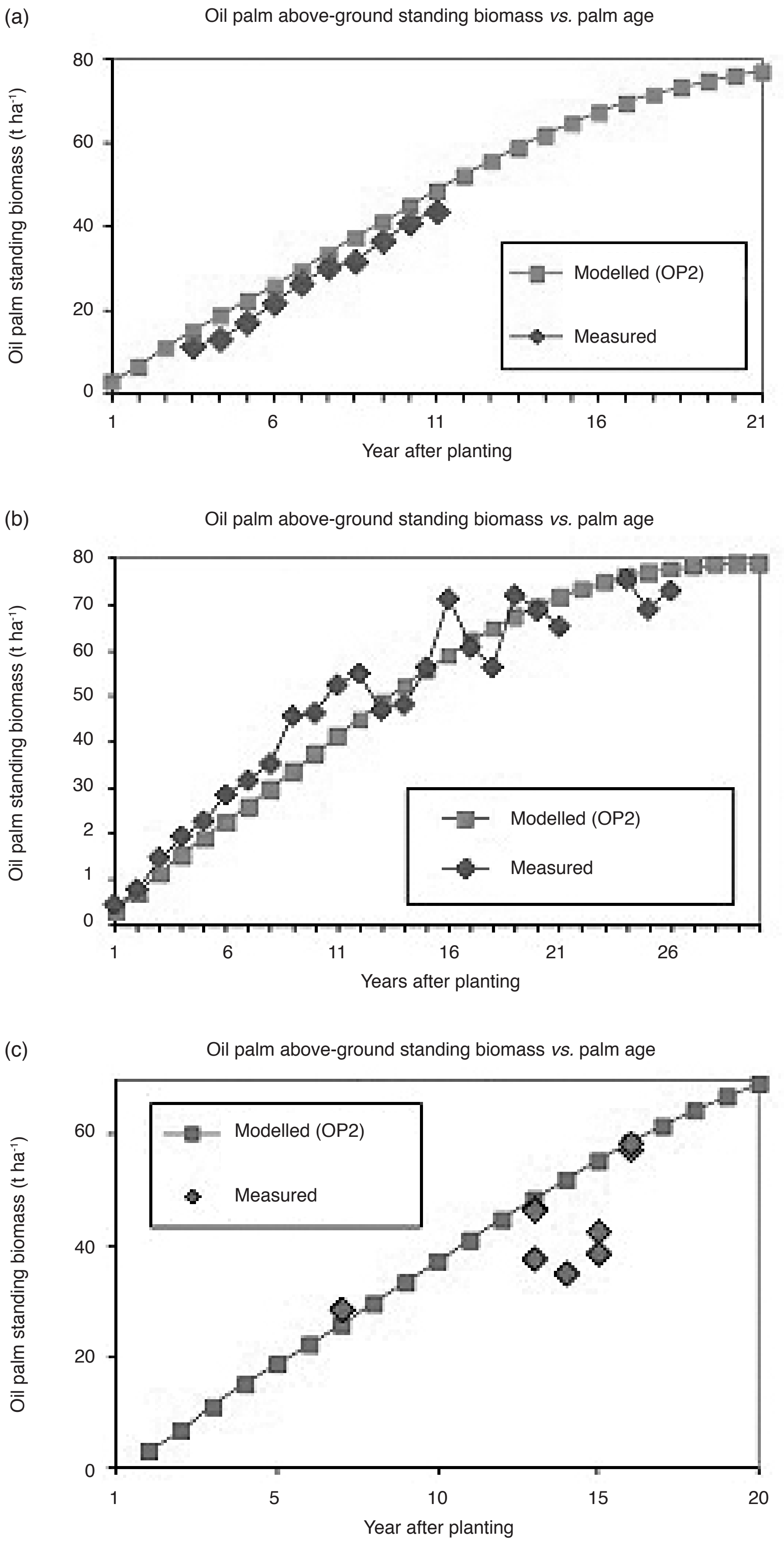

Figure 2. Comparisons between measured and modelled oil palm standing biomass at three sites (a, b, c). Measured data were obtained using standard non-destructive methods (Corley and Tinker, 2015). Modelled data were obtained using the 'vigorous growth' version of the Oil Palm Production Simulator (OPRODSIM) growth simulation model (OP2) as shown by Chase et al. *(2012) and Bessou* et al. *(2014).*

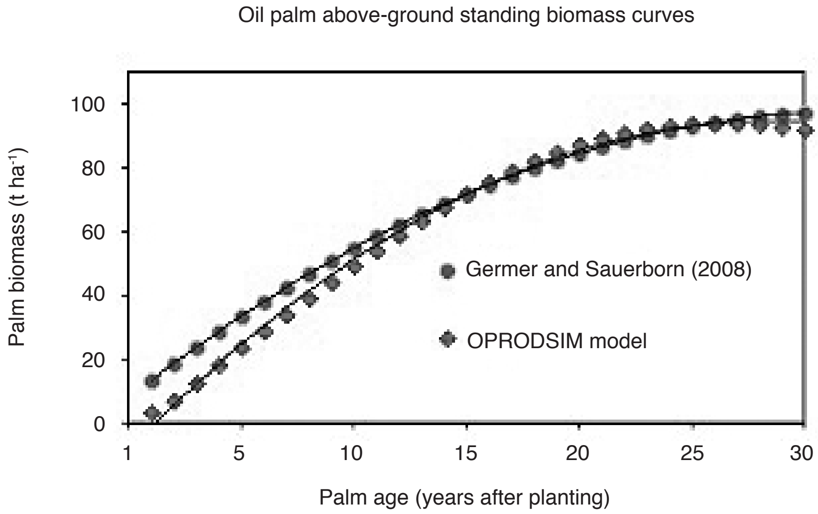

Figure 3. Comparison of two above-ground oil palm biomass curves; one produced using the OPRODSIM model for 'vigorous' growth conditions as shown in Figure 1, *and the other based on the literature review of Germer and Sauerborn (2008). The latter figure, with data fitted using polynomial equations, is modified from Henson (2009a).*

(*Figure 4*)), the failure of frond biomass production to fully compensate for the loss of frond biomass due to pruning and harvesting of fruit bunches, to a reduction in standing bunch biomass with palm age, and to the decline and death of old palms due to diseases such as *Ganoderma*. An example of age-related shedding of pruned frond bases is shown in *Figure 4*. Others are given by Henson *et al*. (2012).

Total Plantation Biomass

In addition to the oil palms themselves, biomass is also present in the plantation in the form of other components that include ground cover vegetation, pruned frond piles, and plantation litter such as shed frond bases, male inflorescences and residual debri from previous crops or vegetation left over from land clearing for new oil palms (some of which is strictly necromass having undergone various phases of decomposition). As with the palms, these components can either be measured *in situ* [*e.g*. Syahrinudin (2005); Khasanah *et al.* (2012)], or estimated using models. An example of the latter is the OPCABSIM model (Henson, 2009b; 2010), that is designed to complement OPRODSIM by catering for these additional forms of carbon sequestration.

The inclusion of plantation components in addition to the palms themselves (*e.g. Figure 5*) results in an increase in the standing biomass in the plantation of from 6% to almost 18% over a 25-year lifetime (Henson and Chase, 2010; Khasanah *et al*., 2012).

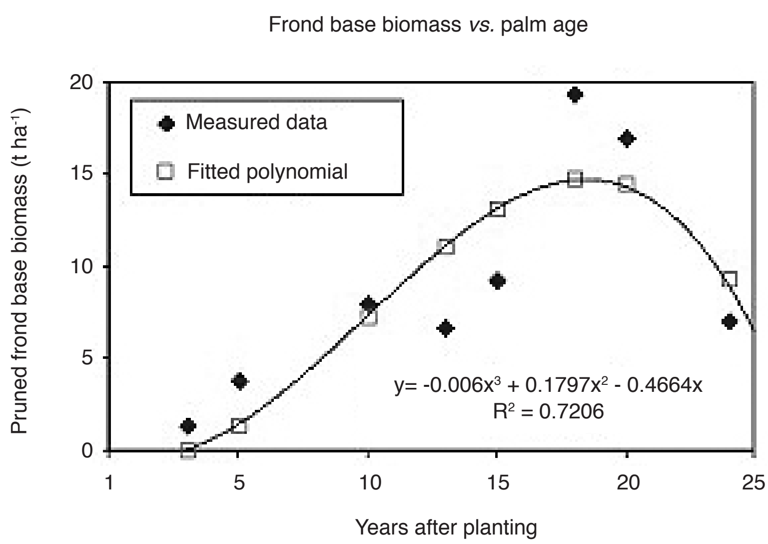

Figure 4. Changes with time in biomass of frond bases adhering to the trunk. Modified from Henson et al. *(2012).*

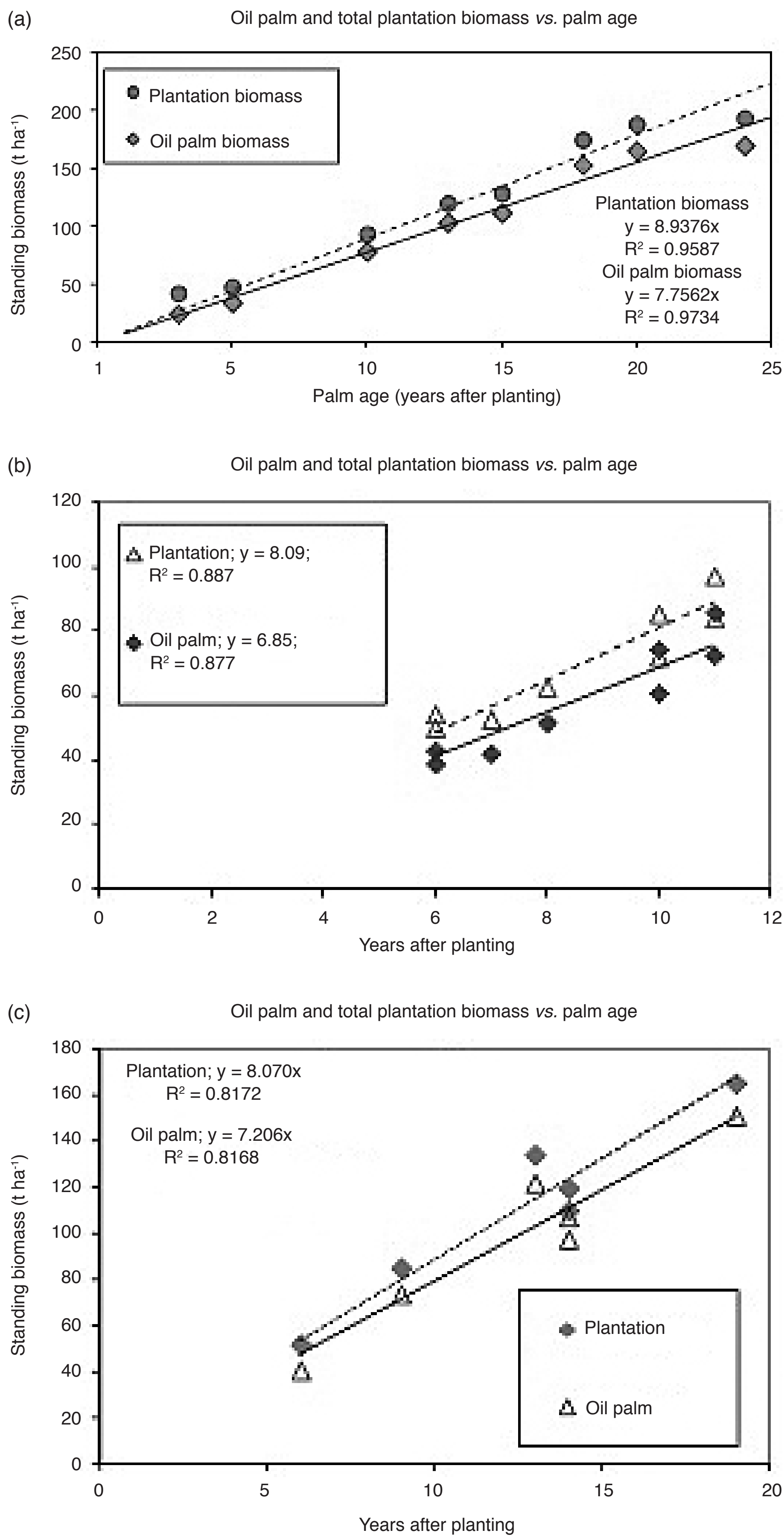

Figure 5. Changes with time in standing biomass of oil palms and other oil palm plantation components as assessed by in situ *measurements at several sites (a, b, c) in Papua New Guinea (Henson and Chase, 2010).*

LINEAR *vs.* NON-LINEAR MODELS

It should be noted that most oil palm growth data exhibit linearity in the early phases of oil palm growth but at this stage the scatter of data can often obscure the actual trend (*e.g. Figure 1*) and it becomes necessary to examine longer-term records in order to determine if the trend is truly linear. In such cases, linear models provide a good fit to measured data but one that clearly deviates from that predicted using OPRODSIM (*e.g. Figure 6*).

Studies by the International Centre for Research in Agroforestry (ICRAF, Indonesia) have, for at a large number of sites, resulted in a series of allometric equations relating above-ground palm biomass to palm age and trunk height. Above-ground palm biomass was found to increase linearly with palm age up to at least 27 years after planting (*Figure 7a*) with a trunk height increase of up to 14 m (*Figures 7b* and *7c*). Only small differences were observed due to soil type such as those between palms on mineral versus peat soils but somewhat larger ones occurring between estate palms and those on smallholdings (the latter being less productive). The actual parameters and the range of the x-axes varied with the source of data (van Noordwijk *et al*., 2010; Khasanah *et al*., 2012; Harja *et al*., 2012).

Root biomass of the palms measured by ICRAF was calculated from the above-ground biomass assuming a fixed root:shoot ratio of 0.25. This is similar to the 30-year mean root:shoot (R:S) value of 0.221 calculated by OPRODSIM for smallholder palms (R:S = 0.221) with average growth, and the ratio of 0.247 generated by OPRODSIM for estate palms with vigorous growth. In view of the paucity of the data, further measurements are desirable for roots, to assess their contribution to total oil palm biomass.

The amounts of carbon in the understory (ground cover, litter and necromass) in the plantations studied by ICRAF were obtained by destructive sampling (Khasanah *et al*., 2012) and are shown in *Table 1*. As with most other plantation data, these are time-averaged values that apply assuming either a 25- or 30-year oil palm replanting cycle. In

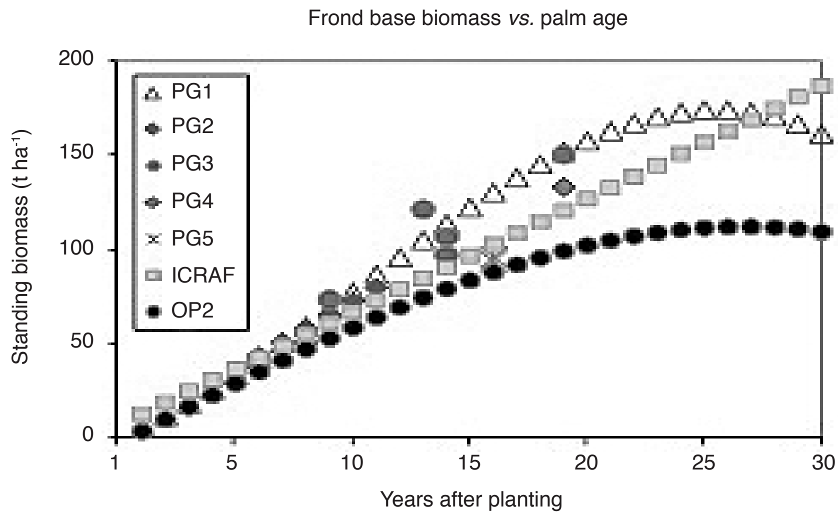

Figure 6. Oil palm biomass measured directly at several sites in Papua New Guinea (PG1 to PG5) compared to biomass simulated using the 'vigorous' growth option of the Oil Palm Production Simulator (OPRODSIM) model (OP2) or to a linear regression of biomass against palm height [Khasanah et al. *(2012) for estate palms on mineral soil (ICRAF)].*

TABLE 1. OIL PALM PLANTATION BIOMASS COMPONENTS ON EX-FORESTED LAND IN INDONESIA AS ASSESSED BY ICRAF*

Soil type	Management system	Time averaged C stock (t ha yr^{-1})					
		Oil palm trunk and fronds	Under-story	Litter	Necro-mass	Roots	Total
Mineral	Estate land	38.60	0.51	2.36	3.60	9.65	54.72
	Smallholdings	33.78	0.51	2.79	3.60	8.45	49.13
Peat	Estate landings	34.00	0.51	2.36	3.60	8.50	48.97

Note: *Indonesian Centre for Research in Agroforestry. Modified from *Table 2* of Khasanah *et al*. (2012). Values were calculated assuming a 25-year replanting cycle.

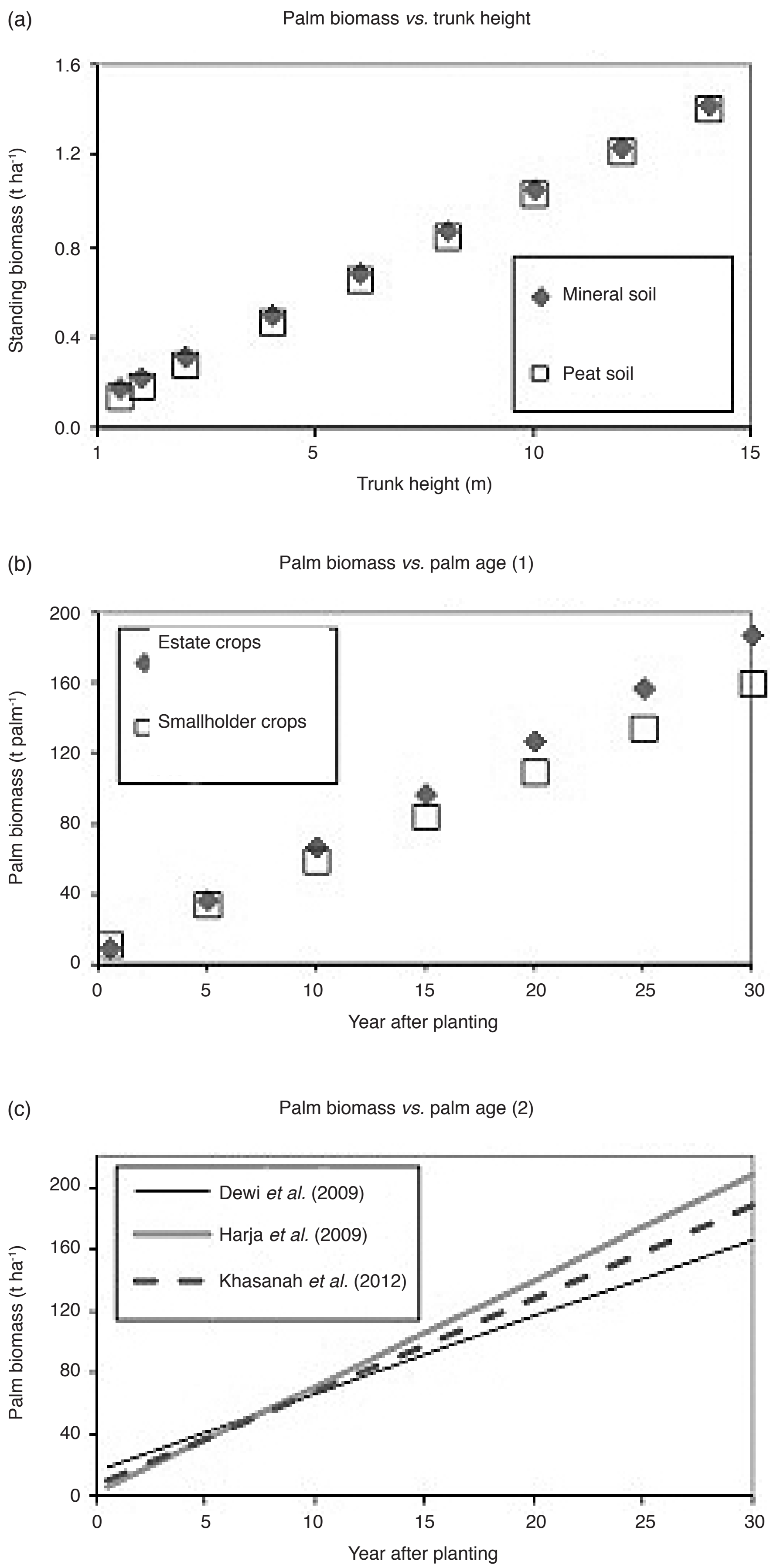

Figure 7. Correlations between (a), above-ground oil palm biomass and trunk height for two soil types, between (b), above-ground oil palm biomass and palm age for two management regimes, and between (c), above-ground oil palm biomass and oil palm age for three data sets.

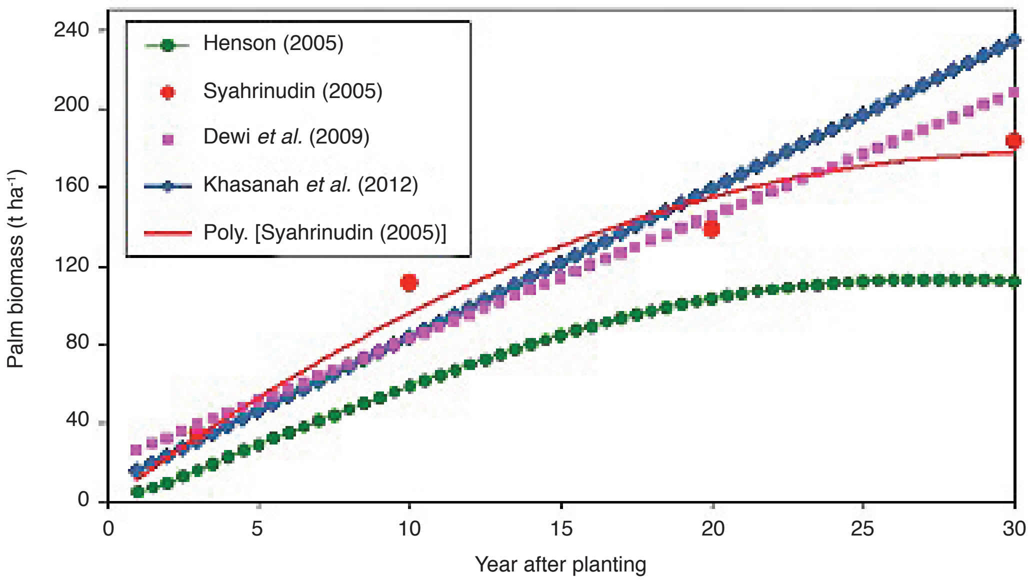

Figure 8. Comparisons between linear and non-linear models of total (i.e. *above- and below-ground) oil palm biomass and data obtained by Syahrinudin (2005) using destructive measurements. The green curve (Henson, 2005) was produced using the Oil Palm Production Simulator(OPRODSIM) model.*

the case of necromass, this was significant only for sites converted to oil palm from rain forest.

With regard to the above-ground oil palm biomass, no equations comparable to those obtained for estate palms have thus far been obtained for smallholder palms on peat.

Comparisons between both linear and non-linear models of palm biomass plotted against palm age are shown in *Figure 8*. The use of the ICRAF equations resulted in substantially greater biomass throughout the life of the plantation than did those using OPRODSIM while destructive measurements undertaken earlier by Syahrinudin (2005) were not too dissimilar from results of ICRAF regressions over the first 20 years. However, after this they exhibited a quite definite non-linear trend.

CONCLUSION

Several models have been developed to assess biomass production and carbon accumulation by oil palm, leading to estimates of carbon sequestration by the palms as well as by other components of the oil palm plantation such as ground vegetation, residual necromass from vegetation present at the time of planting and palm litter such as frond piles, shed frond bases and male inflorescences. The models available differ in several respects but can be broadly divided into those based on destructive measurements (involving the division of whole palms into major growth components such as fronds, trunk and roots), and non-destructive methods that involve measurements on intact palms with only minimal damage to the standing crop. In addition to minimising crop damage, non-destructive techniques have the important advantage of permitting repeated measurements over time on the same palms. They are also generally less time-consuming than destructive measurements and result in less variable assessments partly due to a larger number of palms being sampled. On the other hand, destructive sampling leads to more direct and possibly more accurate assessments of biomass of individual palms, especially for the palm root system which is generally only sampled in part when using non-destructive techniques. Detailed descriptions of the measurements undertaken during non-destructive assessments are given by Corley and Breure (1981), Breure and Verdooren (1995) and Corley and Tinker (2015) amongst others.

Destructive sampling is, in any case required for establishing allometric equations relating empirical (non-destructive) measurements to biomass. But once these are established the use of such equations can greatly simplify biomass assessment. The derivation of biomass from palm height or from palm age (*e.g.* Dewi *et al.*, 2009; Khasanah *et al.*, 2012) are examples of the utility of this approach. Once these relationships are determined they can be readily applied to other oil palm stands with little or no impact on the crop.

There still remains the problem of how to fully assess and include the below-ground biomass and other plantation components such as ground cover and litter that represent additional sites for carbon sequestration by the plantation. Given the variability and poor accessibility of the oil palm root system, assessing roots usually proves to be a difficult and laborious task and inevitably involves some degree of destructive sampling such as that typified by excavating trenches or taking soil cores. Fortunately the impact on the crop as a whole of such sampling is generally small with the samples taken usually representing only a minor proportion of the total soil rooting volume. Also, the frequency of sampling over time is low with annual assessments usually being sufficient. Root data obtained from the same palms as the shoot allow root:shoot ratios to be calculated that can be used to predict root biomass from above-ground biomass of other palms. Presently, however, such data are few and more estimates of root biomass are needed to provide better assessments of both root and whole palm biomass.

SUPPLEMENTARY INFORMATION

Supplementary information on the models can be found in MS Excel file: PalmGHG Crop seq options July 2015 via http://jopr.mpob.gov.my/wp-content/uploads/2017/03/palmGHG.xls, which contains data from the following sources:

1. Oil palm database;
2. Database references;
3. Oil palm models;
4. ICRAF linear models

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