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Palm Oil Green Development Campaign

Grappling with Inordinate Uncertainty

Measuring the Carbon Footprint of Tropical Land-Use Change

A Report by World Growth

Foreword by Dr. David F Smith AM, Senior Fellow,
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Palm Oil Green Development
Campaign

Alleviating Poverty through Wealth Creation

Palm oil provides developing nations and the poor a path out of poverty. Expanding efficient and sustainable agriculture such as Palm Oil Plantations provides small and large plantation owners and their workers with a means to improve their standard of living.

Sustainable Development

Sustainable development of palm oil plantations and growth of the palm oil industry in developing nations can and will be achieved through consultation and collaboration with industry, growers, lobby groups and the wider community.

Climate and the Environment

Palm Oil is a highly efficient, high yielding source of food and fuel. Palm Oil plantations are an efficient way of producing fossil fuel alternatives and capturing carbon from the atmosphere.

Opportunity and Prosperity

Developing nations must be allowed the chance to grow and develop without political intervention by environmental groups or developed nations. It is crucial that developing nations be given the same opportunities which developed nations have benefited from.

Property Rights

Efficient palm oil plantations and the growing demand for palm oil give smaller land holders greater opportunities to make a living off their land, maintain their ownership and support their rights to property and prosperity.

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Foreword by Dr. David Smith

Dr. David F Smith AM, Medal of Australian Agriculture, is a Senior Fellow at the Melbourne School of Land and Environment at The University of Melbourne. He has had wide experience in the developing countries where such production systems are being developed.

In producing this paper, World Growth has made a welcome addition to the literature on transitions from one form of land use to another, in this case to the production of palm oil from plantations. The work recognizes that the palms may be planted on land that has had forest cover removed long ago for farming, or has recently been cleared, specifically for palm oil production.

The paper includes a very thorough review of the literature, highlights the unreliability of some efforts to quantify this impact and throws into relief the gaps in knowledge.

In the modern era, all production systems must be based precisely on 'knowing'— such things as levels of nutrients in the soil, the exact inputs required, target ranges for operations — as so much depends on the efficiency of each stage and the supporting critical analysis. Far too often assertions are made about the footprint of such land-use changes; unfortunately, too often by groups wishing for a bad result for any alternative to trees. The absence of accurate data plays into their hands.

One common practice is to lump all land having some trees present in the landscape with other areas of dense tall trees and describe all as forest. In fact it is not axiomatic that tree cover is superior in environmental terms to ground cover by crops or pasturage. Here in Australia, over the years we have seen tree cover replaced by pasture and crop systems with greatly increased interception of solar energy. Key elements have been the precise addition of fertilizers and the introduction of legumes, enhancing the capture of nitrogen from the atmosphere. Thus there is a substantial increase in the annual capture of carbon dioxide and other emissions, and over the years a major sequestration of carbon in soil organic matter molecules comprised of carbon, nitrogen, sulphur and phosphorus.

This paper is an excellent example of a study embracing all aspects from vegetation removal, planting crops and field practices, describing the engineering aspects of extraction, waste reduction and use and marketing of the oil. It melds economic and agronomic analysis and engineering aspects. It identifies elements that must be more precisely measured — reducing what can only be described as guess work.

Overview

It is fashionable to consider the 'carbon footprint' that day-to-day activities of humans have on planet earth. The rationale for this concept is that it will give us a readily understood indication of the emissions of certain gases – especially carbon dioxide and methane – that are implicated in raising the earth's temperature and the level of the sea which has become the focus of much contemporary concern in the community.

However, the concept also has utility as an indication of how efficiently humans conduct the activities that give rise to these emissions; the production of waste has an economic cost regardless of the consequences of its disposal.

In the application of the concept two considerations are paramount: the calculations must include all aspects of the chain of activities in production, distribution, and utilization, and the values attributed to each step must be based on sound science.

In the case of a product like palm oil, the chain must include:

- Removal and disposal of existing vegetation which may involve clearing of primary or secondary forest or replacing other human activities such as farming and grazing;
- Establishment of the oil palms;
- Net accumulation of carbon during development of the palms and their ground cover;
- Management of the oil palms for weed and pest control and the application of fertilizer;
- Field operations to harvest the fresh fruit bunches and transport them to the processing mill
- Milling the fruit and extracting its oils;
- Treating and disposal of mill waste, including the palm oil mill effluent (POME); and
- Transporting and distributing the oil products to where they are to be utilized.

In each of these activities, the emissions intensity is highly variable, with a wide range of values that may be observed despite intensity metric is used. Table 1 shows just how wide is the range of values in the professional literature.

There is a tendency for different groups to aggregate values along this chain to support their bias. Frequently it is the condemnation of the clearing of forest and production of palm oil. There is scope to arrive at nearly any answer. To illustrate, the biomass of tropical forest suitable for conversion to palm oil production ranges from 10 to 20 tonnes per hectare for pastures or crops to 600 tonnes of above-ground biomass per hectare for closed, mature forest. Choosing a figure within this range can overwhelm all the other data inputs — and 'prove' just about any claim.

The published research has concentrated on primary forest and permanent grassland. Little has been published on secondary forest or degraded forestland. What has been documented, however, highlights the high degree of spatial and temporal variation that exists in such cases due to differences in local environmental factors.

This is highly significant for any assessment of the 'carbon footprint' for palm oil. Most of the recent oil palm development has been on tropical forest land, which has been extensively disturbed or degraded by a combination of fire, harvesting, and clearance for shifting cultivation.

The FAO has sought to overcome these shortcomings by directly estimating forest biomass from timber inventory data provided by national governments. As few national inventories are collected on tropical forests, the FAO relies on 'educated guesswork' to fill the gaps. However, the rigor of such an approach is highly questionable.

The object of this paper is, therefore, to set out logically and coherently the chain of carbon-related events which deliver the palm oil product, to review the literature relating to each stage, and to bring together the data available in a framework which will have utility for a range of readers. The analysis will also identify weaknesses and unreliability in the information and so make recommendations for more research and analysis.

Table 1

Summary of Key Estimates from the Published Literature on Emissions from Palm Oil Production

Stage in production process	Low (a)	Average	High (a)	References
Loss of above-ground biomass due to removal of pre-existing vegetation	negligible	295 t per ha	600 t per ha	Andrade de Castro & Kaufmann 1998 Brown & Lugo 1984 Bulla & Lourido 1980 Germer & Sauerborn 2008 Lasco 2002 Magcale-Macandog 2002 Procter et al 1983 Scfholes & Hall 1996 Whitmore 1984
Loss of below-ground biomass due to removal of pre-existing vegetation	negligible	47 t per ha	100 t per ha	Brown 1997 Brown & Lugo 1984 Germer & Sauerborn 2008 Gijsman et al 1997 Jackson et al 1996 Sanford & Cuevas 1996 Whitmore 1984
Loss of soil carbon due to removal of pre-existing vegetation (mineral soils)	negligible	120 t C per ha	240 t C per ha	Garcìa et al 1994 Germer & Sauerborn 2008 Jobbágy & Jackson 2000
Loss of soil carbon due to removal of pre-existing vegetation (organic soils)	negligible	120 t C per ha	240 t C per ha	Furukawa et al 2005 Germer & Sauerborn 2008 Hadi et al 2000 Inubushi et al 2003 Shimada et al 2001
Average gain in above-ground biomass by oil palms over commercial lifetime	20 t per ha	60 t per ha	100 t per ha	Corley & Tinker 2003 Germer & Sauerborn 2008 Sanchez 200 Syahrinudin 2005
Average gain in biomass in ground cover & plant litter over commercial lifetime	0.5 t per ha	2.5 t per ha	4.0 t per ha	Ezenwa et al 1996 Germer & Sauerborn 2008 Haron et al 2000 Parrotta 1992 Ross 1999
Average below-ground biomass gain by oil palms to maturity	10 t per ha	20 t per ha	30 t per ha	Braconnier & Caliman 1989 Fairhurst 1996 Germer & Sauerborn 2008 Henson & Dolmat 2003 Khalid et al 2000 Syahrinudin 2005
Emissions from use of fertilizers & pesticides on oil palm	1.1 t CO_2e per ha	1.25 t CO_2e per ha	1.4 t CO_2e per ha	Nikander 2008 Wijbrans & van Zutphen 2005

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Notes: (a) based on a 95 per cent confidence interval (i.e. two standard deviations) where the studies in question have disclosed the standard errors of their estimates. (b) Fresh Fruit Bunch

Table 1

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Summary of Key Estimates from the Published Literature on Emissions from Palm Oil Production

Stage in production process	Low (a)	Average	High (a)	References
Rate of production of palm oil mill effluent	0.5 t per tonne of FFB (b)	0.6 t per tonne of FFB (b)	0.7 t per tonne of FFB (b)	Tokyo Electric Power 2009 Yacob 2005 Wahid et al 2006
Methane concentration of palm oil mill effluent (open tank treatment)	13.5%	35%	49%	Brinkmann Consultancy 2009 Yacob et al 2005 Shirai et al 2003
Methane concentration of palm oil mill effluent (closed tank treatment)	35%	54.4%	70%	Brinkmann Consultancy 2009 Yacob et al 2006 Shirai et al 2003
Emissions from petroleum fuels used in oil palm plantation & mill operations	0.18 t CO_2e per ha	0.29 t CO_2e per ha	0.40 t CO_2e per ha	Brinkmann Consultancy 2009 Damen & Faaij 2007 Wood & Corley 1993

Notes: (a) based on a 95 per cent confidence interval (i.e. two standard deviations) where the studies in question have disclosed the standard errors of their estimates. (b) Fresh Fruit Bunch

I. Introduction

The conversion of forest land to agriculture has become increasingly controversial in recent years. The controversies have been most acute over deforestation, forest degradation, and land use change in tropical developing countries. In large part the controversies have reflected increasing public concern about their longer-term consequences for the global climate.

This is driving a growing demand for information on the environmental impact of agricultural products in general and of those grown in tropical countries in particular. This demand has led to calls for the application of concepts such as the 'carbon footprint' with a focus on those tropical agricultural products, such as palm oil, whose global consumption has been among the fastest growing agricultural products in world markets.

The idea that the carbon footprint of products and processes can and should be measured is becoming popular, particularly in the industrialized world. Supermarket chains in the UK are now giving carbon ratings to some products. The European Parliament has mandated that the carbon emissions from indirect land use change be assessed for inclusion in the EU Renewable Energy Directive. Environmental Non-Governmental Organizations, such as WWF, are now proposing a carbon footprint standard be made an additional indicator in the system used to certify the 'sustainability' of palm oil production, which has been developed by the WWF-sponsored Roundtable on Sustainable Palm Oil.

This paper examines what is entailed in defining and measuring the carbon footprint of a product when a change of land use occurs and assesses the reliability and availability of the information that is required to produce a robust estimate. This question has particular currency because of the ongoing negotiations to create a new global instrument to regulate emissions of greenhouse gases. It is considered to be particularly relevant to the impact of deforestation and conversion of forest land for other uses, including agricultural production.

Against that background, this paper critically examines the concept of a carbon footprint and its practical application to issues of land-use change, particularly in the context of developing countries for the purpose of expanding their agricultural sectors to feed growing populations. In doing so, it reviews the published literature on the estimation of greenhouse gas emissions, including the availability of comprehensive and robust data along the supply chain for tropical agricultural products, such as palm oil.

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II. Problems with the Concept

Conceptually, a product's 'carbon footprint' is the total amount of greenhouse gas emissions that are generated as a consequence of the production and consumption of a given amount of the product.

For this purpose, greenhouse gas emissions are generally measured in terms of the Global Warming Potential of each gas, as defined by the Intergovernmental Panel on Climate Change (IPCC).[1] Sometimes the concept is extended to include the subsequent reuse or recycling of the product, as well as its ultimate disposal. As yet there is no consensus on the scope of the concept or its application.

Life cycle assessment (LCA) is an internationally standardized method for evaluating the environmental burdens produced and the environmental resources consumed over the life cycle of a product. It covers the extraction of the raw materials, the manufacture of the product, its use by the final consumer, any subsequent recycling or reuse, and its ultimate disposal. The International Standards Organisation (ISO) has formally recognized the LCA concept and given it operational expression in ISO 14040[2] and ISO 14044.[3] In contrast with the 'carbon footprint' concept, LCA is concerned with all environmental impacts of a product and not just with its greenhouse gas emissions.

The application of the 'carbon footprint' concept to a product requires a sound understanding of the science of those parts of the carbon cycle that affect and are affected by its production and consumption, and robust and comprehensive data on the relevant carbon stocks and flows.

The idea of constructing a 'carbon footprint' for a product has some immediate appeal. It holds out the promise of providing a comprehensive and internally consistent picture of all greenhouse gas emissions along the entire supply chain of a good or service — from the extraction of the raw materials, through the process of producing and distributing it, to final consumption and ultimate disposal, as appropriate.

There are, however, a number of fundamental impediments to the practical application of the carbon footprint concept and they are most pronounced in the case of tropical agricultural products, such as palm oil.

Firstly, every product necessarily has a multiplicity of emission 'signatures' in terms of the total amount of greenhouse gas emissions, which are generated at each stage in the process of its production and consumption — from the extraction of its raw materials, through its manufacture and distribution, to its use and ultimate disposal. At every stage there are multiple possibilities for how or where the activity is to be conducted, each characterized by differences in emission intensity. The feasible combinations of economic stages produce a series of unique production-distribution pathways, each with a different emissions 'signature'.

A kilogram of palm oil grown on a plantation in Malaysia will have a different emissions 'signature' to one grown by a small holder in West Africa, where the nature of the land and the production system is completely different. Equally, if either kilogram were to be transported to the EU and consumed there, the downstream emissions would be significantly different to what would happen were the oil to be consumed locally. The same is true for most other environmental impacts.

It is therefore impossible to speak coherently of a product having a single 'carbon footprint' or a single environmental footprint for that matter.

Secondly, few products have a supply chain where the emissions 'signature' associated with each linkage in that chain is, more or less, a given. From an emissions perspective, most products have a multiplicity of supply chains at any one time. As a consequence, every product has a multiplicity of 'carbon footprints' at any one time.

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[1] IPCC [Intergovernmental Panel on Climate Change], 2007, Climate Change 2007: The Physical Science Basis, in IPCC, 2007a, Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge UK & New York, NY

[2] ISO [International Standards Organization] 14040:2006 *Environmental Management — Life Cycle Assessment — Principles and Framework*

[3] ISO 14044:2006 *Environmental Management – Life Cycle Assessment – Requirements and Guidelines*

This is particularly true for the production of agricultural tree crops, such as palm oil. The provenance of the land that is used to grow them matters greatly from an emissions perspective. The emissions implications of converting primary tropical forest land are quite different to those involved in using existing agricultural land or forest land that has been degraded by shifting agriculture over a long period of time. For each type of tropical forest land, the emission implications of its conversion vary enormously.

Thirdly, the emissions 'signature' that is associated with a given product is constantly changing. Any estimate of a product's emissions 'signature' is contingent on the pattern of final consumption for the product in question and the nature of the various supply chains that support that pattern. Both are changing constantly in response to changes in prices along the supply chain and for substitutes.

Every time the composition of final demand or its supply chain changes, the 'carbon footprint' of the product also changes. This is so, even though there may be no change in the total amount of the product that is consumed globally. As a product's final consumption patterns and supply chains are changing constantly, this means its 'carbon footprint' is also constantly changing in response to constantly changing relative prices at each and every stage of the process.

Finally there are significant problems with our understanding of the science of greenhouse gas emissions from land-use change and the data that are available for estimating emissions from land-use change. These problems are most severe for the estimation of emissions from tropical land-use change and the conversion of forest land to agricultural production. These issues are taken up in greater detail in the following chapters.

There are, however, a number of fundamental impediments to the practical application of the carbon footprint concept and they are most pronounced in the case of tropical agricultural products, such as palm oil.

III. Emissions from Land-Use Change

The conversion of primary forest to oil palm is seen as the major source of greenhouse gas emissions associated with the production and use of palm oil over its life cycle. There are, however, profound and substantial uncertainties involved in the identification and measurement of greenhouse gas emissions associated with changes in land use in general, let alone those associated with the conversion of particular land uses — such as forest, peat lands, or permanent pasture — to oil palm plantations.

This chapter will address the general issues in land use conversion, while the following one will canvass the particular issues associated with conversion for the growing of oil palm.

The global carbon cycle

The Earth's climate is characterized by numerous complex and interrelated physical, chemical, and biological processes that encompass the atmosphere, the continents, and the oceans. These processes are dominated by the global carbon cycle, which is the ultimate determinant of the concentration of greenhouse gases in the atmosphere.

The global carbon cycle involves the movement of carbon between its major global reservoirs or sinks. In broad terms, these reservoirs or sinks are the:

- stocks of fossil fuel resources — such as crude oil, natural gas, and coal — both above- and below-ground;
- ocean ecosystems; and
- terrestrial ecosystems.

The use of carbon compounds, such as fossil fuels, releases carbon into the atmosphere in the form of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_20) and other greenhouse gases, while marine and terrestrial organisms absorb CO_2 from the atmosphere through photosynthesis. As a consequence, large amounts of carbon are stored in marine sediment, trees, and other terrestrial plants, but the quantity can be affected whenever a reservoir is disturbed by human activity or natural change. Such disturbances can affect both the rates of absorption of greenhouse gases and of their release.

In any given accounting period, the net change in the greenhouse gases released to the earth's atmosphere can be defined by the sum of the change in each of its carbon reservoirs or sinks:

Net emissions =
Δ Fossil fuel stocks + Δ Ocean sink + Δ Terrestrial sink[4]

For its Fourth Assessment Report on climate change — its most recent — the Intergovernmental Panel on Climate Change (IPCC) has estimated that, over the 1990s, the net greenhouse gas emissions released to the atmosphere averaged around 3.2 Gt of carbon (C) a year.[5] The total was made up as follows:

3.2 Gt C =	6.4 Gt C	– 2.2 Gt C	– 1.0 Gt C
(± 0.1 GtC)	(± 0.4 GtC)	(± 0.4 Gt C)	(± 0.6 Gt C)
[Net emissions]	[Δ Fossil fuel stocks]	[Δ Ocean sink]	[Δ Terrestrial sink][6]

The above estimates were based on measurements of changes in:

- concentration of each of the greenhouse gases in the atmosphere [Net emissions];
- global primary energy use [Fossil fuel use]; and
- concentration of CO_2 in the oceans and modeling of their movement [Ocean sink].[7]

Most importantly, the contribution of terrestrial ecosystems to global emissions was unable to be estimated independently by the IPCC. The IPCC has inferred its value from its other three estimates.[8] Taken at their face value, the IPCC estimates indicate

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[4] By convention, the change in fossil fuel stocks includes the release of greenhouse gases from the industrial use of carbonate minerals, such as the production of cement from limestone.

[5] IPCC 2007, Table 7.1, p. 516

[6] The estimation errors calculated by the IPCC (2007b) are in the round brackets. They are the equivalent to ±one standard deviation of the central estimate. The standard deviation for a sample or population is a statistical measure of the dispersion in the individual values around the mean.

[7] IPCC 2007, p. 519

[8] ΔTerrestrial sink = Δ Fossil fuel stocks – Δ Ocean sink – Net emissions

that around half of the global emissions from fossil fuel use were absorbed by the oceans and terrestrial ecosystems.

In the case of the IPCC estimate of the carbon that is absorbed by terrestrial ecosystems, the estimation error — based on one standard deviation — is ±60 per cent. This is much larger than the equivalent error for any of the other estimates. One standard deviation means that there is a 68 per cent chance that the actual amount of carbon absorbed by terrestrial ecosystems was somewhere between 0.4 Gt C per year and 1.6 Gt C per year[9] — and a 32 per cent chance that it was outside this range, which is an extremely high risk given the seriousness of the consequences of being wrong.

Reducing that probability necessarily widens the error range around the central estimate. For example, an estimation error of two standard deviations would give a 95 per cent confidence interval around the central estimate — in other words, it reduces the chance of the actual carbon emissions being outside this interval to just 5 per cent — which is more in line with the benchmark that is generally used for econometric and statistical analysis. In the case of the IPCC estimate of the net contribution of terrestrial ecosystems to the atmosphere, the 95 per cent confidence interval would be ± 1.2Gt C per year. This means that there is a 95 per cent chance that its contribution was somewhere between a net *addition* of 0.2 Gt C per year to the atmosphere and a net *removal* of 2.2 Gt C per year from it.

On the face of it, the error associated with this estimate is so great that one cannot be confident about its significance and therefore cannot determine whether terrestrial ecosystems were a net source or sink over the 1990s. The uncertainty has been highlighted by successive attempts by the IPCC to breakdown the total terrestrial ecosystem emissions between their various components, particularly those directly associated with land use change.

Emissions from global land use change

In its Fourth Assessment Report, the IPCC estimated that global land use change over the decade of the 1990s — principally the removal and degradation of forests — accounted for greenhouse emissions that were equivalent to about 1.6 Gt of carbon a year, with the vast bulk of the emissions originating in the tropics.[10] This figure is half of the global net emissions that the IPCC estimated for each year of the decade. Table 2 has a breakdown of the IPCC global estimate by broad geographical region.

In making its estimate, the IPCC drew on the results of two empirical studies of greenhouse gas emissions from global land use change in the 1990s (which have been published in peer-reviewed journals).[11] The first study was conducted by DeFries and her colleagues,[12] while the second was undertaken by Houghton.[13] (Houghton was also one of DeFries' co-authors.) Both sets of results, with estimation errors, are summarized in Table 2.

DeFries and her colleagues estimated that the emissions from land use change in the tropics during the 1990s had averaged around 1.0 Gt C per year.[14] This work was based on a terrestrial carbon accounting model developed by Houghton and others.[15] [16] The Houghton model tracks the carbon in living vegetation, dead plant material, wood products, and soils for each hectare of land that has been cultivated, harvested, or forested. The model is based on changes in certain types of land use and in the carbon stored on or in each hectare of land. The land

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[9] This is known as the 68 per cent confidence interval.

[10] IPCC 2007, p. 516

[11] IPCC 2007, Table 7.2, p. 518

[12] Ruth S. DeFries, Richard A. Houghton, Matthew C. Hansen, Christopher B. Field, David Skole, & John Townshend, 2002, 'Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s', *Proceedings of the National Academy of Sciences*, 99(22), pp. 14,256–14,261

[13] R.A. Houghton, 2003, 'Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000', *Tellus,* 55B(2), pp. 378–390.

[14] DeFries et al 2002

[15] R.A. Houghton, J.E. Hobbie, J.M. Melillo, B. Moore, B.J. Peterson, G.R. Shaver, & G.M. Woodwell, 1983, 'Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO_2 to the atmosphere', *Ecological Monographs*, 53, pp. 235–262

[16] Richard A. Houghton & Joseph L. Hackler, 1995, *Continental scale estimates of the biotic carbon flux from land cover change: 1850–1980*, ORNL/CDIAC-79, NDP-050, Oak Ridge National Laboratory, Oak Ridge, TN

Table 2

Estimates of Greenhouse Gas Emissions from Changes in Land Use by Geographical Region, 1990 to 1999, Gt C Per Year (a) (b)

Source	Tropical Americas	Tropical Africa	Tropical Asia	All Tropical Regions	Non-Tropical Regions	World
DeFries et al 2002	0.5 (0.2 to 0.7)	0.1 (0.1 to 0.2)	0.4 (0.2 to 0.6)	1.0 (0.5 to 1.6)	N.A.	N.A.
Houghton 2003	0.8 (0.5 to 1.1)	0.4 0.2 to 0.6)	1.1 (0.6 to 1.6)	2.2 (1.6 to 2.8)	-0.02 (0.48 to 0.52)	2.2 (1.4 to 3.0)
Achard et al 2004	0.3 (0.3 to 0.4)	0.2 (0.1 to 0.2)	0.4 (0.3 to 0.5)	0.9 (0.5 to 1.4)	N.A.	N.A.
IPCC 2007b	0.7 (0.4 to 0.9)	0.3 (0.2 to 0.4)	0.8 (0.4 to 1.1)	1.6 (1.0 to 2.2)	-0.02 (0.48 to -0.52)	1.6 (0.5 to 2.7)

Notes: (a) estimation errors are in round brackets and represent ± one standard deviation (b) n.a. = not available.

Source: IPCC 2007, Table, 7.2, p. 518.

use changes in question included land clearing for cultivation and pasture, abandonment of agricultural land, harvesting of wood and timber, reforestation, afforestation, and shifting cultivation.

To parameterize the Houghton carbon accounting model, DeFries and her colleagues used data on carbon storage rates under different land uses, which had been previously collected from a range of sources by Houghton and his colleagues, including official statistics together with ecological and anthropological studies.[17] DeFries and her colleagues also used spatial data on tree coverage that they derived from the coarse satellite data collected by the Advanced Very High Resolution Radiometer (AVHRR), which is operated by the US National Oceanic and Atmospheric Administration (NOAA).[18]

In sharp contrast, Houghton estimated that the global greenhouse gas emissions from land use change averaged 2.2 Gt C per year, all of which originated in the tropics.[19] Even though he had used the same carbon accounting model as DeFries and her colleagues[20] — which he had also been instrumental in developing — every one of Houghton's results was substantially higher than those estimated by DeFries and her colleagues. This was true both for the land use emissions from tropics as a whole as well as those from each of the major tropical regions.

Houghton used the data on changes in land use and forest cover over the 1990s that were collected by the FAO as part of its regular Forest Resource Assessment (FRA) process over that decade.[21] [22] However, the estimates of the changes in forest cover that have been

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[17] Houghton et al 1983 and Houghton and Hackler 1995

[18] P.A. Agbu & M.E. James, 1994, *The NOAA/NASA Pathfinder AVHRR Land Data Set User's Manual*, Goddard Distributed Active Archive Centre, Greenbelt, MD

[19] Houghton (2003) estimated that land use change in non-tropical regions of the world represented a net carbon sink but its contribution was negligible in extent.

[20] DeFries et al 2002

[21] FAO [Food & Agriculture Organization of the United Nations], 2000, 'Assessing state and change in global forest cover: 2000 and beyond', *Forest Resources Assessment Programme Working Paper*, Working Paper 31, FAO, Rome

[22] FAO [Food and Agriculture Organization of the United Nations], 2001, *Global forest resources assessment 2000: Main report*, FAO Forestry Paper No 140, FAO, Rome, Italy

derived from satellite observations for all the major tropical regions over the same period, which have been published by DeFries and her colleagues, gave rates of change in forest cover that were significantly less than those suggested by the FRA data.

As has been pointed out many times in the literature to date, questions remain over the accuracy of the FAO data on land use and forest cover.[23] [24] For the FRA process, the data in question are obtained from national governments, with only limited satellite confirmation of its accuracy in the case of the data collected for the 1990s.

The participation of individual countries means that varying definitions of forest cover and time intervals have been used for the collection. Moreover, the database contains a significant number of values that have been estimated by FAO staff, which could also result in unreliability or bias. Although most of the data quality concerns relate to the data on smaller developing countries that lack an established local auditing capacity, there are significant concerns about the quality of the data reported by a number of the larger developing countries, such as China, and the sharpness of the definitions that are used to collect them. In other words, the problems are most acute where most of the tropical deforestation is thought to occur.

As has been pointed out many times in the literature to date, questions remain over the accuracy of the FAO data on land use and forest cover.

Houghton has subsequently admitted that the errors that are associated with his 2003 estimates of emissions at a national or regional level are substantial.[25] In the light of the research by Achard et al[26]and DeFries et al[27], Houghton concluded that his 2003 estimates of emissions from tropical countries may be too high by a factor of two. Given the uncertainty in calculating carbon stocks in tropical forests, Houghton has admitted that an additional error of +50 per cent is a possibility. On this basis he has concluded that

> 'If one considers the uncertainty in estimates of carbon stocks in tropical forests, an additional error of +50% is possible. Thus, these estimates of national sources and sinks of carbon from land-use change are uncertain on the order of + 150% for large fluxes, and + 50 MtC/yr for estimates near zero.'[28]

For its part the IPCC took an unweighted average of the results obtained by DeFries et al and by Houghton.[29] In doing so, the IPCC explicitly ignored Achard et al.[30] Its stated rationale was that the first two studies were the only ones that covered land use changes in both the 1980s and 1990s.[31] This is unconvincing and does not inspire confidence in its results.

Achard et al have estimated the greenhouse emissions from land use change in the tropics over the 1990s were even lower than those published by DeFries et al. They calculated that the emissions were equivalent to 0.9 Gt C per year. Had the IPCC simply included these results in its estimation method, they would have lowered the IPCC estimate of global greenhouse gas emissions from land use change from 1.6 t C per year to 1.4 t C per year — a reduction of nearly 17 per

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[23] Energy Directorate-General [of the European Commission], 2010, 'The Impact of Land Use Change On Greenhouse Gas Emissions from Biofuels and Bioliquids: Literature Review', An in-house review by the Energy Directorate-General for the European Commission's analytical work on indirect land use change, Brussels, July

[24] DeFries et al 2002

[25] R.A. Houghton, undated, 'Data Note: Emissions (and Sinks) of Carbon from Land-Use Change', *Mimeo*, The Woods Hole Research Centre, Falmouth, MA [accessed on 14 December 2010 at http://www.earthtrends.wri.org/downloads/DN-LUCF.pdf]

[26] Frédéric Achard, Hugh D. Eva, Philippe Mayaux, Hans-Jürgen Stibig, & Alan Belward, 2004, 'Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s', *Global Biogeochemical Cycles*, 18, GB2008, doi:10.1029/2003GB002142

[27] DeFries et al 2002

[28] Houghton undated

[29] In the case of the non-tropical regions, the IPCC (2007) used the results from Houghton (2003).

[30] Achard et al 2004

[31] IPCC 2007, Table 7.2, p. 5188

cent. The lower figure is 42 per cent of the IPCC estimate of net global emissions.

More recent research suggests that the result obtained by Achard et al is itself a substantial overestimation and that the global emissions from land-use change are, in fact, less than half of those reported by the IPCC in its Fourth Assessment Report. Using state-of-the-art and spatially explicit datasets on forest area, forest loss, and forest carbon stocks, Harris and her colleagues have estimated the emissions from forest loss in 96 developing countries around the world.[32] They undertook this work as part of the background research that was commissioned by the World Bank for the World Development Report 2010.[33]

Harris and her colleagues have estimated that the gross emissions from the loss of tropical forest cover between 2000 and 2005 were only 0.7 Gt C per year. They also calculated that the standard error of their estimate was ± 0.3 Gt C per year.[34] Based on two standard deviations, the 95 per cent confidence interval around their estimate is ± 0.6 Gt C per year, which is almost as large as the estimate itself.

Unlike Houghton's 2003 estimate, theirs explicitly excludes any allowance for the carbon that is sequestrated by annual forest regrowth. Based on their preliminary analysis of that impact, Harris et al estimate that forest regrowth absorbs 2 to 7 per cent of the gross emissions from the global loss of forest biomass.[35]

More recent research suggests that the result obtained by Achard et al is itself a substantial overestimation and that the global emissions from land-use change are, in fact, less than half of those reported by the IPCC in its Fourth Assessment Report.

A missing carbon sink?

This does not resolve the uncertainty about the terrestrial contribution. It simply means that the carbon accounting identity has to include another carbon sink to make the two sides of the identity balance. The IPCC has attributed the difference between the estimate of the net accumulation of carbon by terrestrial ecosystems and that for the emissions associated with land use change to what it has termed the 'residual terrestrial sink'. The implication is that, over the decade of the 1990s, this 'residual terrestrial sink' absorbed some 2.6 Gt C per year from the atmosphere.[36]

The nature of the 'residual sink' and the science behind it are the subject of considerable and ongoing controversy. Some researchers have hypothesized that increased atmospheric concentrations of CO_2 has accelerated the growth of plants. Although most biological models predict enhanced growth and carbon sequestration by plants in response to rising CO_2 levels, the experimental evidence in support of them has been mixed. Controlled experiments have shown that increased concentration of CO_2 in the atmosphere enhances plant growth — at least initially — but nutrient availability and other limitations may emerge as constraints, depending upon the agricultural management responses that farmers implement. Long-term observations of biomass change and growth rates suggest that such fertilization effects are too small to account for the residual carbon sink on land.

As the amount of organic carbon in soils is far greater than that in living vegetation, soil carbon might be all

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[32] Nancy L. Harris, Sassan S. Saatchi, Stephen Hagen, Sandra Brown, Willian Salas, Matthew C. Hansen, & Alexander Lotsch, 2009, 'New Estimate of Carbon Emissions from Land-Use Change', *Forest Day 2010 Poster*, Winrock International & Applied GeoSolutions LLC, Arlington VA & Durham NC [accessed on 30 May 2010 at http://www.winrock.org/Ecosystems/files/Winrock%20%20New%20Estimate%20of%20Carbon%20Emission%20from%20Land%20Use%20Change%20%20Forest%20Day%20Poster%202010.pdf].

[33] World Bank, 2009, *World Development Report 2010: Development and Climate Change*, World Bank, Washington, DC

[34] Harris et al 2009

[35] Harris et al 2009

[36] IPCC 2007, p. 516

or part of the explanation of the 'missing sink'.[37] [38] Soil organic carbon includes plant, animal, and microbial residues in various stages of decomposition. The half-life of each varies according to the complex biological, chemical, and physical interactions that take place in the soil. Over the long run the amount of organic carbon stored in soil reflects the balance between the rate of accumulation of soil organic carbon inputs and rate of mineralization in each of the organic carbon pools.[39]

The concentration of organic carbon in soil affects the growth of plants and is affected by them. Soil organic carbon has been long recognized as playing a key role in soil fertility and agricultural production. In the humid tropics, forests store more soil organic carbon than the total amount under temperate and boreal forests combined.[40] Accordingly it is critical to understand the role of soil carbon in the global carbon cycle and its potential as a candidate to fulfill the role of the 'residual terrestrial sink'.

The capacity of forests to store carbon in their soils over long periods depends upon the net changes in the storage of those physical forms of soil organic carbon that are most resistant to decomposition.[41] The factors that control the accumulation of organic carbon below the ground, its decomposition, and its retention, however, are very poorly understood.[42]

Practical difficulties have constrained direct measurement of the take-up of organic carbon by soils and little is known about how well it is retained once it is there. Moreover, the sheer complexity of the underground carbon cycle is a major obstacle to accurately modeling how it works. For example, there has to be an adequate supply of other nutrients and they, in part, depend upon fertilizer use. Science has only rudimentary techniques for categorizing the underground carbon cycle into units that can be used to test basic concepts in plant ecology and to model ecosystem response to change.[43]

Soil organic carbon stocks and emissions of greenhouse gases are primarily determined by the soil type. For this reason, the IPCC approach to carbon accounting differentiates between mineral and organic soils, such as those that are associated with peat lands. Oil palm can be grown commercially on both.

The nature of the 'residual sink' and the science behind it are the subject of considerable and ongoing controversy.

A major uncertainty is the vertical distribution of organic carbon over the soil profile and its relationships with climate and vegetation cover.[44] Soil surveys usually measure the soil carbon down to a given depth, typically the first meter of the soil profile. Global surveys based on vegetation and soil categories indicate that soils store between 1,500 and 1,600 Gt of carbon in the top meter of the soil profile.[45] Using the FAO soil classification system, Batjes has estimated that the inclusion of the second meter of the soil profile increases this by 60 per cent.[46]

The only other global assessment of the vertical distribution of soil organic carbon has been made by Jobbágy and Jackson.[47] They estimated that the soil

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[37] W.M. Post & K.C. Kwon, 2000, 'Soil Carbon Sequestration and Land-Use Change: Processes and Potential', *Global Change Biology*, 6, pp. 317–328

[38] IPCC 2007

[39] Post & Kwon 2000

[40] Estaban G. Jobbágy & Robert B. Jackson, 2000, 'The vertical distribution of soil organic carbon and its relation to climate and vegetation', *Ecological Applications*, 10(2), pp.423–436

[41] Willam H. Schlesinger & John Lichter,2001, 'Limited carbon storage in soil and litter of experimental forest plots under increased atmospheric CO_2, *Nature*, 411, p. 466–469

[42] Christian P. Giardina, Dan Binkley, Michael G. Ryan, James H. Fownes, & Randy S. Senock, 2004, 'Belowground carbon cycling in a humid tropical forest decreases with fertilization', *Oecologia*, 139(4), pp. 545–550

[43] Giardina et al 2004

[44] Jobbágy & Jackson 2000

[45] Jobbágy & Jackson 2000

[46] N.H. Batjes, 1996, 'Total carbon and nitrogen in the soils of the world', *European Journal of Soil Science*, 47, pp. 151–163

[47] Jobbágy & Jackson 2000

organic carbon in the top three meters of the soil profile amounts to some 2,344 Gt C globally — 56 per cent more than that found in the first meter of the profile (1,502 Gt) which has been the more or less exclusive focus of most of the IPCC carbon accounting guidelines. The vertical distribution of the global total declined rapidly with increasing soil depth — 64 per cent in the first meter, 21 per cent in the second meter, and 15 per cent in the third.[48] This is in line with the results of earlier research.[49]

This work was based on 2,700 soil profiles taken from three global databases. Although the databases characterize the diversity of agricultural and non-agricultural soils in temperate and tropical plant communities, the sizes of the sub-samples for the tropical plant communities were relatively small — 29 were from tropical deciduous forests; 36 from tropical evergreen forests; and 35 from tropical grasslands or savannas. There are therefore question marks over the statistical robustness of any estimates based on them.

A major uncertainty is the vertical distribution of organic carbon over the soil profile and its relationships with climate and vegetation cover.

The published estimation error for these estimates — based on one standard deviation — was relatively large and increased with soil depth. Jobbágy and Jackson concluded that their estimation error was, at best, coarse as they did not include the effect of any biases due to non-random sampling of the soil profiles.

Other major uncertainties involve the rates of loss and recovery in soil carbon in the wake of particular changes in land-use. A number of such changes have long been known to cause very rapid declines in soil organic matter.[50] [51] [52] [53] [54] Much of the loss in soil organic matter reflects one or more of the following:

- reductions in the return of organic matter to the soil;
- increases in the rate of decomposition of plant residues; and
- reductions in the physical protection of soil organic matter from decomposition, which occur following certain tillage practices.

After reviewing the literature on the subject, Post and Kwon have concluded that there was insufficient data at the time (2000) to determine the amount of soil carbon accumulating in any large region or plot of land with any precision but sufficient to infer the order of the sequestration rate.[55] They found that the maximum rates of accumulation of soil carbon during the early stages of vegetation growth, although substantial, are usually much less than one tonne of carbon per hectare per year.

Post and Kwon estimate that the average rate of accumulation in the density of soil carbon under forest — 0.34 t C per ha per year — is similar to that under grassland — 0.33 t C per ha per year — which is in line with earlier research.[56] In light of the relatively small areas that were involved globally, they have concluded that such rates of carbon sequestration were not enough to account for the missing terrestrial carbon sink.

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[48] Jobbágy & Jackson 2000

[49] Anwar Ghani, Alex Mackay, Brent Clothier, Denis Curtin, & Graham Sparling, 2009, *A literature review of soil carbon under pasture, horticulture and arable land uses*, Report prepared for AGMARDT [the New Zealand Agricultural and Marketing Research and Development Trust], AgResearch Limited, Hamilton, New Zealand, October

[50] H. Jenny, 1941, *Factors of Soil Formation.* McGraw-Hill, New York

[51] E.A. Davidson & I.L. Ackerman, 1993, 'Changes in soil carbon inventories following cultivation of previously untilled soils', *Biogeochemistry*, 20, pp. 161-193

[52] L. K. Mann, 1986, 'Changes in soil carbon after cultivation', *Soil Science*, 142, pp. 279-288

[53] W.H. Schlesinger, 1985, 'Changes in soil carbon storage and associated properties with disturbance and recovery', in J. R. Trabalka and D .E. Reichle (eds.), 1985, *The Changing Carbon Cycle: A Global Analysis*, Springer-Verlag, New York, NY

[54] W.M. Post & L.K. Mann, 1990, 'Changes in soil organic carbon and nitrogen as a result of cultivation', in A.F. Bouwman (ed.), 1990, Soils and the Greenhouse Effect, pp. 401-406, John Wiley & Sons, New York, NY.

[55] Post & Kwon 2000

[56] William H. Schlesinger, 1990, 'Evidence from chronosequence studies for a low carbon-storage potential of soils', *Nature*, 348, pp. 232-234

Key conclusions

Estimates of greenhouse gas emissions rely heavily on a sound understanding of the density of the biomass and the fate of its carbon when the vegetation cover is removed. The published research on this subject has concentrated on primary forest and permanent grassland. Little has been conducted on secondary forest or degraded forestland. This is highly significant for any assessment of the 'carbon footprint' for palm oil. Most of the recent oil palm development has been on former tropical forestland, which had already been extensively disturbed or degraded by a combination of fire, harvesting, and clearance for shifting cultivation.

The FAO has sought to overcome the lack of specific data by directly estimating forest biomass from national timber inventories provided by national governments. As few of them cover tropical forests, however, the FAO relies on 'educated guesswork' to fill the gaps, the reliability of which is highly questionable.

As a consequence the published estimates of greenhouse gas emissions from such changes are subject to very large estimation errors (known unknowns) and substantial uncertainty (unknown unknowns). The known unknowns reflect the lack of comprehensive, robust and finely-grained data on land-use change discussed above. The unknown unknowns are more fundamental: they reflect our lack of understanding about the science that underpins terrestrial carbon stocks and flows.

To illustrate the point, the published biomass estimates imply that there is a 95 per cent probability that the biomass density of tropical forest suitable for conversion to oil palm is somewhere between negligible and 600 tonnes of biomass per hectare. Given this, we really have little idea of the implications of conversion for greenhouse gas emissions. This means that a case-by-case evaluation of each hectare of land is necessary to establish those implications with any accuracy.

IV. Emissions from Land-Use Conversion

On the face of it, one of the major sources of the greenhouse gas emissions associated with palm oil over its life cycle are those associated with the conversion of certain land uses — particularly suitable primary and secondary forest, peat lands, and permanent pasture — to the growing of oil palm. Such conversions generally involve a substantial loss of the carbon that is stored in both above- and below-ground biomass, as well as in the soil which supports the biomass in question. The stored carbon is released by the decomposition or burning of *in situ* biomass to clear the land for the establishment of oil palm.

The literature on this subject has concentrated on estimating the carbon that is lost when primary forest or permanent grassland is cleared to make way for the cultivation of oil palm.[57] There is relatively little on the carbon lost from the removal of other types of vegetation, including secondary forest such as stunted regrowth. This is significant as much of the recent oil palm development has been on forest land that has previously been extensively disturbed (secondary forest) or degraded by fire, timber harvesting, or clearance for shifting cultivation.

Many estimates of the density of forest biomass have been published in peer-reviewed scientific literature. For example, the International Biological Program (IBP) has covered most of the major forest regions of the world.[58] Brown and Lugo have prepared detailed estimates for tropical forests.[59] In all cases, however, the data for the estimates of biomass density have been sourced from ecological studies.[60]

For a number of reasons, the results from ecological studies cannot readily be extrapolated to much larger scales, such as those that are required for a global, continental or national perspective on the carbon cycle:

- Ecological studies are generally designed to characterize local forest structure and the forest sites chosen for examination are neither randomly selected nor representative of the forest population as a whole.[61] Accordingly, they do not provide a valid basis for making inferences about whole forest populations.[62]
- The total area of forest that is covered by ecological studies represents an extremely small sample of the world's forests.[63] Brown and Lugo have calculated the tropical forest sites that had been studied up to that time (1984) represent less than 0.00001 per cent of the global area of tropical forest.[64] Subsequent research is unlikely to have changed that situation.
- Ecologists tend to select study sites based on their ideas about what a forest should look like, namely ones with many large diameter trees.[65] This bias in site selection leads to an overestimation of biomass density for particular types of forest.[66]

Above-ground biomass in forests

In the case of forests, the FAO has sought to overcome these statistical sampling problems by directly estimating the above-ground biomass (AGB) density using the data that it collects from national governments for its global Forest Resources Information System (FORIS).[67]

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[57] Brinkmann Consultancy, 2009, *Greenhouse Gas Emissions from Palm Oil Production: Literature review and proposals from RSPO [Roundtable on Sustainable Palm Oil] Working Group on Greenhouse Gases*, Brinkmann Consultancy, Hoevelaken, The Netherlands, 9 October

[58] David E. Reichle (ed.), 1981, *Dynamic properties of forest ecosystems*, International Biological Programme Synthesis Series No. 23, Cambridge University Press, UK

[59] S. Brown & A.E. Lugo, 1982, 'The storage and production of organic matter in tropical forests and their role in the global carbon cycle', *Biotropica*, 14, pp. 161-187

[60] Brown 1997

[61] S. Brown & A.E. Lugo, 1992, 'Above ground biomass estimates for tropical moist forests of the Brazilian Amazon, *Interciencia*, 17, pp. 8-18

[62] S. Brown, A.J.R. Gillespie, & A.E. Lugo, 1989, 'Biomass estimation methods for tropical forests with applications to forest inventory data', *Forest Science*, 35, pp. 881-902.

[63] Sandra Brown, 1997, *Estimating Biomass and Biomass Change of Tropical Forests: A Primer*, FAO Forestry Paper No. 134, FAO, Rome, Italy [accessed on 17 December 2010 at http://www.fao.org/docrep/w4095e/w4095e00.htm]

[64] S. Brown & A.E. Lugo, 1984, 'Biomass of tropical forests: A new estimate based on forest volumes, *Science*, 223, pp. 1,290-1,293

[65] Brown & Lugo 1992

[66] Brown et al. 1989

[67] FAO[Food and Agriculture Organization of the United Nations], 1993, *Forest resources assessment 1990: Tropical countries*, FAO Forestry Paper No 112, FAO, Rome, Italy

The FAO has calculated AGB density for each forest estate based on the volume of merchantable timber per hectare in the estates covered by FORIS.[68] The formula for doing so is as follows:

AGB density [t per ha] = VOB * WD * BEF

where

VOB is the volume over bark[69]

WD is the volume-weighted average density of wood

BEF is the biomass expansion factor[70]

In principle, this method of estimating the AGB density of a forest slightly underestimates the density of a closed forest — by less than 5 per cent. For an open forest, the inherent error is unknown.[71]

VOB is a commonly used measure of the stock of commercially valuable timber. VOB values are generally estimated from large random samples based on statistically sound sampling designs. In practice few national or sub-national VOB inventories have been collected for tropical forests. Accordingly, the FAO has had to rely on 'educated guesswork for that region'. The reliability of this approach is highly questionable as any errors would be compounded in converting VOB data to biomass density.[72]

Germer and Sauerborn have undertaken the most recent and most comprehensive review of the relevant scientific literature in relation to land use conversion for the establishment of oil palm.[73] The following discussion draws extensively on their results regarding the density of above-ground biomass (AGB) in tropical rain forests.

Germer and Sauerborn found that forest biomass density varies substantially between different local environments. For example, case studies in the Malaysian state of Sarawak have estimated that the AGB density was between 210 t per ha and 650 t per ha for the different forest types in that state. This is more than a three-fold difference.[74]

Some of the disparity in AGB density estimates reflects inconsistencies in the different methods of estimation that have been used. Brown and Lugo have calculated tropical forest AGB density in two quite different ways — by measuring the volume of the wood and by destructive sampling.[75] [76] Based on data on the volume of wood, Germer and Sauerborn have calculated the AGB density of closed primary tropical forest at 176 t per ha. Destructive sampling, however, gave a figure of 283 t per ha — which represents a difference of 61 per cent.

The biomass density of tropical lowland forest — the type that is most frequently converted to oil palm — is

The reliability of this approach is highly questionable as any errors would be compounded in converting VOB data to biomass density.

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[68] Sandra Brown, Louis R. Iverson, & Anantha Prasad, 2001, *Geographical Distribution of Biomass Carbon in Tropical Southeast Asian Forests: A Database*, ORNL/CDIAC-119, NDP-068, Carbon Dioxide Information Analysis Centre Oak Ridge National Laboratory, Oak Ridge, TN, USA

[69] VOB is a measure of timber stocks and is expressed as their gross volume in cubic metres per hectare. It is a measure taken over bark of the free bole — from stump or buttresses to the crown point of the first main branch — of all living trees that are more than (usually) 10 centimetres in diameter at breast height. Estimation of AGB on this basis therefore omits the biomass in the stump and in any forest litter.

[70] BEF is the ratio of above-ground oven-dry biomass of trees to oven-dry biomass of inventoried volume.

[71] Sandra Brown, Louis R. Iverson, Anantha Prasad, & Dawning Liu, 1993, 'Geographical distributions of carbon in biomass and soils of tropical Asian forests', *Geocarto International*, 4, pp. 45–59

[72] Brown 1997

[73] J. Germer & J. Sauerborn, 2008, 'Estimation of the impact of oil palm plantation establishment on greenhouse gas balance', *Environment, Development and Sustainability*, 10, pp. 697–716

[74] John Proctor, J.M. Anderson, S.C.L. Fogden, & H.W. Vallack, 1983, 'Ecological studies in four contrasting lowland rainforests in Gunung Mulu National Park, Sarawak: II Litterfall, litter standing crop and preliminary observations on herbivory', *Journal of Ecology*, 71, pp. 261–283

[75] S. Brown & A.E. Lugo, 1982, 'The storage and production of organic matter in tropical forest and their role in the global carbon cycle', *Biotropica*, 14, pp. 161–187

[76] Brown & Lugo, 1984

usually higher than that of upland forest.[77] Whitmore has reported that the AGB density of lowland primary forest is typically 400 t per ha.[78] The AGB density varies considerably, however, due to the different environmental and human influences that occur at the local level.[79] For example, logging and forest fragmentation can markedly reduce AGB density.[80] Lasco has estimated that logging generally reduces AGB density by between 22 and 67 per cent.[81]

Germer and Sauerborn have estimated that the average AGB density of lowland forests in a climate, which is suitable for the growing oil palm commercially, was 295 t per ha.[82] They calculated the estimation error — based on one standard deviation around the average — was ± 152 t per ha. In other words, 68 per cent of the individual AGB density measurements were between 143 t per ha and 447 t per ha. As a comparison, the 95 per cent confidence interval is from zero to 600 t per ha. These very wide ranges underline the considerable spatial variation that can occur with such forests.

Although the IPCC has proposed somewhat lower default values for forest biomass density — 275 t per ha in the case of insular Asia and 225 t per ha for continental Asia — a critical issue that remains is the large divergence of possible values around those default values.[83]

The establishment of oil palm requires the removal of the existing vegetation from the land in question. Any commercially valuable timber is normally harvested during the clearance process but the residual biomass is either burned, left to decompose naturally, or some combination of the two. The greenhouse gas emissions from harvesting, burning, and decomposition each vary significantly in terms of both emission composition and time horizon.

For any given area that has been cleared of vegetation, the proportion of the removed biomass carbon that is oxidized by fire varies tremendously, even over short distances.[84] Although the IPCC guidelines propose a default fraction of 50 per cent for cleared forest biomass, they recognize that that this value has to be adjusted to reflect local conditions.[85] In contrast, a single burn will often only immediately oxidize less than 20 per cent of the available carbon.[86] Andreae estimates that repeated burning would only release some 40 per cent of the carbon in forest biomass through combustion, while the rest is released rather more slowly through subsequent decomposition.[87] Germer and Sauerborn agree.[88]

The biological decomposition of forest biomass releases nutrients that are taken up by other plants, with most of the remaining carbon emitted as CO_2. In the tropics, the half-life of small litter — leaves and twigs — can be less than a year but that for hardwood tree species is much longer.[89] A study of the central Amazon forest found that 95 per cent of the forest biomass decomposes over 18 years.[90] Although termites can release some of the organic carbon as methane (CH_4), uncertainty over this process has led the IPCC

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[77] Brown & Lugo 1984

[78] T.C. Whitmore, 1984, *Tropical rain forest of the Far East*, Clarendon Press, Oxford, UK

[79] Brown et al 1993

[80] W. F. Laurance, S. G. Laurance, & P. Delamonica, 1998, 'Tropical forest fragmentation and greenhouse gas emissions, *Forest Ecology and Management*, 110, pp. 173–180

[81] R. D. Lasco, 2002, 'Forest carbon budgets in Southeast Asia following harvesting and land cover change', *Science in China Series C-Life Sciences*, 45, pp. 55–64

[82] Germer & Sauerborn 2008

[83] IPCC [Intergovernmental Panel on Climate Change], 1997, *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 2 Workbook*, IPCC, Geneva [accessed on xx November 2010 at http://www.ipcc.ch]

[84] Philip M. Fearnside, 2000, 'Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation', *Climatic Change*, 46(1-2), pp. 115–158

[85] IPCC 1997

[86] T.M. Araújo, J.A. Carvalho, N. Higuchi, A.C.P. Brasil Jr, & A.L.A. Mesquita, 1999, 'A tropical rainforest clearing experiment by biomass burning in the state of Pará, Brazil', *Atmospheric Environment*, 33(13), pp. 1991–1998

[87] M.O. Andreae, 1991, 'Biomass burning: Its history, use and distribution and impact on environmental quality and global climate' in J. S. Levine (ed.), 1991, *Global biomass burning: Atmospheric, climatic and biospheric implications* (pp. 3–21). MIT Press, Cambridge, MA, USA

[88] Germer & Sauerborn 2008

[89] J. M. Anderson & M.J. Swift, 1983, 'Decomposition in tropical forests', in S. L. Sutton, T. C. Whitmore, & A. C. Chadwick (eds.), 1983, *Tropical rain forest: ecology and management* (pp. 287-309), Blackwell, Oxford, UK

[90] Jeffrey Q. Chambers, Niro Higuchi, Joshua P. Schimel, Leandro V. Ferreira, & John M. Melack, 2000, 'Decomposition and carbon cycling of dead trees in tropical forests of the central Amazon', *Oecologia*, 122, pp. 380–388.

to assume that any biomass carbon, which is left after combustion, is emitted as CO_2.[91]

Below-ground biomass in forests

In any tropical forest a significant part of the biomass is below the ground in the root systems of its flora. The ratio of the below- ground (BGB) to above-ground biomass — the BGB-AGB ratio— varies considerably. This can be seen from the estimates of the BGB-AGB ratio reported in the following sources:

- Brown: 0.03 to 0.82 for all tropical forests (based on a series of case studies); [92]
- IPCC: 0.13 for tropical lowland forests;[93]
- Sanford and Cuevas: 0.14 for all tropical forests (based on a literature review);[94]
- Brown and Lugo: 0.17 for tropical moist forests and 0.20 for tropical wet forests;[95]
- Whitmore: 0.20 to 0.25 for tropical forests in East Asia;[96] and
- Germer and Sauerborn: 0.18 for all tropical forests (a meta-analysis of 41 studies).[97]

Based on their estimate of the BGB-AGB ratio, Germer and Sauerborn have calculated the average BGB density for tropical lowland forests at 47 t per ha. Given an estimation error of ± 26 t per ha — based on one standard deviation — there is a 68 per cent chance that the BGB density for a given tropical lowland forest will be somewhere between 21 t per ha and 73 t per ha.

The wide confidence interval underlines the very considerable variation that exists with density measurements at the local level due to differences in tree species, soil, climate, and history of human intervention.

After the removal of the above-ground biomass, a small proportion of the below-ground biomass decomposes rapidly but a large fraction tends to be resistant to decomposition.[98] A study of converted pasture has found the remains of forest tree roots to a depth of 6 cm at least seven years after clearance.[99] There is, however, little published research into the fate of the resistant root fraction in the deeper soil profiles and the IPCC guidelines provide no guidance on this issue.[100]

Biomass in grasslands

The density of the biomass in grasslands is determined by many factors. They include the composition of the plant species, precipitation patterns, soil properties, incidence of fire, and the wildlife populations that they support, directly or indirectly.[101]

The IPCC carbon accounting guidelines define savannas as vegetation formations with a predominantly continuous grass cover and specify default AGB density values of between 4.9 t per ha and 6.6 t per ha.[102] In sharp contrast, the literature reports a much wider range of AGB density estimates. They

There is, however, little published research into the fate of the resistant root fraction in the deeper soil profiles and the IPCC guidelines provide no guidance on this issue.

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[91] IPCC 1997

[92] Sandra Brown, 1997, *Estimating Biomass and Biomass Change of Tropical Forests: A Primer*, FAO Forestry Paper No. 134, FAO, Rome, Italy [accessed on 17 December 2010 at http://www.fao.org/docrep/w4095e/w4095e00.htm]

[93] IPCC 1997

[94] J.R.L. Sanford & E. Cuevas, 1996, 'Root growth and rhizosphere interactions in tropical forests', in S.S. Mulkey, R.L. Chazdon, and A.P. Smith (eds.), 1996, *Tropical forest plant ecophysiology*, Chapman and Hall, New York, NY, USA

[95] Brown & Lugo 1984

[96] Whitmore 1984

[97] Germer & Sauerborn 2008

[98] A. J. Gijsman, H.F. Alarcón, & R. J. Thomas, 1997, 'Root decomposition in tropical grasses and legumes, as affected by soil texture and season', *Soil Biology & Biochemistry*, 29(9-10), pp. 1443-1450

[99] Felipe Garcìa-Oliva, Isabel Casar, Pedro Morales, & José M. Maass, 1994, 'Forest-to-pasture conversion influences on soil organic carbon dynamics in a tropical deciduous forest', *Oecologia*, 99(3-4), pp. 392–396

[100] Germer & Sauerborn 2008

[101] Jayalaxshmi Mistry, 2000, 'Savannas', *Progress in Physical Geography*, 24(4), pp. 601–608.

[102] IPCC 1997

range from 2 t per ha for grass-dominated savannas on poor sandy soils in Venezuela[103] to over 25 t per ha for grasslands with an increasing incidence of shrubs and trees.[104] [105]

In their literature review, Germer and Sauerborn have identified a total of eight studies of the *Imperata* grasslands that dominate the regions that can grow oil palm in South-East Asia.[106] They report AGB densities of between 3.8 t per ha and 23 t per ha. Germer and Sauerborn estimate an average AGB density of 11.2 t per ha for the eight studies, together with a 68 per cent confidence interval for the estimate from 3.9 to 18.5 t per ha.

In all likelihood, the large standard deviation reflects not only local environmental conditions but also the continuous loss of soil fertility that is known to occur in fire-controlled grasslands. Magcale-Macandog has estimated that the annual loss of biomass due to fire reduces new leaf production in *Imperata* grasslands by 47 per cent within 28 years.[107]

The IPCC carbon accounting guidelines do not provide a default value for the BGB density of grasslands generally, let alone those that are suitable for conversion to oil palm.

According to Germer and Sauerborn, moreover, few studies of BGB in grasslands of the humid tropics have even been published.[108] The five studies that they have identified report dramatically different results for the AGB-BGB ratio in tropical grasslands. Their estimated AGB-BGB ratios range from 0.7 — based on a global estimate[109] — to 3.1 — which was an estimate for the Brazilian *cerrado* (or scrub savannah).[110] On the basis of these studies, Germer and Sauerborn estimated a mean AGB-BGB ratio of 1.4 for grasslands suitable for conversion to oil palm.[111]

Soil organic carbon

It is important to recognize that soil is a living ecosystem that constitutes an important store of organic carbon. While the humid tropics are known to store a disproportionate share of all terrestrial carbon, the distribution of carbon within the relevant ecosystems is poorly quantified, as are the rates at which they lose and acquire the carbon.[112] [113] These parameters are primarily determined by the type of the soil so any approach to estimating them has to differentiate between mineral and organic soils. The latter are found in tropical peat lands. Both types can be suitable for growing oil palm commercially.

Jobbágy and Jackson have made the most comprehensive estimates of the carbon content of tropical soils.[114] They estimated that the organic carbon in the top three meters of the soil profile under tropical evergreen forest is, on average, around 279 t C per ha, which is substantially more than is generally found in the forest biomass, both above- and below-ground.

In line with earlier research in this area, Jobbágy and Jackson found that the soil carbon declines rapidly with the depth of the soil — see Table 3 for the details. They estimated that two-thirds of the soil carbon was in the first meter of the profile, 19 per cent in the

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[103] L. Bulla, & J. Lourido, 1980, 'Production, decomposition and diversity in three savannas of the Amazonas territory (Venezuela)', in J.I. Furtado (ed.), 1980, *Tropical Ecology and Development*, Proceedings of the Fifth International Symposium on Tropical Ecology, International Society of Tropical Ecology, Kuala Lumpur, Malaysia, pp. 73–77

[104] Elmar Andrade de Castro & J. Boone Kauffman, 1998, 'Ecosystem structure in the Brazilian cerrado: A vegetation gradient of aboveground biomass, root mass and consumption by fire', *Journal of Tropical Ecology*, 14, pp. 263–286.

[105] R.J. Scholes & D.O. Hall, 1996, 'The carbon budget of tropical savannas, woodlands and grasslands', in A.I. Breymeyer, D.O. Hall, J.M. Melillo, & G.I. Ågren (eds.), *Global change: Effects on coniferous forests and grasslands*, Wiley, Chichester, UK, pp 69-100

[106] Germer & Sauerborn 2008

[107] D.B. Magcale-Macandog, 2002, 'Soil erosion and sustainability of different land uses of smallholder Imperata grasslands in SEA' in J. Juren, W. Lianxiang, W. Deyi, T. Xiaoning, & N. Jing (eds.), *12th International Soil Conservation Organization (ISCO) Conference: Sustainable utilization of global soil and water resources*, Tsinghua University Press, Beijing, People's Republic of China, pp. 306–312

[108] Germer & Sauerborn 2008

[109] R.B. Jackson, J. Canadell, J.R Ehleringer, H.A. Mooney, O.E. Sala, & E.D. Schulze, 1996, 'A global analysis of root distributions for terrestrial biomes', *Oecologia*, 108, pp. 389–411

[110] Fernside 2000

[111] Germer & Sauerborn 2008

[112] Giardina at al 2004

[113] R.A. Houghton, 2005, 'Aboveground forest biomass and the global carbon balance', *Global Change Biology*, 11(6), pp. 945–958

[114] Jobbágy & Jackson 2000

Table 3 Distribution of the Density of Organic Soil Carbon Over the Soil Profile of Tropical Evergreen Forest, Tonnes of Carbon Per Hectare

Depth of soil profile	Global average	Lower estimate (a)	Upper estimate (a)
Zero to one metre	186	82	290
One to two metres	54	23	85
Two to three metres	39	17	61
Zero to three metres	**279**	**190**	**368**

Notes: (a) ± one standard deviation

Source: Jobbágy and Jackson 2000

second meter, and 14 per cent in the third. They also concluded that the relationship between the concentration of soil organic carbon, on the one hand, and climate and soil texture, on the other, was statistically significant at the global level.

That said, there is a large amount of unexplained variation in the density of the soil carbon but it too tends to decline with soil depth.

In the case of native forestland on mineral soils in the moist to wet tropics, the IPCC has proposed default values of between 5 t C per ha and 180 t C per ha for the density of their organic soil carbon. These values explicitly represent the soil carbon in the uppermost 30 cm of the soil profile, depending on soil activity.[115]

After excluding those regions with extended dry periods or sandy soils that are unsuitable for oil palm from the IPCC default values, the density of soil carbon under tropical forest, which is suitable for conversion to oil palm, would range from 60 t C per ha to 180 t C per ha.[116] Again the most notable aspect of these estimates is the extreme breadth of the 68 per cent confidence interval. Its replacement by a 95 per cent chance of not being wrong, would widen the confidence interval to one from zero to 240 t C per ha — which represents an extraordinarily broad range.

In the case of organic soils — such as those associated with tropical peat lands — the amount of soil carbon depends on the depth of the organic layer in the soil profile. In the extensive peat lands of South-east Asia, this organic layer can be several meters thick and is usually waterlogged.[117] In this state, tropical peat lands are a natural source of methane emissions. In Indonesia and Malaysia, substantial areas of peat land have been drained for conversion to oil palm. Drainage accelerates the microbial oxidation of the peat, which generates CO_2 emissions.[118]

On the other hand, drainage reduces methane emissions to the point where the soil eventually becomes a carbon sink.[119] [120] Where peat lands have been converted to oil palm to date, however, the depth of the peat layer has not been well-established.[121] This, in turn, means that the precise extent of the net emissions from conversion of peat lands has yet to be determined.

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115 IPCC 1997

116 Germer & Sauerborn 2008

117 S. Shimada, H. Takahashi, A. Haraguchi, & M. Kaneko, 2001, 'The carbon content characteristics of tropical peats in Central Kalimantan, Indonesia: Estimating their spatial variability in density', *Biogeochemistry*, 53(3), pp. 249–267

118 K. Inubushi, Y. Furukawa, A. Hadi, E. Purnomo, & H. Tsuruta, 2003, 'Seasonal changes of CO_2, CH4 and N2O fluxes in relation to land-use change in tropical peat lands located in coastal area of South Kalimantan, *Chemosphere,* 52(3), pp. 603–608

119 Y. Furukawa, K. Inubushi, M. Ali, A. M. Itang, & H. Tsuruta, 2005, 'Effect of changing groundwater levels caused by land-use changes on greenhouse gas fluxes from tropical peat lands', *Nutrient Cycling in Agroecosystems*, 71(1), pp.81–91

120 A. Hadi, K. Inubushi, E. Purnomo, F. Razie, K. Yamakawa, & H. Tsuruta, 2000, ' Effect of landuse changes on nitrous oxide (N_2O) emission from tropical peat lands. *Chemosphere: Global Change Science*, 2(3), pp. 347–358

121 Germer & Sauerborn 2008

Key conclusions

There are significant gaps and quality problems with the knowledge base and data that are available for estimating 'carbon footprints' from land-use change, particularly in the tropical regions of the world. These problems are most severe for the estimation of emissions from the conversion of tropical forest and peat lands to agricultural crops.

Given this, we really have little idea of the implications of conversion for greenhouse gas emissions. This means that a case-by-case evaluation of each hectare of land is necessary to establish those implications with any accuracy.

Estimates of greenhouse gas emissions rely heavily on a sound understanding of the density of the biomass and the fate of its carbon when vegetation cover is removed. The published research on this subject has concentrated on primary forest and permanent grassland. Little has been conducted on secondary forest or degraded forestland. What has been conducted has highlighted the high degree of spatial and temporal variation that exists in such forest due to differences in a wide range of local environmental factors.

This is highly significant for any assessment of the 'carbon footprint' for palm oil. Most of the recent oil palm development has been on tropical forest land, which has been extensively disturbed or degraded by a combination of fire, harvesting, and clearance for shifting cultivation. Most of the raw data that have been used to estimate forest biomass have been sourced from either small scale ecological studies or the global forest resource database maintained by the FAO. There are serious problems with the data from both sources.

Data on forest biomass from ecological studies cannot be extrapolated as the studies do not provide a statistically valid basis for making inferences about the relevant forest populations. The sites studied were neither randomly selected nor representative of the forest population in question. They were selected by ecologists based on what they thought a forest should look like, namely one with many large diameter trees; this leads to an overestimation of forest biomass. Moreover, the total forest area covered by such studies is a vanishingly small sample of the forests in question.

To date the attempts to address these shortcomings by directly estimating forest biomass from timber inventories have not succeeded. There are few reliable inventories of tropical forests and 'educated guesswork' has been used to fill the gaps. Their reliability is highly questionable.

This means that the published estimates of greenhouse gas emissions from land use changes are subject of very large estimation errors and substantial uncertainty. The estimation errors former are due to an absence of high quality data on land-use changes. The uncertainty reflects our lack of understanding of the basic science that underpins the terrestrial carbon cycle.

To illustrate the point, the published biomass estimates imply that there is a 95 per cent probability that the biomass density of tropical forest suitable for conversion to oil palm is somewhere between zero and 600 tonnes of biomass per hectare. Given this, we really have little idea of the implications of conversion for greenhouse gas emissions. This means that a case-by-case evaluation of each hectare of land is necessary to establish those implications with any accuracy.

V. Carbon Sequestered by Oil Palm

Following its establishment, a commercial oil palm plantation extracts a substantial amount of carbon dioxide from the atmosphere and converts it to biomass as the palms grow to maturity. The amount of carbon that is stored as biomass over the longer term as a result of this process depends on many factors. The primary ones are the size of the palms, the nature of the understory, and the frequency of replanting, which collectively determine the amount of biomass maintained on the land over the longer term.

This chapter canvasses the scientific basis for estimating the carbon that is sequestered as biomass in commercial oil palm plantations. For this purpose it draws heavily on a literature review by Germer and Sauerborn.[122]

Above-ground biomass

The estimates of the above-ground biomass (AGB) in mature oil palm plantations, which have been published in the literature to date, range between 50 t per ha and 100 t per ha.[123] Most of these estimates have been made for oil palms of a given age, rather than for those with specific physical characteristics, such as their actual and maximum trunk height. Moreover, the commercially optimal time for replanting depends more on the height, diameter, and health of the oil palms than on their age.

Most of the published references on the extent of the biomass in a commercial oil palm plantation do not specify the planting density of the palms or the nature of the local environment, both of which significantly influence the physical characteristics of the palms at maturity and the time taken to reach that state.[124] They also contain inherent errors due to the lack of standardized methods for the collection of the field data on which they rely. While some researchers have included the plantation understory in their estimates, others have considered only the oil palms and some of the latter also excluded the biomass in the productive organs of the palms in question.

The most important issue, however, is that the relevant references are not always clear whether their biomass estimate includes the leaf bases on the trunk of the oil palms.[125] There is also the question of accounting for the biomass in the ground cover and the on-ground plant litter; this issue is addressed in section 5.3 later in this chapter.

Typically the rate of biomass formation in a tree crop, such as oil palm, is highest immediately after planting but it progressively slows as the palms approach maturity.[126] For carbon accounting purposes, the IPCC has proposed a linear equation should be used to estimate the growth in forest biomass over time.[127]

In the case of commercial oil palm plantations, however, the IPCC approach has been shown to be biased. It consistently underestimates the relevant biomass by a substantial margin. Based on data from the destructive sampling of oil palms aged between 3 and 25 years in plantations in Sumatra and East Kalimantan, Syahrinudin has specified and estimated an exponential equation to represent the growth of oil palm biomass over time.[128] Compared to his equation, the linear approach that has been proposed by the IPCC underestimates oil palm biomass by around 23 per cent, when averaged over the commercial life of the palms.[129]

Germer and Sauerborn have undertaken a meta-analysis of the published studies of the biomass density

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[122] Germer & Sauerborn 2008

[123] Germer & Sauerborn 2008

[124] J. Germer & J. Sauerborn, 2004, 'Solar radiation below the oil palm (*Elaeis guineensis Jacq.*) canopy and its impact on the undergrowth species composition', *The Planter*, 80(934), pp. 13–27; Henson, 1998; Henson & Dolmat, 2003

[125] Corley and Tinker, 2003

[126] Pedro A. Sanchez, 2000, 'Linking climate change research with food security and poverty reduction in the tropics', *Agriculture, Ecosystems and Environment*, 82(1-3), pp. 371–383

[127] IPCC [Intergovernmental Panel on Climate Change], 2003, *Good Practice Guidance for Land Use, Land-use Change and Forestry*, Institute for Global Environmental Strategies, Hayama, Japan [accessed on 28 January 2011 at http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm]

[128] Syahrinudin, 2005, 'The potential of oil palm and forest plantations for carbon sequestration on degraded land in Indonesia', *Ecology and Development Series*, No. 28, Zentrum für Entwicklungsforschung [Center for Development Research], University of Bonn, Bonn, Germany

[129] Germer & Sauerborn 2008

of oil palm plantations. It was based on their review of 11 studies involving samples from a total of 51 plantations. From their analysis they estimated that the AGB density of oil palm was 60 t per ha, when averaged over the 25-year life of the palms. The estimation error of one standard deviation gives a 68 per cent confidence interval for their estimate, from 40 t per ha to 80 t per ha.[130] The 95 per cent confidence interval is from 20 t per ha to 100 t per ha.

Below-ground biomass

In oil palm plantations the density of the below-ground biomass (BGB) generally increases in line with that for AGB, at least up to some limit. While this limit is strongly influenced by the characteristics of the soil and the availability of moisture, most of the BGB is concentrated in the upper four centimeters of the soil profile.[131] In less favorable environments, however, a significant proportion of the root system may be found at much greater depths.[132]

There are very wide variations in the published estimates of the BGB density for particular oil palm plantations, as the following make clear:

- Fairhurst estimated 7 t per ha of biomass in the top 40 cm of the soil profile under 13-year-old palms in West Sumatra;[133]
- Khalid, Zin, and Anderson found 16 t per ha in the top 60 centimeters of the soil profile under 23-year-old palms in West Malaysia;[134] and
- Braconnier and Caliman calculated 59 t per ha for the top 6 meters of the soil profile under 16-year-old palms on degraded and highly leached soil in West Africa.[135]

The combination of the discrepancies in the depth of the soil profiles studied and the methods that were used to measure the BGB call into question the accuracy of estimating growth functions for oil palm based on either palm age or AGB. Two recent studies have estimated linear equations for the growth of oil palm BGB based on its AGB.[136] [137] While both explained a high proportion of the observed variation in the BGB of adult oil palms over time, they overestimated the root biomass in the younger plants.

After reviewing the relevant literature, Germer and Sauerborn have concluded that the time-averaged BGB density in oil palm plantations was 20 t her ha. An estimation error of one standard deviation gives the 68 per cent confidence interval for this estimate — which is from 15 t per ha to 25 t per ha. The 95 per cent confidence interval is from 10 t per ha to 30 t per ha.

Ground cover & plant litter

In commercial oil palm plantations it is common practice to establish a ground cover to prevent soil erosion, control weeds, minimize the leaching of nutrients, and enrich the organic content of the soil. The latter improves soil structure leading to better aeration, and infiltration and retention of moisture. Legumes are generally essential as ground cover in oil palm plantations; [138] they fix nitrogen in the soil thereby making it available for the palms and also help to build up the concentration of soil organic carbon molecules (complex compounds of carbon, nitrogen, sulphur, and phosphorus).

The amount of biomass in the ground cover vegetation cultivated in an oil palm plantation tends to decrease as the oil palms grow to maturity and provide progressively more shade to the vegetation in the

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[130] Germer & Sauerborn 2008

[131] Christophe Jourdan and Hevré Rey, 1997, 'Modelling and simulation of the architecture and development of the oil-palm (*Elaeis guineensis* Jacq.) root system', *Plant and Soil*, 190(2), pp. 235–246

[132] Germer & Sauerborn 2008

[133] T. Fairhurst, 1996, 'Management of nutrients for efficient use in smallholder oil palm plantations', PhD Thesis, Department of Biology, Imperial College at Wye, University of London, Wye, Ashford UK

[134] H. Khalid, Z.Z. Zin, & J.M. Anderson, 2000,'Decomposition processes and nutrient release patterns of oil palm residues', *Journal of Oil Palm Research*, 12(1), pp. 46–63

[135] S. Braconnier & J.-P. Caliman, 1989, 'Premiers résultats concernant l'étude du systéme racinaire du palmier a` huile en sol dégradé', Rapport Interne, L'Institut de recherches pour les huiles et oléagineux, Paris, France

[136] Ian E. Henson & Mohd T. Dolmat, 2003, 'Physiological analysis of an oil palm density trial on a peat soil', *Journal of Oil Palm Research*, 15(2), pp. 1–27

[137] Syahrinudin 2005

[138] C.W.S. Hartley, 1977, *The Oil Palm*, West African Institute for Oil Palm Research, Longman, London & New York, NY

understory. The amount of biomass also varies with the physical characteristics of the species that is selected for the ground cover, as well as the proportion of dead plant matter — or necromass in the technical jargon — that accumulates on the ground with the living ground cover. Necromass alone can account for more than half of all the biomass that is on or above the ground.

The following results from the published literature gives an idea of the substantial variation that has been observed in the field to date on the density of the on-ground biomass in oil palm plantations:

- Ross calculated the on-ground biomass to be between 8.6 t per ha and 9.3 t per ha. His data were based on fully established ground cover dominated by Pueraria phaseoloides Benth. Some 27 per cent of the biomass in question was dry matter.[139]
- Khalid, Zakaria, and Anderson estimated there was 11.4 t per ha in the biomass of the ground cover under 18-month-old oil palms. Of this 56 per cent was dry matter.[140]
- Ezenwa, Aribisala and Aken'ova found the understory accounted for about four tonnes per ha of biomass under light shade in a 35-year-old plantation.[141]
- In contrast, Parrotta calculated that the on-ground biomass to be less than one tonne per ha under a closed canopy of oil palm.[142]

Assuming a ground cover with a maximum AGB of 10 t per ha and a minimum of 1 t per ha — at canopy closure five years after planting — together with a linear loss of ground cover biomass due to the increasing shade from growing oil palms over the intervening period, Germer and Sauerborn have estimated an average biomass density of 2.5 t per ha for the ground cover over the commercial life of the oil palms.[143] The absolute error for their estimate — based on one standard deviation — is relatively large at ± 1.0 t per ha. In other words, the 68 per cent confidence interval for their estimate ranges from 1.5 t per ha to 3.5 t per ha, while the 95 per cent confidence interval is from 0.5 t per ha to 4.0 t per ha.

Key conclusions

As with the emissions from conversion of primary or secondary forest, there are significant gaps and quality problems with the knowledge base and the data that are available for estimating the greenhouse gas removals by oil palm grown on the commercial plantations that have replaced such forest. The problems, however, are not as severe as in the former case.

As with the conversion emissions, estimation of greenhouse gas removals rely heavily on a sound understanding of the density of the biomass of oil palm on commercial plantations and the fate of its carbon when the palms are replanted or replaced at the end of their commercial life. The published research on this subject is relatively sparse compared to the known variation in biomass density due to differences in its growing environment related to factors such as the age of palms, soil type, amount and distribution of annual rainfall, temperature, nature of ground cover, agronomic and harvesting practices, etc. These factors are significant for any assessment of annual removals of greenhouse gases.

As a consequence, the published estimates of greenhouse gas removals by commercial oil palm plantations are subject to relatively large estimation errors. The published biomass estimates imply that there is a 95 per cent probability that the biomass density of commercial oil palm is somewhere between 30.5 t per ha and 134 t per ha. In other words, the upper endpoint of the range is more than four times its lower endpoint.

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[139] M. Ross, 1999, *Auswirkungen verschiedener Rodeverfahren und des Unterbewuchses auf Bodenfruchtbarkeit, Bodenwasserhaushalt, Erosion, und Bestandsentwicklung eines lpalmenbestandes*, Shaker Verlag, Aachen, Germany

[140] Khalid Haron, Zin Z. Zakaria, & J.M. Anderson, 2000, 'Nutrient cycling in an oil palm plantation: The effects of residue management practices during replanting on dry matter and nutrient uptake of young palms', *Journal of Oil Palm Research*, 12(2), pp. 29-37

[141] Ike Ezenwa, Oluwatoyin A. Aribisala, & M.E. Aken'ova, 1996, 'Research note: Dry matter yields of *Panicum* and *Brachiaria* with nitrogen fertilisation or *Pueraria* in an oil palm plantation, *Tropical Grasslands*, 30, pp. 414–417

[142] John A. Parrotta, 1992, 'The role of plantation forests in rehabilitating degraded tropical ecosystems', *Agriculture, Ecology and Ecosystems*, 41, pp. 115–133

[143] Germer & Sauerborn 2008

VI. Emissions from Oil Palm Plantation Operations

The commercial operation of an oil palm plantation generally involves the initial establishment and subsequent maintenance of the estate and its mill, harvesting fresh fruit bunches (FFBs), and processing them to extract crude palm oil and palm kernel oil. Greenhouse gas emissions are mostly produced by the wastewater from the processing mill, the fertilizers and pesticides that are used on the plantation to maximize fruit yields, and the energy used to power the vehicles, plant and equipment on the plantation estate and in the processing mill.

Palm Oil Mill Effluent

Palm Oil Mill Effluent (POME) is produced as FFBs are processed to extract their oils — crude palm oil and palm kernel oil. Each tonne of FFB that is processed generates about 0.5 to 0.7 tonnes of wastewater.[144] [145] [146]

As POME contains organic materials, it has to be treated prior to disposal. The conventional treatment is anaerobic digestion by bacteria in enclosed ponds or lagoons, followed by extended aeration. Open digestion tanks are used occasionally, when available land is limited. Other treatment methods are less common but include membrane treatment, evaporation, and solidification to separate the waste.

On that basis, POME biogas represents the largest single source of greenhouse gas emissions from the commercial production of crude palm oil, excluding any emissions from land-use conversion prior to the establishment of the plantation in question.

POME produces a biogas, which is a mixture of methane (CH_4) and CO_2 with traces of hydrogen disulphide (H_2S). Laboratory experiments have suggested that methane makes up around 65 per cent of POME biogas under completely anaerobic conditions, although this is generally significantly higher than the small number of measurements that have been taken in a commercial production setting.[147] On that basis, POME biogas represents the largest single source of greenhouse gas emissions from the commercial production of crude palm oil, excluding any emissions from land-use conversion prior to the establishment of the plantation in question. At present, however, data remains unavailable on the total amount of greenhouse gas emissions from the actual waste treatment system used in production of palm oil in countries such as Malaysia.[148]

In terms of the IPCC's Global Warming Potential index, a tonne of methane makes a significantly greater contribution to the greenhouse effect than a tonne of CO_2. Hence the composition of POME biogas and the effectiveness of the treatment of that biogas by the processing mill are critical to any assessment of the total emissions contribution from this source. Moreover there is considerable scope to capture the methane in POME and to use it to generate electricity that could, among other things, power the processing mill; the required technology is already available and demonstration projects are being undertaken to advance its commercialization.[149]

Under commercial operating conditions, the methane concentration of POME varies significantly. It varies

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[144] Tokyo Electric Power Environmental Engineering Co. Inc.,2009, *Feasibility Study Report Palm Oil Effluent (POME) Treatment Co-benefits CDM Project (Summary)*, GEC CDM/JI Support Programme commissioned by the Ministry of the Environment, Japan [accessed on 8 December 2010 at: http://gec.jp/gec/en/Activities/cdm-fs/2008/200812TEE_eMalaysia_rep.pdf]

[145] Mohd Basri Wahid, Chan Kook Weng, Choo Yuen May, & Chow Mee Chin, 2006, 'The Need to Reduce National Greenhouse Emissions: Oil Palm Industry's Role', *Journal of Oil Palm Research*, Special Issue , April, pp. 1-23

[146] Shahrakbah Yacob, Mohd Ali Hassan, Yoshihito Shiraia, Minato Wakisakaa, & Sunderaj Subash, 2005, 'Baseline study of methane emission from open digesting tanks of palm oil mill effluent treatment', *Chemosphere*, 59(11), pp. 1,575-1,581

[147] Ma A.N., Choo, Y.M., Toh Chua, N.S., 1999, 'Renewable energy from palm oil industry', in G. Singh, L.K. Huan, T. Leng, and D.L. Kow (eds.), 1999, *Oil Palm and the Environment: A Malaysian Perspective*, Malaysian Oil Palm Growers' Council, Kuala Lumpur, Malaysia

[148] Yacob et al 2005

[149] Foo-Yuen Ng, Foong-Kheong Yew, Yusof Basiron, Kalyana Sundram, 2011, 'A Renewable Future Driven with Malaysian Palm Oil-based Green Technology', *Journal of Oil Palm & The Environment*, 2, pp.1-7, doi:10.5366/jope.2011.01

with differences in the method of treatment, differences in the sites using the same treatment method, and seasonal differences in operating conditions at the treatment site.

There are, however, only a few primary studies that have directly measured such variations at a commercial scale of mill operation.[150] [151] [152] While there are a great many more articles in the literature that have sought to estimate the extent of the methane emissions from the treatment of POME, all of them rely on the results of the few primary sources that have been reported here for their raw data .

Shirai and his colleagues have measured the methane concentration in the biogas produced by open digesting tank and lagoon systems at two FELDA palm oil mills — Serting Mill and Serting Hilir Mill — in the state of Negri Sembilan in Malaysia.[153] They found that the methane concentrations averaged 35 percent for the open digesting tanks and 45 per cent for the closed lagoon system.[154]

Shirai and his colleagues noted differences between their results and those obtained in the laboratory by Ma et al (1999). They concluded that they were likely to be due to differences in the operating conditions under which the two studies were conducted. They found differences of over 130 percent in the rate of biogas emissions from treatment tanks using the same technology.

Yacob and his colleagues have analyzed POME biogas samples from two open digestion tanks at the FELDA Serting Hilir Palm Oil Mill in Malaysia for each week of a 52-week period.[155] Their measured methane concentrations ranged from 13.5 to 49 percent by weight. They concluded that the fluctuations in biogas production that they had observed were the result of a number of factors. These factors included seasonal cropping of the fruit, operational conditions at the mill, and variations in the quality and quantity of the effluent that was discharged from the mill.

The same authors conducted a similar study of two closed (anaerobic) ponds at the same site over an equivalent period in the following year. In this case, they found that the methane concentration of the POME biogas averaged 54.4 percent by weight.[156] This was significantly higher than the average result for methane in the open digestion tanks from their earlier study. The individual readings from the closed ponds — which ranged from 35 to 70 percent — were also higher than those from open tanks.

Yacob and his colleagues concluded that closed ponds were more efficient than open digesting tanks for treating POME and that two main factors affecting methane emissions were operational conditions at the mill and seasonal variations in the cropping of the fruit.[157]

Emissions from fertilizer & pesticide use

Greenhouse gases are emitted whenever fertilizers and pesticides are used on commercial oil palm plantations. The commonly used fertilizers include urea or ammonia nitrate, phosphate, potash and magnesium, although a better alternative may be to use legumes as ground cover in combination with smaller amounts of chemical fertilizers.

The major greenh ouse gas emissions are nitrous oxide (N_2O). Although emissions also occur when fertilizers and pesticides are produced and transported to the plantations, these emissions are much smaller in quantity than those from the use of those products.

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[150] Yoshihito Shirai, Minato Wakisaka, Shahrakbah Yacob, Mohd Ali Hassan, & Shin'ichi Suzuki, 2003, 'Reduction of Methane Released from Palm Oil Mill Lagoon in Malaysia and Its Countermeasures', *Mitigation and Adaption Strategies for Global Change*, 8(3), pp. 237-252

[151] Yacob et al 2005

[152] Shahrakbah Yacob, Mohd Ali Hassan, Yoshihito Shiraia, Minato Wakisakaa, & Sunderaj Subash, 2006, 'Baseline study of methane emission from anaerobic ponds of palm oil mill effluent treatment', *Science of the Total Environment*, 366(1), pp 187-196.

[153] FELDA is the Federal Land Development Authority of Malaysia and is responsible for resettling the rural poor into newly developed areas. In doing so it has focused on the development of smallholder farms to grow cash crops, such as palm oil. It is now the largest palm oil processor in Malaysia (Yacob et al 2005).

[154] Shirai et al 2003

[155] Yacob et al 2005

[156] Yacob et al 2006

[157] Yacob et al 2006

The emissions from fertilizer and pesticide use are generally measured in the following way. The first involves estimating the rate of usage of each chemical. The results are then multiplied by an estimate of the average greenhouse gas emission intensity factor for the use of the input in question. However, the methodology behind the two sets of estimates is not always transparent and there is considerable uncertainty about the extent of estimation errors in each case. All of this suggests that there is considerable scope for relatively straightforward research to advance our relatively meager understanding of these issues.

Following an extensive review of the relevant literature on this subject, the Brinkman Consultancy concluded that the emissions intensity associated with fertilizer and pesticide use in oil palm plantations was between 1.0 and 1.5 t CO_{2e} per ha.[158] Their conclusion largely supported the estimates that have been made by Nikander (1, 086 kg CO_{2e} per ha)[159] and by Wijbrans and van Zutphen (1,409 kg CO_{2e} per ha).[160]

Many of the published studies, such as that by Nikander, have relied on the default emission intensity values for various emission sources proposed by the UK Renewable Fuels Authority (RFA) as part of the UK Government's obligations under the European Union (EU) Directive 2009/28/EC on renewable fuels.[161] These default values include emission intensity factors in relation to fertilizer and pesticide use.

Emissions from energy use

Diesel distillate is used to power the vehicles, plant and machinery that are used on oil palm plantations in the cultivation of the palms and the processing of the fruit.

Despite a large number of studies into fuel use in the transport sector, there are very few original studies that directly estimate fuel use on commercial oil palm plantations. The studies that have been undertaken have mostly sought to measure emissions from the oil palm sector and have been based on estimates of diesel use per hectare and of emissions intensity of fuel use made by other authors. As such, the differences in the estimates are generally based on assumptions about the average distance travelled, fuel usage, etc.

Based on its extensive review of the relevant literature, The Brinkman Consultancy has concluded that the greenhouse gas emissions from diesel use in vehicles, plant and equipment on oil palm plantations totaled somewhere between 180 and 404 kg CO_{2e} per ha.[162] Its conclusion was largely based on the findings of three published studies.[163] [164] [165] The estimates made by these studies, however, are relatively crude.

Wood and Corley have estimated that diesel usage by the oil palm sector generates 404 kg CO_{2e} per hectare.[166] This estimate was based on the default value of 0.086 kg CO_{2e} per MJ of diesel consumed by the palm oil sector, which has been proposed by the (RFA) for the implementation of the EU Directive on renewable fuels.[167]

Damen and Faaij estimated diesel consumption in the oil palm sector at 1.8 MJ per tonne-kilometer.[168] While the data used were from personal sources and accordingly cannot be verified, the results were consistent with those of the RFA[169] and Nikander[170]

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[158] Brinkmann Consultancy 2009

[159] Sami Nikander, 2008, *Greenhouse gas and energy intensity of product chain: case transport biofuel*, Master of Science in Engineering Thesis, Helsinki University of Technology, Helsinki, Finland, 9 May

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[161] UK Renewable Fuels Agency, 2008, *Carbon and sustainability reporting within the Renewable Transport Fuel Obligation: Technical guidance, Parts 1 & 2*, Office of the Renewable Fuels Agency, London, UK, January

[162] Brinkmann Consultancy 2009

[163] B.J. Wood & R.H.V. Corley, 1993, 'The energy balance of oil palm cultivation' in *Proceedings of the 1991 PORIM International Palm oil Conference – Agriculture*, Palm Oil Research Institute of Malaysia, Kuala Lumpur, Malaysia, pp 130-143

[164] Kay Damen & André Faaij, 2007, *Greenhouse Gas Balances of Biomass Import Chains for 'Green' Electricity Production in The Netherlands*, IEA Bio-energy Task 38, International Energy Agency, Paris, France

[165] Nikander 2008

[166] Wood & Corley 1993

[167] RFA 2008

[168] Damen & Faaij 2007

[169] RFA 2008

[170] Nikander 2008

(discussed below). Based on an average distance travelled of between one and ten kilometers, Damen and Faaij put the emission intensity of the sector at 36 kg CO_{2e} per hectare. They were, however, primarily concerned with biomass imports for electricity generation.

Nikander estimated emissions at 267 kg per ha, made up of 50.2kg CO_{2e} per ha from the vehicles used on oil palm plantations and 217 kg CO_{2e} per ha from their plant and equipment.[171] His estimate was based on the default values published by the RFA. These values were based on RFA estimates that the average distance travelled from oil palm plantation to mill was 17 kilometers and the average yield was 19 tonnes of FFB per hectare. The RFA proposes default values for the emission intensity of diesel use of 0.086 kg CO_{2e} per MJ and for the fuel efficiency of trucks in Asia of 1.8 MJ per tonne-kilometer. The RFA default values are a questionable foundation on which to base emission estimates and they therefore need to be confirmed by further research.

Key conclusions

Greenhouse gas emissions are produced at every stage of the process of growing and cultivating oil palms, harvesting their fruit, and processing that fruit to extract its oils. In comparison to the potential emissions from forest conversion or their sequestration as biomass in oil palm as they grow to maturity, these on-plantation sources collectively account for relatively small quantities of greenhouse gas emissions.

The most notable emissions sources are palm oil mill effluent (POME) together with agrochemical and energy use. POME is by far the most significant of these as mill wastewater tends to be rich in dissolved methane and carbon dioxide, both of which are released to the atmosphere as the wastewater is treated. The quantity of greenhouse gas emissions varies considerably over the year, with the treatment technology used and the operating practices of the mill.

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[171] Nikander 2008

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