Carbon storage and global change: the role of oil palm

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Abstract: *In the context of global change, potential estimations of carbon storage by the oil palm ecosystem in different ecologies have been calculated for the major productive countries in Africa, Asian and American continents. Comparisons were done with other types of planted ecosystems as eucalyptus and coconut as well as different types of natural forests. Carbon budget components as NPP, autotrophic and heterotrophic soil respiration, litter and fine litter contributions were discussed in regards to the very high rate of carbon sequestration by oil palm ecosystem : from 250 to 940 C m^{-2} yr^{-1} (estimations including harvested bunches).*

Key words: *global change, carbon storage, Elaeis guineesis, net primary productivity, soil respiration, ecosystem carbon content*

Introduction

It is generally accepted that there is a link between the increase in average temperature at the earth's surface during the 20th century (0.6 °C +/– 0.2 °C) and the higher concentration of greenhouse gasses (GHG) in the atmosphere, particularly CO_2 which is responsible for 50% of the overall GHG effect, apart from water vapour [1], and its average concentration increased from 290 ppm in 1900 to 360 ppm in 2000, which is a value that had not been reached for at least 420 000 years[1]. For 20 years we have been seeing an average annual increase of 3 GtC (3.10^9 tC) in the atmosphere due to the burning of carbon fossil fuels, and to changes in land use, primarily deforestation (7 GtC and 1 GtC in 2000 [2]). This additional amount only accounts for 0.04% of the C stock in the atmosphere (750 GtC), but at the current rate almost 50% as a cumulated value over 100 years. This would lead by the end of the 21st century to a substantial rise in the average temperature (from +1.4 °C to +5.8 °C depending on the estimates), with major ecological consequences (melting glaciers and ice-floes, rising sea levels, climate change, spread of tropical diseases and changes in biodiversity, etc.).

Aware of these risks, the international community drew up the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 in Rio de Janeiro, the aim being the "*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*". Under this convention, the Kyoto Protocol, signed in 1997 and implemented since February 2005, calls for a reduction in GHG emissions in industrialized countries "*to at least 5% below the 1990 levels in the commitment period 2008 to 2012*". Among the provisions proposed, the CDM (Clean Development Mechanism), provides for the establishment of carbon sinks, through afforestation or reforestation. It should be pointed out that, although only forest species are eligible during this first phase, tropical tree crop plantations may subsequently be involved (www.irrdb.com; www.energybulletin.net).

Of these, oil palm (*Elaeis guineensis*, Jacq.) plantations, which cover over 12 million hectares on the African, Asian and American continents (www.fao.org/waicent/statistics-fr.asp), could prove to be of particular interest. Indeed, their high biomass production and dynamic expansion make them a potentially important carbon sink. On the other hand, the fact that they are partly planted in deforested zones makes it necessary to estimate the amount of carbon fixed by these plantations compared to the original ecosystem. More generally, this type of knowledge serves to clarify the debate on the environmental impact of such crops in the tropics. For several years, particularly since the "smog" episode in 1997 in Southeast Asia[2], oil palm has been at the centre of an environmental controversy [3-6], as oil palm was seen to be a "polluter" using substantial inputs (fertilizers, pesticides), discharging considerable amounts of effluent from oil mills, and consuming large amounts of water during processing. Managers therefore need to have at their disposal not only agricultural results enabling an improvement in bunch yields in plantations, but also an estimation of environmental impacts, of which the carbon balance is a part.

Some clues are available, such as those provided by the Indonesian Oil Palm Research Institute (IOPRI, Medan, North Sumatra) (*table 1*), indicating the strong atmospheric CO_2 fixing potential of oil palm plantations.

The purpose of this article is to go beyond these initial results starting with an analysis of the key points of the carbon cycle in the "oil palm" ecosystem – on a palm scale, then on a stand scale – and assess the different components of the carbon budget depending on the age of the plantations, under different ecological conditions. A general assessment of CO_2 storage potential is given for several palm oil producing countries.

A comparison is made with other planted ecosystems (eucalyptus, coconut). Note that the calculations of this balance only take into account the oil palm growth and production period, and not processing which leads to GHG discharges when making oil.

Carbon flux on a palm scale

Carbon entrance: photosynthesis

It is photosynthesis that enables atmospheric CO_2 to enter the frond when incident radiation is sufficient and when water supply conditions are favourable. Atmospheric carbon assimila-

Table 1. *Ecological data on the oil palm and comparison with tropical forest (IOPRI site, "Indonesian Oil Palm Research Institute", http://www.iopri.id).*

Parameters	Unit	Tropical forest	Oil palm plantation
Biomass production	t DM ha^{-1} yr^{-1}	22.9	36.5
CO_2 fixation	t CO_2 ha^{-1} yr^{-1}	9.62	25.7
Photosynthesis	µmol m^{-2} s^{-1}	13-19	21-24
Absorbed radiation	MJ m^{-2} yr^{-1}	51.4	82.9
Respiration	t CO_2 ha^{-1} yr^{-1}	121.1	96.5
O_2 production	t O_2 ha^{-1} yr^{-1}	7	18.7

[1] (www.ipcc.ch/pub/spm22–01.pdf)

tion is estimated via an initial photosynthesis module taking into account the maximum assimilation values of the plant, the coefficient of light extinction and apparent quantum yield. The curve for photosynthesis response to radiation (PAR: Photosynthetically Active Radiation) is integrated in accordance with the cover (LAI: Leaf Area Index). For oil palm, it is accepted that the carbon assimilated by a frond (source organ) serves first of all for growth requirements (frond, stem, roots), then once those needs have been met the remainder of the available assimilate is directed to the bunches [7].

Under potential conditions

Photosynthesis measurements on the oil palm reveal a considerable disparity in maximum values at saturating light levels, below 5 µmol m^{-2} s^{-1} for Hirsch [8], between 14 and 20 µmol m^{-2} s^{-1} for Corley [9] or between 6 and 9 µmol m^{-2} s^{-1} for Potulski [10]. New values were measured by Dufrêne and Saugier [11] with 23 µmol m^{-2} s^{-1} in Ivory Coast on control family LM2T × DA10D (*figure 1*) and by Lamade and Setiyo [12] on clones, with 32 µmol m^{-2} s^{-1} under optimum conditions for oil palm in North Sumatra. The last values are very high for a C3 plant. The variations found for maximum photosynthesis can be attributed to differences in the measuring methodology, with the instruments becoming increasingly precise and stable under tropical conditions, to the plant material used (more efficient clones), to environmental conditions (e.g. water deficit) or simply to the age of the palm or the position of the frond or leaflet measured.

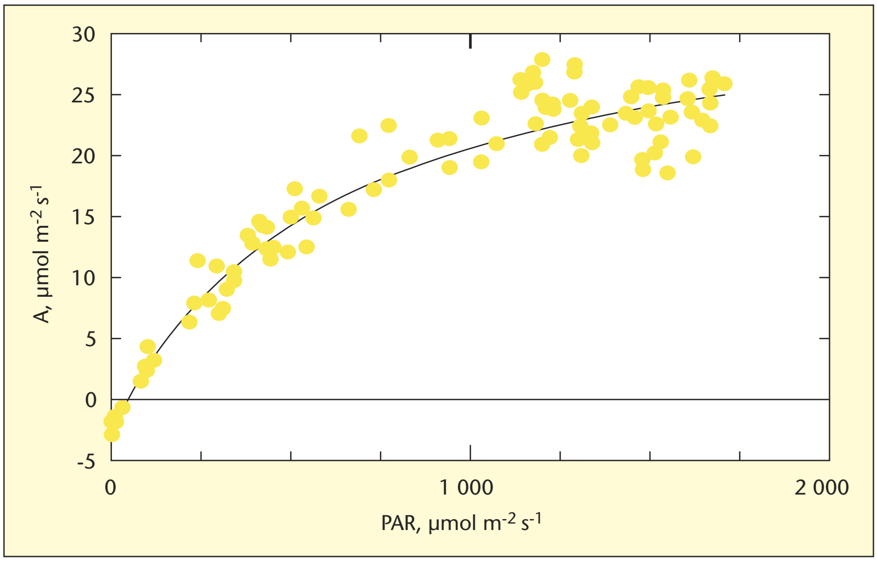

Figure 1. *Response of photosynthetic assimilation (A, in µmol (CO_2) m^{-2} s^{-1}) of the oil palm to radiation (PAR, Photosynthetically Active Radiation, in µmol (photon) m^{-2} s^{-1}), under the ecological conditions of Ivory Coast (figure from [11]).*

Table 2. *Increase in leaf disc weight in one day (according to Dufrêne [7]), A: photosynthetic assimilation of CO_2; number of measurements indicated in brackets.*

Time	Dry weight (g $_{dm}$ m^{-2})	A (µmol (CO_2)m^{-2} s^{-1})
7.30	83 ± 7 (10)	-
9.30	88 ± 3 (10)	25.27 (3)
11.05	96 ± 13 (10)	23.94 (5)
13.10	98 ± 16 (10)	23.54 (4)
15.15	108 ± 13 (10)	21.52 (3)
16.40	102 ± 6 (10)	

A simple way of quantifying the daily carbon gain of leaflets is to monitor the increase in dry weight of leaflet laminae (*table 2*). It can be seen that this is not insubstantial: more than 25 g $_{dm}$ m^{-2} (dm: dry matter) of lamina under conditions at the La Mé station in Ivory Coast.

A variation factor: the age of the palm and the frond

After a year in the nursery, seedlings are planted out in the field: their photosynthesis is already high with values over 19 µmol m^{-2} s^{-1}. From 4 to 9 years, photosynthesis increases up to 32 µmol m^{-2} s^{-1}, with the canopy closing up very quickly from 4 years after planting. During that period, there is a very rapid increase in LAI, reaching 4.5. Young palms quickly produce more than 20 fronds per year, which are increasingly large, reaching from 5 to 8 metres in length. The light interception of the canopy at 9 years is over 80%. This is why few oil palm-based intercropping systems or agroforestry systems are exploited for the entire length of the cycle, unlike other crops such as cocoa, coconut or coffee.

Photosynthesis also varies depending on where the frond lies in the crown. A crown contains between 35 and 42 fronds on average: fronds are regularly pruned when bunches are harvested, respecting precise agronomic practices: 35 fronds in Africa and 42 in Asia. Fronds are arranged in eight spirals. This distribution is due to the specific phyllotaxy of the oil palm (angle of rotation of frond emission varying from 135°7 to 137°5). Fronds are numbered in ranks of 1 to 42, or 56. The oldest fronds have the highest numbers and are found low in the crown. Variations in photosynthesis depending on frond rank have been measured: from 20 µmol m^{-2} s^{-1} for frond ranks 1 to 3, photosynthesis decreases to 10 µmol m^{-2} s^{-1} for frond ranks over 30 [11].

Limiting factors[2]

Oil palms are highly susceptible to VPD variations (Vapour Pressure Deficit: corresponds to a certain level of air dryness): as the air dries out, VPD increases and the plant regulates its transpiration by closing its stomata. In Ivory Coast, Dufrêne and Saugier [11] found a considerable drop in stomatal conductance from a VPD value of 1.7 kPa. In Indonesia, such a drop was found for lower VPD values. It is reflected in a very clear decline in carbon entry into the plant. *figure 2* shows a very clear relation between photosynthesis and stomatal conductance. This limitation of photosynthesis by conductance is substantial in dry periods (due in Africa to seasonal variations during the year, or to the harmattan effect for example), during

[2] The July to November 1997 period was particularly dry in Indonesia, linked to an "El Niño" episode. It was characterized by numerous fires, mostly on the island of Kalimantan and in Riau province (Sumatra) on forest regrowth and on cleared forest intended for oil palm growing. These fires resulted in a thick cloud of smoke over the entire region, covering parts of Malaysia, Sumatra and Kalimantan. The fire in Riau province spread to zones of thick peat. It therefore developed down to a depth of several metres and was very difficult to bring under control. The fires in 1997 and 1998 in Indonesia caused what was considered to be a worldscale ecologial disaster (www.cifor.cgiar.org).

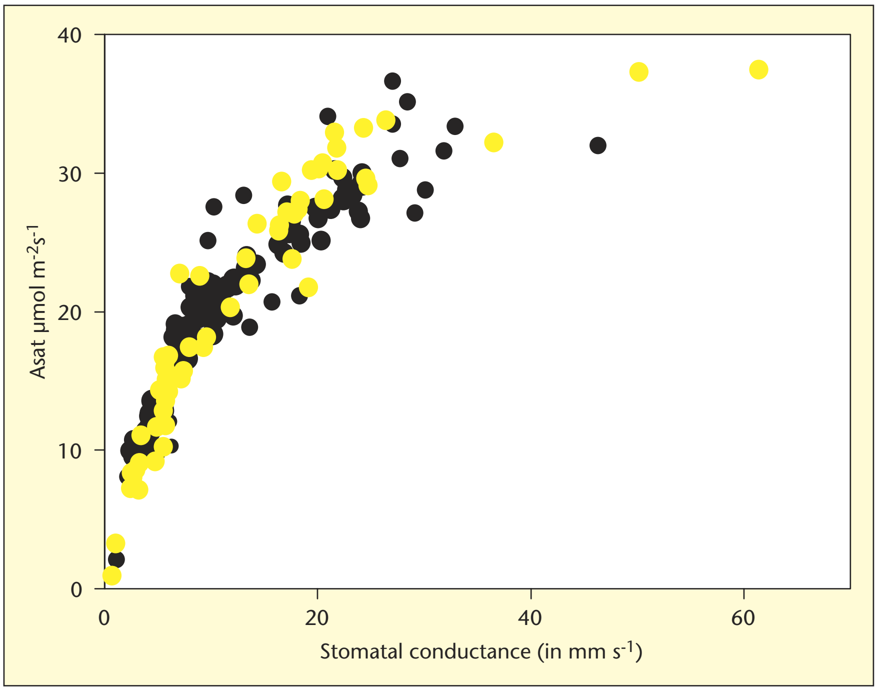

Figure 2. *Relation between photosynthesis (A sat: assimilation with saturating radiation in µmol (CO_2) m^{-2} s^{-1}) and stomatal conductance (opening of stomata) for two oil palm clones under the ecological conditions of North Sumatra (Indonesia).*

more specific climatic events such as *El Niño*, or more commonly at noon when the air temperature is high. It should be noted that temperatures over 36 °C drop photosynthesis and promote respiratory losses at the same time.

Variation in the soil's water reserve is one of the parameters that best explains reduced yields. Under Ivorian conditions, stomata can be seen to close when the water reserve in the soil is less than 67% of the useful reserve [13]. Likewise, variations in the yields found at all the 30 stations in North and South Sumatra, in Indonesia, were primarily explained by the length of the dry season and the severity of the water deficit.

Mineral deficiencies, especially nitrogen, are also a major photosynthesis limiting factor. The photosynthesis of 1-year-old seedlings placed under controlled conditions can be increased by 60% [14] with a standard application of 2 × 35 g $month^{-1}$ NPK (12/12/17) compared to a control without fertilizer.

Estimation of CO_2 assimilation by a whole crown

A preliminary estimation of the net assimilation of an oil palm crown can be carried out using a simple model where the curve for photosynthesis response to radiation (PAR) is integrated in accordance with the cover (LAI) and in line with the exponential variation in radiation in that cover. The SIMPALM model [15] can be used to simulate carbon fixation per palm in two different ecologies, in Africa and Southeast Asia. For an average mature palm in Ivory Coast, a crown consisting of 35 fronds will potentially fix[3] 300 kg C yr^{-1} for a capture area of 315 m^2 of laminae (radiative conditions: 14 MJ m^{-2} day^{-1}). In Southeast Asia, under optimum water supply conditions, carbon fixing amounts to 350 kg C yr^{-1} for a capture area of 340 m^2 (radiative conditions: 16 MJ m^{-2} day^{-1}). By expressing these values on a plantation scale it is possible to estimate the gross primary productivity (GPP) of the ecosystem.

[3] Variations in the carbon content of oil palm organs: in all our calculations, we use "45%" of dry matter carbon content, but this can vary from 42 to 50% (unpublished results from carbon isotope analyses).

Rules of allocation to the different organs

These allocations do not have a preponderant effect on overall carbon storage, but may influence the quantity of carbon returning to the soil, via root turnover and foliage biomass decomposition in the windrows. For oil palm, genetic origin, the ecology and nitrogen fertilization strongly affect these allocation rules.

Marked differences in C allocation to the root system have been seen between different families in Ivory Coast (rainfall = 1415 mm, water deficit = 300 mm, deep sandy soil) and in Indonesia (North Sumatra: rainfall = 2980 mm, negligible water deficit, soils tending towards clay) (*table 3*). In the Ivorian lagoon zone, the oil palm root system reaches a depth of 6 m, whilst in North Sumatra on podzols, the root system mostly develops in the first 40 cm.

Vertical growth can differ in the same ecology: between the two types of germplasm, *Deli × La Mé* and *Deli × Yangambi*, carbon allocation to the stem varies from 36 to 42%.

Carbon allocation to bunches (around 17% of the assimilates produced) is a parameter of paramount importance for growers, but it also determines the amount of material exported from the ecosystem, which is not insubstantial in the case of oil palm.

Carbon release

Respiration

Few direct measurements can be found of respiration that results in CO_2 release from the different oil palm organs. It should be remembered that respiration has been divided into growth respiration and maintenance respiration [16, 17]. It is thus possible to estimate the cost in assimilates of the biomass formed, corresponding to the palm's carbon demand.

The maintenance respiration of the stem measured by Dufrêne [7] varied from 0.2 to 0.4 g C kg_{dm}^{-1} day^{-1} depending on the temperature. These values correspond to a total release of around 30 to 70 g C per day under African conditions.

Respiratory release during inflorescence growth is greater, at 85 g C released daily [7].

Table 3. *Soil carbon contents (%, 0-15 cm) and spatial heterogeneity in the plantation. Changes in soil carbon stock for two genetic stands, Deli × La Mé and Deli × Yangambi, under the ecological conditions of North Sumatra (unpublished data).*

	North Sumatra	North Sumatra	Ivory Coast
Plant material	*Deli × La Mé (%)*	*Deli × Yangambi (%)*	LM2T × DA10D (%)
Leaflets	10	11	7
Rachis	18	22	12
Petioles	14	15	8
Stems	36	42	30
Roots I	9	4	11
Roots II	6	4	16
Roots III+IV	7	2	16

As the leaf respiration rate is directly related to photosynthesis, it is normal to find maximum CO_2 release for frond ranks 8-9-10, which are the most photosynthetically active, and those receiving maximum radiation, up to rank 20, irrespective of the height of the sun [18].

Few measurements or estimations can be found of root respiration, except through more general measurements of soil respiration. A soil respiration study conducted by Lamade et al. [19] at Ouidah (Benin), at an average ambient temperature of 27°C, led to an estimation of carbon loss through root respiration of 76 kg C yr^{-1} $palm^{-1}$ in a 20-year-old plantation. Henson [20] gave an estimate of 32 kg C yr^{-1} $palm^{-1}$ for a younger plantation (10 years old) in Malaysia with a less developed root system.

Using the Penning de Vries formulas [17], the SIMPALM model estimates that the annual respiratory cost in carbon, including growth and maintenance of all the organs of a mature oil palm, amounts to 211 kg C yr^{-1} $palm^{-1}$ in North Sumatra [15] and 202 kg C yr^{-1} $palm^{-1}$ under African conditions.

To conclude, it can be estimated that, on average and under optimum ecological conditions such as those in North Sumatra, a mature palm will release around 750 kg CO_2 yr^{-1}, i.e. the equivalent of 200 kg C yr^{-1} through respiration.

Plant matter:
FFB harvesting and frond pruning

Carbon export through FFB harvesting will vary from 18 kg C yr^{-1} $palm^{-1}$ (at 3 years) to 43 kg C yr^{-1} $palm^{-1}$ (at 9 years) based on production at SOCFINDO (North Sumatra).

During its productive period, an oil palm will undergo two types of pruning, the first to enable ripe bunch harvesting from the crown, the second to maintain an acceptable number of active fronds in the crown. Carbon loss associated with those operations can be estimated at 40 kg C yr^{-1} $palm^{-1}$ on average under North Sumatran conditions. That carbon is not completely lost from the ecosystem as fronds are usually piled in the windrows where they rot. They may also be used by local populations, in which case there is a significant drop in the carbons reserve of the soil: in the case of North Sumatran plantations, the reduction is substantial over a period of 10 years (*table 4*).

Table 4. *Allocation of biomass in mature oil palms (as a % of total dry matter) to the different vegetative organs in two types of ecologies and with two types of planting material (North Sumatra [15]; Ivory Coast: [7]).*

Genetic family and location	*Benin*	*Deli x La Mé*		*Deli x Yangambi*	
Year	1993	1994	2004	1994	2004
Interrow	0.46	3.15	–	2.35	–
Windrow	0.82	2.22	1.94	1.89	1.4
"weeding" circle	0.55	2.17	1.39	1.79	1.38
Harvest path	–	2.1	1.68	1.84	0.83

Carbon storage in elaborated biomass: variation with age

Carbon storage in the biomass elaborated each year primarily depends on the age of the stand, then secondarily on agroecological conditions. For the stem, Jacquemard and Baudoin [21] found three stem growth phases under Ivorian conditions. From 0 to 3 years: growth in width only; from 3 to 6 years: increase in growth rate; from 6 to 25 years: stabilized growth rate, or even declining, from 10 years onwards. Frond size varies over the years, as does the number of leaflets and, finally, the total "capture" area.

Root growth was studied and modelled by Jourdan [22] under Ivorian conditions. The author mentioned an increase in biomass of 21 kg_{dm} $palm^{-1}$ at 4 years old to 385 kg_{dm} $palm^{-1}$ at 16 years old.

Under Asian conditions, Henson [23] found a total annual variation in aerial growth of 1 to 2 t_{dm} ha^{-1} yr^{-1} between 8 and 12 years old. The same author showed an annual root system growth rate of 7 kg_{dm} $palm^{-1}$ between 0 and 5 years old, then 14 kg_{dm} $palm^{-1}$ between 10 and 15 years old, with a notable drop in that annual growth rate between 15 and 28 years old, at 2.3 kg_{dm} $palm^{-1}$.

Plantations: a planted ecosystem

After examining what happens on the scale of a single palm and having quantified carbon storage on an individual palm scale, it is necessary to establish the carbon flux balance between captures and releases on a plantation scale. This is characterized by two main vegetation storeys: the palms, and nitrogen fixing cover crops mixed with invasive species. This ecosystem has specific edaphic characteristics, spatial heterogeneity in soil carbon content, and a particular microclimate.

Components of soil respiration

Soil respiration, *i.e.* total CO_2 release from the soil including the activity of the roots and of the rhizosphere, along with the activity of microorganisms and fauna in the soil, is an essential parameter for estimating the carbon budget of the ecosystem. For oil palm, measurements have already been taken by Henson [22], Lamade and Setiyo [24], under Asian conditions, and by Lamade *et al.* [19] in Benin. Using the Raich and Nadelhoffer equilibrium principle [25], a distinction can be made between the different components of soil respiration (autotrophic respiration (roots), heterotrophic respiration (microorganisms), CO_2 losses linked to leaf litter decomposition and root litter decomposition). Using the same principle, it is possible to estimate total carbon allocation to roots and root turnover. On this basis, total annual carbon release from the soil (Rsol) into the atmosphere differs in Benin (1610 g C m^{-2} yr^{-1}) and North Sumatra (1170 g C m^{-2} yr^{-1}), due to greater respiratory loss from roots in Benin. Total carbon allocation to the roots (in a mature oil palm plantation) varies from 1438 g C m^{-2} yr^{-1} in Benin to around 1025 g C m^{-2} yr^{-1} in North Sumatra. A great difference is found between these two ecologies for root turnover: 535 g C m^{-2} yr^{-1} in North Sumatra under potential conditions for oil palm growing, and less than 354 g C m^{-2} yr^{-1} in Benin (*table 5*). Irrespective of the ecology, CO_2 release in plantations displays typical spatial heterogeneity, in direct relation with the layout of the palms at the tips of equilateral triangles, along with the effect of cultural practices (preferential zones for fertilizer applications, arrangement of pruned fronds on the windrows, slow decomposition of stems in the interrows, etc).

Large differences can be seen between natural forest ecosystems and planted ecosystems, such as oil palm or eucalyptus plantations. Natural forests are characterized by much lower CO_2 release into the atmosphere through soil respiration and greater enrichment of the soil in carbon through leaf litter (*table 5*). However, a similarity is found in results between oil palm and eucalyptus plantations for soil respiration components (*table 5*).

Soil carbon stock and decomposition

Some studies [26-29] measured changes in soil carbon content from destruction of the forest ecosystem to its replacement by an oil palm plantation under Ivorian conditions. When such a replacement is made, there is a notable drop in soil carbon (in the upper horizons, 0-30 cm) in the first 4 years as the young oil palms develop, then that rate seems to stabilize from 9 years old onwards at between 55% and 65% of the previous forest soil content. In the case of replantings, which is now the most common situation, the carbon contribution coming from the slowly decomposing old

Table 5. *Total soil respiration (Rsoil), annual net primary productivity (NPP), growth, and both aboveground and belowground litter for several types of ecosystems, in g C m^{-2} yr^{-1}. D*L(Indo) genetic family Deli × La Mé (North Sumatra); D*Y(Indo): genetic family Deli × Yangambi (North Sumatra). Ash, Interior, Edge Forest: Hawaiian tropical forests (Mauna Loa).*

Ecosystem	Reference	Rsoil	NPP	Leaf litter	Growth	Root litter
*D*L*(Indo)-oil palm	[24]	1167	1719	133	1094	544
*D*Y*(Indo)-oil palm	[24]	1198	1937	179	1312	526
Malaysia-oil palm	[39]	1219	2014	150	1312	844
Benin-oil palm	[19]	1610	937	124	687	345
Ash forest	[32]	900	519	475	219	
Edge forest	[32]	780	375	280	94	
Interior forest	[32]	650	280	250	47	
Merapi (*Pinus merkusii.*, plantation) Indonesia	[34]	980	844	432	407	
Merbabu (*Pinus merkusii.*, plantation) Indonesia	[34]	690	460	192	350	
Eucalyptus (3 yrs plantation) Congo	[33]	1180	1203		676	527

stems, and the rapid contribution from the leaf and root litter of both vegetation storeys (herbaceous and palms) are combined over the years. Henson [20] developed a model for Malaysia for frond decomposition in the windrows depending on the age of the plantation. Maximum decomposition was found at a young age: at 5 years old, frond laminae rot totally within 255 days. At 25 years old, that period extends to 2 years. Under the drier conditions of Benin, frond decomposition is much slower and it is not rare to find windrows 1.5 m high and 3 m wide if fronds are not removed by the local populations. Typical spatial heterogeneity is found for soil carbon variations in plantations (*table 4*) usually with higher contents in the windrows and interrows. African situations (Benin) and Southeast Asian situations (North Sumatra) are seen to be highly contrasting.

Eddy covariance method

An estimation of CO_2, water and energy flows on a stand scale is currently obtained by using the eddy covariance method. For oil palm, this type of study has only been carried out in Malaysia [30, 31]. It proves to be very useful for a satisfactory estimation of the annual CO_2 balance for a large area of vegetation. Henson [31] measured a negative flow (corresponding to the net flow entering the ecosystem) varying from –24 to –29 g CO_2 m^{-2} day^{-1}, *i.e.* –87 to –106 t CO_2 ha^{-1} yr^{-1} under average radiative conditions in Malaysia. Those results differ from the ones we estimated by the Raich method [32] (*table 6*). The eddy covariance method was used by a CIRAD team for coconut in Vanuatu and eucalyptus in Congo [33] at different ages. For 3-year-old eucalyptus maximum values corresponded to around –1 g CO_2 m^{-2} h^{-1}, much lower in absolute values than for oil palm (up to –4 g CO_2 m^{-2} h^{-1}). This lower sequestration is found in the annual balance with a total flow of –15 t CO_2 ha^{-1} yr^{-1}.

Annual balance and carbon sequestration

Estimations were made by Lamade and Setiyo [24] following the work by Raich [32] on several types of ecosystems including 4 types of oil palm plantations located in different ecologies (Malaysia, Benin, Indonesia), 2 *Pinus merkusii* plantations on the island of Java in Indonesia studied by Gunadi [34] and 3 types of forest ecosystems studied by Raich [32] in Hawaii to establish the carbon balance. Net Primary Productivity (NPP) is estimated from growth (stem diameters, heights), from standing biomass, from annual production of aboveground material such as fronds and inflorescences, from the production of root biomass and root turnover. Carbon sequestration is estimated by subtracting the heterotrophic component of respiration. The annual storage of a mature oil palm plantation is very high: without bunch harvesting it is potentially 1340 g C m^{-2} yr^{-1} (*i.e.* 13.4 tC ha^{-1}) under optimum ecological conditions (*table 6*). These values are much higher than those for forest ecosystems (150 g C m^{-2} yrn^{-1} on average). Harvesting and continual exportation of FFB causes this storage level to fall (250 g C m^{-2} yr^{-1}), but it remains higher than that for the tropical forest (43 g C m^{-2} yr^{-1}). Nevertheless, it can be less than other planted ecosystems such as eucalyptus (390-470 g C m^{-2} yr^{-1}) in the hypothesis where plantations serve as carbon sinks. When trunks are utilized at the end of the cycle, the balance turns back in favour of oil palm.

Table 6. *Estimation of carbon storage (g C m^{-2} yr^{-1}) for the oil palm ecosystem (), and comparison with other planted or natural forest ecosystems. (1): Lamade and Setiyo [24]; (2) Henson and Chai [39]; (3) Lamade et al. [19]; (4): Raich [33]; (5): Gunadi [34]; (6): Dewar and Cannell [40]; (7): Nouvellon et al. [37]; (8) Grace and Malhi [41]; (9) Roupsard et al. [42].*

Ecosystems	Location (latitude, longitude) and ecology (elevation, annual rainfall, average temperature)	C storage not accounting for harvesting	Storage after harvesting
D × *L* oil palm (8 years old), Indonesia	2°55N, 99°05E, 370 m, 2900 mm, 24.7°C (1)	1100	620
D × *Y* oil palm (8 years old) Indonesia	Ditto (1)	1230	940
Oil palm, Malaysia	(2)	1340	250
Oil palm, (20 yrs old) Benin	6.23°N, 2.08°E, - , 950 mm, 27°C (3)		650
Interior rainforest, Mauna Loa volcano (Hawaii)	19°45'N, 155°15'W, 1660 m, 2600 mm, 13°C (4)	43	
P. merkusii (Java)	7°30'S, 110°30'E, 800 m, 3700 mm, 21°C. (5)	403	
Temperate forests	England (6)	20 - 50	
Eucalyptus, 3 yrs old Congo	4°S 12°E, 50 m, 1200 mm, 25°C (7)	390 - 470	50
Forests (total)	(8)	150	
Coconut, 20 yrs old Vanuatu	15.29'S, 167°14'E, 40 m, 2900 mm, 25°C (9)	125-530	

Table 7. *Estimation of carbon storage per country and continent, along with corresponding emission credits (Total Africa: 22 countries, Total Asia: 5 countries, Total America: 7 countries).*

Countries and continents	Production Mt	Areas harvested (ha)	Total carbon storage, harvest removed (t)	Emission credits US $
Republic of Benin	244 000	20 000	110 000	2 200 000
Indonesia	55 000 000	3 175 000	24 765 000	595 300 000
Malaysia	68 050 000	3 670 000	9 175 000	183 500 000
Total Africa	15 754 000	4 300 900	27 956 000	559 120 000
Total Asia	128 550 000	7 134 000	43 018 000	860 360 000
Total America	5 620 600	379 549	2 315 000	46 300 000
Total	-------------	----------	73 289 000	1 465 780 000

Emission credit: what oil palm can contribute ...

To round off this evaluation, it is necessary to distinguish between stored carbon (the capacity of an ecosystem to maintain a certain biomass), carbon "parking", which is a more restrictive concept (what happens over a period of twenty years, for example), and sequestered carbon, the net CO_2 taken by the ecosystem from the atmosphere. As a first approximation, we can take a figure of US$ 20 per tonne [35] irrespective of the situation. For oil palm, we simply estimated this emission credit as a function of the areas harvested, of the ecology and of yields, based on the dry matter produced each year. Global carbon storage by the oil palm can be estimated at 73 Mt C yr^{-1} for 12 million hectares (*table 7*). This value is well below the 336 Gt of storage for forest ecosystems, but the areas bear no relation either. The oil palm can store 4 times more per hectare than a forest ecosystem in what are essentially biomass terms. Looking at things another way, the net storage of French forests is 10.5 Mt C yr^{-1} [36]. The most sensitive point for the planted oil palm ecosystem is the low litter production and its decomposition. *figure 3* illustrates the substantial release of CO_2 by the soil in oil palm plantations and a very low return of that carbon via litter, compared to forest ecosystems. In order for this system to increase carbon storage in the soil, management of organic supplies need to be improved. One way would be to limit frond exports by local populations, and reintroduction of empty fruit bunches into the ecosystem (which is already done on some estates), along with waste from oil extraction. In addition, if such storage were remunerated, each planter would be likely to receive US$ 130 per ha per year.

Conclusion: more quantitative studies

We have just seen that a mature oil palm plantation displays considerable net primary productivity (NPP): 2015 g C m^{-2} yr^{-1} in Malaysia compared to 520 g C m^{-2} yr^{-1} for a natural forest in Hawaii, or 845 g C m^{-2} yr^{-1} for a *Pinus merkusii* plantation. However, respiratory losses, particularly from the soil, are also substantial: 1610 g C m^{-2} yr^{-1} in Benin compared to 810 g C m^{-2} yr^{-1} for a eucalyptus plantation in Congo [37]. Another characteristic of the oil palm ecosystem is the lower contribution of leaf litter compared to forest ecosystems: 130-180 g C m^{-2} yr^{-1} in Sumatra compared to 390-500 g C m^{-2} yr^{-1} for natural forests [38]. From that point of view, it is important to have more quantitative data on the herbaceous storey (cover crops invaded by a host of opportunistic species), which is considerable in young stands, in order to estimate carbon balances more effectively. Be that as it may, the oil palm has major potential for atmospheric CO_2 sequestration, and that is a parameter which needs to be taken into account when judging the environmental impacts of this perennial crop. However, the data obtained so far are only very partial and need to be completed by studies applying appropriate methodologies (eddy correlation study design), in different types of ecologies and on a range of ages that are representative of the way an oil palm plantation evolves. Likewise, comparative studies on changes in the carbon balance in plantations derived from deforestation or from a simple rotation may make it possible to quantify more effectively the changes in the soil's carbon stock, which is one of the most important components in the process of carbon storage by an ecosystem.

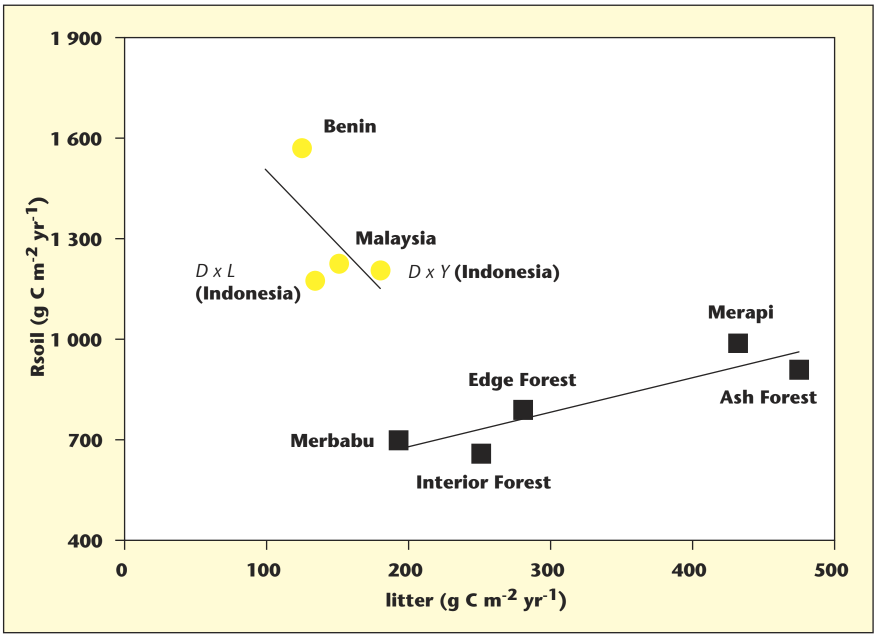

Figure 3. *Relation between total soil respiration Rsoil (heterotrophic and autotrophic) and leaf litter for a group of oil palm plantations ((D × L (Indonesia): Deli × La Mé material located at the Marihat Research Station (North Sumatra); D x Y (Indonesia): Deli × Yangambi, same ecology; Malaysia: plantation located at a coastal site in western Malaysia; Benin: irrigated plantation at Ouidah) and a group of forests and forest planatations (Merbabu and Merapi: pine plantations, Java, Indonesia); Interior Forest, Edge Forest, Ash Forest: Hawaiian tropical forests (figure from [24]).*

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