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Coconut Carbon Sequestration
Part 1 / Highlights on Carbon Cycle in Coconut Plantations

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Abstract

This article reviews scientific information in order to prepare application of coconut plantations to the Clean Development Mechanism CDM of the Kyoto Protocol. It sums up some theories for describing the C cycle within a given plantation, separating the coconut trees, the under-storey and the soil. It synthesizes recent reports about the C cycle (stocks and fluxes) of a chronosequence of coconut plantations, considered to be a reference for productivity (high level of fertility, no drought). It gives figures for the potential C balance of a coconut plantation and compares them to other tropical humid evergreen forests. Although the results should not be extrapolated without caution, they highlight some main traits of this peculiar crop, such as a high productivity and a large C allocation into organs displaying rapid turnover (bunches of fruits, fine roots, leaves, peduncle and spikelets), the fate of which is to be turned into litter. Moreover, results bring new insights into the physiology of this plant, which is of high interest for understanding the components of yield, such as reserve dynamics. They also confirm that litter management is crucial for the C fixation and the sustainability of coconut cultivation, especially when the levels of inputs are low.

Keywords: C balance / Productivity / C allocation / Litter / Soil Organic Matter / *Cocos nucifera* L.

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Introduction

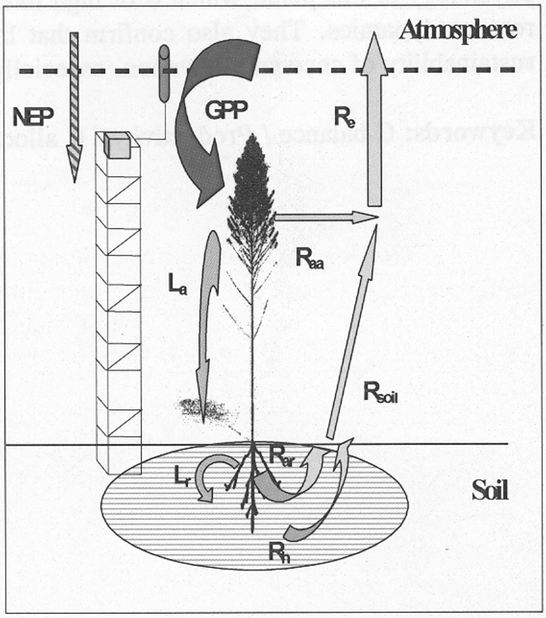
According to (IPCC, 2007), carbon dioxide (CO_2) is, by far, the largest contributor to the anthropogenically enhanced greenhouse effect. The importance of CO_2 to the climate has provided the impetus for research on the global C cycle. The amount of C contained in terrestrial vegetation is about 550±100 Pg and the organic matter in soils is two to three times this amount (1500–2000 PgC in the top meter and as much as 2300 Pg in the top 3 m). Forests are particularly important as a C reservoir because trees hold much more C per unit area than other types of vegetation. Land use change contributed to 1.7 Gt C (±0.8 Gt C yr^{-1}) in the period 1980 to 1989 and is the second source (20%) of GHG emissions in the world and the first in developing countries. When accounting the contribution of terrestrial ecosystem to the global C cycle, measuring the productivity and the C balance of various land uses is of great importance particularly in the tropics.

Productivity and carbon balance of each type of land use are key issues for Clean Development Mechanism (CDM), particularly under the tropics. In addition, the impact of crop management on GHG emissions might become an issue under the second period of commitment of the Kyoto Protocol (>2012). Ecosystem productivity is generally referred to by Net Primary Productivity (NPP: the sum of annual growth and mortality), Gross Primary Productivity (GPP: CO_2 entry in the ecosystem by photosynthesis) or else Net Ecosystem Productivity (NEP: CO_2 balance of the ecosystem, in other words, a proxy for C sequestration, remembering that all emissions sources at the soil-plant-atmosphere interface should be computed, including other GHG, but also all the indirect fluxes (gasoline, enteric emissions, and so on). A table of abbreviations in proposed in Appendix 1.

Reminders on the theory of C cycle in plantations

Fig. 1 illustrates the main fluxes involved in the carbon cycles in forest ecosystems (Saint-André et al., 2007).

Figure 1: The carbon cycle in forest ecosystems. Brown arrows represent upward CO_2 fluxes (autotrophic respiration (R_a) from above- and below-ground plant compartment, (R_{aa}) and (R_{ar}), heterotrophic respiration (R_h) and ecosystem respiration R_e=R_a+R_h). Green arrows represent downward CO_2 fluxes (gross primary production, GPP). Net ecosystem respiration (NEP) is usually a downward flux (fixation), except in certain situations (after clear-cutting for example) when R_e may exceed GPP. Blue arrows represents ecosystem internal fluxes of carbon due to litter fall (L_a) and belowground litter production by fine root turnover (L_r). Losses of carbon by volatile organic compounds (VOC) emission, or by dissolved organic carbon (DOC) leaching have been neglected and are therefore not represented.



When neglecting all inputs from organic fertilizers, all the carbon inputs come from the gross primary production (GPP: the sum of the photosynthesis of the plants of the ecosystem). A significant part of this carbon uptake is lost through autotrophic respiration (*i.e.* plant respiration, R_a) which can be arbitrarily divided into two main components: root respiration, (R_{ar}) and respiration from aboveground (R_{aa}) plant compartments (leaves, branches, stems). The fraction of GPP that is not lost through plant respiration is used to produce new biomass, thus contributing to the Net Primary Production (NPP: the sum of visible growth + litter production):

$$NPP = GPP - R_a \qquad \textbf{Eq. 1}$$

Allocation of NPP to the different plant compartments contributes to tree growth and litter production (L). Among the various plant compartments, we may distinguish between compartments with high turnover rate (fruits, peduncles, leaves, fine roots), contributing to litter production, and compartments with low turnover rate (stem, coarse roots), contributing mostly to biomass accumulation. The stand growth (carbon accumulation in biomass ΔC_B is the difference between NPP and L:

$$\Delta C_B = NPP - L \qquad \textbf{Eq. 2}$$

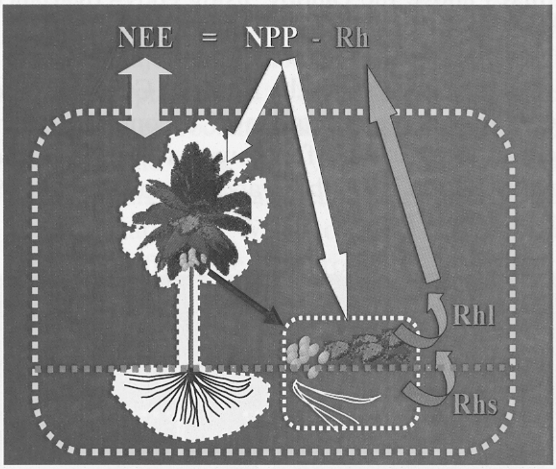
Litter inputs to the soil are decomposed by soil microorganisms. The part that is not oxidized is transferred to the soil organic matter (SOM) pool. Emission of CO_2 through litter decomposition and subsequent SOM oxidation by soil microorganisms both contribute to the so-called 'heterotrophic respiration' (R_h).

A proportion of the litter produced through NPP is thus lost through heterotrophic respiration. The difference between the rate of NPP and R_h controls the rate of net ecosystem production NEP), which is defined by (see also Fig. 2):

$$NEP = NPP - R_h = \Delta C_B + \Delta C_S + \Delta C_L \qquad \textbf{Eq. 3}$$

Equation 3 is crucial for our understanding of C sequestration (NEP) in any ecosystem, especially understanding the link between NEP evaluation by scientific methods (second member of equation 3, but see also equation 4), and by CDM certified methodologies (third member of the equation 3). In particular, the third member of equation 3 is generally simplified in CDM calculations, when only ΔC_B is estimated, and even more frequently, only ΔC_B of aboveground parts. This results in an under-estimation of NEP (less C credits), especially when the other terms are important in the balance, which is very likely in coconut plantations, as will be developed below.

Figure 2: Partitioning of the C balance of the coconut plantation (NEP) into net primary productivity (NPP) and heterotrophic respiration (R_h).



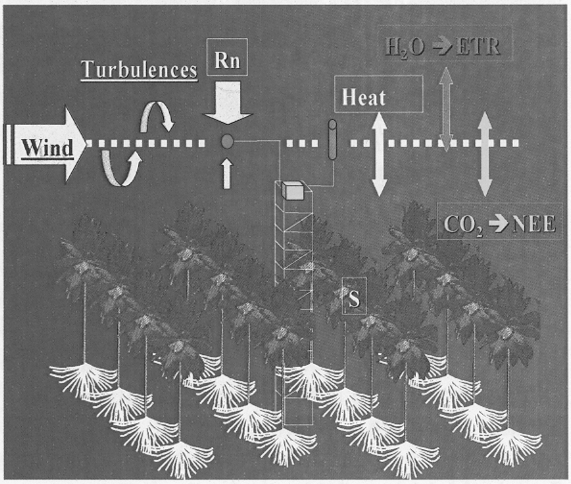
The total respiratory carbon loss by the ecosystem (R_e: ecosystem respiration) results from plant respiration (R_a) and respiration of soil and litter decomposers (R_h). The net ecosystem exchange of CO_2 between the forest and the atmosphere (NEE) is the difference between CO_2 uptake through photosynthesis, and CO_2 emission through ecosystem respiration. This net flux is highly variable both diurnally (due to variations of light, temperature, and air relative humidity), and seasonally, but it can be monitored continuously with the eddy-covariance methodology, and cumulated over time for estimating monthly or annual Net Ecosystem Production:

$$NEP = GPP - R_e = GPP - R_a - R_h = \sum NEE \qquad \textbf{Eq. 4}$$

According to equation 4, the variations of C stocks in soil + biomass + necromass (litter) account for C sequestration (**Stock Method**). However, the main impediment is to cope with the large variability of soil C stock when measurement is desired, either intra-plot or between plots. A synchronic approach, using chronosequences (or time series), is proposed here for estimating the C sequestration on the long term. However, there are no methods accurate enough to measure soil C stocks variations on the short term (a few years).

On the other hand, for the short term (from minutes to a few years), the **Flux Method** is proposed, using direct measurements of the fluxes above the canopy, using eddy-covariance methods (Fig. 3).

Figure 3: Measuring the fluxes of CO_2, H_2O and energy above a plantation of coconut by eddy-covariance, using a flux-tower, where R_n is the net radiation, ETR the evapo-transpiration and S the stock of heat.



late 1990's as a tool for assessing the ecosystem C balance. The methods were standardized and a net of experiments has been displayed on various types of World terrestrial ecosystems (over 250, under the umbrella of **Fluxnet:** http://daac.ornl.gov/FLUXNET/). Tropical ecosystems remain scarce, especially for tropical planted perennials nearly absent (Cirad has displays on eucalypt, rubber tree, coconut, coffee though), and detailed site information can be found on Fluxnet. Only few displays include chronosequences, although this is required for estimating the C sequestration on the long term.

Both methods (Stock and Flux) should ideally complete or cross-validate each-other, in order to really integrate spatial and temporal C variability.

Preparing scientific information for a CDM-C sink application in coconut plantations

All the policy part of this question was reported in the companion paper (Part 2). Scientific measurements of C sequestration (*e.g.* C stocks in chronosequences; CO_2 fluxes by eddy-correlation; GHG emissions by various methods) are not actually required for any application to certified emission reductions (CER). Simple surveys for the baseline and estimations from available literature are generally sufficient to meet the methodologies approved by UNFCCC (http://cdm.unfccc.int/Statistics/). However, considerable advantages result from scientific approaches of C sequestration, especially for coconut plantations, due to the peculiar mode for C allocation:

- More pools of C can eventually be taken into account in the computation of sequestration. A major impediment here is that, contrary to dicot trees, coconut does not allocate much of its C into permanent structures (stems, coarse roots), but allocates more than 86% into perishable structures (fruits, leaves, peduncles, fine roots) that will quickly turn into litter, and be respired by the ecosystem or contribute to the build-up of Soil Organic Matter (SOM). This "litter-oriented" fate of C is very peculiar, and cannot be accounted properly using common C accounting method generally using forestry inventories that focus on aboveground C compartment while underestimating C in SOM and litter.

- Reducing the standard deviation in the measurement of the C stock mainly in belowground compartment and help allocates more than 86% into perishable structures (fruits, leaves, peduncles, fine roots) that will quickly turn into litter, and be respired by the ecosystem or contribute to the build-up of Soil Organic Matter (SOM). This "litter-oriented" fate of C is very peculiar, and cannot be accounted properly using common C accounting method generally using forestry inventories that focus on aboveground C compartment while underestimating C in SOM and litter.

- Reducing the standard deviation in the measurement of the C stock mainly in belowground compartment and help demonstrating statistically a C sink and CER gain, or alternatively demonstrate that one compartment can be neglected (costs reduced).
- Understanding the fate of C is central in the questions of fertility, growth, productivity, sustainability, energy and hence profitability and environment,
- Alternative management of the fertility is key to sustainable development.
- Functional models can be used for simulating the impact of alternative situations (management practices, climate, resources).
- Management practices are candidate to CDM for the second commitment period (>2012) and should be documented.

Materials and Methods

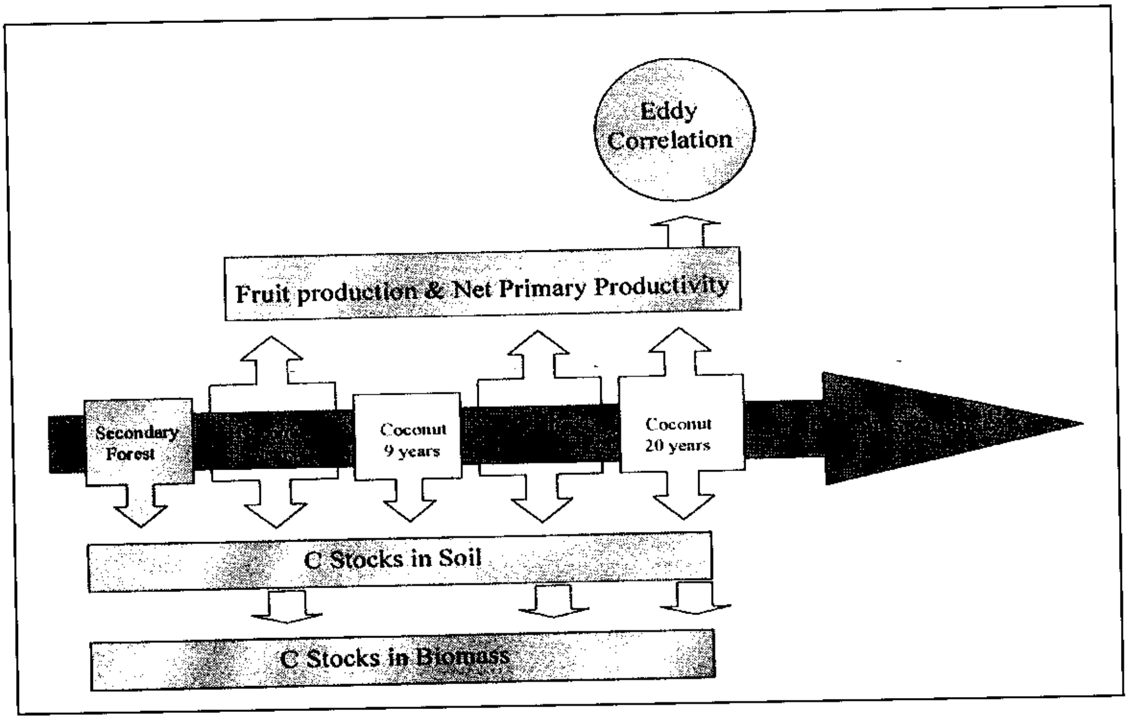
C balance of a coconut plantation

The coconut C balance was assessed on a chronosequence of coconut plantations, placed in optimal conditions (high fertility, no drought, high yielding hybrid VRD x VTT) in VARTC between 2001 and 2007, Santo, Vanuatu, all located within a 450 ha unit (Fig. 4) and tall coconuts from smallholder's plantations (VTT) in an adjacent island with similar conditions (Malo). The stands were all surveyed for C stocks. NEP was assessed in only one stand (around 20 years old) for C flux by eddy-covariance.

The Stock Method is not really standardized in the literature, especially not for coconut plantations with two layers (coconut + grass under-storey) or more vertical layers of vegetation in smallholders plots (coconut trees + fruits trees + grass under-storey). It should be adapted to the system under observation (*e.g.* soil horizontal and vertical variability, management, plant phenology, plant compartments, etc.). Navarro *et al.* (2008) proposed adjusted methods for assessing NPP in coconut plantations (growth and litter production of coconut and grass under-storey), above-ground and also below-ground. The below-ground compartment was clearly the biggest challenge. We also used NIRS (Near Infrared Reflectance Spectrometry) in order to assess soil C, N and organic matter stocks on a large sampling basis (Lamanda et al., 2004a), and after due calibration. Flux methods were reported by Roupsard *et al.* (2006; 2007a) and (Luyssaert et al., 2007).

The initial stage is crucial in the C sequestration result. Our initial ecosystem was a high secondary forest, with a putative large C stock in soil and biomass. Our hypothesis was that the C stock would be depleted after felling the forest and that the sequestration would be negative. However, it was important to assess *(i)* what was the initial loss after planting, *(ii)* if a partial repletion, stagnation or decrease would be observed during the lifespan of the coconut plantation. This might indicate eventually if, starting from an initial ecosystem displaying a low stock, like for example semi-abandoned areas or old coconut plantations, the young coconut plantation would eventually be a good candidate for increasing the C stock, which is the focus of the CDM. In this case, the type of

Figure 4: Diagram of the Cocoflux experiment of VARTC, Santo, Vanuatu, for assessing C sequestration at the scale of a chronosequence of planted coconut hybrids (VRD x VTT), starting from an initial secondary forest.



management during coconut planting might be of crucial importance in order to minimize the initial C losses.

Soil Organic Matter and ecosystem C stock trends along a coconut chronosequence

A survey of the soil organic matter (SOM) in the top soils of fertile areas of Vanuatu has been implemented on chronosequences from 0 to 50 years after coconut planting, including an initial stage of secondary forest, various coconut-based smallholders' cropping systems in the island of Malo (Lamanda et al., 2004b) and large plantations in VARTC-Santo. For example, on smallholders plots, SOM of 12 % in top soil (0-20 cm) and 5 % in sub soil (20 - 35 cm) were measured with an average value of the Corg/Nitrogen ratio of 10 (Lamanda et al., 2004a). Also, the whole ecosystem C stocks were estimated along the chronosequence, and the different stages were compared.

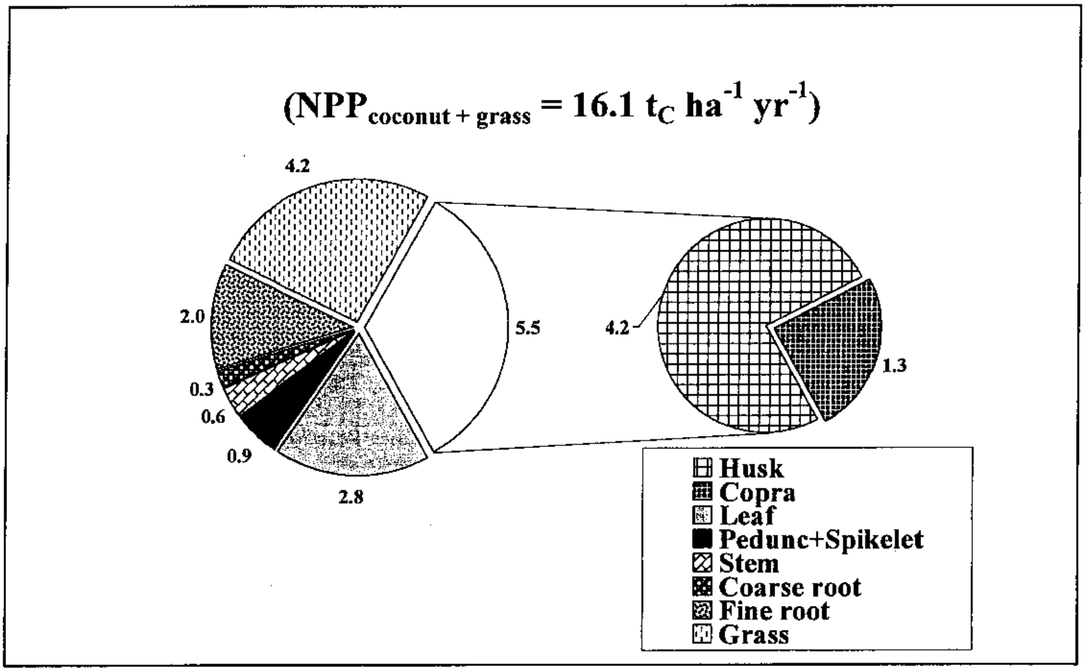
Results and Discussion

The measurements and outputs of models presented here are valid only locally for the real experimental conditions and must be considered as a case-study. Extrapolation should not be done without extreme caution. Modelling would be a key step before extrapolation.

Net Primary Productivity (NPP)

As reported in Navarro *et al.* (2008), NPP includes the annual biomass and litter production of the coconut and the grass under-storey, with the distribution presented in Fig. 5 and a total NPP of 32 t_{DM} ha^{-1} yr^{-1}, of which, around half is assumed to be C (16 tC ha^{-1} yr^{-1}). For the sole coconut trees, NPP was 12 tC ha^{-1}

Figure 5: Net Primary Productivity (NPP) of the plantation Stand (coconut + grass) assessed by monitoring the growth rate of each compartment around 20 years after plantation. Cocoflux experiment of VARTC, Santo, Vanuatu, optimal conditions.



yr^{-1}. Nut production represented 46% of that productivity. Copra yield was 2.7 t$_{DMcopra}$ ha^{-1} yr^{-1}.

A point of major interest here, most of the NPP of the sole coconut tree (89%: fruit + leaves + peduncle & spikelets + grass + fine roots) turned to litter, and only the remaining (11%, for stems and coarse roots) contributed to the annual biomass increment. These traits are highly different from those of dicot tree plantations where most of the NPP can be allocated to trunk, roots and stump growth. In other words, a huge part of the C fixed by the system is expected to be allocated to the litter and then either to the soil organic matter (SOM), or to heterotrophic respiration (then lost). Therefore, it can be assumed that the mode of management of the huge annual litter production will have a crucial impact on SOM build up. Navarro *et al.* (2008) reported also that NPP + R_a (34.3 tC ha^{-1} yr^{-1}) matched eddy-covariance GPP (35.3 tC ha^{-1} yr^{-1}), which is consistent with the theory presented in equation 1. However, seasonal variations were of lower magnitude for NPP + R_a than for GPP, and maximum tree NPP was lagged by 6 months with respect to the most favourable season (high radiation, high tree GPP). Vegetative compartments of the tree grew on a remarkably steady pace, but fruits accounted for 46% of tree NPP and explained most of its seasonal variations. Navarro *et al.* (2008) put forward the hypothesis that in this fruit tree, growing and fruiting continuously in favourable conditions, reproductive phenology (flowering, relative growth rate of fruits, abortion) drives the seasonality of NPP more directly than its photosynthesis.

Net Ecosystem Productivity (NEP), variability and comparison with tropical forests

Roupsard *et al.* (2007) reported that a tropical plantation of coconut tree with a grass under-storey (total LAI of around 6 for the two layers) and placed in close-to-optimum growing conditions (high level of fertility, no seasonal drought, evergreen, continuous growth) displayed productivity (GPP and NPP) characteristics close to tropical evergreen humid forests, *i.e.* amongst the highest levels encountered in global forest biomes (Luyssaert *et al.*, 2007). Climate, fertility, LAI and phenology appeared to be key elements for ranking productivity of ecosystems, irrespective of their status (from artificial to natural). This is an appealing result, notably for other tropical perennial crops grown in fertile conditions and in absence of drought, such as *e.g.* oil palm, coffee, rubber tree. It would deserve further investigations, together with other annual tropical crops. In actual field conditions, high and balanced soil fertility (optimum crop nutrition) is seldom achieved (only under experimental station conditions).

Roupsard *et al.* (2007) reported also a three-year average apparent NEP (the actual ecosystem C balance for the coconut plantation), being 8.1 tC ha^{-1} yr^{-1} (Tab. 1), according to their own calculations. According to standardized calculations (FLUXNET), NEP of this coconut plantation would rather be 4.7 tC ha^{-1} yr^{-1}. This latter estimation is close to the average 4 tC ha^{-1} yr^{-1} reported by Luyssaert *et al.* (2007) for tropical humid evergreen forests. However, copra from the nuts is always exported and contributes by ca. 11% to NPP of coconuts palms, so its contribution has to be accounted for in the final C balance. Here, copra was also exported every 2 months out of the plantation, and thus did not contribute to R_e: this amounted to around 1.3 tC ha^{-1} yr^{-1}, hence reducing the apparent NEP to a corrected NEP possibly ranging from 6.8 to 3.4 tC m^{-2} yr^{-1}.

It strongly appears that C Sequestration mainly involving the palm and its rhizosphere depends on the growth and productivity of the tree (or per ha) over time, a resultant of palm genetics, crop nutrition, climatic conditions (rainfall and temperature mainly) and soil conditions (moisture, aeration, microbial populations). Future field studies in C Sequestration should be able to present results obtained under average coconut farm conditions in coconut producing countries, under selected commercial coconut planting materials as the dominant tall and dwarf varieties and hybrid cross, in annually from planting time to full-bearing stage. The age of 20 years (as optimum production) may appear rather old. Experience in the Philippines indicated that full-bearing stage of coconut is normally attained in 7 years (dwarfs), 10 years (hybrids) and 12 years (talls) with adequate nutrition (S. Magat, pers. comm.). If the total biomass and C sequestration in a plantation/farm is considered, situations under coconut + other tree crops (fruit tree and/industrial tree crops) agro-ecosystems must be understood and quantified as under such ecosystems compared to coconut mono-cropping, the biomass and C sequestration in plant parts and the soil are theoretically higher. This means higher carbon credits and value (subsidies) under intercropping coconut farms with perennial tree crops.

Coconut tree reserves

Mialet-Serra *et al.* (2005) reported that the average stock of non-structural carbohydrates (mainly sucrose reserves) in the coconut tree would amount to around 25 kg per tree (at around 20 YAP), *i.e.* around 8% of their standing biomass. The physiological function of the large amounts of sucrose stored mainly in its stem is not known. However, reserve storage or de-storage might play a major role in explaining intra-annual schedule in NPP, allowing NPP to become rather independent from the seasonal fluctuations of the C supply (GPP). The reserve dynamics were reported by (Mialet-Serra et al., 2008). They investigated the dynamics of dry matter production, yield and yield components and concentrations of non-structural carbohydrate reserves. The underlying hypothesis was that reserve storage

Table 1: Net Ecosystem Productivity (NEP or ecosystem C balance) of the coconut plantation during 3 consecutive years, 2001 to 2003, in conditions where only copra is exported and all the rest of litter left inside the plantation. Positive values mean here that C is being retrieved from the atmosphere and stored into the plantation. A range of results is given, according to the way fluxes were calculated, using the same raw data. Cocoflux experiment of VARTC, Santo, Vanuatu, optimal conditions.

	tC ha^{-1} yr^{-1} Roupsard et al. (2007), their own calculations	tC ha^{-1} yr^{-1} Standardized FLUXNET Calculations
Apparent NEP (average of 3 years)	8.1	4.7
Copra exported	1.3	1.3
Corrected NEP	6.8	3.4

and mobilization enable the crop to adjust to variable sink-source relationships at the scale of the whole plant. Sink-source imbalances were partly compensated by transitory reserve and more importantly by variable light-use-efficiency in the short term, and by adjustment of fruit load in the long term.

Managing coconut litter for enhancing soil organic matter and helping sustainable development

Horizontal and vertical variability of SOM content

The horizontal and vertical variability of SOM in one coconut plantation + grass, aged 20 years old (eddy-covariance plot) after felling the forest and planting has been assessed in VARTC-Santo (unpublished results). The horizontal variability was assessed corresponding to the general pattern of one windrow (coarse debris accumulated), one row and one clear inter-row. We observed highly significant effects for horizontal and vertical gradients. On top, C contents were 0.038 gC $\mathrm{cm_{soil}^{-3}}$ (0.0039 gN $\mathrm{cm_{soil}^{-3}}$ for nitrogen). They decreased exponentially till 100 cm, reaching 0.005 gC $\mathrm{cm_{soil}^{-3}}$. The C content of windrow (coarse debris) was higher (0.022 gC $\mathrm{cm_{soil}^{-3}}$) than the row (0.019 gC $\mathrm{cm_{soil}^{-3}}$), and the free inter-row (0.015 gC $\mathrm{cm_{soil}^{-3}}$).

We also observed that soil respiration, fine root density, soil humidity, SOM content were consistently higher in the windrow, that dry bulk density was lower (less compaction), that temperature fluctuations were lower. This horizontal variability indicates that management has a measurable impact on SOM distribution, creates gradients and privileged nutrition areas. This can be of major importance during for instance drought stress, for providing a refuge area for root nutrition and water supply and maintaining the production. We argue that the windrow behaves like an "island of fertility for the coconut sustainability", allowing the trees to feed and also to survive during difficult climate conditions (*e.g.* drought periods).

We did not compare this system with alternative litter management systems yet, although it would be of major interest for helping optimizing the C sequestration in the soil.

Trend of SOM along a chronosequence

Lamanda *et al.* (2004) reported the effect of year after planting (YAP: 1 to > 35 YAP) on surface SOM content. Despite a large variability observed between age classes, there was a significant depletion of almost 20% during the first twenty years after the coconut planting, as compared to the initial stages of secondary forest. Although this depletion was not catastrophic during the first rotation, it might become serious during the next planting, especially for soils of lesser initial SOM content. In most cases, the depletion occurred during the early stages of planting, indicating that planting might be the crucial phase. Therefore, management techniques during planting are important for C sequestration (*e.g.* progressive rather that clear cut, soil cover during planting, etc.). Later on, the stocks appeared to be quite steady, indicating that plantations did not clearly recover C stocks. It must be reminded too that, apart from SOM, an important C loss is expected in the total biomass, when comparing the initial forest and the coconut plantation. This can be eventually modulated, keeping some trees within the plantation.

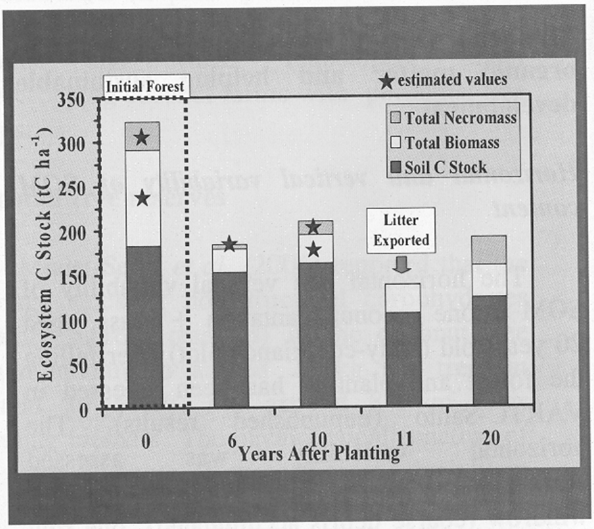
Solutions must be proposed to restore/ maintain the fertility: improved fallow is certainly one, or replanting with legumes, etc. Fallow is traditional in Vanuatu and all the forest are in fact secondary forests. Traditional cultivation techniques, including fallow periods proved to be sustainable, if fallow duration is sufficient.

Ecosystem C stocks in the chronosequence

Fig. 6 gives a rough estimation of the time trend of C stocks by compartment (plants and soil) along a chronosequence of coconut cultivation after felling the secondary forest. Although this result is mixing experimental and estimated values (symbol *), we believe that in principle, most of the C stock is to be expected in the soil (in particular for the coconut plantations), and little stock is in the biomass for the coconut plantation (very different from forest). As a matter of fact it sounds highly irrealistic that coconut cultivation would ever recover the initial C stocks displayed by the forest. The major consequence is that for CDM-A/R projects, only reference baseline ecosystems displaying little initial C stock are worth being targeted before coconut cultivation.

Although it is clear here that soils cultivated with coconut were below C saturation, from recent advances in SOM or SOC research it must be stressed that (i) not all accumulated C in the soil is protected against losses, and the amount of SOC accumulated does not continue to increase with time with increasing C inputs; (ii) An upper limit or C saturation level occurs which controls the ultimate limit of soil C sink and the rate of C sequestration in mineral soils, independently of C input rate; (iii) an understanding of the mechanisms involved in C stabilization in soils is needed for controlling and enhancing soil C sequestration.

Figure 6: Rough estimation of the time trend of C stocks by compartment (plants and soil) along a chronosequence of coconut cultivation after felling the secondary forest in Santo, Vanuatu. Unpublished results. Mix of experimental and estimated values (*) from literature.



H2O fluxes

Using same eddy-covariance techniques, evapo-transpiration fluxes were reported by Roupsard *et al.* (2006). They monitored stand evapo-transpiration by eddy-covariance (E), tree transpiration (T) by heat-dissipative sapflow, soil (G) and stand (J) heat storage during 3 years. On a yearly time step, E represented 40% of rainfall, the sensible heat flux (H) was 26% of net radiation and the Bowen ratio was 0.39, all indicating that water availability was close-to-optimum. T represented 68% of E, close to the 75% of soil coverage by palms. The seasonal variability was pronounced, driven by radiation and vapour pressure deficit (VPD). The canopy conductance of coconut palms appeared to be strongly controlled by VPD. Given its constant LAI, its continuous growth and its simple architecture, the coconut palm appears to be an ideal candidate for physiological work and agroforestry modelling, especially for coupling H_2O fluxes and C fluxes, e.g. through the water-use efficiency (Roupsard *et al*, 2007b).

Modelling light absorption, C and H_2O fluxes

The modeling work is going on (Roupsard et al., 2008), first to estimate light absorption by the canopy of coconuts, according to their structure, age and planting density. Second, to estimate H_2O and CO_2 fluxes. The modelling approach was chosen a Sun-shade model (de Pury and Farquhar, 1997), with comparison to a reference 3D architectural model (3DM, (Dauzat and Eroy, 1997; Dauzat et al., 2001); (Mialet-Serra et al., 2001); (Lamanda et al., 2008). The gap fractions of the whole cover, fraction of intercepted PAR (*f*IPAR), clumping index and leaf orientation derived from LAI-2000 (PCA) were closely matching the simulations 3DM. *f*IPAR and plant area index (PAI) were compared with the coconut literature and an empirical model was proposed for estimating *f*IPAR using only age and planting density. The coefficient of extinction, K, was adjusted to 0.33 for the regular range of planting density. Using this simple relationship, it is proposed (Roupsard *et al.* 2008) and (Roupsard et al., 2007b) to infer PAI, *f*IPAR, and NPP on large scales, using field surveys of age and density to calibrate remote-sensing vegetation indexes (NDVI, EVI), and light-use efficiency or water-use efficiency information to estimate NPP.

Conclusion and perspectives

Coconut plantations, when settled in optimal conditions (high fertility, no seasonal drought, selected varieties, optimum age) displayed amongst the highest levels of photosynthesis (Gross Primary Productivity) and of Net Primary Productivity (NPP: the sum of growth and of litter production) encountered in all the forests of the globe, reaching annual GPP and NPP values close to the most productive systems, *i.e.* the tropical evergreen broadleaved forests. The levels of ecosystem respiration (R_e) were consistently very high, and *in fine* this kind of coconut plantation displayed substantial, but rather regular levels of ecosystem C balance (Net Ecosystem Productivity, NEP), as compared to tropical forests. NEP is in fact the measurement of C sequestration, when we ignore all other greenhouse gases and consider solely CO_2.

A major characteristic of coconut trees is that, contrary to dicot trees, coconut does not allocate much of its NPP into permanent structures (stems, coarse roots), but allocates more than 85% into perishable structures (fruits, leaves, peduncles, fine roots) that will quickly turn into litter, and be respired by the ecosystem or contribute to the build-up of Soil Organic Matter (SOM). This "litter-oriented" fate of C is very peculiar, and cannot be accounted properly using regular forestry inventories of C sequestration, such as simple evaluation of C build up in the stems: it will certainly require detailed studies of C accumulation in the SOM, in addition to the C accumulated in the biomass and in the necromass (litter).

Key before preparing Kyoto CDM or Non-Kyoto projects is to gather relevant figures regarding the potential of C fixation by the ecosystem of reference (baseline to be chosen amongst poor or degraded ecosystems), and by the coconut plantation: C balance, net primary productivity (NPP), partitioning of the fixed C between organs (especially between semi-permanent organs such as stems and non-permanent organs rapidly turned into litter), partitioning between the coconut and the understorey, impact of the management of the huge amounts of litter, fate of the copra (used for regular oil or for energy oil), production of other greenhouse gases, build-up of C in the SOM, etc.

It has been argued that scientific assessment of C fluxes could bring figures for preparing the certification, starting from local measurement, and extrapolating using modelling. It is recommended to the APCC community to invest more into coconut research, especially in order to:

- understand how litter management influences C sequestration,
- what are the fluxes of other GHG in coconut plantations, according to management
- how different soils, climate influence C cycle and yield
- validate models over different coconut plantations and different climate conditions, especially under drought conditions
- simulate the C balance on the long term, using past or forecasted climate files
- simulate and validate at the regional scale, with the help of remote sensing

In addition, scientific assessment also brought new insights into some mechanisms of coconut physiology, yield, productivity and ecosystem functioning. Linking these fields together enlightens which factors limit both yield and C sequestration.

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