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Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Edited by E.K.S. Nambiar, J. Ranger, A. Tiarks and T. Toma. CIFOR 2004.

Measuring Carbon and Water Fluxes from *Eucalyptus* Stands in the Congo

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Introduction

In recent years, there has been a growing interest in developing methods to estimate carbon fluxes and sequestration from ecosystems. Following the Kyoto Protocol, carbon sequestration from growing forests may be accounted to help countries to meet their CO_2 emissions targets. Studies on the role of forests in the sequestration of carbon have been facilitated by developments in micrometeorological methods such as eddy covariance (EC), that allows continuous and long-term measurements of water and CO_2 fluxes between the forest and the atmosphere (e.g. Aubinet *et al*. 2000, Berbigier *et al*. 2001). These measurements provide valuable information to assess the functional responses of the forests to environmental factors such as water stress, and to develop and validate forest process-based models.

In the Congo, about 42 000 ha of clonal eucalypt plantations have been established on native savannas around Pointe-Noire. A study has been established to measure and model carbon, water and energy exchanges, primary production, stand growth and carbon sequestration from these plantations. The experiment is intended to: (1) estimate carbon stocks (soil and trees) in a clonal chronosequence of eucalypts; and (2) measure water and CO_2 fluxes by an eddy correlation system, meteorological variables, water balance, soil respiration, litter decomposition and tree growth in one stand from the chronosequence, over a two year-period. An overview of this experiment is given in this paper, together with some preliminary results.

Materials and Methods

Experimental Area

The plantations around Pointe-Noire (4ºS 12ºE; altitude 50-100 m) are based on two natural hybrids (*Eucalyptus* PF1, and *E. tereticornis* x *E. grandis*), and the artificial hybrid *E. urophylla* x *E. grandis*. They have been established on cleared

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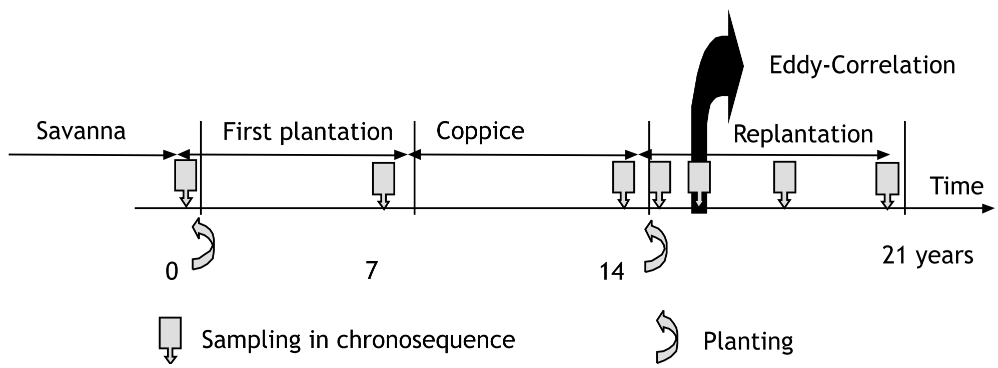
Figure 1. Diagram of the sampling strategy in the chronosequence



native savannas, on sandy, ferralitic, and low fertility soils. The climate is characterised by annual rainfall of about 1200 mm, with a dry season between May and September, mean annual temperature of about 25°C, and high relative humidity (85% on average), with low seasonal variations (2%). The clone selected for this experiment is the clone *E.* PF1 1-41, the most productive clone of the hybrid *E.* PF1. This clone covers more than 7000 ha in the planted area.

Estimation of Carbon Stocks in a Chronosequence

Carbon sequestration by trees and soils is being estimated in a diachronic chronosequence of 21 years (Fig. 1), that is representative of the silviculture applied in these plantations: a first plantation on native savannas followed by a coppice crop and then a new plantation. A 'replantation' chronosequence approach offers several advantages: (1) the age effect over productivity can be accounted for, and (2) regarding carbon sequestration in the soils, chronosequences can be used for cross-validation between estimates obtained from continuous fluxes measurements and estimates obtained from stocks measurements. On the other hand, chronosequence approach may also present disadvantages such as possible soil variation within the sequence and climate variation during the rotation. Six stands have been selected for carbon storage and soil respiration measurements (Fig. 1): (1) a plantation forest at the end of the first rotation; (2) 7-year-old coppice (end of the second rotation); and (3) 1-, 3-, 4-, and 6-year-old stands in third rotation (replantations).

In each of these stands, aboveground, belowground and litter biomass, and carbon stocks in the soils are estimated annually. Tree growth is monitored every 15 days. Soil respiration is periodically measured with a portable closed-path Licor 6200. Root production, lifespan and turnover are estimated from ingrowth cores and rhizotrons.

Measurements of Water and CO_2 Fluxes in the 3-year-old Stand

The 3-year-old stand of the third rotation has been selected for continuous measurements of CO_2, H_2O and sensible heat fluxes using an Eddy correlation system. These measurements started on September 2000. In this stand (42 ha), tree density is 567 trees ha^{-1}. Between January 2001 and October 2001, mean height and basal area increased from 11.2 to 14.9 m, and from 4.4 to

Table 1. Parameters monitored in eddy-correlation stand

Parameters	Measurement	Reference
Energy, H_2O, CO_2 fluxes	Eddy-correlation: closed path: Li-6262 + Sonic Young 8100	Aubinet *et al.* (2000)
Climate	Campbell: Rn (NR-lite, Kipp&Zonen), Rg, PAR,T, H, Wind	
Water availability	TDR (Trase: 0-5m) + leaf water potential (PMS)	
Heat storage	Thermocouples in soil, trunks, air	
Sapflow	Thermal dissipation	Granier (1985)
Rhizospheric/non rhizospheric soil respiration	Portable closed path (Li-6200) + soil temp. + soil humidity (Thetaprobe). Trenched plots + CENTURY model	Epron *et al.* (1999), Parton *et al.* (1987)
Water-use efficiency	Sapflow + dendrometers + eddy-correlation	
Stem growth	Dendrometers, stem profile, biomass	
Root growth and turn-over	Rhizotrons, ingrowth cores, biomass	Jourdan (1995)
LAI and litterfall	LAI-2000+Litter-traps+SLA and biomass	
Litter mass remaining	Litter-bags + NIRS	Gillon *et al.* (1999)

5.8 m^2, respectively. Leaf area index (LAI) of the stand exhibited important seasonal variations, with maximum value (1.6) at the end of the rainy season, and minimum value (0.98) at the end of the dry season.

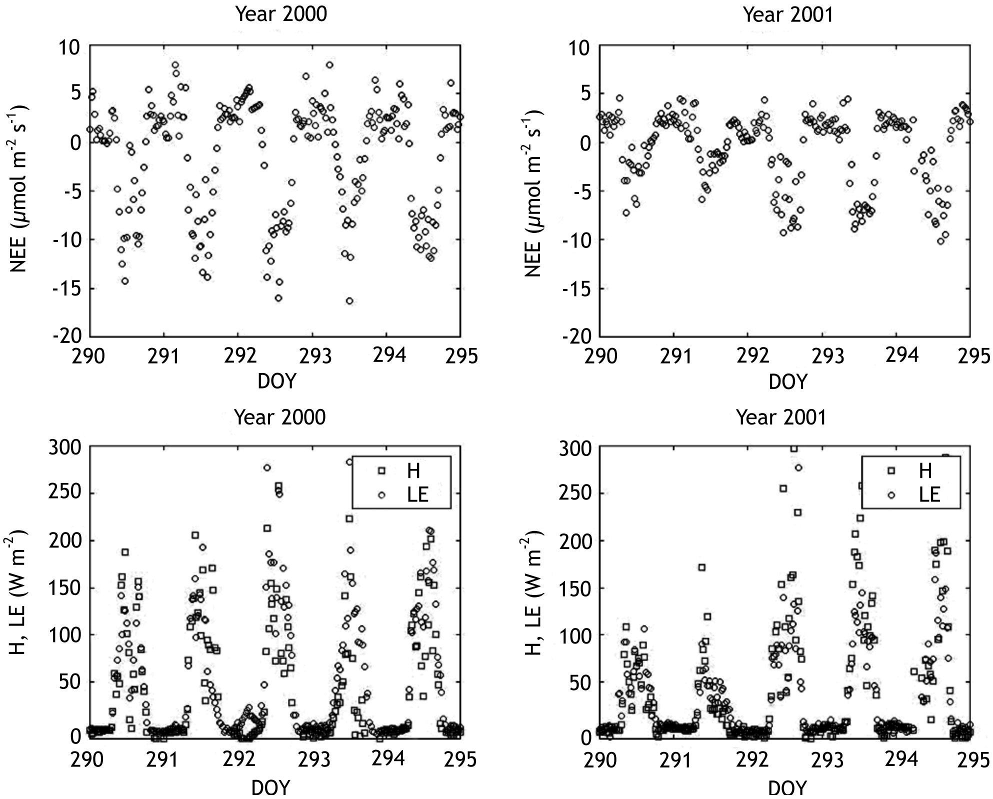
Flux measurements are obtained from a three-dimensional sonic anemometer (Sonic Young 8100) and a closed path Licor 6262 CO_2/H_2O analyser, positioned at 22 m above ground level, on a tower erected in the middle of the stand. Meteorological variables (precipitation, air temperature and relative humidity, net and global radiation, wind speed) are also measured (Table 1). Other measurements on this stand include sap flow measurements (8 trees), soil temperature and water content profiles, litter fall, litter decomposition and soil respiration profiles (Table 1). The parameters obtained on this stand will be used to estimate carbon sequestration, and to validate process-based model of water and CO_2 exchanges, tree growth and soil respiration.

Results

Some early results are presented below.

Eddy correlation measurements started at the end of the dry season of year 2000 (end of September 2000). Daily minima of Net Ecosystem Exchanges (NEE) reached values around -20 mmol m^{-2} s^{-1} during the rainy season, and -10 mmol m^{-2} s^{-1} during the dry season. Due to an unusual prolongation of the dry season, CO_2 fluxes in October 2001 were lower than in October 2000 (Fig. 2). Most of the diurnal variations in NEE were explained by those of incoming photosynthetic active radiation (PAR). Daily values of NEE varied from around 0 g C m^{-2} day^{-1} at the end of the dry season down to around -4 g C m^{-2} day^{-1} during the rainy season, and were strongly correlated with both the daily incoming PAR, and the daily evapotranspiration estimated from eddy correlation measurements of latent heat flux (LE).

Figure 2. Net carbon ecosystem exchange (NEE), sensible heat fluxes (H), and latent heat fluxes (LE), measured by eddy correlation at the 'Hinda' site from day of year (DOY) 290 to DOY 295 in 2000 and 2001

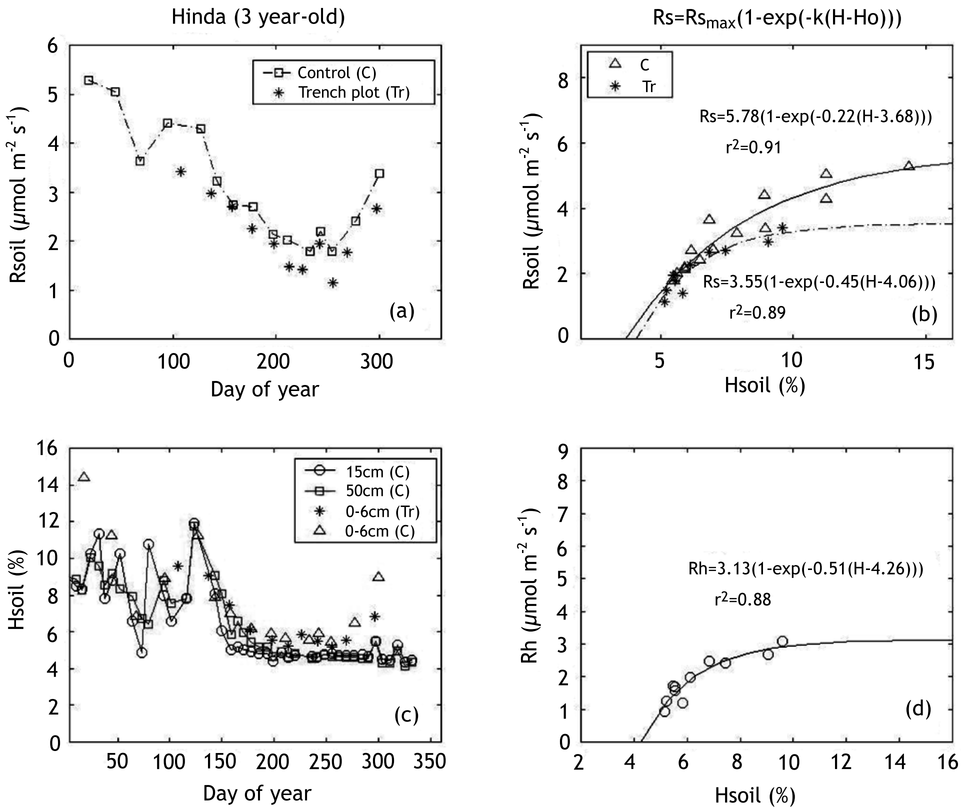


Soil respiration showed a marked seasonal pattern, with maximum values (around 5.3 mmol m^{-2} s^{-1}) during the wet season, and minimum values (around 1.5 mmol m^{-2} s^{-1}) at the end of the dry season. (Fig. 3a): this pattern was mostly explained by the strong correlations obtained between surface (0-5 cm) soil water content and soil CO_2 effluxes (Fig. 3b,d). This soil moisture effect on soil respiration is easily described by a 3-parameter equation:

$$R_s = R_{smax}\{1\text{-}\exp[-k(H\text{-}H_0)]\}$$

where R_{smax} is the soil respiration for high soil water content, and H_0 is the soil moisture for which soil respiration tends to zero. The contribution of root respiration to total soil respiration was estimated by comparing soil CO_2 effluxes obtained from trenched plots to effluxes obtained from the main plot (Fig. 3a). On average, root respiration accounted for 27% of total soil CO_2 efflux, while the heterotrophic component (Rh) accounted for 73% of total soil respiration. For nights with low wind speed, ecosystem respiration could not be directly estimated from EC measurements of NEE, due to CO_2 storage in the air layer from the soil surface to the height at which EC measurements are obtained. As for soil respiration, ecosystem respiration obtained for night with sufficient wind speed showed a marked seasonal pattern, with maximum values obtained during the wet season, and minimum values obtained at the end of the dry season.

Figure 3. The seasonal dynamic of soil CO_2 efflux on trenched plots (Tr), and on the control plot (C) (a), and of soil volumetric water content (c), at the Hinda site; Relationship between soil CO_2 effluxes and soil water content (b), and between heterotrophic soil respiration (Rh) and soil volumetric water content (d)



Discussion and Conclusions

Carbon sequestration in clonal eucalypt stands in the Congo is being estimated using: (1) carbon stocks measurements over a chronosequence; and (2) continuous, multi-year measurements of carbon exchanges with an eddy correlation system. The first results obtained in a 3-year-old stand have confirmed the major role played by ecosystem respiration in the annual carbon balance of these plantations: more than half of the gross carbon gain (GPP=NEE+Re) was lost through ecosystem respiration. On this 3-year-old stand daily EC estimates of carbon sequestration varied between 0 to 4 g C day^{-1}, depending on soil water status and daily incoming PAR. Fine root production data are being processed to estimate litter production by roots (L_R). This information, together with measurements of above- and belowground living biomass increments (G_A, G_B), and litter production by aerial compartment (L_A), will be used to estimate NPP ($NPP=G_A+G_B+L_A+L_R$), and net carbon gain (NEP=NPP-Rh), that will be compared to the annual net carbon gain estimated by eddy correlation. Other results obtained in this experiment (water and energy fluxes, LAI measurements, etc.) are being used to develop and validate models that simulate the carbon, water and energy budgets of these plantations.

References

Aubinet, A. *et al.* 2000. Estimates of the annual net carbon and water exchange of forests: the Euroflux methodology. Advances in Ecological Research 30:113-175.

Berbigier, P., Bonnefond, J-M. and P. Mellmann. 2001. CO_2 and water vapour fluxes for 2 years above Euroflux forest site. Agriculture and Forestry Meteorology 108:183-197.

Epron, D., Farque, L., Lucot, E. and P-M. Badot. 1999. Soil CO_2 efflux in a beech forest: the contribution of root respiration. Annales Science Forestière 56:289-295.

Gillon, D., Joffre, R. and A. Ibrahima. 1999. Can litter decomposability be predicted by near infrared reflectance spectroscopy? Ecology 80:175-186.

Granier, A. 1985. Une nouvelle méthode pour la mesure du flux de sève dans les troncs des arbres. Annales Science Forestière 42:193-200.

Jourdan, C. 1995. Modélisation de l'architecture et du développement du système racinaire du palmier à huile (*Elaeis guineensis* Jacq.). Académie de Montpellier, Université Montpellier II, Montpellier, France. 241p.

Parton, W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Journal of Soil Science Society of America 51:1173-1179.