

Soil carbon balance in a clonal Eucalyptus plantation in Congo: effects of logging on carbon inputs and soil CO₂ efflux

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Abstract

Soil CO₂ efflux was measured in clear-cut and intact plots in order to quantify the impact of harvest on soil respiration in an intensively managed Eucalyptus plantation, and to evaluate the increase in heterotrophic component of soil respiration because of the decomposition of harvest residues. Soil CO₂ effluxes showed a pronounced seasonal trend, which was well related to the pattern of precipitation and soil water content and were always significantly lower in the clear-cut plots than in the intact plots. On an annual basis, soil respiration represented 1.57 and 0.91 kg_C m⁻² yr⁻¹ in intact and clear-cut plots, respectively. During the first year following harvest, residues have lost 0.79 kg_C m⁻² yr⁻¹. Our estimate of heterotrophic respiration was calculated assuming that it was similar to soil respiration in the clear-cut area except that the decomposition of residues did not occur, and it was further corrected for differences in soil water content between intact and clear-cut plots and for the cessation of leaf and fine root turnover in clear cut. Heterotrophic respiration in clear-cut plots was estimated at 1.18 kg_C m⁻² yr⁻¹ whereas it was only 0.65 kg_C m⁻² yr⁻¹ in intact plots (41% of soil respiration). Assumptions and uncertainties with these calculations are discussed.

Keywords: carbon budget, clear-cut, decomposition, eucalyptus, forest management, litterfall, soil respiration

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Introduction

Stabilizing greenhouse gas concentration is a great challenge for next decades and forest ecosystems might play a role in mitigating the rise of atmospheric CO₂ concentrations (Houghton *et al.*, 1995). Within this context, there is a growing need of knowledge on the impact of perturbation and management practices on forest carbon balance. In tree plantations managed on short rotations, where aboveground biomass is frequently removed and transformed into wood products with short lifetimes (mainly paper pulp and charcoal), soil is the only compartment for durable carbon sequestration and, therefore, requires a particular attention.

Carbon sequestration in soils of tree plantations results from the difference between carbon inputs from litterfall, root turnover and residues left at logging stage, and carbon losses by heterotrophic respiration, and by dissolved organic carbon transport with water flow (Dewar & Cannell, 1992; Curtis *et al.*, 2002). The release of harvest residues in managed forests will increase aboveground amounts of dead organic matter and very likely also organic carbon in soil (Mund, 2004). Heterotrophic respiration is the component of soil carbon efflux which is associated with the mineralization by soil microorganisms of soil organic matter and of aboveground and belowground litter and detritus (Bowden *et al.*, 1993; Boone *et al.*, 1998; Epron *et al.*, 1999b; Epron *et al.*, 2001). Forest floor of northern hardwood stands are known to lose carbon for several years after clear-cutting (Covington, 1981), but it is still under

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debate whether this carbon has been released in the atmosphere as CO₂ and if it has been transferred in the mineral soil (Yanai *et al.*, 2003). The strength and the duration of the source would mainly depend on species, climate and soil properties and elapsed time from exploitation to replantation, but it would also depend on forestry practice like residue management and soil preparation for afforestation (Johnson & Curtis, 2001).

Logging is, therefore, a key step in plantation management and a better understanding of its impact on the soil carbon budget is needed. Clear-cuttings of forest plantations have shown conflicting effects on soil CO₂ efflux (Edwards & Ross-Todd, 1983, Ewel *et al.*, 1987a; Weber, 1990; Toland & Zak, 1994; Marra & Edmonds, 1996; Lytle & Cronan, 1998, Striegl & Wickland, 1998). Soil CO₂ efflux is thought to be affected in many ways after clear-cutting. Soil temperature is frequently increased since more radiation is reaching the ground (Witkamp, 1971; Marra & Edmonds, 1996). Soil water content can be either reduced by higher evaporation or increased because of suppressed transpiration. Tree removal is thought to decrease the autotrophic component of soil CO₂ efflux (i.e. root and rhizospheric respiration after a variable time lag (Nakane *et al.*, 1983)). The heterotrophic component would increase depending on the amounts and the decomposition rates of residues left on and in the soil. Additional disturbances that may be caused by vehicle traffic or slash burning for instance would also alter soil CO₂ efflux.

Up to now, most studies on the impact of forest clear-cutting on soil carbon budget have dealt with coniferous plantations under temperate or boreal climate (Lytle & Cronan, 1998; Striegl & Wickland, 1998), while little information is available on changes in soil carbon efflux following harvest in tropical plantations, despite their relevance to the 'Clean Development Mechanism' of the Kyoto protocol. A metaanalysis indicates that changes from pasture or native forest to plantation lead to a decrease in soil carbon, but the effect depends on species and site quality (Guo & Gifford, 2002). Soil respiration is less limited by unfavourable temperature in tropical ecosystem than in temperate or boreal forests (Epron *et al.*, 2004b) and residues are thought to be decomposed more rapidly in warm sites than in cool sites (Johnson & Curtis, 2001). In addition, root turnover increases from boreal to tropical zone for a given functional type (Gill & Jackson, 2000). In Hawaii, Bashkin & Binkley (1998) reported no change in soil carbon following afforestation of sugarcane fields with *Eucalyptus saligna*, but growing *Eucalyptus* plantations over tropical savannah in Brazil has shown contrasting effects on soil organic carbon after the first rotation (Zinn *et al.*, 2002). In addition to previous land use, the ability of *Eucalyptus* plantations to sequester carbon into soil in the long

term would also depend on the effects of clear-cutting on their soil carbon budget. *Eucalyptus* plantations account for 25% of tropical plantations and cover about 1.5×10^5 km². In the past 25 years, 430 km² of clonal *Eucalyptus* plantations have been established in the littoral savannas of Congo. They are intensively managed for pulpwood production with short rotations (about 6–9 years).

The objectives of this study were first to quantify the impact of harvest on soil CO₂ efflux in an intensively managed *Eucalyptus* plantation, and to assess the increase in heterotrophic component of soil respiration because of the decomposition of harvest residues. Soil CO₂ efflux, soil temperature and soil water content were measured in clear-cut and intact plots within a mature stand, and the contribution of residue decomposition to soil CO₂ efflux was evaluated from biometric estimates of harvest residues and their rate of decomposition in litter bags.

Methods

Study site

The *Eucalyptus* plantation zone covers about 430 km² along the Atlantic coast in the Pointe Noire region in Republic of Congo. The mean annual air humidity and air temperature are high (85% and 25 °C) with low seasonal variations (about 2% and 5 °C, respectively). Annual precipitation (1998–2003) averages 1400 mm with a dry season between May and September. The stand (Kondi) was located on a plateau (4.35°S, 11.75°E, 100 m elevation, 0.15 km²). The deep sandy soils with poor water retention and low ionic content are arenosol according to classification adopted by the Food and Agriculture Organization of the United Nations, and they lay on a geological bedrock composed of thick detritic layers of continental origin dated from plio-pleistocene (Jamet & Rieffel, 1976; Laclau *et al.*, 2000). Native vegetation is a savannah dominated by the Poaceae *Loudetia arundinacea* (Hochst.) Stend.

The 9-year-old stand (18 ha) was planted in January 1992 on a burned savannah with the clone PF1 1–41 at a stocking of 530 trees ha⁻¹. This clone was the most extensively planted one decade ago (see Bouillet *et al.*, 2002 for details on this clone). Before harvesting, mean dominant height was 31.5 m, mean diameter at breast height was 21.1 cm and stand volume was 210 m³ ha⁻¹.

In March 2001, most of the stand area had been clear-cut and replanted thereafter in May 2001 with a more productive clone (UG 18–52) at a higher stocking (800 trees ha⁻¹). This artificial hybrid *E. urophylla* ST Blake × *E. grandis* Hill ex Maiden is now increasingly used for afforestation in this area. Stumps were

chemically killed to prevent regrowth using glyphosate. Herbaceous understorey vegetation was kept sparse by chemical weeding with glyphosate. Only debarked, commercial-sized boles (diameter >6 cm) and coarse branches (diameter >2 cm) were removed from the clear-cut area for pulpwood (boles) or charcoal production (coarse branches). Leaves, barks, bole tops and small branches were left on the ground, following the silvicultural practice of the plantation's manager. A small part of the stand (10% of initial area, 1.8 ha) was kept intact and used as control. Care was taken when assigning the uncut area that it was representative of the whole stand on a tree size basis.

Two plots were first delimited within the intact part of the stand and three additional plots were delimited within the clear-cut part of the stand after harvest and plantation. The distance between two adjacent plots was less than 120 m. Each plot potentially contained 25 trees (5 × 5) and covered four interrows (320 m²). The study was not truly replicated since the five plots were in the same stand and the two control plots in the same uncut area. Therefore, the plots were not randomly assigned within the stand but they were randomly assigned within their respective areas.

Soil CO₂ efflux

Soil CO₂ efflux was measured using the Li 6000–09 soil respiration chamber (LiCor Inc., Lincoln, NE, USA) in which the increase of the CO₂ concentration was recorded with the Li 6250 infrared gas analyser (LiCor Inc.) as already described (Epron *et al.*, 1999a). The CO₂ concentration within the soil respiration chamber was dropped 15 μmol mol⁻¹ below ambient, and the increase in the CO₂ concentration was recorded until it increased by 30 μmol mol⁻¹.

Soil temperature was monitored simultaneously with soil CO₂ efflux using a copper/constantan thermocouple penetration probe (Li6000–09 TC, LiCor Inc.) inserted in the soil to a depth of 10 cm in the vicinity of the soil respiration chamber. Soil temperature data are lacking for 3 days because of sensor dysfunction. The volumetric soil water content in the topsoil layer (0–6 cm) was monitored with a Theta Probe (ML2, Delta-T Device Ltd, Cambridge, UK) just after respiration measurement at the chamber location. The theta probe has been calibrated for this soil. For a subset of measurements, probe output was first read then a soil core (6 cm depth) was collected and used for gravimetric determination of soil water content ($n = 76$, $R^2 = 0.89$).

For each day of measurement, soil CO₂ efflux, temperature and water content were recorded at 12 locations within each plot, leading to a total of 24 measurements over the intact plots and 36 measure-

ments over the clear-cut plots per day. Soil CO₂ efflux were recorded between January 2001 and February 2002 in intact plots (18 dates of measurements) and between May 2001 and February 2002 in clear-cut plots (15 days of measurements).

Aboveground and belowground biomass at harvest

Before harvest, below- and aboveground biomasses of the PF1-41 stand were estimated from a stand inventory by means of allometric relationships between biomass of tree compartments and tree height and diameter in order to quantify the amounts of residues left on or in the soil at harvest. We used age-related equations that have been established for this *Eucalyptus* clone by Saint André *et al.* (2005) using six stands aged between 11 and 135 months for model calibration (72 trees) and nine stands aged between 12 and 109 months for model validation (122 trees). Individual component equations were of the general form of $y_{im} = a_m + b_m X_i^{c_m} + \varepsilon_{i,m}$, where $y_{i,m}$ was the dry matter of tree i for a given component m ; X_i was the independent variable (either d or d^2h ; d and h are, respectively, the diameter at breast height and the total tree height); a_m , b_m and c_m are the age-related parameters for each component; $\varepsilon_{i,m}$ are the residual variations not explained by the models. This error component $\varepsilon_{i,m}$ was supposed to be proportional to X^k : $E[\varepsilon_{i,m}^2] = \sigma_{i,m}^2 = \sigma_m^2 X_i^{2k}$ (where σ^2 is the residual variance of the weighted model). The system of equations was fitted using the SUR regression (proc model of SAS software, package ETS; SAS, 1990) which fits component equations all together and takes the cross-correlation between component into account (Parresol, 2001). When applied to a stand inventory, the system of equations accounted for the correlation between tree compartments and allowed simulating both the mean and the standard deviation of both aboveground (leaves, branches, trunk wood, bark and stumps) and belowground (coarse, medium and fine roots) biomasses (Saint André *et al.*, 2005). In order to check that our estimations of predicted aboveground biomasses were accurate for the stand under study, it was decided to use 10 trees that have been harvested at the time of clear-cutting. Measured biomasses were compared with the estimated ones and no major deviation was identified: measured points were mostly included in the confidence interval of estimates at 95% level of confidence except for bark and leaves where five trees among the 10 were outside the confidence interval. The bias for leaves may originate from the date of tree felling (seasonal effect that is not accounted for in the global model), whereas the bias for bark remained unexplained (more 9-year-old stands of various growing conditions should be felled for a better understanding).

Because these two compartments account for a large part of the biomass left on the soil after harvesting, we refitted the equations of these two compartments using the 10 felled trees in order to get unbiased estimates of stand biomasses at harvesting for these two compartments.

Residue decomposition

After harvest, rates of residue decomposition were followed in litter bags. Six kinds of residues (leaf, bark, small branches, and coarse, medium and fine roots) were obtained from logged trees and stored in a cold room (4 °C) until being processed. Residue samples were first wet weighted and then placed in litter bags (2 mm mesh size), and wet mass were subsequently corrected for the water content to get the initial dry mass of the samples. We used fresh mass/dry mass ratio obtained on aliquots that were first wet-weighted, oven-dried and then dry weighted. Litter bags were laid over the ground for aboveground residues, and buried at 10 cm depth for belowground residues. For each kind of residues, 10 litter bags were recovered after 1 year of decomposition in April 2002. The remaining materials were oven-dried at 65 °C till constant weight and weighed. Ash contents were determined after combustion of pooled samples in a muffle furnace at 450 °C for 6 h, and used to correct the dry mass for soil contamination (Misra, 1994).

Aboveground detritus and litterfall

In February 2002, 11 months after clear-cutting, the amount of litter and residues lying on the forest floor was estimated in both the intact and the clear-cut stand from samples collected on 18 locations within a 0.25 m² frame. Samples were sorted into leaf, bark, woody debris and undetermined debris and oven-dried at 65 °C till constant weight and weighed.

Aboveground litterfall was recorded using 16 litter traps and litter collected every week in these traps was sorted into leaf, bark and branch, oven-dried and weighed. Fine root litter production had not been measured in this study but it was assumed that fine root turnover was the same as the leaf turnover (White *et al.*, 2000). Fine root biomass was estimated from a stand inventory by means of allometric relationships. These relationships have been validated on nine stands including the one we have studied (Saint André *et al.*, 2005).

Soil carbon balance

Cumulative soil carbon effluxes between January 2001 and February 2002 in intact plots and between May

2001 and February 2002 in clear-cut plots were calculated by weighting daily averages by half the time elapsed between the two adjacent days of measurement. These cumulative effluxes were then used to estimate an annual soil respiration for both intact and clear-cut areas (R_{SI} and R_{SCC}).

In order to calculate the contribution of residue decomposition to soil respiration, it was assumed that 80% of carbon was lost as CO₂ during the decomposition process (microbial efficiency of 0.2, see 'Discussion'). Two different fluxes were calculated in the clear-cut area from residue decomposition: respiratory carbon loss from leaf, and root decomposition that were already included in measured soil CO₂ efflux (R_{Ra}), and respiratory carbon loss from stump, bark and branch decomposition that were not already included in measured soil CO₂ efflux (R_{Rb}) because of their size (they were avoided during soil respiration measurements because their size was not compatible with chamber dimensions). Assuming that autotrophic respiration was negligible in the replanted area during the first 9 months, heterotrophic respiration in this area (R_{HCC}) was calculated by adding respiratory carbon loss from stump, bark and branches decomposition to soil respiration (R_{SCC}):

$$R_{HCC} = R_{SCC} + R_{Rb}. \quad (1)$$

The assumption that autotrophic respiration was negligible in the clear-cut area was supported by the fact that roots of the previous stand were chemically killed and new root growth was very limited during the first year following planting (Thongo Mbou, unpublished data).

Heterotrophic respiration in intact area (R_{HI}) was assumed to be similar to those in the clear-cut area except that the decomposition of residues did not occur:

$$R_{HI} = R_{HCC} - (R_{Ra} + R_{Rb}) = R_{SCC} - R_{Ra}. \quad (2)$$

Because of higher turnover rates of leaves and fine roots in our site, we have tried to constraint the error because of neglecting cessation in aboveground and belowground litter inputs in the clear-cut area whereas it still occurred in the intact area by considering the amount of carbon released by leaf and fine root decomposition during 1 year in the control plots (R_{Rc}):

$$R_{HI} = R_{SCC} - R_{Ra} + R_{Rc}. \quad (3)$$

We then corrected our estimation of R_{HI} by estimating R_{SCC} at the soil water content measured in intact plots to account for differences in soil water content between intact and clear-cut plots (Epron *et al.*, 1999b). For that, we fitted a second-order polynomial on the relationship between soil CO₂ efflux and soil water content in clear-cut plots ($r^2 = 0.91$), and ran this empirical model using soil water content of the control plots to calculate a

corrected value for R_{SCC} (R'_{SCC}):

$$R'_{HI} = R'_{SCC} - R_{Ra} + R_{Rc}. \quad (4)$$

Finally, autotrophic respiration in intact area (R_{AI}) was calculated by subtracting heterotrophic respiration from soil respiration (R_{SI}):

$$R_{AI} = R_{SI} - R'_{HI}. \quad (5)$$

Carbon content in litter and residues was not determined in this study and it was set to 0.5 g g^{-1} for calculation. A similar assumption was made by Keith *et al.* (1997) for *E. pauciflora* in Australia and by Giardina & Ryan (2002) for *E. saligna* in Hawai.

Data analyses

Analyses of variance were conducted to assess the difference in soil respiration, temperature and water content between intact and clear-cut areas (treatments) with plots nested within treatments for each day of measurements (R software, www.r-project.org). Student's *t*-tests were used to test for significant differences in the amount of aboveground detritus between intact and clear-cut areas. Means are given with their standard deviations. Significance for statistical analyses was accepted at α lower than 0.05.

Results

Soil CO_2 efflux

Year 2001 was rather dry (rainfall of about 1170 mm) when compared with a 6-year average value ($1410 \pm 190 \text{ mm}$ between 1998 and 2003) and the dry season lasted from early June until November without precipitation. Soil temperatures ranged between 25°C in June 2001 and 32°C in December 2002 and were slightly higher in clear-cut plots than in intact plots. In contrast, soil water contents were significantly enhanced in the clear-cut plots except during the dry months when differences were not significant (Fig. 1).

Soil CO_2 efflux showed a pronounced seasonal trend that was well related to the pattern of precipitation and soil water content (Fig. 2). In the intact plots, soil CO_2 efflux decreased from $8.0 \mu\text{mol m}^{-2} \text{ s}^{-1}$ in February 2001 to about $2 \mu\text{mol m}^{-2} \text{ s}^{-1}$ in August 2001 when soil water content dropped below 4% and remained low until the new rainy season in November. Then, soil CO_2 efflux increased again, up to $8.3 \mu\text{mol m}^{-2} \text{ s}^{-1}$ in January 2002.

Measurements in clear-cut plots began in May 2001, after harvest and plantation, at the end of the rainy season. There was no pretreatment data for clear-cut plots. However, care was taken when assigning the uncut area that it was representative of the whole stand on a tree size basis. Soil CO_2 effluxes were always significantly lower (Table 1) in the clear-cut plots than in the intact plots (difference of about $1.5 \mu\text{mol m}^{-2} \text{ s}^{-1}$

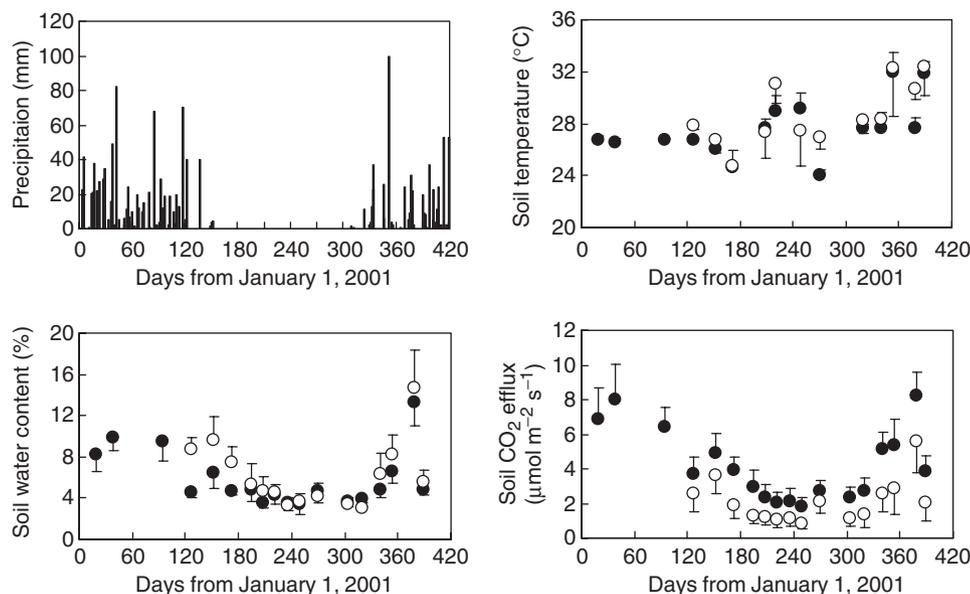


Fig. 1 Seasonal courses of precipitation, mean soil temperature at 10 cm depth, mean soil volumetric water content in the top 6 cm and mean soil CO_2 efflux in both intact (closed symbols) and clear-cut plots (open symbols). Vertical bars, when larger than the symbol, indicate standard deviations. In March 2001, most of the stand area was clear-cut and replanted thereafter in May 2001 (days of year 90–120).

on average, except on day 270). As plot effects within treatments were not significant except on three occasions (nested ANOVA, Table 1), we assumed that differences between clear-cut and control plots were caused by the treatment rather than due to spatial variability.

Annual soil respiration was estimated at $1.57 \text{ kg}_C \text{ m}^{-2} \text{ yr}^{-1}$ in intact plots in 2001. Cumulative soil carbon effluxes between May 2001 and February 2002 were 0.99 and $0.57 \text{ kg}_C \text{ m}^{-2}$ in intact and clear-cut plots, respectively. Clear-cut plots released 42% less carbon than intact plots during this 9-month period. Annual soil respiration in clear-cut plots during the year following exploitation ($0.91 \text{ kg}_C \text{ m}^{-2} \text{ yr}^{-1}$) was estimated by applying this ratio to the annual soil respiration estimated for the intact plots.

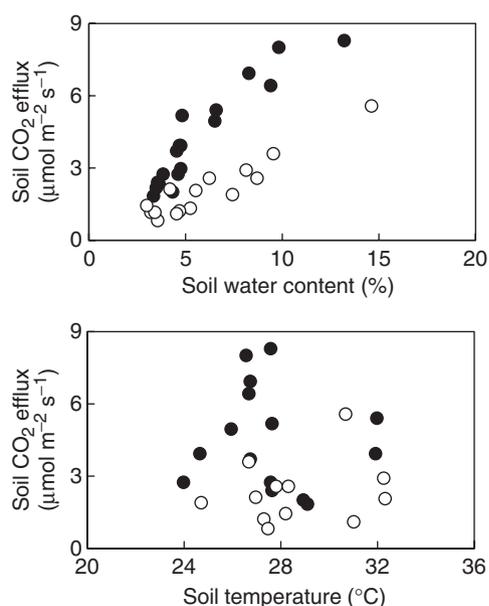


Fig. 2 Relationship between mean soil CO_2 efflux and mean soil volumetric water content in the top 6 cm, or mean soil temperature at a depth of 10 cm, in both intact (closed symbols) and clear-cut plots (open symbols).

Table 2 Amounts of residues left at logging stage in clear-cut plots, relative mass remaining (RMR) in litter bags after 1 year, and estimated mass losses after 1 year

	Amount ($\text{kg}_{\text{DM}} \text{ m}^{-2}$)	RMR ($\text{kg}_{\text{DM}} \text{ kg}_{\text{DM}}^{-1}$)	Mass loss ($\text{kg}_{\text{DM}} \text{ m}^{-2} \text{ yr}^{-1}$)
Leaf	0.24 ± 0.01	0.42 ± 0.02	0.14 ± 0.01
Bark	0.56 ± 0.01	0.63 ± 0.14	0.21 ± 0.08
Branch	0.30 ± 0.04	0.58 ± 0.03	0.13 ± 0.02
Stump	0.84 ± 0.06	–	0.35^*
Coarse root (>10 mm)	1.13 ± 0.05	0.58 ± 0.07	0.47 ± 0.08
Medium root (5–10 mm)	0.07 ± 0.01	0.36 ± 0.05	0.04 ± 0.01
Fine root (<5 mm)	0.33 ± 0.02	0.25 ± 0.05	0.25 ± 0.02

Mass losses were calculated by multiplying the amounts of residues by $(1 - \text{RMR})$.

*Stump decomposition was not studied. RMR for coarse roots were used to estimate mass loss.

Litterfall and residues

The amounts of residues left on or in the soil at harvest were estimated by means of allometric relationships between biomass of tree compartments and tree height and diameter (Saint André *et al.*, 2005). The amount of leaves, bark and branches that was left on the ground during harvest represented $1.10 \text{ kg}_{\text{DM}} \text{ m}^{-2}$ and the amounts of roots left into the soil was $1.53 \text{ kg}_{\text{DM}} \text{ m}^{-2}$. Stumps represented $0.84 \text{ kg}_{\text{DM}} \text{ m}^{-2}$ (Table 2). The residues accounted for 24% of the previous standing biomass ($14.39 \text{ kg}_{\text{DM}} \text{ m}^{-2}$).

Table 1 Differences in mean soil CO_2 efflux ($\mu\text{mol m}^{-2} \text{ s}^{-1}$) between intact and clear-cut plots and *F* statistic values of nested ANOVA for testing differences between treatments, and between plots within treatments

Day of year	Differences Uncut–clear-cut	<i>F</i> statistic values	
		Treatments	Plots (in treatment)
127	1.12	16.30***	3.03*
152	1.34	20.75***	1.35
172	2.04	107.08***	1.65
194	1.68	75.32***	1.73
208	1.18	52.80***	0.5
221	0.93	39.85***	0.94
236	1.02	44.23***	4.63**
249	1.01	70.65***	1.38
270	0.65	13.95***	1.52
303	1.18	63.59***	0.59
320	1.35	39.77***	1.21
340	2.61	120.46***	7.17***
354	2.50	33.99***	0.82
379	2.68	39.58***	2.34
389	1.84	41.12***	0.41

F values significantly higher than 1 were followed by

* $\alpha < 0.05$,

** $\alpha < 0.01$ and

*** $\alpha < 0.001$.

Table 3 Annual litterfall in intact plots and amounts of aboveground detritus in both intact and clear-cut plots in February 2002

	Litterfall ($\text{kg}_{\text{DM}} \text{m}^{-2} \text{yr}^{-1}$)	Amounts on soil ($\text{kg}_{\text{DM}} \text{m}^{-2}$)	
		Intact	Clear-cut
Leaf	0.42 ± 0.09	0.35 ± 0.02	$0.05 \pm 0.01^{***}$
Bark	0.10 ± 0.01	0.19 ± 0.05	$0.50 \pm 0.04^{**}$
Wood	0.15 ± 0.04	0.57 ± 0.07	$1.13 \pm 0.07^{**}$
Other	–	1.09 ± 0.05	$1.44 \pm 0.03^{***}$
Total		2.20 ± 0.14	$3.12 \pm 0.23^{**}$

All differences in the amount of aboveground detritus between intact and clear-cut areas were significant at either

**0.01 or

***0.001.

Decomposition of logging residues was followed in litter bags. One year after harvest, there were strong differences of mass remaining between the different kinds of plant materials (Table 2). Bark was the least decomposable material whereas fine roots decomposed very rapidly. During the first year following harvest, residues had lost 46% of their initial mass.

Annual leaf litterfall in intact plots was twice as high as the amount of leaves left on soil at logging stage ($0.42 \text{ kg}_{\text{DM}} \text{m}^{-2} \text{yr}^{-1}$ vs. $0.24 \text{ kg}_{\text{DM}} \text{m}^{-2}$), but bark and branches left on soil after harvest were, respectively, fivefold and twofold higher than annual litterfall (Tables 2 and 3). Assuming that fine root turnover was similar as the leaf turnover (1.75 yr^{-1}), annual production of fine root litter in intact plots was estimated at $0.58 \text{ kg}_{\text{DM}} \text{m}^{-2} \text{yr}^{-1}$.

Masses of aboveground detritus accumulated on the forest floor 1 year after harvest in both clear-cut and intact plots are given in Table 3. Amounts of leaf detritus were significantly lower in the clear-cut area than in the intact one whereas the opposite was observed for other types of detritus.

Soil carbon balance

During the first year following harvest, residues have lost $1.58 \text{ kg}_{\text{DM}} \text{m}^{-2} \text{yr}^{-1}$ ($0.79 \text{ kg}_{\text{C}} \text{m}^{-2} \text{yr}^{-1}$). The contribution of residue decomposition to surface carbon efflux was, therefore, estimated at $0.63 \text{ kg}_{\text{C}} \text{m}^{-2} \text{yr}^{-1}$ assuming that 80% of the carbon lost during the decomposition process was lost as CO_2 and carbon content in litter and residues of $0.5 \text{ g}_{\text{C}} \text{g}_{\text{DM}}^{-1}$. CO_2 effluxes coming from leaf and root decomposition that were already included in measured soil CO_2 efflux (R_{Ra}) accounted for 57% of total contribution of residue decomposition, and CO_2 efflux coming from stump, bark and branches decomposition that were not already included in mea-

Table 4 Soil carbon fluxes ($\text{kg}_{\text{C}} \text{m}^{-2} \text{yr}^{-1}$) in both intact and clear-cut plots

	Intact (i)	Clear-cut (cc)
Heterotrophic respiration (R_{H})	0.55^* 0.75^\ddagger 0.65^\S	1.18^\ddagger
Autotrophic respiration (R_{A})	0.92^\parallel	–
Annual soil carbon efflux (R_{S})	1.57	0.91

* R_{HI} , uncorrected for lack of fine root and leaf turnover in clear-cut plots and for difference in soil water content between intact and clear-cut plots, Eqn (2).

‡ Eqn (5).

§ R_{HCC} , including respiratory carbon loss from stump, bark and branch decomposition that were not already included in measured soil CO_2 efflux because of their size, Eqn (1).

$^\parallel$ R_{HIV} , corrected for lack of fine root and leaf turnover in clear-cut plots, Eqn (3).

$^\parallel$ R_{HIV} , corrected for lack of fine root and leaf turnover in clear-cut plots and for difference in soil water content between intact and clear-cut plots, Eqn (4).

asured soil CO_2 efflux (R_{Rb}) accounted for 43%. Assuming that autotrophic respiration was negligible in the replanted area during the first 9 months, heterotrophic respiration in this area (R_{HCC}) was then estimated at $1.18 \text{ kg}_{\text{C}} \text{m}^{-2} \text{yr}^{-1}$ (Eqn (1), Table 4). Assuming that heterotrophic respiration in intact area (R_{HI}) was similar to those in the clear-cut area except that the decomposition of residues did not occur, it accounted for $0.55 \text{ kg}_{\text{C}} \text{m}^{-2} \text{yr}^{-1}$, Eqn (2). Additional corrections accounting for the cessation of leaf and fine root turnover in clear-cut plots, Eqn (3), and for differences in soil water content between intact and clear-cut plots, Eqn (4), have opposite effects on the partitioning of soil respiration. When both corrections were applied, R_{HI} was estimated at $0.65 \text{ kg}_{\text{C}} \text{m}^{-2} \text{yr}^{-1}$ (41% of soil respiration). Thus, autotrophic respiration in intact area (R_{AI} , Eqn (5)) accounted for 59% of soil respiration ($0.92 \text{ kg}_{\text{C}} \text{m}^{-2} \text{yr}^{-1}$, Table 4).

Discussion

Our annual rate of soil respiration ($1.57 \text{ kg}_{\text{C}} \text{m}^{-2} \text{yr}^{-1}$) and aboveground litterfall ($0.34 \text{ kg}_{\text{C}} \text{m}^{-2} \text{yr}^{-1}$) were higher than those reported for mature *E. pauciflora* stand under cool temperate climate in Western Australia (0.66 – 0.71 and 0.25 – $0.28 \text{ m}^{-2} \text{yr}^{-1}$, respectively, Keith *et al.*, 1997). In contrast, Giardina & Ryan (2002) reported higher rates of soil respiration and aboveground litterfall than ours (1.61 – 2.51 and 0.38 – $0.47 \text{ kg}_{\text{C}} \text{m}^{-2} \text{yr}^{-1}$, respectively) for young *E. saligna* stands in Hawaii, but our site was dryer and less fertile. Indeed, temporal variation in soil respiration was

largely explained by soil water content in this area, as already observed (Epron *et al.*, 2004b). Then, the magnitude of annual soil carbon efflux might have been affected by the long dry season in 2001. Similar rates of soil respiration (Epron *et al.*, 2004b) and of aboveground litterfall (Bernhard-Reversat, 1993) were previously reported for nearby stands. Our estimate of annual soil respiration fell within the 95% confidence interval of predicted R_{SIC} from annual litterfall using the linear relationship derived from data from 12 young forests (Davidson *et al.*, 2002). As pointed out by Davidson *et al.* (2002), higher rates of soil respiration in young than in mature forests for a given aboveground litterfall reflected a greater carbon investment belowground.

Comparisons of soil respiration between clear-cut area or artificial gaps and intact, undisturbed area have frequently been used to separate autotrophic from heterotrophic respiration (Nakane *et al.*, 1983; Brumme, 1995; Nakane *et al.*, 1996; Stiegl & Wickland, 1998; Ohashi *et al.*, 2000). Clear-cut areas can be seen as large trenched plots with the same limitation than true trenched plots (i.e. uncertainties with residue decomposition pattern and difference in soil water content between clear-cut and undisturbed area; Epron *et al.*, 1999b). Heterotrophic respiration in intact area (R_{HI}) was first assumed to be similar to soil respiration in the clear-cut area except that the decomposition of residues did not occur. The additional heterotrophic respiration because of the decomposition of killed roots and leaves and bark left on soil in the clear-cut area was estimated ($0.36 \text{ kg}_C \text{ m}^{-2} \text{ yr}^{-1}$) and subtracted from soil respiration recorded in the clear-cut area ($0.91 \text{ kg}_C \text{ m}^{-2} \text{ yr}^{-1}$). Under this assumption, R_{HI} was $0.55 \text{ kg}_C \text{ m}^{-2} \text{ yr}^{-1}$. Cessation in aboveground and belowground litter inputs in the clear-cut area while it still occurred in the intact area would lead to an underestimate of R_{HI} . Nakane *et al.* (1983) discussed that it was negligible in a mature *Pinus densiflora* forest. We did not have enough information on the timing of belowground litter production to properly account for this bias. However, because of higher turnover rates of leaves and fine roots in our case, we have tried to constraint this error by considering the amount of carbon released by leaf and fine root decomposition during 1 year. The soil water content in the clear-cut area was higher than in the intact area during the wet season. R_{HI} might, therefore, be overestimated and we also attempted to constraint this error. We estimated soil CO_2 efflux in clear-cut plots at the soil water content measured in intact plots (Epron *et al.*, 1999b). Combining corrections for both soil water content and leaf and fine root turnover, R_{HI} was finally estimated at ($0.65 \text{ kg}_C \text{ m}^{-2} \text{ yr}^{-1}$). Another potential limitation of artificial gaps is an increase in soil temperature because of change in incoming global radiation, but it was not

significant in this study. Because root biomass was very low the year after planting in the clear-cut area (Thongo Mbou, unpublished data), our assumption that autotrophic respiration was negligible in the afforested clear-cut area would cause minor overestimation of both R_{HCC} and R_{HI} . Two additional assumptions have been made in our computations. First, fine root turnover was assumed to be similar to leaf turnover (White *et al.*, 2000). The high rate of fine root turnover we used is consistent with published values on *E. globulus* (Kätterer *et al.*, 1995) or other tropical forests (Gill & Jackson, 2000) and with preliminary results on nearby sites (Thongo Mbou, unpublished data). Second, it was assumed that 80% of carbon was lost as CO_2 during the decomposition process (i.e. a microbial efficiency of 0.2). *In situ* estimates of microbial efficiency are very scarce. Using ^{13}C depleted leaf litter, Ngao *et al.* (2005) reported a microbial efficiency of 0.2 for leaf decomposition in a temperate beech stand. This is smaller than the one assumed for carbon flow from plant residues in the CENTURY or in the G'DAY models (Parton *et al.*, 1987; Corbeels *et al.*, 2005) but similar to the one used in the Rothamsted turnover model (Jenkinson, 1990). Dewar (1991) used values ranging between 0.2 and 0.5 depending on the kind of residues. Assuming 0.4 rather than 0.2 for microbial efficiency only marginally affect our computation of R_{HCC} (less than 6%), and R_{HI} and R_{AI} (less than 2%) as previously mentioned (Silver *et al.*, 2005). Partitioning of autotrophic and heterotrophic respiration from trenching, clear-cutting or girdling experiments rely on the assumptions that changes in the rate of rhizodeposition or in the rate of nutrient and easily accessible carbon release from residue decomposition would not affect heterotrophic respiration by their impacts on microbial communities (priming effect). Putative effects of disturbances on relatively stable pools of soil organic matter are also neglected. As long as these assumptions cannot be verified, uncertainties in partitioning will remain.

Despite these uncertainties, the partitioning between an heterotrophic component and an autotrophic component (41% and 59%) fell within the 95% confidence interval of predicted R_A and R_H values from R_S using the nonlinear relationship derived from data from 54 forest sites (Bond-Lamberty *et al.*, 2004). Few data are actually available for tropical ecosystems, and especially tropical plantations. The low contribution of root respiration to soil CO_2 efflux that has been recently reported for two lowland tropical forests (24–35%, Silver *et al.*, 2005) contrasted with higher contribution reported for tropical plantations, and was associated to a high heterotrophic respiration because of a rapid rate of carbon turnover in litter and soil. The contribution of R_A increased with stand age in *Pinus elliottii* plantations,

from 51% in a 9-year-old stand to 62% in a 29-year-old stand (Ewel *et al.*, 1987b). The contribution of R_A varied spatially from 60% to 76% in an *Elaeis guineensis* plantation in Benin (Lamade *et al.*, 1996).

In our Eucalyptus stand, R_{HI} was slightly higher than aboveground and belowground annual litter inputs (0.65 against 0.62 kg_C m⁻² yr⁻¹), indicating that the soil of a 9-year-old plantation over savannah might be a weak source of carbon (0.03 kg_C m⁻² yr⁻¹). However, uncertainties in R_{HIC} and fine root turnover, and the fact that both fluxes are known to be prone to inter-annual variations (Pypker & Fredeen, 2002; Epron *et al.*, 2004a) precluded any definitive statement on the sign of this difference. Dividing litterfall by the amount of detritus indicated a low residence time of carbon aboveground (3.3 years). However, increase in stump and root biomasses as estimated from stand inventories also account for belowground carbon storage in these young plantations (0.08 kg_C m⁻² yr⁻¹), more than in a mature *E. pauciflora* stand in Australia (0.05–0.06 kg_C m⁻² yr⁻¹, Keith *et al.*, 1997) but less than in young *E. saligna* stands in Hawaii (0.21 kg_C m⁻² yr⁻¹, Giardiana & Ryan, 2002).

Soil respiration was lower in the clear-cut area than in the intact area (–42%). Similar decreases in soil respiration following harvest have been reported for temperate or boreal plantations (Edwards & Roos-Todd, 1983; Nakane *et al.*, 1983; Weber, 1990; Nakane *et al.*, 1996; Striegl & Wickland, 1998; Kolari *et al.* 2004), whereas others reported no change or an increase in soil respiration following harvest (Ewel *et al.*, 1987a; Toland & Zak, 1994; Marra & Edmonds, 1996; Mallik & Hu, 1997; Lytle & Cronan, 1998; Laporte *et al.*, 2003). This lower soil respiration in the clear-cut area reflected the high contribution of root respiration in this site before exploitation, and it indicated that the suppression of root respiration was not compensated by the respiration associated to the decomposition of the large amounts of residues left in and on the soil after harvest. It also suggested that the previous roots were efficiently killed by the chemical treatment applied to the stumps after harvest, and it is in agreement with low living root biomass 1 year after afforestation.

Heterotrophic respiration in the clear-cut area, including the contribution of residue decomposition (R_{HCC}), was strongly enhanced after harvest (+115%). Residue decomposition (including root) accounted for 53% of heterotrophic respiration in the clear-cut area. Indeed, a large amount of residue was left both in and on the soil, and exhibited high rates of decomposition. No attempt was made in this study to compare post-harvested soil carbon content with soil carbon content in intact plots because changes would have probably been small when compared with the stock at this time scale (Smith, 2004). Soil carbon content was estimated at

5.5 kg_C m⁻² in a nearby plantation at 80 cm depth (Epron *et al.*, 2004b). Because of high spatial variation in soil carbon content, any differences because of clear-cutting would have probably been not significant as frequently reported (Edward & Ross-Todd, 1983; Lee *et al.*, 2002). In addition, 54% of logging residues still remained in and on the soil 1 year after harvest. This is well illustrated by the higher amount of detritus aboveground in the clear-cut area than in the intact area (+42%), as already reported for a boreal *Pinus banksiana* forest where most residues were left on the ground (Howard *et al.*, 2004).

Net accumulation of carbon in plantation soils is dependent on the rate of decomposition processes and the inputs of carbon from litter and root turnover (Turner & Lambert, 2000). Despite the cessation of carbon inputs from litterfall, the inputs of residues were 46% higher than heterotrophic respiration in the clear-cut area during the first year (1.72 kg_C m⁻² vs. 1.18 kg_C m⁻² yr⁻¹). Soil in the clear-cut area might therefore act as a sink of carbon during the year following harvest. It was argued that the increase in carbon stock in and on soil after harvest is probably a short-term process and carbon stock will probably re-equilibrate to lower levels (Johnson & Curtis, 2001). Indeed, logging residues will of course be further decomposed the following years, but litter inputs from the re-established plantation will also rapidly recovered their initial values, within 2 or 3 years (Laclau *et al.*, 2000), counterbalancing the decomposition of logging residues. A similar conclusion was drawn for a boreal mixed-wood forest showing that carbon stock and flux into the forest floor was quickly recovered because of the rapid re-establishment of the vegetation cover (Lee *et al.*, 2002).

Our results suggest that the stock of carbon in and on the soil may slightly increase after each rotation when large amounts of residues are left at logging stage. These results agree with the conclusion of a meta-analysis of 73 studies showing that sawlog harvest, in contrast to whole tree harvest, caused an increase in soil carbon in the mineral soil especially for coniferous species (Johnson & Curtis, 2001). This was well predicted for *Populus* plantation in temperate area (Dewar & Cannell, 1992), but it still needs to be demonstrated in our Eucalypt plantation. It would depend on physical, chemical and biochemical abilities of soil to stabilize organic matter (Li *et al.*, 2005). Knowing what it will happen in the long term after several rotations with either tree replanting or tree pruning (coppice) is of major interest but would require carbon stock inventories along a chronosequence.

In conclusion, this study highlighted the importance of harvesting methods and residue managements for soil carbon sequestration. Inputs of high amounts of

residue, in addition to sustainability of these plantations through replenishment of nutrients (Laclau *et al.*, 2000; Nzila *et al.*, 2002), avoid a net carbon loss from soil during the year following harvest. However, high amounts of residues might in turn increase the fire risk in a region that is prone to fire.

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