# Biomass sustainability, availability and productivity

**Abigail Fallot[1], Laurent Saint-André[2], Jean-Paul Laclau[3], Yann Nouvellon[3], Claire Marsden[3], Guerric Le Maire[2], Thiago Silva[4], Marie-Gabrielle Piketty[4], Olivier Hamel[5], Jean-Pierre Bouillet[3]**

[1] CIRAD – Biomass Energy Research Unit, CATIE, Costa Rica
[2] CIRAD - Plantation Ecosystems Research Unit, Montpellier/Nancy, France.
[3] CIRAD - Plantation Ecosystems Research Unit, USP-Esalq, Brazil
[4] CIRAD – UMR Moisa, USP, Brazil
[5] CIRAD, Forest Resources Research Unit, Montpellier, France

fallot@cirad.fr

Research conducted on biomass for Ulcos ("Ultra-Low $CO_2$ Steelmaking" European Integrated Project) has progressively focused on charcoal supply from tropical eucalyptus plantations. The sustainability of such plantations is being investigated from the viewpoint of their carbon, water and nutrient budgets: they must all be neutral or positive. Field research is producing results at the tree or stand level in several sites of Congo and Brazil, while a spatial model is developed to identify the conditions of biomass neutrality at the scale of the forest ecosystem. The productivity of biomass has been analyzed through the description of practices along the various supply-schemes that competitively feed the steel industry in Brazil and the identification of bottlenecks for further expansion.

## Introduction

When coke from mineral coal is burnt, carbon is released in the atmosphere after having been stored underground for millions of years.

When an equivalent amount of energy is consumed from a biomass product, the same amount of carbon is released in the atmosphere as with coke. The difference is that this carbon had been stored for a few years during biomass growth and will be stored again in a few years, if we can ensure that only renewable and sustainable biomass is used. This is why greenhouse gas emissions can potentially be mitigated through biomass use in substitution to fossil energy.

Biomass represents the possibility to avoid an irreversible release of carbon and to substitute it by a temporary release, preceded and followed by carbon storage measurable at human scale.

To confirm the relevance of this possibility for steelmaking, we first had to ensure the existence of biomass potentials, including dedicated plantations and agricultural residues: are these potentials significant at the scale of the European steel industry? Would biomass supply for other purposes than food, be part of a sustainable global scenario? How do technical options compare? Those initial questions were investigated globally during Ulcos's first phase where a combination of possibilities was assessed, with either: agricultural residues or wood from dedicated plantations, to be used under solid, liquid or gaseous forms.

### Biomass potentials should not include agricultural residues

Agricultural residues are generated globally in very large volumes (quantified in billions of tonnes and tens of ExaJoule of primary energy equivalent) during agricultural activities (Guille, 2007). More than half of globally generated residues are required for soil fertility and other direct agricultural uses such as animal feed and litter. What remains for non agricultural uses, to produce energy for instance, is potentially important at a global scale but diverse and scattered. Due to the relatively low energy density of residues (resulting in a few tens of GJ per hectare), high costs of mobilisation and pre-treatment for homogenisation and energy densification are to be expected in any industrial large-scale use. This intrinsic weakness leads to the diagnosis that the large scale centralised transformation opportunity that the steel industry could offer will not be able to successfully compete with more local opportunities such as heat and electricity cogeneration. The possible contribution of residues as a temporary complement to dedicated plantations may deserve attention in some cases that have been judged too specific at the scale of the Ulcos project.

### The availability of land to produce biomass for steelmaking is real but not granted

The potential of dedicated biomass production has been assessed as the availability of land for plantations combining high yield (in terms of tons of wood per hectare) and high productivity (fast-growing on short-rotations). A worldwide assessment of potentially available land for productive forestry activities (Eucalyptus, Pine and Acacia) was conducted by Vincent Dameron (Fallot et al., 2006, Piketty et al.

2009). The idea was to account for suitable land (with adequate temperatures, rainfall and soil inclination for the three mentioned species) that would not directly compete with current and priority uses: agriculture, forests, protected areas, urban zones. Basically what remains of such screening are areas of savannas and extensive grasslands in the tropical areas of Central and East Africa and of Latin America. Some 400 Mha located in tropical areas of Africa and Latin America have been identified on the basis of global data for the year 2000 and a precision level of 1km$^2$ while a prospective study relying on the integrated assessment model Image, showed that such potential could be reduced down to 175 Mha by 2050 in the less favourable of Image global scenarios.

Those values are twenty-five to one hundred times larger than the 4 to 7 Mha that the fulfilment of the Ulcos objective (50% mitigation in European steelmaking) would require with the sole charcoal-from-tropical-plantation option. This gross estimation relies on assumptions of current and future best practices of wood production through high-yield Eucalyptus plantations (16 to 20 ton of dry matter per year and per hectare), of carbonisation (30 to 42% gravimetric yield for charcoal with 80% fix carbon and 10% loss in handling and transport) and of coke-to-charcoal substitution in blast-furnaces (0.41 to 0.45 ton of fix carbon per ton of hot metal).

However, potentially available land is also coveted for other productions including second-generation biofuels and pulp for paper, as well as for non productive uses, given for instance the need to counteract threats on biodiversity exerted by the extension of planted areas.

On this first aspect of competing uses leading to possible biomass availability problems, Michel Griffon has conducted a global exercise of imbricated scenarios by 2050 (Griffon, 2006). Considering rising biomass demand linked to factors of demography, food preferences and energy transition, Griffon has shown that tensions are inevitable on land uses. Though technically, there is still margin for the improvement of agricultural yields in various parts of the world, this will not be enough to meet all food and energy needs as anticipated in scenarios built by the Food and Agriculture Organization (FAO) and by energy experts (Nakicenovic et al., 1998 and Dessus, 2003) counting with a 20% biomass share in the global energy matrix. The worsening of observed environmental problems (deforestation, biodiversity loss and lack of water) and crises in the agricultural and the energy sectors are to be expected.

In that context, though biomass potentials are real, they are not specific or earmarked for the steel industry. Feasibility will depend on how the biomass supply-scheme to the steel industry compares with other biomass uses, in terms of performance and capacity to include environmental and social safeguards.

For the second phase of the Ulcos project, biomass activities have been therefore devoted to three interrelated questions:

- Can biomass be sustainably produced?
- Can land availability be granted in tropical areas for high-yielding plantations?
- Is biomass a reliable and cost-effective mitigation option?

## Biomass sustainability

We focus on the biomass production by Eucalyptus planted forests in tropical areas. Sustainability implies neutral to positive carbon, water and nutrient budgets of plantations at the forest ecosystem scale. These budgets vary with climate conditions and forest management in a complex way due to numerous interactions amongst factors and amongst cycles of carbon, water and nutrients.

Because of this complexity, we need to couple the scientifically sound information that can be obtained from measurements at the stand scale, with modeling tools encompassing larger scales.

**At the stand scale, the components of the nutrient and water cycles have been measured**. They imbricate:

- Geochemical sub-cycles through atmospheric deposits, weathering, drainage and run-offs;
- Biological sub-cycles with canopy exchanges, nutrient uptake, immobilization of nutrients within the trees, litter falls and the mineralization of organic matters;
- Biochemical sub-cycles with translocations between organs. (Laclau et al. 2001b; Saint-Andre et al. 2002b)

Still at the stand scale, the quantified components of the carbon cycle include (figure 1): gross primary production through photosynthesis (Nouvellon 2008b), respiration of the different components of the ecosystem (Epron et al. 2004; Epron et al. 2006; Marsden et al. 2008a; Marsden et al. 2008b; Nouvellon et al. 2008), tree growth, carbon and nutrient stocks (Nzila et al. 2002; Saint-André et al. 2002a; Cornillon et al. 2003; Saint-Andre et al. 2005; Saint-André et al. 2008; D'Annunzio et al. 2008; Laclau et al. 2009; Nouvellon et al. 2009), litter fall (Nouvellon et al. 2008c), root inputs and drainage (Laclau 2000; Laclau et al. 2001a; Bouillet et al. 2002; Laclau et al. 2004; Jourdan et al. 2008, Laclau 2009b).

Understanding and quantifying these processes at the stand scale leads to identifying general laws that would apply at the forest or regional scale.

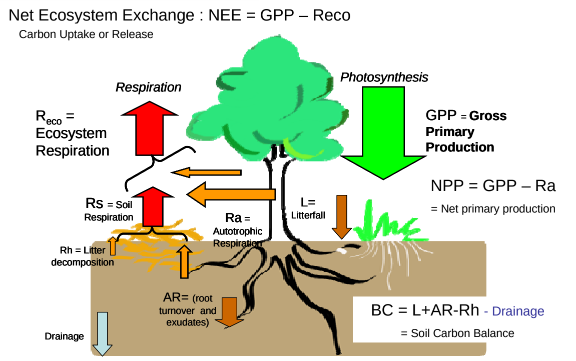


**Figure 1**: The carbon cycle in a forest: Main processes and acronym definition. In a 4-year-old eucalyptus stand in Congo, the following values were obtained during the Ulcos project: NEE=4.7 $tC.ha^{-1}.year^{-1}$; GPP= 18.4 $tC.ha^{-1}.year^{-1}$; Ra=6.7 $tC.ha^{-1}.year^{-1}$; NPP=11.7 $tC.ha^{-1}.year^{-1}$; L = 3.1 $tC.ha^{-1}.year^{-1}$; AR = 2.6 $tC.ha^{-1}.year^{-1}$; Rs = 11.1 $tC.ha^{-1}.year^{-1}$; Rh= 7.0 $tC.ha^{-1}.year^{-1}$; Re =13.7 $tC.ha^{-1}.year^{-1}$.

Research sites rely on eddy-covariance flux towers and networks of stands in several eucalypt plantations, mostly in Congo and in Brazil. The main results on tropical sandy soils include:

– Nutrient budgets are mainly determined by harvest and fertilizer inputs, weathering being almost zero and drainage being very low and concentrated in the first year after clear felling when deep soil horizons are recharged with gravitational waters (rainfall). In the following years, the fast root-growth and nutrient uptake by trees prevent nutrient losses through leaching. Fertilizer applications must then be fitted to the sole tree requirements: our studies showed that Brazilian current practices could be economically optimized through the reduction of N inputs, and that KCl applications could be partly substituted by NaCl (Laclau et al. 2009, Laclau et al. 2008, Rojas et al. 2008).

– On sandy soils with low carbon contents, carbon budgets are not significantly affected by site preparation (whether mechanical by disk harrowing or chemical with herbicide) when the slope is not pronounced (Nouvellon et al. 2008). During the rotation, under current management practices, Eucalypt plantations are carbon sinks (Maquère et al., 2008). A large part of the carbon available for biomass production is allocated to litter production (leaves, and fine root turnover), the biological sub-cycle being predominant in these ecosystems. Therefore burning or removing the litter would be detrimental to long-term soil fertility, soil carbon contents, and wood production (D'Annunzio et al. 2008, Saint-André et al. 2008). Finally, the mean amount of carbon that can be exported over the length of the rotation is estimated to range from about 5.0 tC per hectare and per year under unfavorable soil conditions (e.g. eucalypt plantations in Congo) up to ~ 15.0 tC per hectare and per year at more fertile sites (e.g. Eucalypt plantations in Southern Brazil) (Nouvellon et al. 2008b).

– In Congo, water uptake is higher in plantations than in savannah but drainage remains sufficient (500mm). The risks of depleting the water table recharge depend on the annual rainfall and the water retention capacity of the soil. Low tree growth during the dry season prevents high water uptake in the absence of rainfall. Mosaics with Plantations/Savannahs/Natural forests also limit the impact of plantations on water table recharge.

### Models are used to extrapolate carbon, water and nutrient budgets across local conditions and forest management practices.

Two types of models complementarily represent the determinants of wood production:

1. The process-based models give a representation of the $CO_2$ fluxes composing the carbon cycle and the water cycle.
2. The growth and yield models focus on tree growth (height and basal area) and biomass accumulation which depend on clone, stand density and fertilization.

These models are generic; the same structure applies for different sites and even different species.

Though nutrient availability can have a strong influence on the carbon budget, there are few models that address the nutrition issue by linking nutrient fluxes to water and carbon fluxes.

G'Day (Generic Decomposition And Yield, Comins and McMurtrie 1993) is one of them, developed in the nineties in Australia and it was selected to deal with Ulcos problematics. This model is a sequence of numerical relations representing the main ecosystem processes controlling C, $H_2O$ and N balances on a homogeneous, even-aged plantation stand.

### Water, nutrient and carbon cycles are simulated in real time at a regional scale.

So as to generate weekly or monthly maps of water use, wood production, carbon and nutrient budgets, scaling tools combine the G'day model, ecophysiological parameters, soils and climate maps, and satellite images.

- The forest is considered as a mosaic of independent stands

- G'Day is parameterised and run on each stand composing the mosaic to simulate balances;

- Parameterization is done with the available data; remote sensing allows the determination of spatially variable parameters.

Satellite images are a crucial tool to monitor plantation dynamics at a regional scale. They allow the calculation of the normalized difference vegetation index (NDVI), the time series of which represent the dynamics of the leaf area index (LAI), a key variable driving many ecophysiological processes.

NDVI is calculated using the reflectance of the canopy in red and near infrared spectral bands. Field work is then necessary to assess the relation between NDVI and stand characteristics. We worked on 18 stands of different ages and productivity levels in the Brazilian state of São Paulo and verified that LAI dynamics alone can explain a large part of the variability of productivity levels (Marsden et al. 2008c, Marsden et al. 2009).

Concluding on the sustainability of plantations, for which the central issue is to avoid detrimental effect of land use changes and forest management on carbon, water and nutrient cycles:

- A major outcome of Ulcos research is a methodology for coupling the scientifically sound information obtained from measurements at the stand scale with modeling tools encompassing larger scales;

- Eucalypt plantations in Congo show positive carbon budgets at all levels (biomass, litter, soil) under the condition that fires are prevented, and balanced nutrient budgets except for nitrogen where the introduction of *Acacia* might be recommended (Bouillet et al. 2008; Laclau et al. 2008); limited impact on water quantities, positive impact on water qualities (filtering effect of roots).

- in Brazil, carbon budgets are positive at both the litter and the soil levels. Nutrient budgets can be improved by lowering inputs; other budgets and their sensitivity to local conditions and management practices are subject to ongoing research (figure 2).

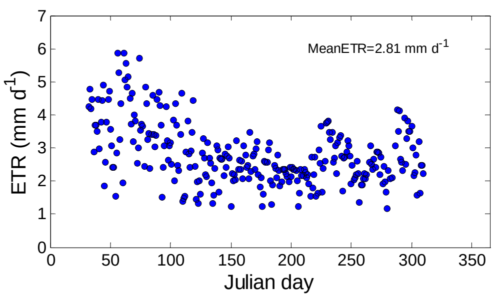


**Figure 2**: Daily evapotranspiration (mm per day) measured in a 5 year-old eucalypt plantation in southern Brazil (February 2008-present)

## Biomass availability (Piketty et al., 2009)

Land use results from a combination of social, technological, economic, and geo-climatic factors that theoretically cannot be addressed separately. However, priority-setting amongst land uses and the necessity to protect some ecosystems can translate into simple exclusive rules, and, similarly, expert judgments on forest plantation can translate into geo-climatic selection criteria. Those simple rules and criteria were applied in the aforementioned global assessment of land potentials for plantations where countries with significant potentials were identified and assessed on the basis of global data (see introduction).

We then used national data to revise the initial global

| STATE | Technical potential | Risks of land rights | Risk of Invasions | Land Price | Productivity | per capita GDP and HDI |
|---|---|---|---|---|---|---|
| Mato Grosso | + + + + | + + + – | + + + – | – – – – | – – – – | + + + – |
| Tocantins | + + + + | + + + + | + + + + | + + – – | + + – – | + + + – |
| Maranhão | + + + + | + + + – | + + + + | + + + + | – – – – | + + + + |
| Piauí | + + + - | + + + + | + + + + | + + + + | – – – – | + + + + |
| Goiás | + + + - | + + + + | + + – – | – – – – | + + – – | + + + – |
| Minas Gerais | + + - - | + + + – | + + – – | + + – – | + + + + | + + – – |
| Pará | + + - - | + + + + | + + + + | + + + + | + + – – | + + + – |
| Bahia | + - - - | + + – – | + + – – | + + – – | + + + + | + + – – |
| Mato Grosso do Sul | + - - - | + + + – | + – – – | – – – – | + + + + | + + – – |

NB: Indicators are relative for comparisons amongst the nine States of Brazil with good technical potential.

assessment, because:

- technically, the global data we used, on land cover for instance, are usually of lower quality than more local land cover data that we could not initially use because of the lack of homogeneity amongst national maps;

- practically, some additional factors of land availability need to complete the analysis so as to better correspond to reality.

We focused on Brazil for its favoured situation (land, climate...) and its large-scale experience in highly productive Eucalypt plantations developed primarily for the pulp and paper industry and now increasingly for charcoal use in ironmaking (Brito et al., 2006).

In Brazil, charcoal production represented 22% of round wood industrial consumption from planted forests in 2006: 35 out of 156 $hm^3$.

The planted forest sector benefits from decades of research and development on genetic material, row spacing, fertilization, planting techniques, control of pests and diseases, forest management, etc. Mean yields of *Eucalyptus* plantations increased from 14 $m^3.ha^{-1}.y^{-1}$ during the 1970's, to 38 in 1995. Currently, the mean annual productivity in commercial *Eucalyptus* plantations is around 40 $m^3.ha^{-1}.y^{-1}$.Taking into account planted forests, high productivity and also low operational costs; the total wood production cost in Brazil is much lower than in Northern countries.

Existing assessments of land that would be potentially available for plantations in Brazil are not systematic nor do they all use the same methodology.

We therefore built our own methodology to compare the different Brazilian states and to tackle the issue of practical availability.

The validation step consisted in indicating:

- previously unidentified zones of population density higher than 80 inhabitants per square kilometre or annual rainfall lower than 800 millimetres ;

- Indian reserves, national and state parks.

Such revision led to a reduction by a third of the potential availability of land for energy plantations, down to 77 Mha: 25.6 Mha grassland, mainly in the Central-Western region (13.7 Mha); and 51.1 Mha savannas, mainly in the Northeast region (20.2), North (13.4) and Central-Western (13.1).

This first assessment bears the risk of under or over-estimating potentials, depending on the region.

Institutional, social, and economic factors differ amongst the Brazilian states with highest technical potentials and may change State ranking for the practical implementation of plantations.

We therefore conducted a qualitative assessment to underline possible trade-offs between technical, socio-economic and institutional determinants of land use availability in Brazil (Figure 3).

**Figure 3.** Indicators of practical availability for the 9 Brazilian states with highest technical potential

Given that the best States under one criterion are not the same as those under another criterion, a major conclusion is the importance of considering alternative charcoal production development schemes rather than the mere optimisation of profitability and transportation costs. We namely underlined the development of small scale plantations (tens of hectares) benefiting from better land access and social acceptance. How do such plantations compare with industrial plantations (tens of thousand hectares) benefiting from best yields and infrastructure?

## Biomass productivity

The supply-chain under study articulates:

(i) forestry plantation, including the setting up of an eucalyptus plantation and its maintenance; (ii) plantation harvest; (iii) wood transportation to the charcoal producing unit; (iv) wood carbonisation; (v) charcoal transport to the steel mill.

Data collection and analysis was carried out in the state of Minas Gerais, counting with Brazil's largest experience in charcoal production from eucalyptus plantations. Industrial firms have progressively created competitive advantages by increasing labour and capital productivity and mitigating the emission of greenhouse gases and other environmental externalities (Rosillo Calle et al., 2000, Campos Ferreira 2000).

Because of increasing land prices and opposition to the further extension of industrial plantations in some States, but also for reforestation purposes, small-scale plantations are developing under private and public incentive schemes, called forest farmer programmes. Reliable data is still scarce on these programmes that have not completed a whole plantation cycle for most of them in the energy-for-steel sector. The pulp-and-paper industry has longer experience on small scale plantations. .

Plantation activities are organised around 6 to 7 year rotations where planting is followed by one or two coppices and therefore occurs every 14 to 21 years.

Planting of seedlings and the maintenance that follows in the two first years of the rotation are quite intensive in labour and inputs because of the requirements for weeding, pest management and irrigation. In industrial plantations, outsourcing is growingly observed for interventions that are punctual, specific or require special equipment. In forest farmer plantations, technical assistance is provided.

Industrial and small scale plantation costs have been estimated (field work by Thiago Fonseca Morello (Morello and Al. 2009)):

- on first rotation (planting) at 4529 Reais per hectare, equivalent to 1811 Euros at the exchange rate of 0.4 R$/€ (May 2008);

- on second rotation (coppicing) at R$2142/ha, equivalent to €857.

Small scale plantation costs have been estimated for the first rotation only, at R$2850, i.e. €1140/ha, with lower capital and labour costs than in industrial plantations.

Harvesting operations (logging, twig and leaf elimination, skidding, chipping, extraction and piling) are growingly mechanized where allowed by site conditions, in particular land inclination and accessibility for feller-buncher or other machines of this calibre. Mechanized harvest productivity reaches 17 to 24 cubic meter of wood per working hour, some seventy times more than the alternative semi-mechanized scheme including the use of chainsaws. Harvest costs are estimated between R$ 13 and R$ 16 per cubic meter of wood, R$ 5 when unmechanized.

Plantation productivity varies between 31 and 48 cubic meter of wood per hectare and per year, depending mostly on site conditions and seedling quality. 36 $m^3$/ha/yr has been calculated as an average value for industrial plantations. Lower average land productivity is expected on forest farmers' plantations for different reasons. One reason is that because forest farmer programmes are still quite recent, it is currently mentioned that ten years are necessary to reach the best fitting of seedling variety and management practices to site conditions. Another challenge is to maintain productivity along successive forestry cycles. The issue there is of sustainability as detailed above.

Wood cost has been estimated to vary from R$ 25.6 a 43.4 (€10,2 a 17.4). It is still difficult to compare industrial and forest farmer schemes on an even playing field since the latter do not offer enough reliable data yet. The question remains then, whether productivity of forest farmer plantations can equal or even exceed that of industrial plantations, once enough experience has been accumulated on forest farmer schemes. Were it not the case, the profitability of forest farmer scheme would depend on differences in land prices and wood prices.

Today (May 2008), land prices in zones where eucalyptus is growing at large scale varies from R$ 1,500 to R$ 8,000 per hectare (€ 600 to € 3,200/ha).

Charcoal industrial production is done on sites at a small distance from plantation (less than 30km), where a series of kilns (up to more than 100) are converting the wood and producing ten to fifty thousand tons of charcoal per year.

Carbonisation activities include wood truck unloading, kiln loading, carbonisation process start up and control, kiln unloading and charcoal truck loading.

Kilns are mainly of two types:

- rectangular kilns out of bricks with a metal armature, an inner volume of 200 $m^3$ or more, and a corresponding annual capacity from 127 to more than 2000 tons of charcoal. They represent an investment cost of some R$ 240,000 (€ 96,000) per kiln for a yearly capacity of around 1300 tons of charcoal and a 15 year lifetime;

- circular kilns out of bricks or clay, with 8 to 20$m^3$ of inner volume and corresponding annual capacity of 42 tons of charcoal to 89. The latter represents an investment of approximately: R$ 800 (€ 320) per kiln for a 3 year lifetime.

Carbonisation cycle varies from 6 to 13 days, depending on the kiln size and on the cooling process (without any device, by pouring water or with more sophisticated water cooling device).

Gravimetric yields of the production of a charcoal with 75 to 80% fix carbon vary from 27 to 36%. Innovation currently implemented to improve yields mainly goes through a better control of the carbonisation process and implies qualified and trained staff (systematic weighing, temperature control through measurement or smoke observation, modelling of the process…). Reducing losses (fines…) and using co-products (tar) also improve yields. Additionally to saving the wood resource, yield improvements offer prospects for carbon credits since they are correlated to methane mitigation.

Productivity-increasing innovation aims at mechanizing truck wood unloading and charcoal loading, filling more completely the kiln, increasing its size and accelerating its cooling. Some trade-off may therefore occur between productivity and yield as a better control of carbonisation is more difficult in larger kilns or with faster processes.

Further innovation implies new types of metallic kilns, allowing either continuous carbonisation or improved batch processes (modular, under pressure…). Cost data are not consolidated yet and subject to confidentiality.

Carbonisation costs in rectangular kilns have been estimated to R$ 12 (€ 4.8) per cubic meter of charcoal of a 0.26 t/$m^3$ density, that is around R$ 46 (€ 18.5) per charcoal ton (Morello and al. 2009). Capital represents one third of this cost, as well as services (outsourced labour and some equipment rental). Hired labour represents one fourth of carbonisation costs. In circular kilns, carbonisation costs have been estimated to be slightly lower, at R$ 10 (€ 4) per cubic meter, that is R$ 39 (€ 15.6) because of lower capital costs.

For one cubic meter of charcoal, transportation costs have been estimated at R$12 (€ 4.8) for wood transport (on an average distance of 27km) and R$ 25 (€ 10) for charcoal transport (on an average distance of 296km).

The total charcoal production cost has been estimated at R$ 105/$m^3$ (€ 162/t) in the industrial plantation case. It is expected to be lower with wood originating from forest farmer plantation and undergoing the same carbonisation process (R$ 98/$m^3$). Our literature review shows values within the interval R$/$m^3$ [54; 122], while market prices in Minas Gerais where we investigated, reached levels of R$ 170/$m^3$ in May 2008 (€ 262/t).

Though a systematic effort was made on data collection and treatment for comparability purposes, information on the charcoal supply-chain from eucalyptus plantation remains quite fragmentary because of its dependency to specific situations.

Amongst factors that mainly determine charcoal costs, we identified: land price and the way it is accounted for in cost computations; mechanization degree in harvesting operations; and kiln productivity. The importance of the latter, relatively to carbonisation yield, might evolve with increases in wood costs, driven by higher land prices.

## Conclusion

Synthesizing the scientific questions addressed on biomass sustainability, availability and productivity, we can state the following points: (i) in the dedicated ecosystems under study, biomass can be produced in a sustainable way if the biological subcycle is not disturbed by detrimental forest managements such as burning or slash removal, (ii) as first approximates of the sustainability of such plantations, the main issues to be quantified are the recharge of the water table and the nutrient losses by harvesting, (iii) the development of biogeochemical models gathering all the presented results and linking nutrient, carbon and water cycles are of primary importance to simulate correctly the future production and the environmental impact of these plantations; (iv) potential land availability for energy plantations would reach 400 Mha globally and 77 Mha in Brazil, where it would be distributed in nine States with diverse socio-economic and institutional conditions; (v) eucalyptus plantation can alternatively be large scale industrial or small-scale with “forest farmer programmes” offering lower costs in the current conditions of Minas Gerais; (vi) wood carbonization can alternatively be conducted in large rectangular kilns or in smaller circular kilns offering a slightly lower cost; (vii) charcoal production cost in the reference case of large scale plantations and rectangular kilns has been estimated at 162 €-eq/t.

The detail of these results feeds a life-cycle-analysis (LCA) of charcoal originating from a Brazilian eucalyptus plantation and finally used in the European steel industry. The aim of such a LCA made within the Ulcos project is to compare biomass with other mitigation options.

On-going research on biomass sustainability, availability and productivity includes:

- on biophysical aspects, further data collection on carbon, nutrients and water budgets so as to calibrate a spatial model and assess budget sensitivity to local conditions and management practices;
- on socio-economic aspects, the analysis of the expansion prospects of alternative schemes of eucalyptus plantation and wood carbonisation.

## Acknowledgements

The authors are grateful to Jean-Pierre Birat for useful comments and stimulating discussions; and to the European Commission and Ulcos’s core members for financial support.

Our results on biomass productivity would not have been obtained without the extremely valuable help of companies, public institutions and academics visited in Minas Gerais, Brazil. Without involving them in possibly remaining errors and insufficiencies, we would like to thank them, in particular Augusto Valencia Rodriguez and Paulo Cesar Pinheiro.

## References

Bouillet, J.P., J.P. Laclau, M. Arnaud, A.T. M'Bou, L. Saint-Andre and C. Jourdan 2002. Changes with age in the spatial distribution of roots of Eucalyptus clone in Congo - Impact on water and nutrient uptake. Forest Ecology and Management. 171:43-57.

Bouillet, J.P., J.P. Laclau, J.L.M. Gonçalves, M.Z. Moreira, P.C.O. Trivelin, C. Jourdan, E.V. Silva, M.C. Piccolo, S.M. Tsai and A. Galiana 2008. Mixed-species plantations of Acacia mangium and Eucalyptus grandis in Brazil: 2: Nitrogen accumulation in the stands and biological N2 fixation. Forest Ecology and Management. 255:3918-3930.

Brito, J., J.-P. Laclau, M. Riom and W. Quirino 2006. Charcoal production in Brazil. Bois et forêts des tropiques, 289(3):59–68.

Campos Ferreira, O. 2000. Emission of greenhouse effect gases in the production and use of charcoal in metallurgy. Economy and Energy. Available from: ecen.com/eee20/omar20be.htm.

Comins, H.N. and R.E. McMurtrie 1993. Long-Term Response of Nutrient-Limited Forests to CO2 Enrichment - Equilibrium Behavior of Plant-Soil Models. Ecological Applications. 3:666-681.

Cornillon PA., Saint-André L., Bouvet J-M., Vigneron Ph., 2003, Using B-Splines for growth curves classification : applications to Eucalypt clones. Forest Ecology and Management 176(3):75-85.

D’Annunzio R., Conche S., Landais D., Saint-André L., Joffre R., Barthes B. 2008 Pairwise comparison of soil organic particle-size distributions in native savannas and Eucalyptus plantations in Congo. Forest Ecology and Management 255:1050-1056.

Dessus, B. 2003. Effet de serre: les marge de manœuvre. La jaune et la rouge - Le réchauffement climatique, numéro spécial, Paris.

Epron, D., Y. Nouvellon, O. Roupsard, W. Mouvondy, A. Mabiala, L. Saint-Andre, R. Joffre, C. Jourdan, J.M. Bonnefond, P. Berbigier and O. Hamel 2004. Spatial and temporal variations of soil respiration in a Eucalyptus plantation in Congo. Forest Ecology and Management. 202:149-160.

Epron, D., Y. Nouvellon, P. Deleporte, S. Ifo, G. Kazotti, A.T. M'Bou, W. Mouvondy, L. Saint Andre, O. Roupsard, C. Jourdan and O. Hamel 2006. Soil carbon balance in a clonal Eucalyptus plantation in Congo: effects of logging on carbon inputs and soil CO2 efflux. Global Change Biology. 12:1021-1031.

Fallot A., P. Girard, V. Dameron and M. Griffon 2006. The assessment of biofuel potentials on global and regional scales in the tropical world. Energy for sustainable development, X(2): 80-91

Griffon, M. 2006. Nourrir la planète : pour une révolution doublement verte. Odile Jacob, Paris.

Guille, T. 2007. Evaluation du potentiels des résidus agricoles pour une valorisation énergétique. Mémoire de fin d'études Supagro. www.cirad.fr/ur/biomasse_en ergie.

Nackicenovic, N., A. Grübler and A. Mc Donald 1998. Global Energy Perspectives. International

Institute for Applied Systems Analysis. World Energy Council, Cambridge University Press.

Jourdan, C., E.V. Silva, J.L.M. Gonçalves, J. Ranger, R.M. Moreira and J.P. Laclau 2008. Fine root production and turnover in Brazilian Eucalyptus plantations under contrasting nitrogen fertilization regimes. Forest Ecology and Management. 256:396-404.

Laclau, J.-P., J.C.R. Almeida, J.L.M. Goncalves, L. Saint-Andre, M. Ventura, J. Ranger, R.M. Moreira and Y. Nouvellon 2009. Influence of nitrogen and potassium fertilization on leaf lifespan and allocation of above-ground growth in Eucalyptus plantations. Tree Physiology. 29:111-124.

Laclau, J.P. 2000. Dynamics of mineral functioning of a Eucalyptus plantation. Influence of afforestation on a savanna soil of the Congolese littoral; consequences for the management of industrial plantations. Institut National Agronomique Paris-Grignon, INAPG.

Laclau, J.P., M. Arnaud, J.P. Bouillet and J. Ranger 2001a. Spatial distribution of Eucalyptus roots in a deep sandy soil in the Congo: relationships with the ability of the stand to take up water and nutrients. Tree Physiology. 21:129-136.

Laclau, J.P., J.P. Bouillet, J. Ranger, R. Joffre, R. Gouma and A. Saya 2001b. Dynamics of nutrient translocation in stemwood across an age series of a eucalyptus hybrid. Annals of Botany. 88:1079-1092.

Laclau, J.P., F. Toutain, A.T. M'Bou, M. Arnaud, R. Joffre and J. Ranger 2004. The function of the superficial root mat in the biogeochemical cycles of nutrients in Congolese Eucalyptus plantations. Annals of Botany. 93:249-261.

Laclau, J.P., J.P. Bouillet, J.L.M. Gonçalves, E.V. Silva, C. Jourdan, M.C.S. Cunha, M.R. Moreira, L. Saint-André, V. Maquère, Y. Nouvellon and J. Ranger 2008. Mixed-species plantations of Acacia mangium and Eucalyptus grandis in Brazil: 1. Growth dynamics and aboveground net primary production. Forest Ecology and Management. 255:3905-3917.

Laclau J.P., J. Ranger, J.L. de Moraes Gonçalves, P. Deleporte, V. Maquère, A.V. Krushe, A. M'Bou Thongo, Y. Nouvellon, L. Saint-André, J.P. Bouillet 2009b. Biogeochemical cycles of nutrients in tropical plantation forests: 10 years of monitoring in Congo and Brazil. Keynote presentation, IUFRO conference on Productivity of Tropical Plantations, 10-14 Nov. 2008, Porto Seguro, Brazil. http://www.ipef.br/iufro2008/program.asp.

Maquere, V., Laclau, J.P., Bernoux, M., Saint-André, L., Gonçalves, J.L.M., Cerri, C., Piccolo, M., Ranger, J., 2008. Influence of land use (savanna, pastures, *Eucalyptus* plantations) on soil organic matter stocks in Brazil. European Journal of Soil Science. 59:863-877.

Marsden, C., Y. Nouvellon and D. Epron 2008a. Relating coarse root respiration to root diameter in clonal Eucalyptus stands in the Republic of the Congo. Tree Physiology 28:1245-1254.

Marsden, C., Y. Nouvellon, A. Thongo M'Bou, L. Saint Andre, C. Jourdan, A. Kinana and D. Epron 2008b. Two independent estimations of stand-level root respiration on clonal Eucalyptus stands in Congo: up scaling of direct measurements on roots versus the trenched-plot technique. New Phytologist. 177:676-687.

Marsden, C., G. le Maire, J. L. Stape and Y. Nouvellon 2008c. Analysis of Modis-NDVI time series of Eucalyptus stands in South-eastern Brazil. Oral presentation, IUFRO conference on Productivity of Tropical Plantations, 10-14 Nov. 2008, Porto Seguro, Brazil. http://www.ipef.br/iufro2008/program.asps.

Marsden, C., G. le Maire, J.L. Stape, D. Lo Seen, O. Roupsard, O. Cabral, D. Epron, A.M. Lima, and Y. Nouvellon 2009. Relating MODIS vegetation index time-series with structure, light absorption and stem production of fast-growing Eucalyptus plantations. Submitted for publication in Forest Ecology and Management.

Morello T.F., Fallot A., Piketty M.G., 2009. Produção de carvão vegetal a partir de plantações de eucalipto em Minas Gerais : vantagens econômicas da carbonização e do cultivo em pequena e larga escala. Paper submitted to the First Brazilian Conference on Florestas Energeticas, 02-05/06, Belo Horizonte, MG (Brazil)

Nouvellon, Y., D. Epron, A. Kinana, O. Hamel, A. Mabiala, R. D'Annunzio, P. Deleporte, L. Saint-Andre, C. Marsden, O. Roupsard, J.-P. Bouillet and J.-P. Laclau 2008. Soil CO2 effluxes, soil carbon balance, and early tree growth following savannah afforestation in Congo: Comparison of two site preparation treatments. Forest Ecology and Management. 255:1926-1936.

Nouvellon, Y., J.L. Stape, J.M. Bonnefond, H. da Rocha and J.P. Laclau 2008b. Seasonal variation of carbon dioxide and water vapour fluxes above an eucalypt plantation in Brazil. Oral presentation, IUFRO conference on Productivity of Tropical Plantations, 10-

14 November 2008, Porto Seguro, Brazil. http://www.ipef.br/iufro2008/program.asp

Nouvellon, Y., L. Saint-André, D. Epron, A. Mabiala, A. Kinana, A. Thongo M'Bou, C. Jourdan, O. Roupsard and J.P. Laclau 2008c. Leaf production and canopy dynamics in a clonal eucalypt plantation in Congo: effect of soil water content. Oral presentation, IUFRO conference on Productivity of Tropical Plantations, 10-14 Nov. 2008, Porto Seguro, Brazil. http://www.ipef.br/iufro2008/program.asp.

Nouvellon, Y., J.P. Laclau, D. Epron, A. Kinana, A. Mabiala, O. Roupsard, J.M. Bonnefond, G. Le Maire, C. Marsden, and L. Saint-André 2009. Within-stand and seasonal variations of specific leaf area in a clonal Eucalyptus plantation in the Republic of Congo. Forest Ecology and Management, In Press.

Nzila, J.d.D., J.-P. Bouillet, J.-P. Laclau and J. Ranger 2002. The effects of slash management on nutrient cycling and tree growth in Eucalyptus plantations in the Congo. Forest Ecology and Management. 171:209-221.

Piketty, M.-G., M. Wichert, A. Fallot and L. Aimola 2009. Assessing land availability to produce biomass for energy: The case of Brazilian charcoal for steel making. Biomass and bioenergy. 33:180–190.

Rojas, J.S.D, J.P. Laclau, J.R. Almeida, J.L. Moraes Gonçalves, J.L. Stape, J. Ranger, Y. Nouvellon and O. Roupsard 2008. Effects of K2SO4 and NaCl applications on tree transpiration and water-use efficiency in a 3-year-old Eucalyptus grandis plantation in Brazil. Oral presentation, IUFRO conference on Productivity of Tropical Plantations, Porto Seguro.

Rosillo Calle, F. and G. Bezzon 2000. Production and use of industrial charcoal. In: Rosillo-Calle F, Bajay SV, Rothman H, editors. Industrial uses of biomass energy. The example of Brazil, New York and London. Taylor and Francis. 183–99.

Saint-André L., Laclau J-P., Bouillet J-P., Deleporte P., Miabala A., Ognouabi N., Baillères H., Nouvellon Y., 2002a, Integrative modelling approach to assess the sustainability of the eucalyptus plantations in Congo. Fourth workshop, IUFRO Working Party S5.01.04 « Connection between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software». Harrison Hot Springs Resort, British Columbia, Canada, September 8-15, 2002. p. 611-621.

Saint-Andre, L., J.P. Laclau, P. Deleporte, J. Ranger, R. Gouma, A. Saya and R. Joffre 2002b. A generic model to describe the dynamics of nutrient concentrations within stemwood across an age series of a eucalyptus hybrid. Annals of Botany. 90:65-76.

Saint-Andre, L., A.T. M'Bou, A. Mabiala, W. Mouvondy, C. Jourdan, O. Roupsard, P. Deleporte, O. Hamel and Y. Nouvellon 2005. Age-related equations for above- and below-ground biomass of a Eucalyptus hybrid in Congo. Forest Ecology and Management. 205:199-214.

Saint-André L., Laclau J-P., Deleporte Ph., Gava J.L., Gonçalves J. L. M., Mendham D., Nzila J. D., Smith C., du Toit B., Xu D.P., Sankaran K.V., Marien J.N., Nouvellon Y., Bouillet J-P., Ranger J. 2008. Slash and Litter management effects on eucalyptus productivity : a synthesis using a growth and yield modelling approach. /In, Nambiar, E.K.S. (Editor) Site Management and Productivity in Tropical Plantation Forests. Proceedings of Workshops in Piracicaba (Brazil) 22-26 November 2004 and Bogor (Indonesia) 6-9 November 2006/. Bogor, Indonesia: Center for International Forestry Research (CIFOR), 2008.CIFOR 2008. p 173-189.