EVALUATION OF THE GREENHOUSE GAS BALANCE IN THE *EUCALYPTUS GLOBULUS* SECTOR IN PORTUGAL

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Summary

This study evaluates the greenhouse gas balance in the *E. globulus* sector in Portugal. Removals and emissions of carbon dioxide (CO_2) and methane (CH_4) were calculated along the whole forest sector, including the forest ecosystem, the industrial processing of wood and the stages of use and final disposal of forest products. The greenhouse gas balance was calculated by subtracting to the net carbon removal, the fossil carbon emissions and the additional emissions of carbon as CH_4. Two different approaches were applied for estimating the net carbon removal in the sector: the stock-change and the atmospheric-flow approach.

The global greenhouse gas balance was a net removal of carbon that varied between 401 and 1033 Gg C_{eq} yr^{-1}, respectively with the stock-change and the atmospheric-flow approaches. The difference between the two estimates is equivalent to the carbon exported in wood and forest products. Both forest and forest products were carbon sinks, as their stocks have been increasing. About 94% of the total change in carbon stocks in the sector was due to forest, whereas paper was the forest product with the major contribution to the increase of carbon stocks. Fossil carbon emissions accounted for 13% of the total carbon emissions in the sector and decreased the net carbon removal by 18 and 34%, respectively with the atmospheric-flow and the stock-change approaches. Carbon emitted as CH_4 was of minor importance and, consequently, was responsible for a decrease in the net carbon removal of only 4 and 8%, respectively with the atmospheric-flow and the stock-change approaches.

Keywords: Carbon dioxide; *Eucalyptus globulus*; forest sector; greenhouse gases; methane; Portugal

Resumen

Este estudio evalúa el balance de gas invernadero en el sector del *E. globulus* en Portugal. Las eliminaciones y las emisiones de dióxido de carbono (CO2) y el metano (CH4) fueron calculadas a lo largo en todo el sector forestal, incluyendo el ecosistema forestal, el tratamiento industrial de madera y las etapas de empleo y la disposición final de productos forestales. El balance de gas invernadero fue calculado restándose la eliminación de carbono neto a las emisiones de carbono fósil y sumándose las emisiones de carbono como el CH_4.

El balance global de gas invernadero fue una eliminación neta de carbono que varió entre 401 y 1033 Gg C_{eq} yr^{-1}, respectivamente con el cambio de reservas y los accesos de flujo atmosférico. La diferencia entre las dos estimaciones es equivalente al carbón exportado en productos de madera y forestales. Tanto productos forestales como forestales eran sumideros de carbono, como sus reservas han estado aumentando. Aproximadamente el 94 % del cambio total de reservas de carbono en el sector era debido al bosque, mientras que el papel era el producto forestal con la contribución principal al aumento de reservas de carbono. Emisiones de carbono de fósil consideradas para el 13 % de las emisiones totales de carbono en el sector y disminuido el retiro neto de carbono por 18 y el 34 %, respectivamente con el flujo atmosférico y los cambio de reservas. El carbón emitido como CH4 tuvo la importancia menor y, por consiguiente, era responsable de una disminución en el retiro neto de carbón de sólo 4 y el 8 %, respectivamente con el flujo atmosférico y los accesos de cambio de reservas.

Palabras clave: Dióxido de carbono; *Eucalyptus globulus*; sector forestal; gases efecto invernadero; metano; Portugal

Introduction

The adoption of the Kyoto Protocol implies the development of policies and measures at national level to ensure that the quantified targets for reduction of greenhouse gas emissions are met. The forest sector can significantly contribute to the mitigation of greenhouse gas emissions. Forests are important carbon pools and may act as carbon sinks when managed in a sustainable manner, decreasing the carbon dioxide levels in the atmosphere. On the other hand, forest products, both in use and in landfills, contribute to the storage of carbon and substitute fossil fuels and more energy-intensive construction materials. Furthermore, energy consumed in the forest-based industry is largely based on biofuels.

The *Eucalyptus globulus* forest is very important in Portugal in terms of both land occupation and industrial utilization. The *E. globulus* forest has an occupation area of 672,000 ha, which represents 21% of the total forest area in Portugal (DGF, 2001). Approximately half of the wood harvested from the Portuguese forest consists of *E. globulus* wood (INE, 2001), which is mostly used in the pulp and paper industry. *E. globulus* wood is the main raw-material for this industry, corresponding to about 80% of the total wood consumed, which also includes imported eucalypt and maritime pine wood (Celpa, 2001). Other minor applications of the Portuguese *E. globulus* wood are the production of sawnwood and wood-based panels.

The objective of this study was to evaluate the greenhouse gas balance for the *E. globulus* sector in Portugal in year 2000. The removals and emissions of carbon dioxide (CO_2) and methane (CH_4) were quantified along the whole forest sector, including the forest ecosystem, the industrial processing of wood and the stages of use and final disposal of forest products.

Methods

The net carbon removal in *E. globulus* forest was estimated as the difference between the carbon stocks measured at two points in time (IPCC, 2003), according to Equations 1 and 2.

$$NCR = (C_{t2} - C_{t1}) / (t2 - t1) \qquad \text{Equation 1}$$

where NCR is the net carbon removal in living aboveground biomass (ton C yr^{-1}), C_{t1} is the total carbon stock in biomass calculated at time t1 (ton C) and C_{t2} is the total carbon stock in biomass calculated at time t2 (ton C).

$$C = SV \times BEF_{SV} \times CF \qquad \text{Equation 2}$$

where, C is the total carbon stock in biomass (ton C), SV is the standing wood volume (m^3), BEF_{SV} is the biomass expansion factor for conversion of standing wood volume to aboveground tree biomass (ton dry matter m^{-3}) and CF is the carbon fraction of dry biomass.

Carbon stocks were estimated from standing wood volumes given in *E. globulus* inventories performed in years 1992 and 1998 (Acel and DGF, 1993; DGF, 2001). These volumes are expressed as stem wood over bark with top. Biomass expansion factors for standing wood volumes (Table 1) were established based on measured data by RAIZ (Instituto de Investigação da Floresta e Papel). The carbon fraction of dry biomass was assumed to be 0.50 (IPCC, 2003).

Table 1 - Biomass expansion factors for conversion of standing wood volume to aboveground tree biomass

Age class (years)	Biomass expansion factor (ton dry matter m^{-3})
0-3	0.869
4-7	0.648
8-11	0.588
12-15	0.562
>16	0.558

The net carbon removal in year 2000 was assumed to be equal to the average net carbon removal between 1992 and 1998. The gross carbon removal (due to forest growth) in year 2000 was calculated using Equations 3 and 4.

$$GCR = NCR + CL \quad \text{Equation 3}$$

where GCR is the gross carbon removal in living aboveground biomass (ton C yr^{-1}) and CL is the carbon loss (ton C yr^{-1}).

$$CL = HV \times BEF_{HV} \times CF \quad \text{Equation 4}$$

where, HV is the harvested wood volume (m^3) and BEF_{HV} is the biomass expansion factor for conversion of harvested wood volume to aboveground tree biomass (ton dry matter m^{-3}) and CF is the carbon fraction of dry biomass.

Harvested wood volume in year 2000 was provided by DGRF (Direcção-Geral dos Recursos Florestais) and is expressed as stem wood under bark without top. The biomass expansion factor for harvested wood volume was 0.807 ton dry matter m^{-3}, for a typical harvest age of 10 years.

Of the total harvested wood in year 2000, 83% was used for pulp production, 9% was exported, 4% was burnt, 2% was used for wood-based panels production and 2% was used for sawnwood production.

Renewable carbon emissions arising from *E. globulus* biomass in pulp production comprise those from wood cooking liquor and bark burning, and those from solid waste and wastewater decay. In paper production, the only renewable emissions are those from solid waste and wastewater decay. Total carbon emissions from biomass burning in pulp production were obtained by carbon balances performed at the mill level, using real data provided by the mills. They were estimated as the difference between the inflow of carbon to the mills (in wood and bark) and the outflow of carbon from the mills (in pulp, solid wastes and wastewater). Carbon emissions from bark burning were determined as the difference between the amount of carbon contained in bark and the amount of organic carbon contained in the ashes of the bark boiler. Carbon emissions from wood cooking liquor were obtained by the difference between total carbon emissions from biomass burning and carbon emissions from bark burning. Emissions from wastewater decay were calculated considering that carbon contained in wastewater is immediately released to the atmosphere. Regarding emissions from solid waste decay, it was considered that 60% of the solid waste produced in pulp and paper mills was mostly used as fertilizer in agricultural and forest lands (Celpa, 2004), and that the carbon they contain was immediately released to the atmosphere. The remaining solid waste was disposed of in landfills (Celpa, 2004), where decay occurs under anaerobic conditions, without biogas burning, and 45% of the carbon contained in solid waste remains permanently stored in landfills (IPCC, 2000). In addition, it was assumed that carbon emissions in landfills are immediate and half of the carbon in biogas is released as CH_4 (IPCC, 2000). A global warming potential of 23 kg CO_2 kg^{-1} was considered for CH_4 (IPCC, 2001), meaning that 1 kg of carbon emitted as CH_4 is equivalent to 8.36 kg of carbon emitted as CO_2.

Renewable carbon emissions in sawnwood and wood-based panels production result from solid waste burning and decay. Carbon contained in solid waste was considered to be immediately released to the atmosphere. Calculation of these emissions relied on information provided by wood-based panels mills and AIMMP (Associação das Indústrias de Madeira e Mobiliário de Portugal).

The changes in carbon stocks in paper, sawnwood and wood-based panels, during both the use stage and the final deposition in landfills, were estimated based on a country-specific lifetime method (Dias, 2005), being equal to the difference between the input of carbon into the pool of forest products and the output of carbon from that pool. The input of carbon was estimated based on statistical data of consumption of forest products and the output of carbon was estimated from the lifetimes of the forest products (Table 2) by assuming an exponential decay. Landfills include both sanitary landfills, where decay was assumed to occur totally in anaerobic conditions, and open dumps, where only 60% of the products were considered to decay anaerobically (IPCC, 1997). The decay of wood products under aerobic conditions in open dumps was assumed to be complete and immediate. Under anaerobic conditions, 45% of the carbon contained in forest products remains permanently stored in landfills (IPCC, 2000). It was also considered that half of the carbon in biogas was released as CH_4 (IPCC, 2000).

Table 2 - Average lifetimes of forest products, both in use and in landfills

Forest product	Average lifetime (yr)	
	In use	In landfills
Sawnwood and wood-based panels		
For construction	30	20
For furniture	20	20
For packaging	2	20
Paper		
Printing and writing	10	20
Other	1	20

In year 2000, the final disposal of discarded paper in Portugal was: 58% to sanitary landfill, 22% to incineration, 14% to open dumps and 6% to composting. For sawnwood and wood-based panels, the final disposal consisted on: 3% to sanitary landfill, 1% to open dumps and 96% for other alternatives (including composting and incineration). For forest products going to composting and incineration, it was assumed that the carbon they contain was immediately released to the atmosphere.

The net carbon removal in the whole *E. globulus* forest sector was determined with two distinct approaches, the stock-change and the atmospheric-flow approach, which differ from each other in their system boundaries (Brown et al., 1999). The stock-change approach considers that the net carbon removal is equivalent to the net change in carbon stocks both in forest and forest products, within national boundaries. Thus, the system boundaries are around the country. In the atmospheric-flow approach, the net carbon removal is calculated by the difference between gross carbon removal by the forest ecosystem and total carbon emissions arising from the decay and burning of the forest biomass throughout the forest sector, within national boundaries. This approach considers that the system boundaries are between the atmosphere and the country.

Fossil carbon emissions in forest management activities and industrial processing were calculated using Equation 5 (IPCC, 1997).

$$FCE = \sum_i C_i \times NCV_i \times CEF_i \times FCO_i / 1000 \quad \text{(Equation 5)}$$

where, FCE is the fossil carbon emissions (ton C yr^{-1}), C_i is the annual consumption of fuel i (ton yr^{-1}), NCV_j is the net calorific value of fuel i (MJ kg^{-1}), CEF_i is the carbon emission factor of fuel i (kg C GJ^{-1}) and FCO_i is the fraction of carbon oxidized for fuel i.

Fossil carbon emissions from forest management include those associated with motor-manual and mechanized operations performed in site preparation, stand establishment, stand tending, logging and infrastructure establishment. The type of operations and their frequency was established by adopting a typical forest management model for *E. globulus* stands in Portugal. The consumption of fossil fuels in each operation was determined based on the effective work time needed to perform the operations and the respective hourly fuel consumption. The net calorific value, the carbon emission factor and the fraction of carbon oxidized for the fuels consumed in forest operations, namely diesel oil and gasoline, are given in Table 3 and were taken from IPCC (1997).

Table 3 - Properties of fossil fuels consumed in the *E. globulus* sector

Fuel	Carbon emission factor (kg GJ^{-1})	Net calorific value (MJ kg^{-1})	Fraction of carbon oxidized
Diesel oil	20.2	43.33	0.99
Fuel oil	21.1	40.19	0.99
Gasoline	18.9	44.80	0.99
Natural gas	15.3	44.85	0.995
Propane	17.2	47.31	0.995

Fossil carbon emissions from the industrial processing of *E. globulus* wood comprise those associated with internal consumption of fossil fuels, both for energy production and other uses (internal transports, lime kiln in pulp mills, etc.), and those associated with the trade of electricity between the mills and the national grid. The amounts of fuel consumed and electricity traded were provided by the industry. The properties of the fuels consumed are specified in Table 3. An emission factor of 143 g C kWh^{-1} was adopted for the electricity produced in the national grid (Martins *et al*., 2001). This emission factor was applied for both the electricity purchased and exported by the mills. It was assumed that exported electricity avoids the production of an equivalent amount of electricity in the national grid.

Results

Table 4 summarizes the main carbon flows in the Portuguese *E. globulus* sector in year 2000.

The gross carbon removal due to forest growth was 2843 Gg C yr^{-1}, of which 54% was released to the atmosphere from the decay and burning of biomass in the different stages of the forest sector, 24% remained stored in the forest, forest products and industrial waste pools, and 22% was exported.

Renewable carbon emissions amounted to 1576 Gg C_{eq} yr^{-1} (Figure 1), of which 42% resulted from wood cooking liquor burning in pulp production. Another important source of renewable carbon emissions was the decay of slash (bark, branches, tops and foliage produced as harvesting residue), representing 38% of total renewable emissions. Emissions of CH_4 from the anaerobic decay of both forest products and industrial waste from pulp and paper production represented only 4% of the total renewable carbon emissions.

Table 4 - Carbon flows in the Portuguese *E. globulus* sector in year 2000

Flow	Carbon (Gg C_{eq} yr^{-1})
Gross removal in forest	2843
Change in stocks	686
Exportation	632
Renewable emissions	1576
Fossil emissions	233

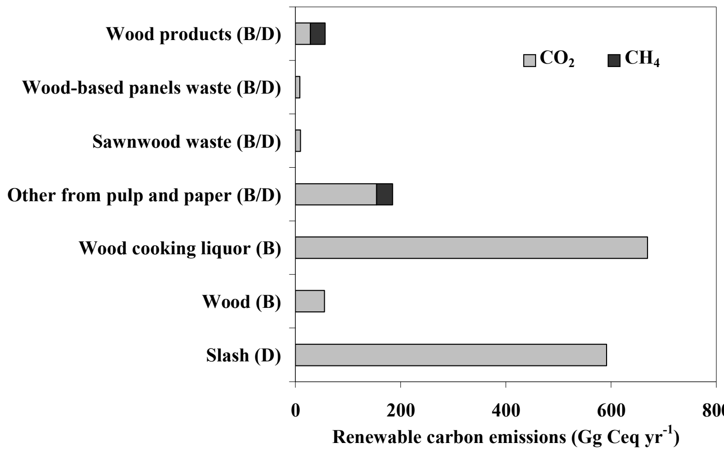

Figure 1 - Renewable carbon emissions in the Portuguese *E. globulus* sector in year 2000. B = burning; D = decay

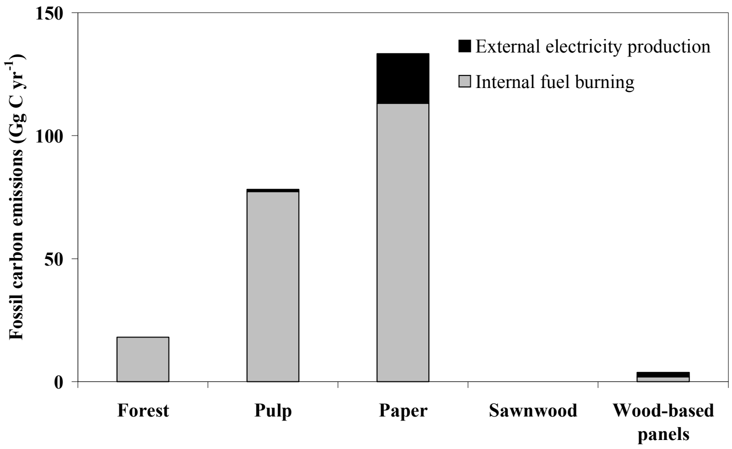

Figure 2 - Fossil carbon emissions in the Portuguese *E. globulus* sector in year 2000

Fossil carbon emissions totalized 233 Gg C yr^{-1} (Figure 2), representing 13% of the total carbon emissions in the *E. globulus* sector. Paper production was the major source of fossil carbon emissions, being responsible for 57% of these emissions. Pulp production also emitted a significant part of these emissions (33%). Most of the fossil emissions in the sector (90%) derived from internal fuel burning.

The total change in carbon stocks amounted to 686 Gg C yr^{-1} (Figure 3), of which 94% were due to the forest ecosystem (643 Gg C yr^{-1}). Paper contributed to almost 70% for the increase in the carbon stocks in forest products, which amounted to 37 Gg C yr^{-1}. About 55% of the change in carbon stocks in paper was associated with paper disposed of in landfills. Carbon accumulation in sawnwood and wood-based-panels in landfills was insignificant. Carbon accumulation in industrial waste disposed of in landfills was also of minor importance (6 Gg C yr^{-1}).

The net carbon removal in the whole sector was estimated as 686 and 1318 Gg C yr^{-1}, respectively with the stock-change and the atmospheric-flow approaches (Figure 4). The difference between the results obtained with the two approaches is equivalent to the carbon contained in wood and forest products exported (632 Gg C yr^{-1}). The major part of carbon was exported in pulp (53%), paper (23%) and wood (22%).

The global greenhouse gas balance in the *E. globulus* sector was calculated by subtracting to the net carbon removal, the fossil carbon emissions and the additional emissions of carbon as CH_4 (due to the greater global warming potential of CH_4 in relation to CO_2). The global greenhouse gas balance amounted to 401 and 1033 Gg C_{eq} yr^{-1}, respectively with the stock-change and the atmospheric-flow approaches (Figure 4).

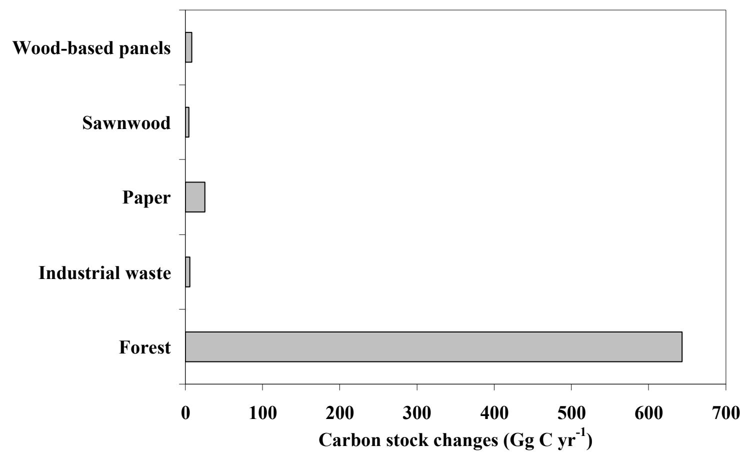

Figure 3 - Change in carbon stocks in the Portuguese *E. globulus* sector in year 2000

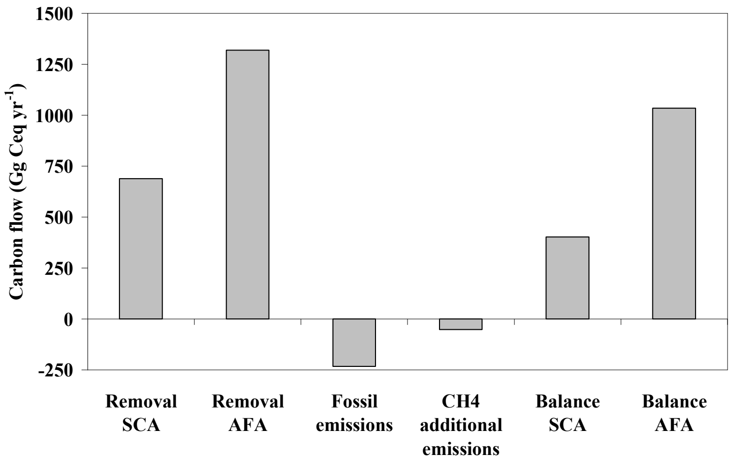

Figure 4 - Net carbon removal, fossil carbon emissions, CH_4 additional emissions and carbon balance in the Portuguese *E. globulus* sector in year 2000.
SCA = stock-change approach; AFA = atmospheric-flow approach

Discussion

In this study, the global greenhouse gas balance in the *E. globulus* sector in Portugal was quantified, based on the net carbon removal in forest and forest products, fossil carbon emissions and CH_4 emissions.

The *E. globulus* forest was responsible for 94% of the change in carbon stocks in the sector. Some other studies also suggest that the increase in carbon stocks is higher for forests than for forest products (Skog and Nicholson, 2000; Flugsrud *et al.*, 2001). In a previous study also performed for the Portuguese *E. globulus* forest sector (Arroja *et al.*, 2006), the change in carbon stocks in forest was smaller than in forest products. In that study, the change in carbon stocks in forest products (including solid waste) ranged between 21 and 54 Gg C yr^{-1}, being similar to the result obtained in the present study (43 Gg C yr^{-1}), but the change in carbon stocks in forest amounted to only 18 Gg C yr^{-1}, which is much smaller than in the present study (643 Gg C yr^{-1}). This great difference in the results obtained is mainly explained by the fact that in the study carried out by Arroja *et al.* (2006) the change in carbon stocks is an average between years 1992 and 1996, whereas in the present study is an average between years 1992 and 1998.

Paper played a major role in the change in carbon stocks in forest products, because almost 70% of the total carbon contained in the forest products produced from *E. globulus* and consumed in Portugal was in paper. The greatest accumulation of carbon in paper took place in landfills, which is common when products have short lifetimes in use and, simultaneously, their fluxes into landfills are high (Pingoud *et al.*, 1996; Skog and Nicholson, 2000).

Renewable carbon emissions greatly exceeded fossil fuel emissions in the forest-based industry. In fact, renewable carbon emissions accounted for 66, 71 and almost 100% of the total carbon emissions, respectively in the production of paper, wood-based panels and sawnwood. This is an expected result since the energy consumed in the forest-based industry is largely based on biomass. It should be noted that near 70% of the total energy consumed by the Portuguese pulp and paper industry in year 2000, and almost 55% of the total energy consumed by the Portuguese solid wood products industry in year 2001 was originated from biomass (AIMMP 2002; Celpa 2004).

The majority of fossil carbon emissions in the whole sector were originated in the wood industry. Fossil carbon emissions arising from forest operations accounted only for 8% of the total fossil carbon emissions, which is in agreement with the results obtained in other studies (Liski et al., 2001; Manriquez, 2002).

Conclusions

The main conclusions drawn from this study are:

- the global greenhouse gas balance in the *E. globulus* sector in Portugal in year 2000 consisted in a net removal of carbon that varied between 401 and 1033 Gg C_{eq} yr^{-1}, respectively with the stock-change and the atmospheric-flow approaches;
- the net carbon removal estimated with the stock-change approach amounted to 686 Gg C yr^{-1}. The major part (94%) of this removal was due to the forest ecosystem. Paper was the forest product with the major contribution to this removal;
- the net carbon removal obtained with the atmospheric-flow approach amounted to 1318 Gg C yr^{-1};

- the fossil carbon emissions accounted for 13% of the total carbon emissions in the sector and decreased the net carbon removal by 18 and 34%, respectively with the atmospheric-flow and the stock-change approaches;
- CH_4 emissions represented only 4% of the total carbon emissions in the sector and, consequently, led to a decrease in the net carbon removal of only 4 and 8%, respectively with the atmospheric-flow and the stock-change approaches.

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