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ABSTRACT

Numerous international and national policy frameworks were recently put into place to promote renewable energy sources, including biomass. Among the wide range of possible feedstocks, dedicated energy crops such as short rotation coppices (SRCs) are considered prime candidates. They produce good-quality biomass that is easy to harvest, while reducing the competition for forest products between energy and other end-uses when grown on agricultural land. Besides technical, social and economical aspects, environmental issues are important to take into account when developing SRCs. For this purpose, a life cycle assessment (LCA) was implemented to provide an accurate and comprehensive estimate of the environmental impacts of delivering 1 GJ of heat from SRC wood chips. The LCA was applied to various scenarios of eucalyptus SRC in France, based on the established SRC pulp scheme and extended to more theoretical systems of very short rotation coppices (VSRCs) with 3-year rotations.

Compared to equivalent fossil chains, all eucalyptus scenarios achieved savings of fossil energy and greenhouse gas (GHG) emissions in the 80%-90% range. The transportation of wood chips contributed the highest share of fossil primary energy consumption and GHG emissions. The second most important item was fertilization, especially in the case of the VSRC schemes due to the evergreen character of eucalyptus.

The possibility of including ecosystem carbon dynamics was also investigated, by translating the temporary sequestration of atmospheric CO_2 in the above- and below-ground biomass of eucalyptus, relative to a reference land use (in this case a land parcel reverting to wilderness after removal of a vineyard) as CO_2 savings using various published equivalence factors. This offset the life-cycle GHG emissions of heat provision from eucalyptus SRCs by 70 to 400%.

1. Introduction

The recent European Directive on renewable energy set ambitious targets for all Member States, in order for the EU to reach a 20% share of energy from renewable sources by 2020 (European Commission, 2009). Amongst renewable energy sources, the biggest contribution (63%) may come from biomass, as suggested by a foresight analysis in Europe (European Commission, 2005). At present, biomass already contributes about 4% of the total EU energy supply, predominantly as heat, and combined heat and power applications to a lesser extent. The production of liquid biofuels for transport from biomass increased several-fold in the last decade, and is currently a major issue.

Among various sources of biomass (organic waste, forestry products, cereal straw, etc.), dedicated crops such as short rotation coppices are currently being investigated. These systems involve the cultivation of a fast growing ligneous species with short to very short harvesting cycles. Species with a capacity to sprout after cutting are particularly interesting as they make it possible to harvest the same plantation several times over the lifetime of the trees. Eucalyptus (*Eucalyptus sp.*) is one of the most widely known species used for biomass oriented short rotation coppice, particularly for pulp and paper industries (Iglesias-Trabado and Wisterman, 2008). Poplar (*Populus sp.*) and willow (*Salix sp.*) have been used more recently for energy purpose for example in northern Europe (Lindroth and Båth, 1999, Wilkinson *et al.*, 2007) or in Italy (Manzone *et al.*, 2009).

In France, short rotation coppices (SRCs) were developed with poplar and eucalyptus in the mid 1980's on the initiative of pulp companies. Nowadays, some 2000 ha of pulp SRC are still present although only eucalyptus is still being used in the south-western part of France with an average rate of 100-200 ha planted every year (Nguyen The et al., 2004). The typical plantation scheme is based on 10-year rotations with a stand density of 1250 stems ha^{-1} (on a 4 m x 2 m grid). Three harvests in 30 years are expected with an average productivity of 10 oven-dry metric tons (ODT) ha^{-1} yr^{-1} with the currently-used specie: *E. gundal*, an hybrid between *E. gunnii* and *E. dalrympleana* (Cauvin et al., 1994). The recent drive for renewable energy sources and concerns with the sustainability of biomass production (Robertson et al., 2008; Scharlemann and Laurance, 2008) have sparked interest for SRC given its presumed low environmental impacts since it requires less inputs than agricultural crops (WWI, 2006).

The traditional pulp and paper SRC scheme may be directly transposed to biomass production for biofuel, heat or power production purposes. Since SRC is expected to be mainly grown on former cropland, silvicultural schemes with shorter cycles than the traditional 10 year pulp rotation, are being investigated in order to be closer to usual farming systems. Growing cycles may be shortened to 7 years with the same productivity as long as stand density is kept within a 2000-2500 stems ha^{-1} range, as was already tested with poplar (Berthelot et al., 2004). Similarly, so-called very short rotation coppice (VSRC) are being tested and developed with an objective of 3-year harvesting cycles. This scheme was illustrated with willow (Dimitriou and Aronsson, 2005), and requires far higher stand densities, between 10 000 stems ha^{-1} and 15 000 stems $^{-}$ha^{-1}. Such systems are currently being trialled in France with eucalyptus and poplar.

Independently of economic and technical issues, it is important to consider the environmental performance of these new energy crops. Several issues were raised regarding their actual GHG benefits, impacts on water resources or biodiversity (Robertson et al., 2008; Monti et al., 2009). Here, we chose the LCA methodology to address these issues for eucalyptus SRC, since it is widely-used for bioenergy assessment and is a multi-criteria, holistic method (von Blottnitz and Curran, 2007; Cherubini, 2010). No such assessments have been reported for eucalyptus SRC, to the best of our knowledge, although they exist for traditional eucalyptus forests (Jawjit et al., 2006; Lopes et al., 2003). There is also a growing literature on the LCA of other lignocellulosic feedstocks, whether annual arable crops (Kim and Dale, 2005), perennial grasses such as miscanthus and switchgrass (Monti et al., 2009; Shurpali et al., 2010), or other types of SRC such as willow and poplar (Gasol et al., 2009; Goglio and Owende, 2009), whose performance may be compared with eucalyptus. The objectives of this work were two-fold: i/ to apply LCA to eucalyptus SRCs in southern France, based on the currently existing pulp scheme, and extended to very-short rotation coppices (VSRCs), and ii/ to investigate the possibility of including the temporary storage of atmospheric CO_2 in ecosystem carbon pools in the GHG balance of heat provision from eucalyptus SRC, following the approach suggested by Moura-Costa and Wilson (2000) for forest products. Eucalyptus biomass was used to generate heat, and compared to equivalent fossile energy sources.

2. Materials and methods

The eucalyptus pulp SRC system was chosen as a basis for the study. This species and its silvicultural scheme have been studied in France for almost 30 years and many technical references already exist (Cauvin and Melun, 1994). This SRC was designed for pulp production but may easily be extended to bioenergy production.

2.1. Scope, functional unit and system boundaries for the LCA

The function studied here is heat production from the combustion of SRC wood chips in a boiler. The functional unit selected was therefore 1 GJ of final heat, which means that life-cycle impact indicators were calculated relatively to the production of 1 GJ of heat.

The system studied is described on Figure 1, and comprises five main stages:

1. The production of cuttings from selected eucalyptus clones, which corresponds to current practices. It includes the production of mother trees in a biotechnology facility and

transportation to a nursery. In the inventory, we used data pertaining to a research laboratory, therefore not designed nor optimized an industrial-scale production of cuttings.

2. Plantation establishment and removal, including site preparation, fertilization, plantation and weed control during the first 2 years, as well as stump removal at the end of the project.

3. Harvest, including felling, forwarding and chipping for SRCs and silage harvester for VSRCs. This stage also includes the transportation of harvesting machines to the tree parcel.

4: Transportation of wood chips from the collection site to the boiler. We used a distance of 80 km corresponding to the actual average distance between eucalyptus plantations and the pulp mill of Saint-Gaudens (South-Western France).

5: Handling and combustion of wood chips in a boiler.

2.2. Management scenarios

The reference scenario was the pulp SRC scheme based on three 10-year harvest cycles (ie a total duration of 30 years), with a stand density of 1250 stems ha^{-1}. From this baseline we designed a scenario dedicated to biomass production for energy by doubling the stem density (2500 stems ha^{-1}) with three harvests every 7 years for a total duration of 21 years. Next, a very short rotation coppice (VSRC) scenario was designed with a density of 5000 stems ha^{-1}, which represents in the present context the maximum possible density considering the costs of eucalyptus cuttings. The scenario plans harvests every 3 years, that is 7 successive harvests over the same 21-year time interval.

A set of technological variants technical aspects likely to influence LCA results were considered to enlarge the number of management scenarios:

1. Harvest mechanization: approximately 50% of pulp SRCs are currently harvested with felling machines rather than manual felling with chainsaws. Felling machines have a better productivity and make mechanical debarking possible in the field, which results in higher rates of nutrient returns to soils. On the other hand, felling machines consume more fuel and emit more GHGs. VSRCs are usually harvested with adapted agricultural harvesters.

2. Productivity: for SRCs, a yield of 10 oven dry metric tons (ODT) ha^{-1} yr^{-1} considered as a robust average value taking into account the mortality of trees and their partial ground cover. It corresponds to a final cut at a diameter of 7 cm (commercial cut). The full stem harvest leads to an extra 20% of biomass, including leaves (Nguyen The and Deleuze, 2004). For the 2nd and 3rd harvest, a 25% gain in biomass production is usually observed due to a faster growth (D. Lambrecq, Fibre excellence, Saint-Gaudens, pers. comm.). For VSRCs, for lack of more accurate references, we assumed the same average figure of 10 ODT ha^{-1} yr^{-1}

3. Fertilizer inputs: Pulp SRCs are currently not fertilized in France because it is not considered as a relevant operation for the sustainability of biomass production. Nevertheless, this is a very critical point, especially for VSRCs whose nutrient exports are expected to be significantly higher thant SRCs. Therefore, we assumed in all scenarios fertilizer input rates corresponding to the estimated exports of nutrients at harvest. The differences between scenarios were particularly acute across harvesting techniques, whether including debarking (with the mechanical harvest) or harvesting full stems or logs. Eucalyptus being an evergreen species, harvesting full stems rather than wood logs would lead to far larger nutrient exports because of the high nutrient contents of the leaves. The amount of N, P and K applied were calculated using state-of-the-art knowledge and data on nutrient exports of VSC and VSRC with eucalyptus in France (Nguyen The et al., 2004 and 2010a) and atmospheric deposition rates (Croisé et al., 2002).

As a result of the above variants, a total set of 5 scenarios was implemented, whose characteristics are summarized in Table 1.

2.3. LCA methodology

The cut-off threshold for neglecting system components was set at 3.6 10^{-6} %. The production of laboratory equipment was excluded because cuttings production was only a marginal part in the use of this equipment overt its total life cycle. The transportation of pesticides and fertilizers (N, P, K and Mg fertilizers in the nursery, herbicides for site preparation and plantation maintenance, field fertilization) were not taken into account due to a lack of accurate information.

Chemical inputs in the nursery were exclusively attributed to the production of cuttings, except for fungicides and hormones which were neglected due to the very low dosages used. Nursery propagators were also excluded due to the lack of information on this material (jiffy pellets made from peat). Neither waste nor co-products are produced during the life cycle of SRCs, which alleviated the need for allocations. As usually assumed in the LCA of bioenergy systems, the global warming potential of the CO_2 emitted during the combustion of biomass was considered nil (Cherubini, 2010).

LCA calculations were done with the TEAM 4.0 software package (Ecobilan-PWC, Paris) with the EcoInvent 2000 database (V2.01, St-Gallen, Switzerland). Field emissions related to the input of fertiliser N and P were calculated using the methods proposed in the Ecoinvent report (Nemecek et al., 2003). However, the model proposed for nitrate leaching was found unsuitable for eucalyptus, and this flux was thus neglected. The leaching risk was low because fertilizers are usually applied in spring after the winter drainage, and taken up before the onset of drainage in autumn. In addition, nitrate leaching under forests is generally minimal (Galloway et al., 2003). Impacts were characterized with the CML (2001) method, as described in Guinée et al. (2002), and the following categories considered: non-renewable energy consumption, global warming (with a 100-year timeframe), acidification, eutrophication, and photochemical ozone creation potential (POCP).

2.4. Accounting for ecosystem C dynamics and land-use changes

In a first variant relative to our baseline LCA calculations, we investigated the possibility of accounting for the temporary storage of atmospheric CO_2 in the biomass of eucalyptus stands. The principle is to derive an equivalence factor with permanently-stored CO_2 based on the cumulative radiative forcing of atmospheric CO_2 over time. Moura-Costa and Wilson (2000) derived such as factor from the number of years over which the reduction in radiative forcing would be identical between the temporary and permanent storages. They estimated the duration for break-even to approximately 55 years, yielding an equivalence factor of 1/55 or 0.0182. However, other factors are presently under discussion in relation to carbon trading. Two other factors were thus tested here: a coefficient of 1/26 proposed by the French Ministry for Agriculture (MAP, 2009), corresponding to an economical calculation involving an annual discount rate of 4 %, and the 1/100 factor proposed by PAS (Bsi, 2008) for consistency with the IPCC time horizon in the cilmate change scenarios (2100). Following the above approach, the temporary effect of C storage may be calculated as :

Mitigating effect (in t CO_2 eq.) = Qc x T x EF

where Qc is the amount of C stored in tree biomass (t C ha^{-1}), T is the duration of storage (years), and EF the equivalence factor (unitless). The *Qc x T* component of the equation actually corresponds to the cumulative sum of C stored through time, except for the last year when the stand is harvested (Figure 1).

The C sequestration of eucalyptus SRC should be compared to a baseline scenario in terms of land-use. Here, we chose abandoned agricultural land (referred to as wildland in the following), which typically occurs after vineyard removal in southern France. Eucalyptus SRCs would therefore be established on former vineyards in our scenario, which excludes indirect land-use change effects. The global C storage was therefore calculated by substracting the C storage of SRC by C storage of wildland.

The carbon stored in the above-ground biomass (AGB) of the eucalyptus stands was calculated from the C content of harvested wood, considering that the C content of biomass was 47% (dry weight basis; Paixao et al., 2006 ; Tanabe et al., 2006). Below-ground biomass (BGB) was estimated with an allometric relationship as a fixed proportion of AGB, set to 30% (Tanabe et al., 2006).

For the wildland, aboveground biomass was considered constant at 0.9 t C ha^{-1} yr^{-1}, which is the peak value for grasslands in warm temperate, dry climates given in the IPCC guidelines for GHG inventories (Tanabe et al., 2006). It is in the lower end of the 0.8 - 3.2 t C ha^{-1} yr^{-1} range reported in Europe for former arable fields up to 3 years after abandonment (Hedlund et al., 2003), ie in the early years of fallow regeneration. The belowground biomass was set at 2.0 t C ha^{-1} yr^{-1} (Tanabe et al., 2006), which is slightly lower than the 2.5 – 3.5 t C ha^{-1} yr^{-1} range in annual returns to soils estimated in the classical Rothamsted (UK) long-term wilderness experiments, where arable fields were allowed to undergo natural woodland regeneration in the 1880's (Jenkinson et al., 1992). In the beginning of the transition from arable to wildland, only herbaceous species are involved and their net annual biomass production is entirely returned to soils as litter. Further on during the 30-year life cycle of the eucalyptus plantation, it is likely that some woody species may also appear in the wildland and start accumulating biomass from one year to the next, although the exact dynamics of that transition has not been documented to the best of our knowledge. Over a longer time-frame, observations in the 'Geescroft wilderness' experiment in Rothamsted (UK), an arable field allowed to undergo natural woodland regeneration in 1885, may give us some insight into this process and provide an upper limit for this component. In this plot, the accumulation of AGB was estimated at 0.6 t C ha^{-1} yr^{-1} over the first 100 years of the transition (Grogan and Matthews, 2001), which we considered as the upper limit of what would happen in the first 30 years of wildland growth after abandonment (the lower limit being no accumulation at all). A below- to above-ground biomass ratio of 1:3 was assumed for the wildland (Grogan and Matthews, 2001), which is similar to the value used for eucalyptus trees.

It is likely that the differences in soil organic carbon (SOC) will appear between the SRC eucalyptus and the baseline land-use over time, due to differences in litter and below-ground inputs (Grogan and Matthews, 2001). However, since eucalyptus SRC systems are relatively recent, there are no long-term experiments documenting the dynamics of SOC after conversion to eucalyptus, let alone comparing them with other land-uses such as arable farming or wildlands. We therefore elected to exclude differences in SOC between eucalyptus SRC and wildland in our analysis. The effect of this hypothesis is addressed in the Discussion section.

3. Results

3.1. LCA results

Life-cycle consumption of non-renewable energy ranged from 77.0 to 92.7 MJ GJ^{-1} heat output from eucalyptus biomass (Table 2). It was lowest for the S1 scenario with lower stem density and manual harvest, and highest for the very short rotation scenario (S5). In all scenarios, wood chips transport represented the main energy consumption hotspot with a share of 46% to 55 %. Harvesting operations came second with 30 to 36 % of total energy consumption, except for the very short rotation scenario, where their share was only 3.3 %. This is due to the use of an adapted silage harvesting machine instead of heavy, fuel-consuming forestry machines. In the VSRC scenario, the most important steps were fertilization and plant production. Fertilizer inputs were larger than with the SRC schemes because the harvest of whole stems including leaves lead to higher nutrient export rates and enhanced fertilizer requirements. Stem density is also twice higher in the VSRC scenarios compared to the SRC energy scenarios, and this had a significant impact on energy consumption since the production of cuttings takes place in an energy-intensive biotechnology laboratory. The shorter rotations and higher stem densities associated with VSRCs further enhanced this trend, making this scenario the most energy-intensive. Its energy ratio (ratio of heat output to fossil energy inputs) was also the lowest of all scenarios, at 10.8. This ratio increased with decreasing harvesting frequency, leading to the pulp scheme achieving the highest value (13).

Life-cycle GHG emissions (excluding ecosystem C pools) varied in a narrow range for the four SRC scenarios, from 8.2 (S1) to 8.5 (S4) t CO2-eq. GJ^{-1}. They were 50% higher for the VSRC scheme (Figure 3), due to its requiring 2 to 3 times more NPK fertilizer inputs than the SRC schemes, altogether with a 20-30% lower productivity (Table 1). The relative importance of the various steps of the life-cycle followed a similar pattern for all scenarios with an important contribution of fertilisation (38 to 44 % of total), transport (32 to 33 %) and harvest (18 to 22 %). The very short rotation scenario (S5) had lower emissions than the short rotation scenarios in the harvest step due to the use of a agricultural harvesters. Its GHG emissions were thus dominated by fertilization, which accounted for 68% of the total emissions.

Indicators for the eutrophication impact ranged from 48 (S1) to 152 (S5) g PO_4^{2-} eq. GJ^{-1} (Figure 3), and were dominated by the fertilization phase. The losses of P from the plantation by runoff and erosion made up 90% of the impact related to fertilization, while ammonia volatilization contributed the remainder, the impacts of NO emissions from soils being negligible. Because of its larger fertilizer requirements, the very short rotation system had nearly 3-fold higher eutrophication impacts than short rotation ones. Although the latter also received varying rates of fertilizer inputs (Table 1), differences in productivities compensated for these variations and all short rotation schemes had a similar eutrophication impact within a 5% relative range. Interestingly, the best scenario was the one with the highest biomass productivity (S4) and not those that with the least fertilizer inputs per ha (S2) which only achieved a mid-range performance.

The acidification indicator ranged from 39 (S1) to 110 (S5) g SO_2 eq. GJ^{-1}, following a pattern similar to eutrophication (Figure 3). The very short rotation scenario had again a 3-fold larger impact than the other scenarios, and for the same reason: its higher fertilizer inputs, which translated in higher field emissions of ammonia and nitric oxide, and indirect emissions due to fertilizers' manufacturing. However, the harvest and transport steps played a more impotant role than for eutrophication, and the breakdown differed between the scenarios. The share of harvest ranged from 20 to 30% for the SRC, while it was nearly negligible (at 2%) for the VSRC. This stems from the major advantage of the VSRC schemes, namely the use of agricultural machines in lieu of forestry ones which are far more resource-intensive. However the associated savings did not compensate for the large requirements of synthetic fertilizer inputs for the VRSC compared to SRC.

The photochemical ozone creation potential (POCP) indicator ranged from 2.4 (S5) to 6.8 (S1) g C_2H_2 eq. GJ^{-1}, with harvest operations and wood chips transport contributing the most (Figure 3). The much higher emissions of photo-oxidants occurring with the scenario S1 is explained by the chainsaws used for manual felling. The chainsaws used in France are seldom equipped with catalytic exhaust pipes and release volatile organic compounds which have a high potential for ozone formation. These emissions also occur to a lesser extent with the mechanized felling option (in scenarios 2 to 4) because chainsaw operators are necessary for the 2nd and 3rd harvest to thin the coppice before felling machines can be used.

For all impact indicators, the results were strongly influenced by the distance between the plantation and the boiler, which was set at 80 km in the baseline calculations. Table 3 illustrates the influence of various distances on the five LCA impacts for scenario S1. Energy consumption was the most sensitive indicator: it dropped by 28% when halving the transport distance, while GHG emissions and acidification impacts were only reduced by 16%, photo chemical ozone formation by 10 % and eutrophication by 3%. The energy ratio increased from 13.0 to 18.0 when the transportation distance decreased from 80 km to 40 km, and reached 25.2 with a 10 km distance (Figure 4). The other indicators were less sensitive to this parameter,

A comparison with fossil energy sources was carried out to assess the environmental advantages and drawbacks of using SRC biomass as a substitute to coal, fuel oil and natural gas (Figure 5). In all scenarios, the provision of heat from SRC biomass consumed 90% less fossile energy than when using fossile energy sources. Similarly, GHG emissions were reduced by more than 80 % with the SRC biomass. However, the patterns with the local to regional-range impacts (acidification, eutrophication and photochemical ozone formation) were less clear-cut. Biomass-derived heat had generally much lower acidification and photochemical ozone formation impacts than fossile-based heat except with natural gas, which out-performed the VRSC scenario for eutrophication and scenario SRC S1 (pulp SRC with manual felling) for ozone formation. Natural gas had 2 to 30 times lower impacts than the other fossile sources, especially coal. Conversely, the eutrophication impacts were in the 50-135 g PO_4^{3-} eq. GJ^{-1} range for the eucalyptus scenarios, and in the 5-40 g PO_4^{3-} eq. GJ^{-1} range for the fossiles, pointing to a weakness of the biomass-based chain. The two-fold higher eutrophication impacts of the VSRC compared to the other scenarios were clearly due to the larger fertilizer inputs required by the former.

3.2. Inclusion of ecosystem C dynamics

Figure 6 depicts the dynamics of aboveground and belowground biomass in the eucalyptus plantation (Scenario 1) and the baseline wildland representing the baseline alternative land-use. Over the 30-year period of the eucalyptus life-cycle, biomass accumulation was several-fold larger in the SRC than in the wildland, even when considering the appearance of ligneous species in the latter. This hypothesis had a significant impact since it leads to a 8-fold higher estimate of total biomass after 30 years compared a wildland solely composed of annual species. The larger biomass accumulation in the eucalyptus SRC was due to a higher net primary production and an important storage in the belowground compartment, which kept increasing though the cuts. When averaged over the 30 years of the SRC rotation, the differences between SRC and wildland range from 16 to 24 t C ha^{-1} for the aboveground biomass, and from 26 to 37 t C ha^{-1} for the total biomass (Figure 6). These gaps represent the net ecosystem CO_2 gains incurred when substituting wildland with SRC, for instance after the abandonment of a vineyard. They are related to land-use effects may be included in the life-cycle GHG emissions of eucalyptus biomass production by using equivalence factors to account the temporal value of C sequestration in the biomass. This lead to savings of 0.57 to 5.16 t CO_2-eq ha^{-1} yr^{-1} (Table 4), depending on the equivalence factors and the carbon pools taken into account. Including these CO_2 savings the LCA of eucalyptus-derived heat offset GHG emissions by 70 to 400 % (Figure 7), and therefore had a large impact on the global warming indicators. With the most favorable equivalence factors (1/26 and 1/55), the C stored in eucalyptus biomass resulted in heat provision being a net GHG sink.

4. Discussion

4.1 Benefits and drawbacks of eucalyptus SRC

Substituting fossile sources with biomass from eucalyptus SRC leads to a 80-90% abatement of life-cycle GHG emissions and fossil energy consumption per MJ of heat supply, for all SRC management scenarios. These figures confirm the strong benefits of bioenergy chains and are consistent with other LCAs of heat from biomass. For instance, Reinhardtt et al. (2000) reported a 95% abatement in GHG emissions and energy consumption when displacing oil or natural gas with short-rotation willow for district heating in several European countries. In addition, inclusion of the temporary storage of CO_2 in the plant biomass, which was ignored in previous literature, more than doubled the GHG savings compared to fossil sources. The relevance of this hypothesis is discussed in subsection 4.3.

Conversely, the benefits of SRCs were far from obvious for the other impact categories, especially when displacing natural gas which had 3 to 4-fold lower impacts per functional unit than the other fossile sources. This trade-off between global impacts (global warming and fossil energy consumption) and local impacts has often been reported for bioenergy chains (Reinhardt, 2000; Gabrielle and Gagnaire, 2008), and is almost inevitable because of the gaseous and leaching losses of nutrient occurring upon the feedstock production phase. Despite the relatively low fertilizer N requirements of eucalyptus stands compared to arable crops, none of the management scenarios achieved lower eutrophication impacts than the fossil-based alternatives. Furthermore, the impact estimates were conservative because some losses of nutrients were neglected, as discussed in subsection 4.2.

In terms of management scenarios, the very short rotation scenario (VSRC) was outperformed by the conventional SRC scenarios for all impact categories except ozone formation, by a factor of 50% to 250%. Since the economics of this system are also unfavourable (Nguyen The et al. 2010b), VSRCs do not emerge as a good candidate compared to short rotation scenarios. Thus, the benefits from a quicker biomass growth and simplified harvesting made possible by the 3-year growing cycle of VSRC were outweighed by their larger fertilizer input and stem density requirements. The only advantage of VSRCs over SRCs appeared in the photochemical ozone creation potential (POCP), in which harvesting operations were predominant. However, VSRCs only out-performed SRC systems by a margin of 20%, which is within the uncertainty range of this indicator given the uncertainties on the characterization factors of ozone precursors (Labouze et al., 2004).

To our knowledge, no LCAs have been carried out so far on eucalyptus SRCs, whether for energy or pulp and paper. Our results may still be compared with those pertaining to traditional eucalyptus plantations published by Jawjit et al (2006) in Thailand. Their study used system boundaries and characterization factors similar to ours, but found much lower impact values in general. Plant-gate life-cycle GHG emissions were estimated at only 3.1 kg CO_2-eq. GJ^{-1}, compared to the 8-12 kg CO_2-eq. GJ^{-1} range we obtained here. The acidification impact was 22 g SO2-eq. GJ^{-1} in the Thailand study compared to our 40-110 g SO_2-eq. GJ^{-1} range, while the photo-chemical ozone formation potential amounted to 1.6 g C_2H_2-eq. GJ^{-1} in

Thailand compared to our 2.5-7.0 g C_2H_2-eq. GJ^{-1} range. Eutrophication was an exception with similar impacts between Thailand and France, at 41 g PO_4^{2-}-eq. GJ^{-1} and an average of 50 g PO_4^{3-}-eq. GJ^{-1} for the SRC systems, respectively.

Some of these discrepancies are explained by the higher yields of 17.4 ODT ha-1 yr^{-1} achieved by eucalyptus under the tropical conditions of Thailand, compared to the 9.5 – 14 ODT ha-1 yr^{-1} range assumed here. The eutrophication impact was relatively higher because 35% to 20% of the fertiliser N and P applied was supposed to leach to water bodies in this Thailand study, whereas those losses were neglected here, as they were in other LCAs on herbaceous and tree species for lack of specific references (Gasol et al., 2009; Monti et al., 2009).

Our results on eucalyptus SRC may be compared more broadly to other ligenocellulosic feedstocks: willow in France (Reinhardt, 2000) and Italy (Goglio and Owende, 2009), poplar SRC in Italy (Gasol et al., 2009), reed-canary grass in Finland (Shurpali et al 2010), and four perennial grasses in Italy (Monti et al 2009). All of these studies used similar system boundaries with the exception of the combustion step, and relied on the same set of characterization coefficients (from Guinée et al., 2002). Most of them also used the EcoInvent data base for the life-cycle inventory phase.

Compared to the poplar SRC system assessed by Gasol et al. (2009) in Italy, the production and harvest of eucalyptus biomass consumed 1.8 to 2.5 more primary energy, essentially because the harvest was 3-fold less energy-intensive per ton of biomass than eucalyptus (for the SRC system) or because poplars required 4-fold less fertilizers (for the VSRC systems). Also, the data on fuel consumption by farm machinery were adapted from the EcoInvent database based on local records but the exact corrections were not given by the authors. When including the transportation of wood chips, albeit with a shorter distance than our nominal hypothesis (25 vs. 40 kms), the GHG emissions of poplar totalled 1.93 kg CO_2-eq.

GJ^{-1}, kg CO2 GJ^{-1}, which is 4 to 6 times less than our 8-12 kg CO_2-eq. GJ^{-1} range for eucalyptus. The gap was even wider for the other impact categories: the eutrophication impact of poplar was estimated at 3.4 g PO_4^{3-} -eq. GJ^{-1} vs. 40-135 g PO_4^{3-} -eq. GJ^{-1} for eucalyptus ; acidification amounted to 15.7 g SO_2-eq. GJ^{-1} vs 40-110 g SO_2-eq. GJ^{-1} for eucalyptus ; and POCP totalled 0.3 g C_2H_2-eq. GJ^{-1} for poplar compared to 2.4- 7 C_2H_2-eq. GJ^{-1} for eucalyptus. Besides differences in management and inventory data for farm machinery, these large discrepancies arise because direct field emissions contributed only a minor share of the impacts in the Gasol et al. study, whereas they predominated in our LCA. There are reasons to believe some of these emissions were somehow under-estimated: for instance, N_2O emissions from Gasol et al. were similar to our estimates on a ha basis, whereas NO emissions were 2-fold lower. This contradicts current literature, which indicates that NO and N_2O emissions fall within a similar range (Stehfest and Bouwman, 2006). Our estimate of N_2O emissions also included background emissions (ie non anthropogenic) and the contribution of eucalyptus residues.

Our LCA results for eucalyptus are overall closer to those reported by Reinhardt (2000) and Goglio and Owende (2010) for short-rotation willow in Germany and Ireland, respectively. These authors reported energy consumptions of 33 MJ GJ^{-1} heat and 56.4 MJ GJ^{-1}, respectively, compared to our 55.6 MJ GJ^{-1} figure for scenario 1 (S1) with a similar transportation distance (40 kms). The lower figure from Reinhardt (2000) was due to a less energy-intensive harvest for willow, whereas the Goglio and Owende (2009) study involved a drying phase prior to combustion. The GHG emissions were very similar, at 7.13 kg CO_2-eq. GJ^{-1} for willow in Germany vs 6.80 kg CO_2-eq. GJ^{-1} for the S1 eucalyptus system here, while the eutrophication impact for willow was 94 g PO_4^{3-} -eq. GJ^{-1}, well within the 40-135 g PO_4^{3-} -eq. GJ^{-1} range reported here for our systems, although it should be noted that the estimation of nitrate and phosphate losses was not explicitly described in the willow study. Lastly, the acidification emissions of willow in Germany totalled 174 g SO_2-eq. GJ^{-1}, compared to a 40-110 g SO_2-eq. GJ^{-1} range for eucalyptus SRCs. This is probably due to higher combustion emissions of acidifying compounds in the Reinhardt (2000) study than listed in the EcoInvent database, which pertains to more recent technologies. For the same reason, POCP impacts were also larger with willow, at 18 C_2H_2-eq. GJ^{-1} in comparison to 6.1 C_2H_2-eq. GJ^{-1} g for the S1 system. Lastly, eucalyptus SRCs may be compared to the range of perennial grasses assessed by Monti et al. (2010), involving miscanthus, switchgrass, cynara and giant reed, with a cradle to farm-gate system boundary. Energy consumption ranges from 33 to 142 MJ GJ^{-1} biomass energy content, compared to approximately 35 MJ GJ^{-1} for eucalyptus SRC (Table 2), putting the latter on a par with the best performers, giant reed and miscanthus. However, their GHG emissions were significantly lower, at 1.75 kg CO_2-eq. GJ^{-1} compared to 5.5 – 9.4 for kg CO_2-eq. GJ^{-1} eucalyptus. The same applied to eutrophication impacts, ranging from 4 to 20 g PO_4^{3-}-eq. GJ^{-1} for grasses and from 45 to 132 g PO_4^{3-}-eq. GJ^{-1} for eucalyptus, and also to acidification impacts, which are 2 to 2.5 lower for the grasses than eucalyptus. As with the Gasol et al. (2009) study, it may be that field emissions were under-valued, since fertilizer N input rates were rather higher than the eucalyptus SRC systems (at 80 kg N ha^{-1} yr^{-1} compared to a 6-40 kg N ha^{-1} yr^{-1} range for eucalyptus). The Monti et al. (2010) paper does not mention direct emissions of nitrate or P in the field.

Because of differences in local contexts, in the sources of life-cycle inventory data and estimation methods for field emissions, it is not possible to directly compare the eucalyptus systems tested here with other coppices or herbaceous plants since these differences are likely to overrule the differences between feedstocks per se. With the exception of the Gasol et al. (2009) study, the LCA indicators of eucalyptus were within the range of impacts reported for other lignocellulosic feedstocks, but no robust patterns emerged in terms of ranking with other species.

4.2 Uncertainties in the life-cycle inventories

Field emissions are particularly difficult to correctly address in the LCA of agricultural or forestry systems as they depend to a large extent on local conditions (soil properties, climate) and on their interactions with management practices, which govern the fate of chemical or organic inputs. Since very little data on field emissions has been published for eucalyptus SRC in temperate zones, we used estimation methods developed for other species, or assumed some emissions were negligible. Such was the case for nitrate leaching and P losses, which may have lead to an under-estimation of eutrophication impacts. Lopes et al. (2003) found these emissions negligible in their LCA of eucalyptus-derived paper, and so did Jawjit et al. (2006) although their estimates of nitrate and phosphate emissions from eucalyptus plantations were rather large: they assumed that 35% and 20% of fertilizer N and P inputs were leached to water bodies, respectively, according to the 1997 IPCC guidelines for GHG inventories. The 35% emission factor for nitrate (which was revised to 30% in the 2006 IPCC guidelines – Tanabe et al., 2006) should in principle apply to managed forests, but no reference specific to forest or energy plantation is given in the literature base that served to determine this value. Further research is therefore warranted to provide a more accurate estimate of nitrate leaching for eucalyptus SRC. The same applies to P losses, and also to gaseous emissions of N_2O, NH_3 and NO. The latter were calculated according to the IPCC (2006) guidelines for managed ecosystems, using default emission factors which are characterized by a large uncertainty range (Stehfest and Bouwman, 2006). Unfortunately, no literature data were found for eucalyptus SRC or forests in Europe to refine those estimates.

4.3 Relevance of including ecosystem C dynamics

Accounting for variations in ecosystem C stocks, compared to the alternative land-use (wildland in our case) had a drastic effect on the GHG balance of eucalyptus-derived heat, whose magnitude depended on the factor chosen for the equivalence between C stored in ecosystem pools and atmospheric CO_2. Even when using the most conservative value of 1:100 (ie that least favorable to eucalyptus), ecosystem C pools offset GHG emissions by 50 to 70%, depending on the inclusion of below-ground biomass. This made net eucalyptus a nearly carbon-neutral source of heat, and stresses the influence of ecosystem C dynamics in relation to land-use changes (LUC) in LCAs, already noted by Ndong et al. (2009) for biodiesel from jatropha in West Africa, and Shurpali et al. (2010) for reed-canary grass in Finland. Note that the latter authors effectively used an equivalence factor of 1:1, since they used measurements of net ecosystem exchanges of CO_2 over reed-canary grass, as cumulated over one year, as a measure of the C sink strength of the field where this crop was grown. Such hypothesis was also implicit in the GHG budgets of farmland and woodland management computed by Palm et al. (2010) in 2 villages in Africa, or by Ceschia et al. (2010) for cropping systems across Europe. In both references, ecosystem C fixation was put on a par with CO_2 emissions from fossil sources or N_2O emissions from soils. This may be justified on a short-term basis, but is misleading in the long-run since most of the C taken up by ecosystems on a given year will be released back to the atmosphere after a few years since it enters fresh organic matter pools with rapid turnover (Jenkinson, 1990). From a life-cycle perspective, whereby one attempts at estimating the cumulated past and future effects of substituting one product by another, using such an hypothesis would have over-emphasized the sink capacity of SRC stands compared to wildland, and given wrong results on the actual GHG benefits of eucalyptus biomass. The use of equivalence factors, which are up to 2 orders of magnitude lower, is thus fully justified.

Of course the magnitude and direction of this effect strongly depends on the LUC hypotheses made in the LCA. Adverse effects were conversely noted for biofuels when including indirect land-use change effects whereby the displacement of food crops for biofuels in the US entailed the conversion of natural ecosystems to arable farming in other parts of the world

(Fargione et al., 2008). Our scenarios for eucalyptus growth did not involve such effects since they considered the farming of eucalyptus SRC as an opportunity to value former arable land or vineyards that had been abandoned because of a drop in the market prices of wine.

Soil organic matter (SOM) pools were not included in the ecosystem pools for lack of robust estimates of SOM variations under both eucalyptus SRC and wildland. This pool was actually responsible for most of the land-use offset of GHG emissions in the LCA of Jatropha by Ndong et al. (2009). Similarly, given the differences in net primary production between the SRC stands and the wildland, it is likely that the former have a higher SOM content than the latter, and therefore further accrue their GHG benefits. Grogan and Matthews (2001) thus argued from a very preliminary modelling study that 'short-rotation coppice systems have the capacity to sequester substantial amounts of carbon, comparable to, or even greater than, an undisturbed naturally regenerating woodland'. This results from C inputs from SRCs being higher than from the regenerated woodland, which is comparable to our wildland system here.

Field samplings were carried out in our study area to estimate SOM contents under vineyards, eucalyptus SRC of various ages, wildlands and arable land. Although the comparison was confounded by soil clay content, SOM was clearly lowest under the vineyards and comparable between wildlands and SRCs. Conversion shortly after vineyard abandonment would therefore maximize the benefits of eucalyptus SRCs in terms of SOM gains from land-use change. Further work (in particular SOM modelling) is nevertheless required to provide more robust estimates of the magnitude of these potential gains.

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Figure captions

Figure 1: Calculation of the cumulative amounts of carbon stored in eucalyptus biomass over time in the 10-year interval between two cuts.

Figure 2. System boundaries and steps of the life-cycle.

Figure 3. LCA results for global warming, eutrophication acidification, photo-chemical ozone creation potential, per GJ of heat delivered.

Figure 4. Energy ratio as a function of the transportation distance from the eucalyptus plantation to the boiler for scenario S1.

Figure 5. LCA indicators weigthed by the average impact of an European inhabitant and compared to fossil energy sources.

Figure 6**.** Dynamics of above-ground (top) and above- and below-ground (bottom) C storage by pulp eucalyptus SRC (solid line) and wild land with (dotted line) or without (dashed line) consideration of C accumulation in woody species, in the years following conversion to SRC.

Figure 7. Greenhouse gas emissions (g CO_2 eq. GJ^{-1} heat) due to sowing and harvesting operations, fertilization and transport of chips, and CO_2 savings from CO_2 sequestration in ecosystem biomass using various equivalence factors and the lower and upper estimates.

Figure 1: Calculation of the cumulative amount of carbon stored in eucalyptus biomass over time in the 10-year interval between two cuts.

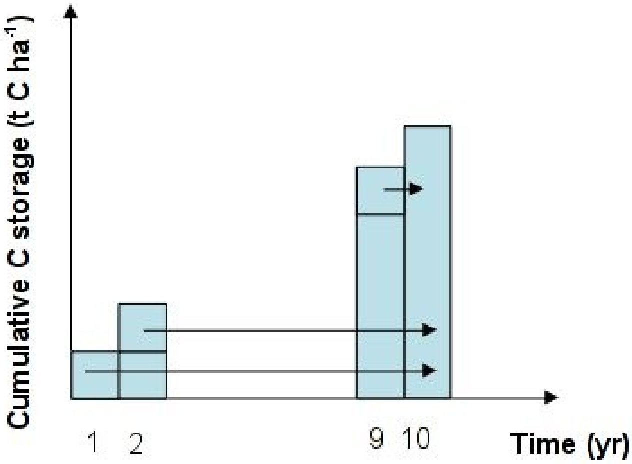


Figure 2. System boundaries and steps of the life-cycle.

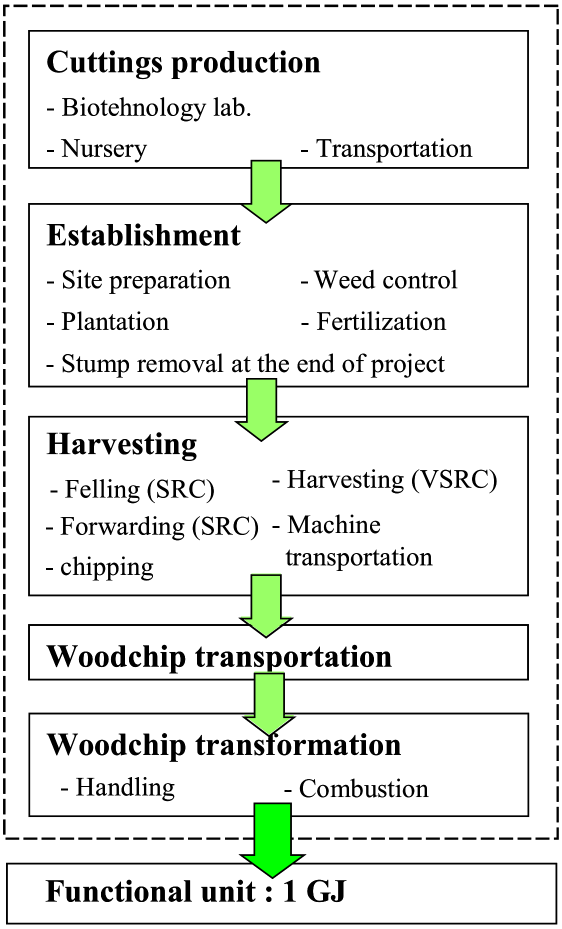


Figure 3. LCA results for global warming, eutrophication acidification, photo-chemical ozone creation potential (POCP), per GJ of heat delivered.

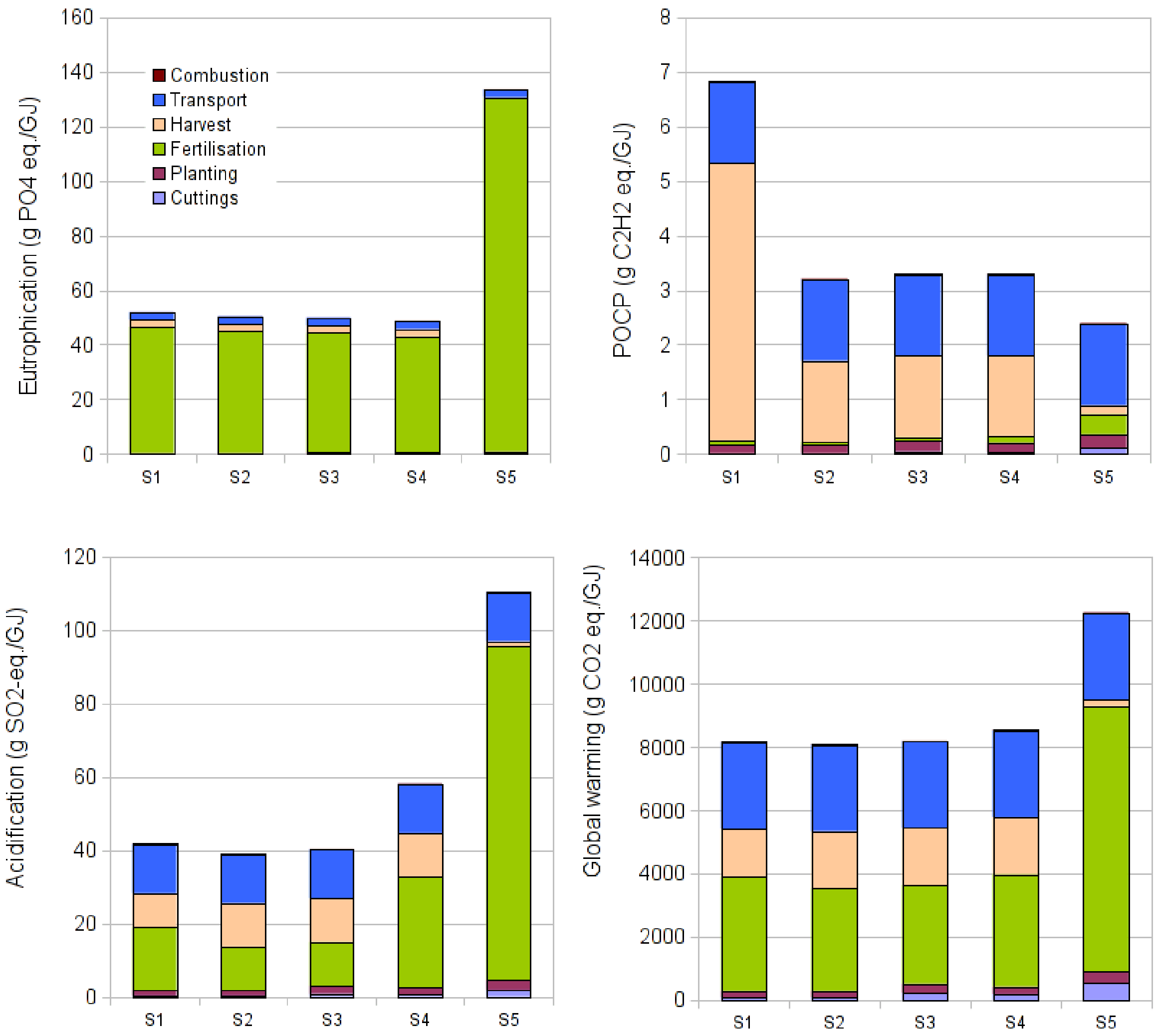
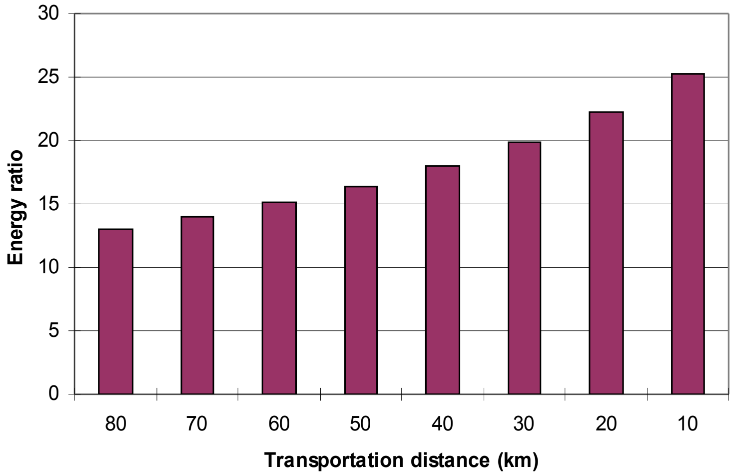
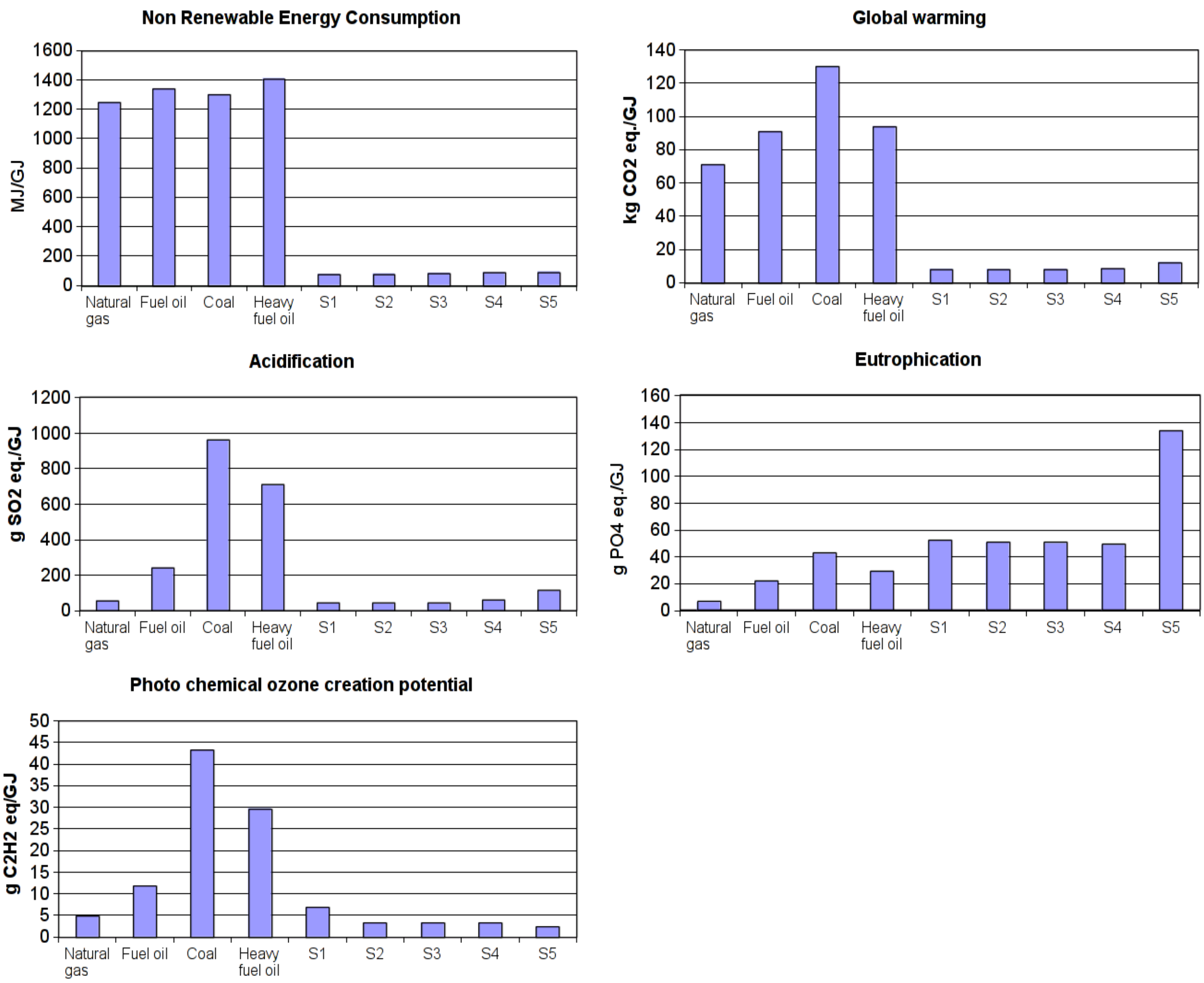


Figure 4: Energy ratio as a function of transportation distance from field to boiler for scenario S1.



Figue 5. LCA impacts per GJ of heat compared to various fossil energy sources.



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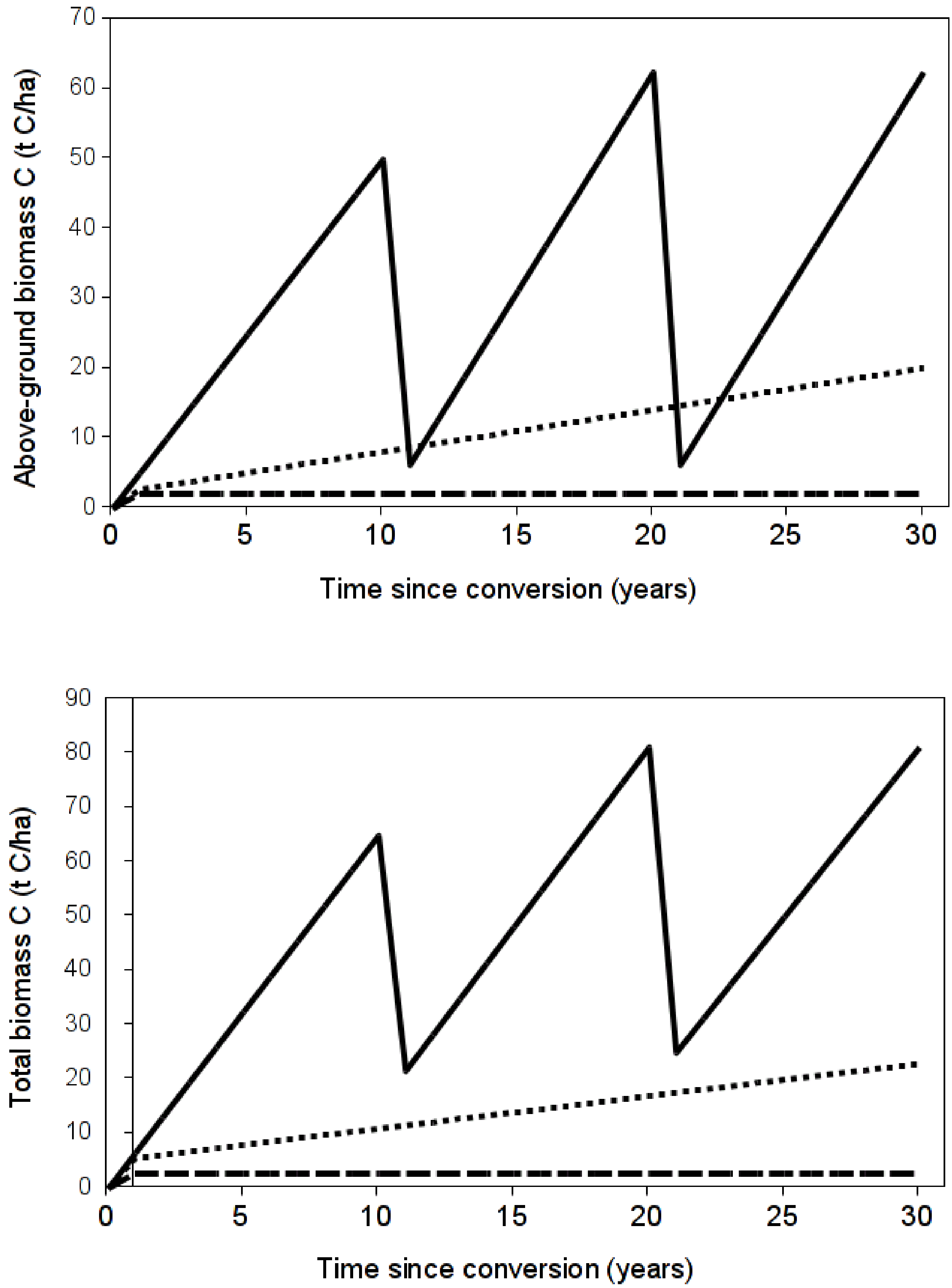

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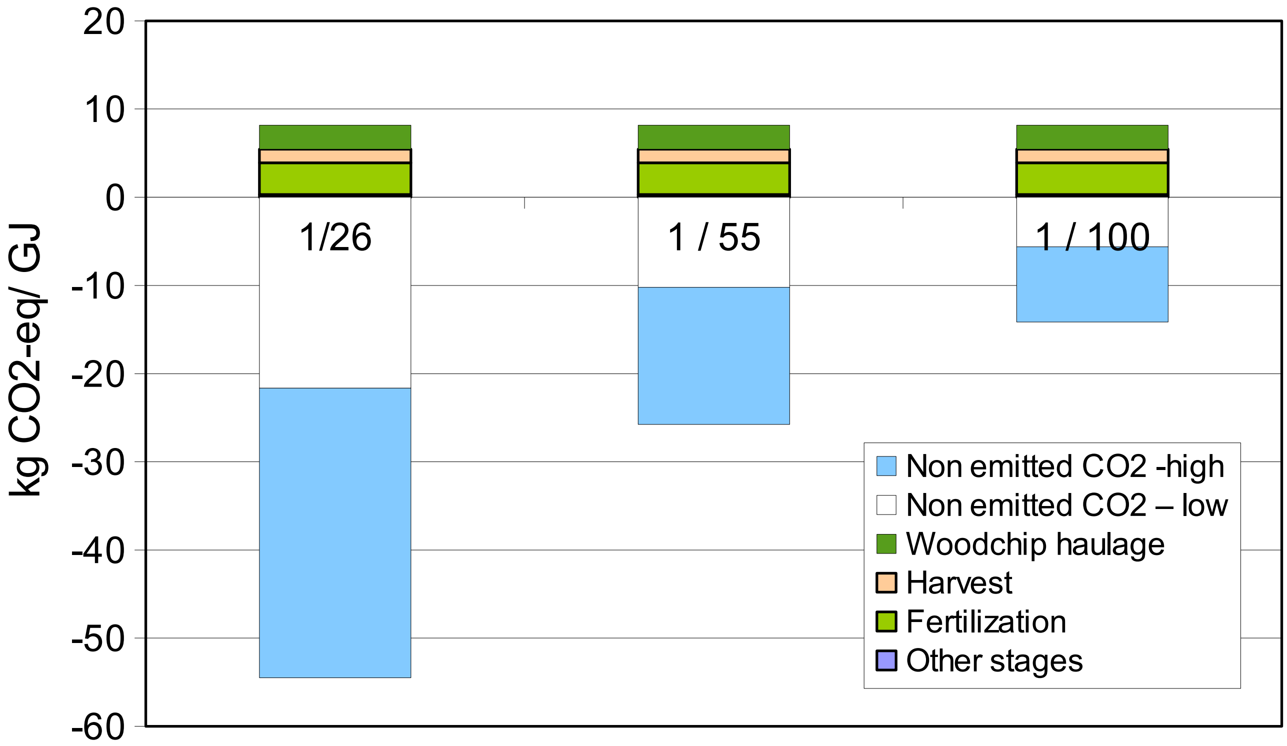

Table 1. Selected characteristics of the eucalyptus management scenarios for the short rotation (SRC) and very short rotation (VSRC).

	Scenario name	Characteristics	Productivity ($ODT^{1}\ ha^{-1}\ yr^{-1}$)	Fertilizer inputs ($kg\ ha^{-1}\ yr^{-1}$)	Duration
Pulp SRC 1250 stems ha^{-1}	**S1**	Chainsaw operator - Log harvest	11.7	N: 10 P_2O_5: 8.7 K_2O: 14.8	3 x 10 years
	S2	Felling machine - Log harvest	11.7	N: 6.4 P_2O_5: 7.8 K_2O: 10.1	3 x 10 years.
Energy SRC 2500 stems ha^{-1}	**S3**	Felling machine - Log harvest	11.7	N: 6.4 P_2O_5: 8.3 K_2O: 10.1	3 x 7 years
	S4	Felling machine - Full stem harvest	14.0	N: 23.4 P_2O_5: 11.2 K_2O: 25.2	3 x 7 years
Energy VSRC 5000 stems ha^{-1}	**S5**	Harvester - Full stem harvest	10	N: 40.0 P_2O_5: 18.8 K_2O: 49.8	7 x 3 years

1: ODT: oven-dry metric ton

Table 2. Non-renewable energy consumption per life cycle stage of the various SRC systems ($MJ\ GJ^{-1}$), and ratio of energy delivered to primary energy consumption.

Scenario	Cuttings production	Site prep.	Fertilisation	Harvest	Transport	Boiler	Total	Energy ratio
S1	1.84	2.96	5.69	23.52	42.67	0.29	77.0	13.0
S3	1.84	2.96	3.99	27.30	42.67	0.29	79.0	12.7
S7	5.24	4.23	4.00	27.30	42.67	0.29	83.7	11.9
S8	4.34	3.51	9.47	27.28	42.67	0.29	87.6	11.4
S9	12.85	5.18	28.63	3.08	42.67	0.29	92.7	10.8

Table 3. Influence of woodchips transportation distance from plantation to boilers on LCA indicators for scenario S1, per GJ of heat.

	Transportation distance (km)			
	80	40	20	10
Non-renewable energy consumption (MJ)	77.0	55.6	45.0	39.6
Acidification (g SO_2-eq.)	41.7	35.0	31.7	30.0
Eutrophication (g PO_4-eq.)	52.0	50.5	49.8	49,4
Photochemical ozone formation (g C_2H_2-eq.)	6.8	6.1	5.7	5.5
Global warming (kg CO_2-eq.)	8.16	6.80	6.11	5.77

Table 4. Carbon storage in the eucalyptus SRC stands (management scenario 1), relative to the baseline wildland, as averaged over the 30-year duration of the project, in the above-ground and above- and below-ground biomass pools (t CO_2 ha^{-1}). The lower-end of the range corresponds to the emergence of woody species in the wildlands, which is ignored for the upper-end value. C stored in biomass pools are transformed into CO_2 sequestration rates using the 3 possible equivalence factors detailed in the text.

Ecosystem pools	Equivalence factors		
	1/26	1/55	1/100
Above-ground biomass	2.21 – 3.43	1.05 – 1.62	0.57 – 0.89
Above-ground and below-ground biomass	3.67 – 5.16	1.73 – 2.44	0.95 – 1.34