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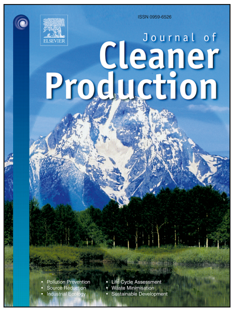

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Cradle-to-gate life cycle assessment of *Eucalyptus globulus* short rotation plantations in Chile

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Short rotation woody crops appear to be a promising option of biomass for bioethanol production. The traditional short rotation periods for *Eucalyptus globulus* vary between 8 and 12 years, however intensive forest management practices and genetic improvement have increased the productivity of plantations and reduced the rotation periods up to 5 years. This study aims to assess the potential environmental impacts associated with Chilean short rotation *E. globulus* plantations for bioenergy production from a Life Cycle Assessment perspective. Thus, for the first time it is presented a detailed life cycle inventory and environmental assessment of a forest system in Latin America. Forest operations carried out over a lifespan of 12 years, with rotation periods of 4 years, were divided into four phases: crop establishment, harvesting, hauling and logistics infrastructure. The managed life cycle inventory included forest site data from a representative plantation dedicated to *Eucalyptus* chips production for energy purposes, and the inventory of the fuels production in Chile was also determined to fulfil the information requirement. The environmental profile was analysed in terms of several impact categories: climate change, ozone depletion, terrestrial acidification,

freshwater y marine eutrophication, photochemical oxidant formation, human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, water depletion and fossil fuel depletion.
The harvesting phase was the main contributor to almost all the impact categories with contributing ratios higher than 56%. Within the harvesting phase, fertilisation and forwarding were the main processes responsible for derived environmental impacts. The results in terms of climate change and terrestrial acidification were compared with those reported for *Eucalyptus* biomass production in European countries. The comparison was performed considering the same system boundaries and functional unit. Differences identified were related to different forest management activities carried out as well as different biomass yields. The LCA study remarked those stages where the researchers need to improve the environmental performance. The results suggested that both fertiliser dosage and fuel consumption in forest activities should be optimised in order to decrease most effectively the global environmental impacts.

Keywords: *Eucalyptus globulus Labill., Life cycle Analysis, Forest operations inventory, Short rotation woody crops,.*

1 Introduction

The replacement of fossil fuels with wood biomass for energy production is an important strategy that is gaining increasing awareness all over the world (Palmer et al., 2014). Wood biomass will be an important source of renewable energy in the coming decades (Volk et al., 2004), today is a commercial reality as solid fuel in the form of wood chips,or pellets, and particular emphasis has been paid on the production of energy crops as feedstock for the growing energy markets (Mola-Yudego et al., 2014; Rahman et al., 2014). Short Rotation Woody Crops (SRWCs) are a type of energy crops based on forest plantations managed under agricultural practices i.e.: high intensive regimes in comparison with usual forestry practices (Heller et al., 2003), that are a promising source of cellulosic biomass for different final uses (Hinchee et al., 2009). These systems can contribute to mitigate the effects of climate change by sequestering CO_2 during the biomass growth (Briceño-Elizondo et al., 2006).. Some woody crops have the advantage of growing in lands considered marginal which increases the production of biomass at the same time that improves the economic development in rural areas, while not competing with the production of food or feed crops (Rahman et al., 2014). The resulting woody biomass can be used as solid fuel or, transformed into biofuels like bioethanol via biochemical platform or on the generation of *syngas* via pyrolysis (Dias and Arroja, 2012; Pérez-Cruzado et al., 2011).

In general, SRWCs make use of fast growing tree species that enable high biomass yields to be produced in short rotations (IEA, 2009). The crop rotation periods vary from 3-15 years (Rahman et al., 2014). Among those species used for SRWC, *Eucalyptus* is of high importance due to, among others: the large areas planted, accounting for 38% of total forest plantations throughout the world (Pérez-Cruzado et al., 2011), its high biomass yield and its lower water and nutrient requirements in comparison with other short rotation woody species such as poplar and willow (Catry et al., 2013; Pérez-Cruzado et al., 2011; Searle and Malins, 2014) and the well known silvicultural treatments (Rubilar et al., 2008). Specifically, *Eucalyptus globulus* Labill. (Tasmanian blue gum) is one of the most important hardwood species, having great economic relevance due to its use as raw material in pulp industries (Calviño-Cancela and Rubido-Bará, 2013). In 2004, there were about 2.5 million hectares planted worldwide (Catry et al., 2013), and special interest is being paid on the production of bioethanol from *Eucalyptus* biomass with a potential estimation ranging between 335 $L\cdot t^{-1}$ and 371 $L\cdot t^{-1}$ (Gonzalez et al., 2011).

In Chile, *E. globulus* is the second most abundant woody harvested species, and represents about 21% of the total planted forest area. *Eucalyptus* provides the main raw material source for the Chilean wood chip based industry, accounting for 54% of the total wood chip production. Especially relevant is the Region of Bio Bio with more than 38% of the total cultivated forests areas in the country contributing with 57% of the total national wood consumption for industrial uses Bleached *Eucalyptus* Kraft Pulp, paper, sawmilling, boards, wood chips and others.. In addition, 90% of the total forest plantations in the region have been established on eroded soils (without vegetation, sandy soils or depleted soils by farming practices) (INFOR, 2011).

The crop rotation periods of *E. globulus* vary from 8 to 12 years (FAO, 2001). However, during the last decades, research has been focused on intensive management practices and genetic improvement. These improvements have increased the productivity between 20% and 50% as well as reduced the rotations between 2 and 5 years (Rubilar et al., 2008), providing an enormous potential as bioenergy crop (Pérez-Cruzado et al., 2011). At the same time, the sustainability of SRWCs has been questioned, mainly due to their effects on soil nutrient levels and water use (Dimitriou et al., 2009). Since SRWCs are grown under more intensive management practices than traditional forestry, they comprise a larger number of operations that may cause several environmental undesired effects. The combustion emissions from fossil fuels (diesel or petrol) from machinery used in the harvesting and transportation activities contribute to numerous impact categories such as climate change, acidification and photochemical oxidation (González-García et al., 2009a). Also, nitrogen based emissions (such as N_2O or NO_3^-) derived from fertilisers, that affect impact categories such as climate change and eutrophication (González-García et al., 2013). To address this issue, Life cycle assessment (LCA) has been chosen as the tool to assess the environmental impacts derived from forest activities and forest products manufacture (Berg, 1997; Ronning and Brekke, 2014)

Previous studies have addressed the environmental impacts derived from *Eucalyptus* biomass production in European countries (Dias and Arroja, 2012; González-García et al., 2009b). However, the environmental conditions and locations in which forest biomass grow considerably affect tree growth rates, management systems and the wood-based products characteristics (May et al., 2012). Thus, the forest practices can considerably vary, not only between countries but also between regions (Berg and Lindholm, 2005; May et al., 2012). However and up to our knowledge, there is not any study available about the quantification of environmental impacts of forest practices in South American countries, such as Chile, being important forest biomass producers.

The purpose of this study is to estimate the potential environmental effects of *E. globulus* short rotation plantations dedicated to energy production in Chile, providing a collection of life cycle inventory data for a representative Chilean *Eucalyptus* SRWC system, and using the inventory of the production of fuels in Chile. The study aims to identify the most critical environmental issues (environmental *hotspots*), particularly focused on the production of biomass for bioethanol production.

2 Materials and methods

LCA is a quantitative procedure to evaluate the environmental burdens associated with a product, and to identify opportunities to attain environmental advantages. Thus, this methodology identifies the consumption of natural resources and the emissions to environmental compartments associated with the life cycle of the product under analysis (ISO, 2006a).

2.1 Goal and scope definition

The environmental assessment of a typical forest production scenario of *E. globulus* biomass in Chile has been performed following the ISO 14040 specifications (ISO, 2006) in order to identify and evaluate its environmental profile.

An intensive management scenario for *Eucalyptus* chip production for using in the second generation bioethanol production has been considered for the assessment, taking into account real forest management practices currently performed in the Region of Bio Bio, Chile. The assessment has been carried out from a cradle-to-gate perspective, i.e.: from raw materials production up to having the wood chips at forest gate. The predominate temperate in this region is characteristics of a Mediterranean climate (Díaz et al., 2009) with an average temperature of 17 ºC in the summer and 9 ºC in the winter, the average rain ranges between 20 mm and 250 mm per month in summer and winter, respectively.

2.2 Functional unit

The functional unit considered was defined as one cubic meter of fresh chips, including bark, at moisture of 60%, ready to be delivered to the bioethanol producing facility. This functional unit was selected due to all harvested wood (including bark) has the potential to be converted to ethanol (Gominho et al., 2012; Neupane et al., 2011). An average bark content of 10% (in volume) has been considered (INFOR, 1989). The average density considered for the *Eucalyptus* chips is 506 kg·m^{-3} (dry basis) (Labbé et al., 2013).

2.3 System boundaries

The forest scenario considers a standard hectare of commercial *Eucalyptus* cultivated in Chile for a total lifespan of 12 years under short rotation management, with rotation periods of 4 years (**Table 1**). The forest management scenario has been assessed from cradle (raw materials production) to forest gate perspective.

Table 1 around here

Thus, the further distribution and final conversion of *Eucalyptus* chips into bioethanol have been excluded from the assessment. The production of capital goods such as forest machines (e.g. tractors, chainsaws, forwarders, chipper, backhoe and spreaders) and implements (e.g. front blade and ripper) has been included within the system boundaries. The production of agrochemicals (herbicides and fertilisers) and *Eucalyptus* stems (seedlings), as well as their transportation up to the forest gate, has also been included within the system boundaries. The proposed production system of *Eucalyptus* chips has been divided in four main phases (**Figure 1)**:

***Figure 1** around here*

Phase 1 – Crop establishment

This phase consists of site preparation and stand establishment. The site preparation is based on deeply breaking-up compacted soils using a tractor connected with a ripper. Next, it is carried out a weed control to eradicate grass and perennial weeds. An herbicide (glyphosate) is applied using a spreader. Stand establishment consists of three activities: planting, application of herbicides and fertilising. The plantation is manually established at a density of 5,000 stems·ha^{-1}. The stems are planted in a double row system with 2 m between rows and 1 m between stems. After that, an herbicide (glyphosate) is applied using a spreader. Finally, the fertilisation is manually performed and a ternary fertiliser (16-8-12) is applied.

Phase 2 - Harvesting

The harvesting phase consists of three harvests or cutting cycles. In each cutting cycle, all processes are repeated every 4 years. First, agrochemicals are applied to remove undesirable vegetation and to improve the soil nutritional quality. The agrochemicals are separately applied at rates of 2 L·ha^{-1}

(using a spreader) and 100 kg·ha^{-1} (manually) for herbicide (glyphosate) and fertiliser (diammonium phosphate) respectively. These doses are also repeated three times, once per harvesting event (**Table 1**). After four years, all trees are manually harvested using chainsaws. Diameter at breast height (DBH) vary between 5 and 12 cm (Geldres et al., 2004). Finally, the biomass is extracted from the plantations with a forwarder and chipped on the forest road. The average biomass yield is around 18.8 m^{3}·ha^{-1}· yr^{-1}.

Phase 3 – Hauling

Activities related to the hauling take place at the end of the last cutting cycle. After all remaining trees have been harvested for last time, the stumps are removed with a backhoe. First the stumps collected are left in the forest; afterwards, the stumps are uprooted and chipped and the biomass is scattered on the soil in order to improve the soil quality.

Phase 4 – Logistic infrastructure

This phase includes the activities related with infrastructure maintenance and building. The necessary forest roads and firebreaks are carried out in the first year of the cultivation, whereas the activities related to the infrastructure maintenance of roads and firebreaks take place only once, during the last year, Both road and firebreak building and maintenance are performed with backhoe and tractor, implemented with a front blade.

2.4 Allocation

In this cradle-to-gate analysis, the total biomass production was considered as a whole. Thus, allocation has not been required since it has been considered that all biomass is chipped and delivered to bioethanol facilities. The remaining biomass generated in the forest site such as leaves, branches and stumps have not been computed in the analysis as by-products. It has been assumed that they remain in the plantation contributing to improve the soil quality. That perspective is in agreement with other forest-related LCA studies (Berg and Lindholm, 2005; Dias and Arroja, 2012; González-García et al., 2009b).

2.5 Life cycle inventory

Because the LCA was done in a "*cradle to gate*" perspective, the system of study is considered from the production of *Eucalyptus* stems. Special attention has been paid to this process since there is not available information in the literature concerning activities and procedures in a *Eucalyptus* nursery. Seedling production process includes all the activities performed at the nursery from the plantation of the seed until the seedling is ready to be sent to the forest plantations. The nursery is considered to be located at 75 km from the plantation area. The inventory data for the seedling production has been directly collected by means of surveys with workers at the nursery. **Table 2** details the inventory data related with the production of one stem. The seedling production includes two main stages: sprout production and stems production. Both stages are carried out in the same expanded polystyrene based pot using pine bark as substrate. The seeds are collected from the forest and stored in the nursery. However, seeds production has not been included in this study due to the lack of available information. The exclusion of seeds production from the system boundaries is in agreement with other forest-related LCA study reported in literature (González-García et al., 2014).

Table 2 *around here*

The seeds are manually planted at a rate of 200 seeds per m^2. It is important to remark that all the activities performed in the nursery are done manually. Seedling production takes place during a first stage of 4 weeks, requiring one initial application of fertiliser (urea) and fungicide ($4\ g \cdot m^{-2}$ and $1.5\ mg \cdot m^{-2}$ respectively). The irrigation is every 8 hours ($0.5\ L \cdot m^{-2}$). After that, half of the seedlings are manually selected. Seedling final production stage is performed during 3 months where a ternary fertiliser is manually applied once a week ($1.5\ g \cdot m^{-2}$) and insecticide once a month ($10\ mL \cdot m^{-2}$). The irrigation is every 12 hours ($0.35\ L \cdot m^{-2}$).

The estimation of fuel requirements in site preparation, stand establishment, harvesting, hauling and logistic infrastructure related activities were collected directly by surveys with forest landowners and estimated from local trials and experts knowledge. Primary and site-specific inventory concerning the forest machinery and implements used (operating hours and input rates) are presented in **Table 1** and their respective sources in **Table 3**. Nitrogen based emissions to air from fertilisers have been calculated following the emissions factors proposed by Nguyen et al. (2011). Phosphate emission to water has been calculated according to the emission factor proposed by Rossier (1998). Inventory data concerning logistic infrastructure related stage (road and firebreak building and maintenance) has been taken from Dias and Arroja (2012) assuming the same conditions. The inventory data for the fossil fuels (diesel and petrol) have been estimated according to the production in Chile (Morales et al., 2015).

Table 3 *around here*

The summarised inventory data managed for the forest management operations associated with the production of the functional unit (1 m^3 *Eucalyptus* chips including bark) is shown in **Table 4**.

***Table 4** around here*

Following the methodological approach taken in previous LCA studies of forest systems, the forest production system under study has been assumed to be in a steady state with respect to both carbon stock and management operations (Dias et al., 2007; May et al., 2012). It involves that there is no change in the forest biomass productivity, soil organic matter stocks, availability of nutrients and water over the steady state. The amount of CO_2 uptake during the biomass growth has been assumed to be equal to the amount of CO_2 released to the atmosphere due to wood oxidation at the end of its life cycle (Dias and Arroja, 2012; González-García et al., 2013).

Finally, the environmental assessment has been carried out using the ReCiPe Midpoint method (H), version 1.06 for the Life Cycle Impact Assessment (LCIA) (Goedkoop et al., 2009). The midpoint methodology was used to understand the complexity of impacts to air, water and soil to the environment for the scenario of *Eucalyptus* chips production under study. The analysis for the forest system has been calculated in terms of thirteen impact categories: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), photochemical oxidant formation (POF), human toxicity (HT), terrestrial ecotoxicity (TET), fresh- water ecotoxicity (FET), marine ecotoxicity (MET), water depletion (WD) and fossil fuel depletion (FD). The LCA software SimaPro v7.8 (Prè-Consultants, 2014) has been used to construct the LCA model and undertake the impact assessment calculations.

3 Results

Results summarized in **Table 5** show the potential environmental impacts of the short rotation forest crop for bioenergy system under study and the contributions to the global environmental profile for each phase (**Figure 2**) involved in the *Eucalyptus* chips production life cycle. Phase 2, considering three repeated harvesting cycles, is the most responsible stage of the environmental burdens in all the categories under assessment with ratios ranging from 56% to 99%.

***Table 5** around here*

***Figure 2** around here*

Figure 3a displays the distribution of environmental impacts derived from the harvesting phase per cutting events. Since it was assumed that the yield of *Eucalyptus* biomass and the processes in the plantation under assessment are the same for each harvesting event, the distributing ratios are exactly the same.

***Figure 3** around here*

Each harvesting cycle is divided into five processes or activities: application of herbicides, fertilisation, felling, forwarding and chipping. **Figure 3b** details the contribution of each process involved in each harvesting cycle. The main process responsible of the highest contributing ratios in all the impact categories under assessment is fertilisation. The contributions range from 35% to 99% depending on the category. The impact categories more affected by fertilisation are TA (92%), FE (97%), ME (92%), OD (65%), CC (72%), TET (84%), FET (53%), MET (57%) and WD (95%) mostly due to emissions derived from the fertiliser production (such as nitrogen). Moreover, emissions derived from fertiliser application, such as ammonia emission into air and phosphate and nitrate emission into water, present an outstanding contribution in terms of TA, ME and CC.
The second key process according to **Figure 3b** is the forwarding activity with contributing ratios higher than 30% in categories such as OD, HT, FET, MET and FD. It is mainly due to emissions derived from the machinery production (such as Halon 1301 and barium), the production of diesel requirements and their corresponding tailpipe emissions.

The chipping process contributes with ratios lower than 10% in all the impact categories evaluated, except in HT, POF and FD (15%, 21% and 25% respectively). The chipping step is a highly energy intensive process. Thus, the environmental loads derived from this forest process are mainly related with the emissions derived from the production and use of diesel. HT is mainly caused by water emissions such as barium and manganese derived from diesel production. The fossil requirement also affects to FD. While, the derived tailpipe emissions such as NO_x affect POF.

The felling process presents a negligible contribution (lower than 1%) to all the environmental impacts derived from the cutting cycle. This low contribution is mostly related with the low petrol consumption since this activity is performed using a chainsaw.

Finally, the process related to the application of herbicides presents a negligible contribution in all the impact categories (lower than 0.1%) being the environmental loads derived from the herbicide production itself.

It is important to highlight that the fuel requirements in Phase 2 represent around 57% of the total fuel consumed for all the forest activities. Thus, two activities are the main responsible of these results: the forwarding and the chipping processes with ratios of 24% and 32% respectively regarding the total fuel consumed.

Figure 3c details the relative contributions from each factor involved in the fertilising process (the main environmental *hotspot*). The fertilising related factors are the fertiliser production, the fertiliser distribution up to the forest gate (in this case, by lorry) and the emissions (to air and water) derived from its application. The diammonium phosphate production requires large amounts of energy and minerals, which considerably affect the environmental profile. However, categories such as CC, TA and ME are mainly affected by nitrogen (N_2O, NH_3 and NO_3^-) and phosphate emissions derived from the fertiliser application.

The second most important phase in terms of environmental burdens is Phase 1 (crop establishment). This stage includes the site preparation and the stand establishment related activities. Contributions from this phase add to 37% in OD and, in the remaining categories, the contributing ratios are lower than 10% (**Figure 2**). The following activities have been considered: ripping, weeding with herbicides (site preparation), planting, application of herbicides (stand establishment) and fertilising. As shown in, **Figure 4a**, the ripping process is the main responsible of environmental loads derived from the crop establishment related activities except in terms of WD, TET, OD and TA. In the remaining categories, the contributing ratios range from 31% to 72%. A large machine (a tractor connected with a ripper) mechanically performs the ripping process. Thus, the contributions derived from the ripping are associated with the production of the machinery, the production of diesel requirements as well as with the corresponding diesel combustion emissions.

The planting process contributes mainly in OD (80%), TET (49%) and WD (84%). In the remaining categories, the contributions range from 13% to 29%. **Figure 4b** shows the activities related to the planting process: the seedling production, the transport of stems from the nursery to the forest site and the planting in itself. However, this last activity has not been included in the figure due to its negligible contribution since it is manually performed using shovels. The seedling production is the main responsible of impacts derived from the planting process in almost all the impact categories except in the categories of CC, POF, and FD (44%, 27% and 44%, respectively). In the remaining categories, it contributes with ratios higher than 60%, mainly due to insecticide production, pine bark production (used as substrate) and emissions derived from agrochemicals application (such as NO_2, N_2, NO_x, NH_3 and phosphate).

The fertilising process is the main contributor in categories such as TA (62%) and FE (48%) as well as this process presents a remarkable contribution in ME and CC (33% and 36% respectively) (**Figure 4a**). The fertiliser used in Phase 1 is a ternary fertiliser (16% N, 8% P_2O_5, 12% K_2O). In line with the results reported for Phase 2, the environmental impacts derived from the fertilising step are mainly related with its production as well as with the NH_3 and phosphate emissions associated with the application of this agrochemical.

The diesel requirements in Phase 1 represent only 3% of the total diesel consumption all over the life cycle of the forest system under study. This is due to ripping being the unique process with diesel requirements.

Figure 4 *around here*

The third phase with an outstanding contribution to the environmental profile derived from *Eucalyptus* chips production is Phase 4 (Logistic infrastructure) (**Figure 2**). This phase involved the building and maintenance of roads and firebreaks. The main impact categories affected by this stage are: HT, POF and FD with contributing ratios ranging from 12% to 17%. **Figure 5** details the distribution of environmental loads derived from Phase 4.

According to the **Figure 5**, the road building process is the main responsible of contributions derived from Phase 4 in all categories (28%-61% of total contributions to all the categories), followed by road maintenance (~23% in all of them). While, the activities related to firebreak building and firebreak maintenance are responsible in all the impacts categories under assessment for ratios ranging from 10% to 25% and 5% to 23%, respectively.

Large machines perform all these activities: tractors connected to front blades and backhoes. Thus, contributions to environmental impact categories are associated with the production of this machines and diesel requirements as well as with the corresponding tailpipe emissions.
Moreover, diesel requirements in this phase are 32% of the total diesel consumption all over the life cycle of the forest system under assessment.

Figure 5 *around here*

Phase 3 (related to the hauling) is the stage with the lowest contributing ratios in the environmental profile of the forest system under analysis (**Figure 2**). This phase contributes with ratios ranging from 5% to 8% in categories such as CC, OD, HT, POF, FET, MET and FD. However, the contribution to TA, FE and ME was lower than 1%. The diesel requirements in this phase represent 8% of the total diesel consumption in all the forest activities.

Table 6 displays the contributions from each process involved to the different impact categories under assessment. Thus, the environmental key factors (or *hotspots*) can easily be identified. The three fertilising activities and the forwarding processes (all of them performed in Phase 2) are the environmental *hotspots* in the environmental profile derived from the *Eucalyptus* chips production system under a short rotation crop regime.

Table 6 *around here*

4 Discussion

This study analyses the environmental effects caused by the production of *E. globulus* chips, a potential raw material for energy and bioethanol production.

The fertilising activities followed by the forwarding process were the environmental *hotspots* identified in the life cycle of *Eucalyptus* biomass production. The on-field emissions derived from the fertiliser application as well as the fertilisers production also showed important contributions to the environmental impact categories evaluated. In addition, the felling process (i.e. harvesting) and the forwarding process were also identified as *hotspots* in similar studies (Dias and Arroja, 2012; González-García et al., 2009b).

However, the results showed some differences concerning previous studies on the environmental assessment of *E. globulus* biomass production in Portugal (Dias and Arroja, 2012; Dias et al., 2007) and Spain (González-García et al., 2009b). The European scenarios presented several methodological differences in terms of functional unit, and system boundaries. For instance, whereas this study presented the environmental results respect to a functional unit of one cubic meter, including bark, of fresh chips, these European studies were presented per cubic meter of fresh roundwood under bark (i.e.: excluding the bark content). With respect to the bark content, our study considered 10% (by volume) with 60% of moisture. However, González-García et al. (2009b) considered a bark content of 16% (by volume) and 40% the moisture content.

Similarly, there were differences regarding the systems boundaries considered. In this study, all the forest activities involved from site preparation to chipping (also in the forest site) have been taken into account, including the seedling production, whereas these previous studies excluded the chipping (which is commonly performed in sawmills) and the production of seedlings although included all forest activities performed in the stand from site preparation to biomass harvest, considering also the loading of logs into the trucks for final distribution. Concerning the inclusion or not within the system boundaries of activities involved in the production and maintenance of roads and firebreaks, there are also disagreements. These activities were included in our study and also in the Portuguese case studies, but they were excluded in the Spanish case study. Yet again, this study included the production of forest machinery whereas it was excluded from the system boundaries in the European scenarios.

The environmental profiles could be compared in terms of two impact categories (climate change - CC and acidification - TA) harmonising the same functional unit and system boundaries for the Chilean, Spanish and Portuguese case studies. A simple method would be to use a common functional unit based on 1 m^3 roundwood under bark and year (1 m^3ub·yr), and excluding in the system boundaries the chipping process, the seedling production process, the logistic infrastructure related activities, the machinery production and the log loading into trucks. **Figure 6a** shows the fluctuations found on the environmental results in terms of these impact categories. The results reflect that the differences in forest management between European and Chilean plantations of *Eucalyptus* affect the type of machinery required (large or small machines), the fuel consumption, the agrochemicals requirement and the productivity of the plantations. For example, in the Spanish case study, the stand was not managed under a short rotation regime and a lifespan of 15 years was assumed. In the Portuguese case study lifespans of 36 years were considered with three rotation intervals of 12 years each. Concerning operations, in the Spanish case study, only ripping and cut-over clearing processes were performed using tractors implemented with discs and rippers, and in the Portuguese case studies, more activities were carried out: the stump removal, the clearing step, the ripping, the subsoiling and the fertilising. All of them required tractors with the corresponding implements. In Chile, a ripping process followed by herbicide application was performed before planting. The ripping was performed with a ripper connected to tractor and the herbicide application with a spreader, with no fertiliser application. Between the planting (in all case studies, manual) and the felling, different processes could be carried out. These processes depended on the lifespan, the soil quality and the rotation cycles. Thus, in the Spanish case only one cleaning, one pesticide application and two fertilising processes were performed. In the Portuguese case studies up to eight cleaning and six fertilising processes were conducted all over the lifespan. In our case study, there was not any cleaning process and up to four fertilising and weeding activities were performed.

All these differences on the forest activities resulted on large differences on the fossil fuels requirements (either petrol or diesel). **Figure 6a** shows the fuel requirements in MJ.

Figure 6 *around here*

Concerning the dosage of fertiliser, in the Portuguese case, it was required an application of 0.3 $kg \cdot m^{-3} ub \cdot yr^{-1}$ of ternary fertiliser, 0.5 $kg \cdot m^{-3} ub \cdot yr^{-1}$ of N-based fertiliser and 1.2 $kg \cdot m^{-3} ub \cdot yr^{-1}$ of superphosphate fertiliser all over the forest system. In the Spanish case study, it was applied 2.3 $kg \cdot m^{-3} ub \cdot yr^{-1}$ of ternary fertiliser. While in our study, the total fertiliser dosage was slightly lower than the European cases: 0.2 $kg \cdot m^{-3} ub \cdot yr^{-1}$ of ternary fertiliser and 1.5 $kg \cdot m^{-3} ub \cdot yr^{-1}$ of diammonium phosphate fertiliser. These differences on the fertiliser doses are related with differences on the soil quality and the intensity of cultivation regime (Rubilar et al., 2008). An optimization in the fertiliser dosage together with the choose of the best moment of application may reduce nutrients losses in the soil (González-García et al., 2009b). Thus, the environmental impacts related to the production and use of fertilisers could be reduced.

Finally, remarkable differences also exist concerning the biomass yields between countries (**Figure 6b**) In European conditions, a biomass yield of around 10 $m^3 ub \cdot ha^{-1} \cdot yr^{-1}$ was assumed regardless the management regime (Portuguese case), whereas in Chilean plantations, an average biomass yield of up to 16.9 $m^3 ub \cdot ha^{-1} \cdot yr^{-1}$, due to more suitable climatic and soil conditions in addition to the intensive forest activities performed in the SRWC regimes compared to the plantations without rotation cycles, as the intensive agricultural regime in short rotation plantations increases the biomass production (González-García et al., 2012).

5 Conclusions

This is one of the first studies, up to the authors' knowledge, providing an environmental life cycle analysis concerning wood biomass for bioenergy production in Chile. The results achieved in this study showed that the harvesting phase is the main responsible of environmental impacts with a remarkable contribution to all the categories. The fertilising and forwarding processes were identified as the environmental *hotspots* mainly due to the fertilisers and diesel requirements. A similar performance was found between this study and other LCA studies of eucalypt forest systems in Europe. These results suggested that both fertiliser dosage and fuel consumption in forest activities should be optimised in order to decrease most effectively the global environmental impacts. The LCA study presented provides a solid basis to build comprehensive environmental studies for wood products in Chile. The results reported will be useful in decision making especially concerning forest industries using *E. globulus* as raw material, especially those focused to liquid biofuels production.

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Table 1. Labour sequence considered in the eucalyptus chip production system under assessment based on real practices performed in Chile.

Phase	Time (year)	Operation		Machinery A		Implement		$h \cdot ha^{-1}$	Fuel consumption ($L \cdot ha^{-1} \cdot yr^{-1}$)	Input rates
					Power (kW) Weight (kg)		Weight (kg)			
Phase 1	-1	Site Preparation	Ripping	Tractor	205 9357	Ripper	4250	5	5.4	-- --
			Herbicides application	Spreader	-- 4.3	--	--	12	--	3.5 L/ha Herbicide [b]
	0	Stand establishment	Planting	--	-- --	--	--	--	-- [a]	5000 stems
			Herbicides application	Spreader	-- 4.3	--	--	12	--	2.5 L/ha Herbicide [b]
			Fertilising	--	-- --	--	--	--	-- [a]	32 kg/ha Ternary fertiliser [c]
Phase 2	1	1st cutting cycle	Herbicides application	Spreader	-- 4.3	--	--	12	--	2 L/ha Herbicide [b]
			Fertilising	--	-- --	--	--	--	-- [a]	100 kg/ha Diammonium phosphate [d]
	4		Felling	Chainsaw	3.4 5.6	--	--	28	0.8	-- --
			Forwarding	Forwarder	125 12000	--	--	11.8	14.5	-- --
			Chipping	Chipper	66.2 770	--	--	6	19.9	-- --
	5	2nd cutting cycle	Herbicides application	Spreader	-- 4.3	--	--	12	--	2 L/ha Herbicide [b]
			Fertilising	--	-- --	--	--	--	-- [a]	100 kg/ha Diammonium phosphate [d]
	8		Felling	Chainsaw	3.4 5.6	--	--	28	0.8	-- --
			Forwarding	Forwarder	125 12000	--	--	11.8	14.5	-- --
			Chipping	Chipper	66.2 770	--	--	6	19.9	-- --
	9	3rd cutting cycle	Herbicides application	Spreader	-- 4.3	--	--	12	--	2 L/ha Herbicide [b]
			Fertilising	--	-- --	--	--	--	-- [a]	100 kg/ha Diammonium phosphate [d]
	12		Felling	Chainsaw	3.4 5.6	--	--	28	0.8	-- --
			Forwarding	Forwarder	125 12000	--	--	11.8	14.5	-- --
			Chipping	Chipper	66.2 770	--	--	6	19.9	-- --
Phase 3	12	Stump removal	Backhoeing	Backhoe	119 20000	--	--	6.5	15.1	-- --

Phase 4	1	Infrastructure establishment	Road building	Tractor	205 9357	Front blade	930	1.7	15	-- --
	12		Road maintenance	Tractor	205 9357	Front blade	930	0.6	14	-- --
	1		Firebreak building	Backhoe	119 20000	--	--	0.23	15	-- --
	12		Firebreak maintenance	Backhoe	119 20000	--	--	0.06	14	-- --

[a] Manual activity, no fuels requirements; [b] Glyphosate; [c] 16%N, 8% P_2O_5, 12% K_2O; [d] 18%N, 46% P_2O_5

Table 2. Inventory data associated with the seedling production of *E. globulus* (per unit of stem).

Inputs	**Value**	**Unit**
Inputs from Technosphere		
Pine bark	2.40	dm^3
Expanded polystyrene	6.30	µg
Agrochemicals		
Urea	0.04	g
Fungicide [a]	15	µg
Ternary fertiliser [b]	0.19	g
Insecticide [c]	0.30	mL
Inputs from Environment		
Water	1.08	L
Outputs	**Value**	**Unit**
Output to Technosphere		
E. globulus stem	1	stems
Output to Environment		
Emissions to air		
NO_2	1.31	mg
N_2	3.91	mg
NO_x	0.62	mg
NH_3	3.30	mg
Emissions to water		
PO_4^-	0.13	mg

[a] Thiram fungicide; [b] Phostrogen fertiliser: 12% N, 10% P_2O_5, 27% K_2O; [c] Cyperkill

Table 3. Summary of data used for the environmental analysis of eucalyptus plantations.

Data required	**Data source**
Machinery type, operation hours, agrochemical rate Fuel consumption in forest machinery Agrochemicals supply (distance, transport mode) Seedling production Biomass production per ha and year	Field data compiled from forest landowners and local trials*
Fossil fuels production	Morales et al. (2015)
Agrochemicals production	Ecoinvent database ® (Althaus et al., 2007)
Machinery production	Ecoinvent database ® (Nemecek and Kägi, 2007)
Pine bark production	González-García et al. (2014)
Expanded polystyrene	Ecoinvent database ® (Hischier, 2007)
Diffuse emissions from agrochemicals application	Nguyen et al. (2011) and Rossier (1998)
Combustion emissions from forest machinery	Ecoinvent database ® (Nemecek and Kägi, 2007)
Combustion emissions from transport	Ecoinvent database ®(Spielman et al., 2007)
Infrastructure establishment	Dias and Arroja (2012)

* Data provided by the Soils, Nutrition and Sustainable Forest Production lab and the Forest Biomass & Bioenergy lab, Faculty of Forest Sciences, Universidad de Concepción, Chile.

Table 4. Inventory data for the forest management operations associated with the production of *E. globulus* chips (per functional unit).

Inputs	**Value**	**Unit**
Inputs from Technosphere		
E. globulus stems	22	stems
Fossil fuels		
Diesel	0.68	kg
Petrol	7.78	g
Lubricants	30	g
Agrochemicals		
Herbicide [a]	87	g
Ternary fertiliser [b]	0.14	kg
Diammonium phosphate [c]	1.33	kg
Transport		
Lorry 3.5 t	0.52	tkm
Outputs	**Value**	**Unit**
Output to Technosphere		
Wood chips	1	m^3
Output to Environment		
Emissions to air		
SO_2	7.26	g
NO_x	40	g
CO_2	2.38	kg
CO	9.17	g
VOC	5.40	g
N_2O	24	g
Pentane	0.24	g
NMVOC	24	mg
CH_4	97	mg
Particulates	0.89	g
N_2	70	g
NH_3	59	g
Emissions to water		
NO_3^-	1.51	kg
PO_4^-	12	g

[a] Glyphosate ; [b] 16%N, 8% P_2O_5, 12% K_2O; [c] 18%N, 46% P_2O_5

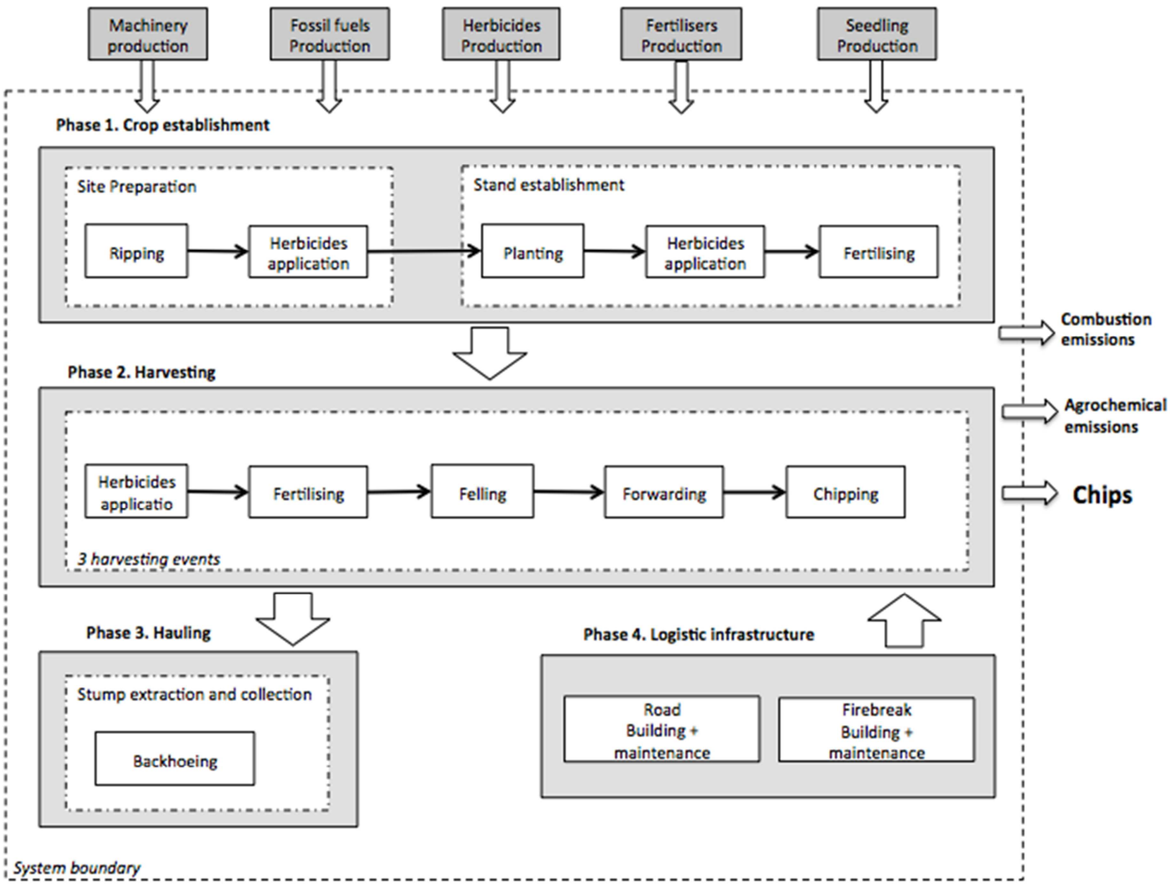
Table 5. Impact assessment results associated with the production of 1 m^3 of *Eucalyptus* chips.

Impact category	**Unit**	**Total**
Climate change (CC)	kg CO_2 eq	16.3
Ozone depletion (OD)	kg CFC^{-11} eq	$7.3 \cdot 10^{-7}$
Human toxicity (HT)	kg 1,4-DB eq	4.6
Photochemical oxidant formation (POF)	kg NMVOC	$7.3 \cdot 10^{-2}$
Terrestrial acidification (TA)	kg SO_2 eq	0.25
Freshwater eutrophication (FE)	kg P eq	$3.8 \cdot 10^{-2}$
Marine eutrophication (ME)	kg N eq	0.36
Terrestrial ecotoxicity (TET)	kg 1.4-DB eq	$1.3 \cdot 10^{-3}$
Freshwater ecotoxicity (FET)	kg 1.4-DB eq	$7.4 \cdot 10^{-2}$
Marine ecotoxicity (MET)	kg 1.4-DB eq	$8.4 \cdot 10^{-2}$
Water depletion (WD)	m^3	0.29
Fossil depletion (FD)	kg oil eq	3.6

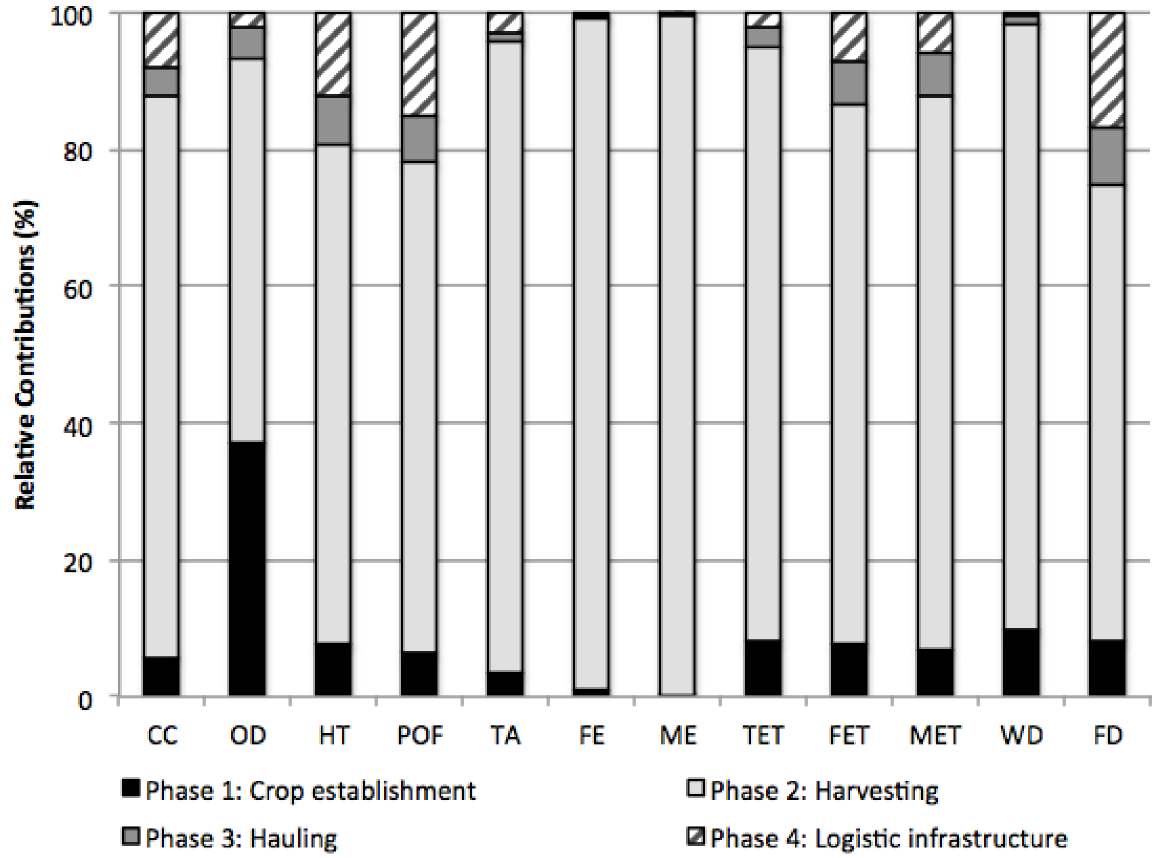
Table 6. Contributions of forest activities involved in *Eucalyptus chips* production to environmental flows.

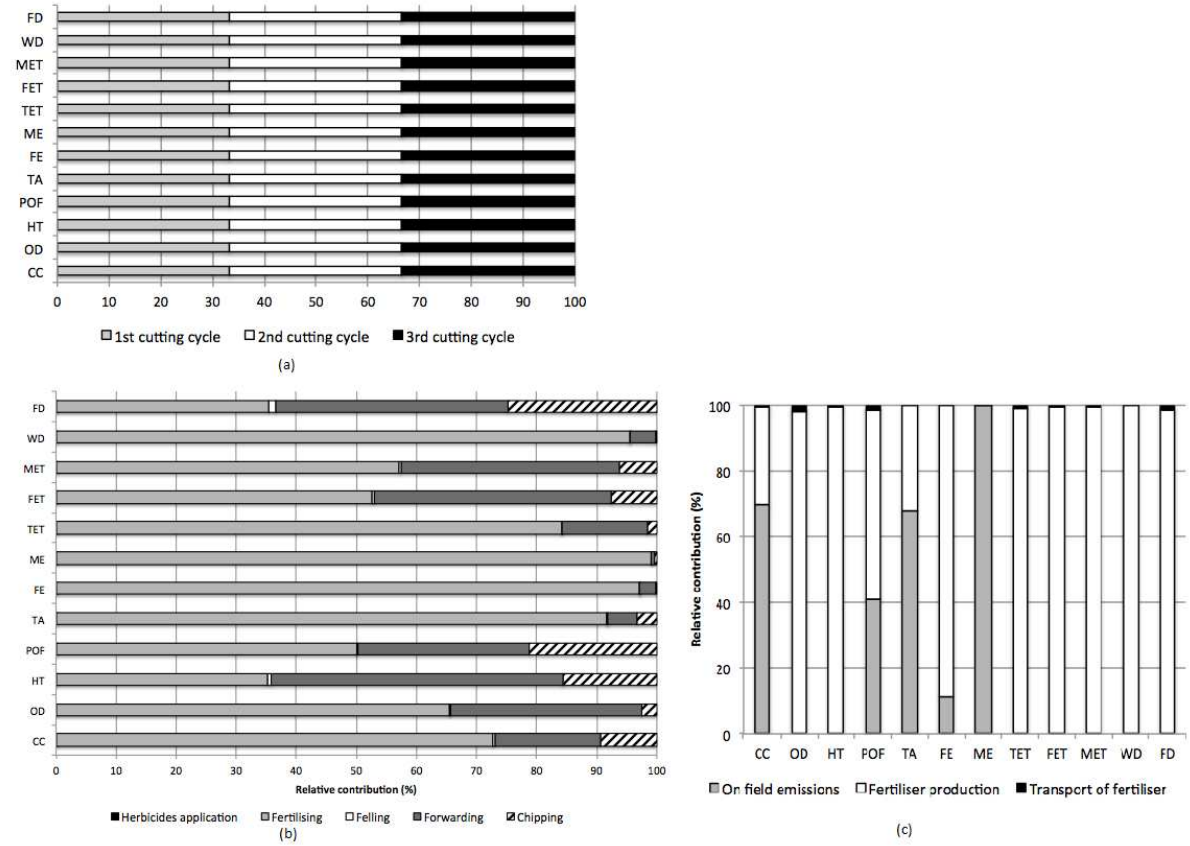
Operation			CC	OD	HT	POF	TA	FE	ME	TET	FET	MET	WD	FD
Phase 1	Site preparation	Ripping												
		Herbiciding												
	Stand establishment	Planting												
		Herbiciding												
		Fertilising												
Phase 2	1st cutting cycle	Herbiciding												
		Fertilising												
		Felling												
		Forwarding												
		Chipping												
	2nd cutting cycle	Herbiciding												
		Fertilising												
		Felling												
		Forwarding												
		Chipping												
	3rd cutting cycle	Herbiciding												
		Fertilising												
		Felling												
		Forwarding												
		Chipping												
Phase 3	Stump removal	Backhoeing												
Phase 4	Infrastructure establishment	Road building												
		Road maintenance												
		Firebreak building												
		Firebreak maintenance												

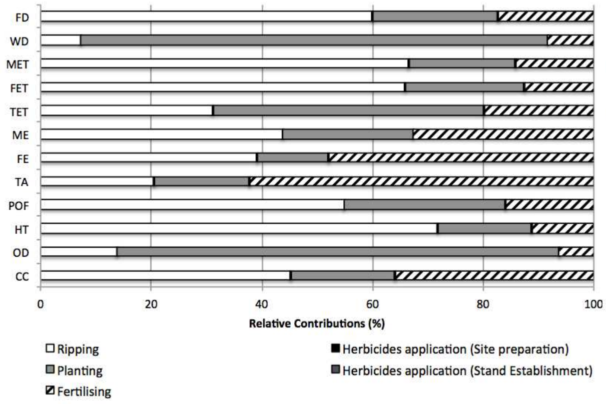
< 0,99%	1-2,99%	3-6,99%	7-9,99%	10-19,99%	20-29,99%	>30%



Machinery production
Fossil fuels Production
Herbicides Production
Fertilisers Production
Seedling Production
Phase 1. Crop establishment
Site Preparation
Ripping
Herbicides application
Stand establishment
Planting
Herbicides application
Fertilising
Combustion emissions
Phase 2. Harvesting
Agrochemical emissions
Herbicides applicatio
Fertilising
Felling
Forwarding
Chipping
Chips
3 harvesting events
Phase 3. Hauling
Stump extraction and collection
Backhoeing
Phase 4. Logistic infrastructure
Road Building + maintenance
Firebreak Building + maintenance
System boundary


100
80
60
40
20
0
Relative Contributions (%)
CC
OD
HT
POF
TA
FE
ME
TET
FET
MET
WD
FD
Phase 1: Crop establishment
Phase 2: Harvesting
Phase 3: Hauling
Phase 4: Logistic infrastructure


FD
WD
MET
FET
TET
ME
FE
TA
POF
HT
OD
CC
0 10 20 30 40 50 60 70 80 90 100
1st cutting cycle
2nd cutting cycle
3rd cutting cycle
(a)
Relative contribution (%)
Herbicides application
Fertilising
Felling
Forwarding
Chipping
(b)
Relative contribution (%)
CC OD HT POF TA FE ME TET FET MET WD FD
On field emissions
Fertiliser production
Transport of fertiliser
(c)


FD
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MET
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TET
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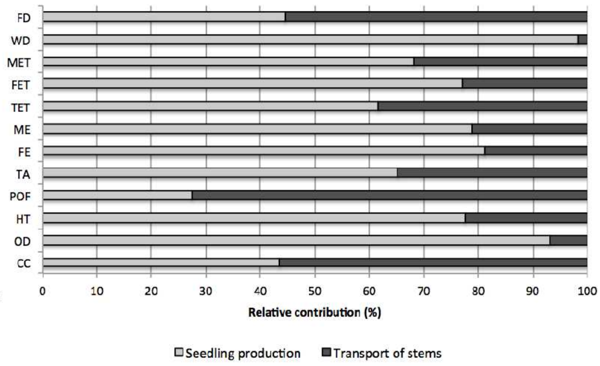
FE
TA
POF
HT
OD
CC
0
20
40
60
80
100
Relative Contributions (%)
Ripping
Planting
Fertilising
Herbicides application (Site preparation)
Herbicides application (Stand Establishment)

(a)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CC
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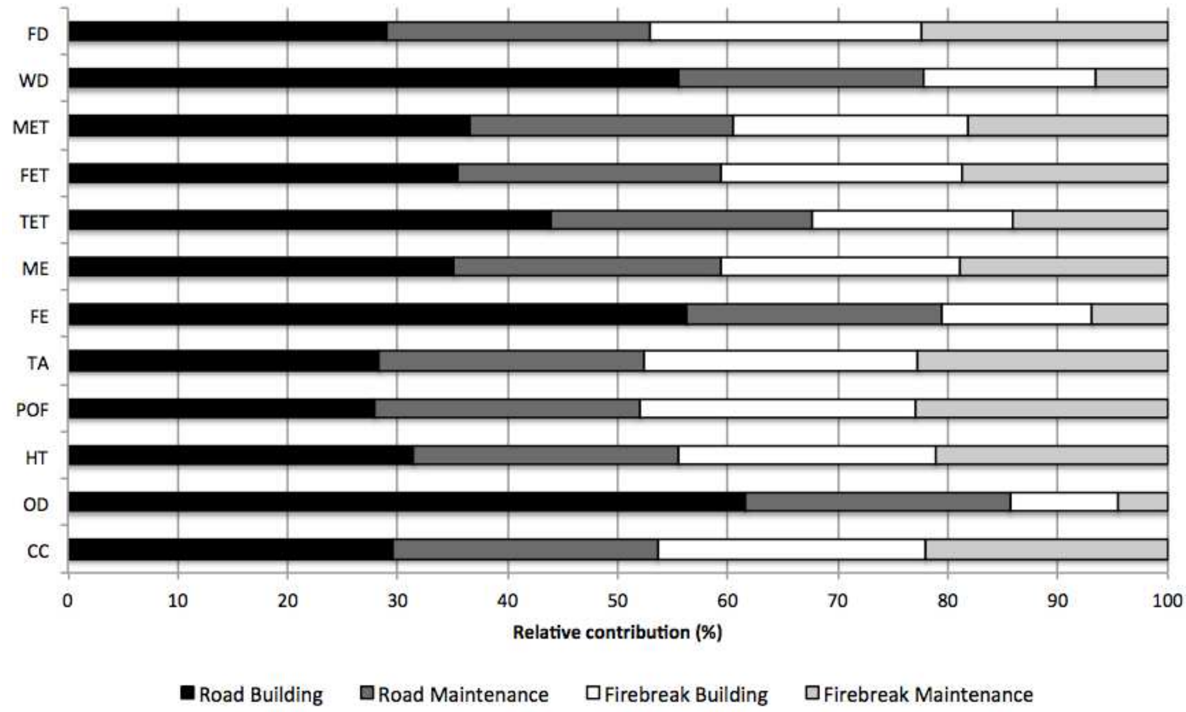
70
80
90
100
Relative contribution (%)
Seedling production
Transport of stems

(b)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CC
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10
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50
60
70
80
90
100
Relative contribution (%)
Road Building
Road Maintenance
Firebreak Building
Firebreak Maintenance

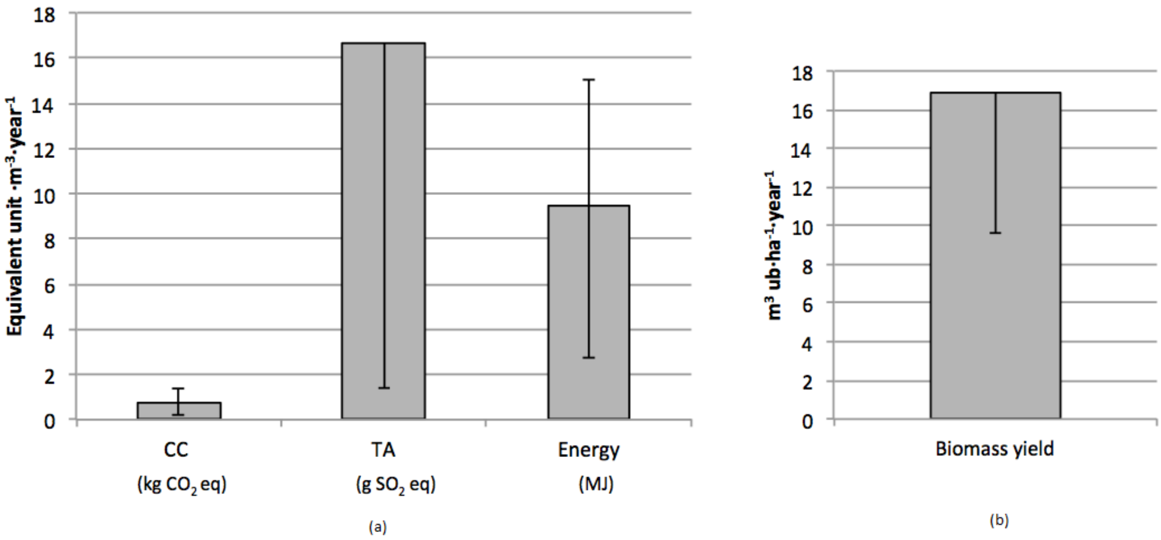
18
16
14
12
10
8
6
4
2
0
Equivalent unit ·m-3·year-1
CC
(kg CO2 eq)
TA
(g SO2 eq)
Energy
(MJ)
(a)
m3 ub·ha-1·year-1
Biomass yield
(b)

FIGURE CAPTIONS

Figure 1. Scheme of the system boundaries considered for the production of eucalyptus chips.

Figure 2. Contributions to the environmental profile per each phase involved in eucalyptus chips production life cycle.

Figure 3. Distribution of environmental impacts derived from Phase 2 - Harvesting. a) Distribution per cutting cycles; b) Distribution per processes involved in each cutting cycle; c) Distribution per factors involved in the fertilising process.

Figure 4. Contribution to environmental profile corresponding to the Phase 1- Crop establishment. a) Contribution from process involved in Phase 1 b) Contribution from planting process.

Figure 5. Contribution to environmental profile from processes involved in Phase 4- Logistic infrastructure.

Figure 6. a) Fluctuations on environmental impacts in terms of Climate Change (CC) and terrestrial acidification (TA); b) Fluctuations on the biomass yield derived from *E. globulus* plantations according to the literature.

Highlights

1. LCA of short rotation *E. globulus* for bioenergy production was performed
2. Real forest information corresponding to Chilean practices was considered
3. The forest scenario considers a lifespan of 12 years under a short rotation regime
4. The harvesting phase was the main responsible of environmental impacts
5. Fertilising and forwarding processes were identified as the environmental *hotspots*