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Title: Environmental Life Cycle Assessment of Industrial Pine roundwood production in Brazilian forests

Article Type: Research Paper

Keywords: Brazil; Environmental profile; LCA; Forest system; Pinus oocarpa

Corresponding Author: Ms. Sara González-García, Dr.

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Abstract: Pine (Pinus oocarpa) wood has great economic importance in Brazil. Pine stands represent the second largest reforested area in the country due to their industrial interest. Combining the relevance of industrial pine stands in the country and corresponding environmental concerns, this current study aims to identify and quantify the environmental impacts derived from industrial pine roundwood production in Brazil. The environmental study was developed considering the Life Cycle Assessment (LCA) methodology according to ISO14040 framework. The study convers the life cycle of pine roundwood production from cradle-to-forest gate perspective and considers the current practices in the country. The production system was divided in five main stages: Soil preparation, Seedlings plantation, Forest management, Forest harvesting and Infrastructure establishment. The environmental profile was estimated considering characterization factors from the ReCiPe method, in terms of twelve impact categories. According to the results, Forest harvesting stage was identified as the environmental hotspot being the main responsible of contributions to nine impact categories under assessment with contributing ratios ranging from 21% (e.g., freshwater eutrophication) to 76% (e.g., photochemical oxidants formation). The high amount of fossil fuel required by heavy machinery used in the activities involved in this stage is behind this result. Soil preparation stage reported also an outstanding contribution in categories such as freshwater eutrophication (37%) and toxicity related categories (≈35%). The rationale behind these contributions is associated with the use of chemical fertilizers, mostly superphosphate. The identification of the environmental hotspots in forest biomass production can assist the Brazilian forest practitioners to improve the environmental profile by means of the optimization of forest practices.

Response to Reviewers: Dear Dr. Paoletti, Ms. Ref. No.: STOTEN-D-18-02684 ”Environmental Life Cycle Assessment of Industrial Pine roundwood production in Brazilian forests”

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Looking forward to hearing from you.
Yours sincerely,

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*Title Page

Environmental Life Cycle Assessment of Industrial Pine roundwood production in Brazilian forests

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[3]Department of Chemical Engineering, School of Engineering, University of Santiago de Compostela. 15782- Santiago de Compostela, Spain.

* Corresponding author: sara.gonzalez@usc.es

***Author agreement**

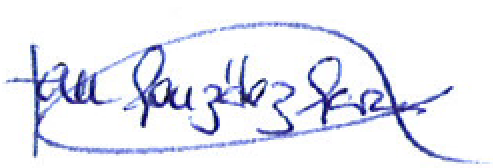
Author's agreement

We the undersigned declare that the manuscript entitled " **Environmental Life Cycle Assessment of Industrial Pine roundwood production in Brazilian forests**" is original, has not been full or partly published before, and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by the undersigned.

We understand that the Corresponding Author is the sole contact for the editorial process. The corresponding author **Dr. Sara González-García** is responsible for communicating with the other authors about process, submissions of revisions, and final approval of proofs."

Signature of all authors :



Dr. Sara González-García on behalf of all the authors

Prof. Dr. Elena PAOLETTI

Associate Editor

Science of the Total Environment

20th May 2018

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Abstract

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1. Introduction

In Brazil, the forestry activities have great relevance not only due to the extensive forest cover that exists in the country but also because of their employment capacity and incomes generation within the sector. The last study performed by the Brazilian forest service (IBÁ, 2017) showed that approximately 60% of the Brazilian national territory (493.5 million ha) is covered by forest. Moreover, it was estimated that the forestry sector derived on 3.7 million direct and indirect jobs and the income generated by the sector was around 3 billion US dollars (IBÁ, 2017).

Regarding to the reforestation area in Brazil, it corresponds to 7.84 million ha, and of this total, around 20% corresponds to pine-based reforested stands. Pine is the second most important forest specie planted in the country, after Eucalyptus ~~specie, in which most of this planting are~~, being mostly destined ~~for~~to the production of ~~pulp~~ cellulosic pulp (IBÁ, 2017). Throughout many years, different pine species originating from different countries all over the world were introduced in Brazil to produce the biomass used as raw material in wood industry for multiple applications (Shimizu, 2006). European pine such as *Pinus canariensis* was introduced in Brazil for silvicultural purposes in 1936 (Shimizu, 2006). American pine species such as *Pinus palustris*, *Pinus echinata*, *Pinus elliottii* and *Pinus taeda* were introduced by Forestry Service of São Paulo State (Shimizu, 2006) in 1948. *Pinus elliottii* and *Pinus taeda* stand out between others due to their fast growth in Southern and Southeastern Brazilian regions (Shimizu, 2006). The increase in the demand ~~for~~of wood ~~of these specie required~~derived into new ~~Pinus~~pine-based plantations. As a result, new species started to be planted and commercialized such as *Pinus caribaea* and *Pinus oocarpa*, ~~besides that, became species~~being the cultivation of ~~great economic importance in the country. However,~~ the ~~planting of *Pinus oocarpa* in Brazil can be~~latter highlighted~~, since it has~~ in the country due to its high potential ~~for~~ growth in ~~areas of~~ low fertility areas.

The forest area dedicated to pine stands in Brazil was around 1.5 million hectares in 2012 (ABRAF, 2013). Around 90% of this total area is concentrated in Southern regions

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mostly due to the climate and soil conditions. The State of Paraná leads the ranking of total planted area (39.7%), followed by Santa Catarina (34.5%), Rio Grande do Sul (10.5%) and São Paulo (9.3%) as displayed in Figure 1 (ABRAF, 2013). Regarding the average production of pine roundwood in the country mostly dedicated to industrial use, it was around 47.6 million m^3 in 2012 (ABRAF, 2013).

<Figure 1 around here>

After harvesting, the timber can be allocated to the laminating industry for plywood manufacturing (Iwakiri et al., 2005), to construction purposes (Zenid et al., 2009; Icimoto, 2012) or it can also be destined to the production of woody products such as pulp and paper (Morais et al., 2005), medium density fibreboards (Silva et al., 2014), sawn wood (Murara Junior et al., 2005) or furniture (Mattos et al., 2008). Moreover, woody residues from forest plantations and wood processing can be used as biomass for heat and energy generation (Cargnin, 2005).

In recent years, forest activities are receiving special attention concerning the quantification of their environmental profiles to be more competitive at global scale (González-García et al., 2014a). Life Cycle Assessment (LCA) is a standardized methodology that allows assessing environmental impacts associated to materials, products and services throughout their production systems, as well as it can support on decision-making strategies towards sustainability (Baumann and Tillman, 2004).

Numerous environmental studies are available in literature with the aim of identifying the environmental profiles of dedicated industrial forest systems by means of LCA methodology. Examples can be found in Finland and Sweden with regard to the production of Norway spruce and Scots pine (Berg and Karjalainen, 2003), Maritime pine in Portugal and France (Dias and Arroja, 2012; González-García et al., 2009b; González-García et al., 2014a; González-García et al., 2014b), eucalyptus in Portugal, Spain, Brazil and Chile (Dias et al., 2007; González-García et al., 2009a; Dias and Arroja, 2012; Silva et al., 2013; Morales et al., 2015), willow in Sweden (González-García et al., 2012a); poplar in Italy and Spain (Gasol et al., 2009; González-García et al., 2012b) and European beech in Germany (Berg et al., 2012).

Thus, having in mind the relevance of the production of pine biomass in Brazil as well as the increasing environmental concern mainly regarding greenhouse gases emission and climate change consequences, this study aims to identify and quantify environmental impacts derived from industrial production of pine roundwood in forest stands located in the Southeastern region of Brazil, following the LCA approach. To do so, current practices carried out in Brazilian stands were considered and assessed in detail. *Pinus oocarpa* was ~~choose~~chosen as the target species due to ~~your~~its great economic ~~importance~~relevance in ~~Brazil~~the country and because its management is considered representative for other species of ~~Pinus~~pine planted in ~~the country~~Brazil.

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2. Methodology

2.1 Goal and scope definition

The main goal of this research paper is to identify the environmental profile associated with industrial pine plantations located in the Southeastern region of Brazil that is, the most productive areas. The study covers the whole life cycle of pine (*Pinus oocarpa*) roundwood production system from a ~~gate~~cradle-to-forest gate perspective, i.e, from the extraction of the raw materials to the loading of the logs onto trucks ready to be delivered to woody industries. The environmental assessment was performed following the ISO 14040 (2006) standard.

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The Southeastern region of Brazil is composed by three states (Rio Grande do Sul, Santa Catarina and Paraná). It is an important industrial pole with regard to timber production and woody products, such as wood based panels, furniture, pulp and paper, resin and sawn wood (ABRAF, 2013). Furthermore, around 90% of the total pine biomass produced in the country derives from that region (ABRAF, 2013). Figure 1 shows the main areas of forest pine plantations in the country. The wooden biomass obtained from the forest scenario under analysis is dedicated to the mentioned industrial uses so high quality logs are not required.

2.2 Functional unit

Firstly, as reported in ISO 14040 and 14044 standards (ISO 14040, 2006; ISO 14044, 2006), the functional unit must be defined since it will provide the reference flow to which all the inputs to and outputs from the forest production system will be referred (ISO 14040, 2006). According to literature, one of the most common functional units considered in previous LCA studies of forest systems is referred to the volume of harvested wood under bark (ub) since it is also used by industrial practitioners (Berg and Lindholm, 2005; Dias and Arroja, 2012, González-García et al., 2009a; González-García et al., 2014a, Michelsen et al., 2008). Therefore, one cubic meter ub of pine roundwood ready to be delivered to woody industries for further applications was considered in this study to report the environmental impacts. The typical basic-density of the specie analyzed is around 400 $kg \cdot m^{-3}$.

2.3 System boundaries

All the activities performed in the forest pine stands were considered and analyzed in detail. The average lifespan, which includes from the forest site preparation up to roundwood loading onto trucks at forest road site, are 12 years. As displayed in Figure 2, all the forest activities were classified in four main stages or subsystems: Soil preparation (SS1), Seedlings plantation (SS2), Forest management (SS3) and Forest harvesting (SS4). In addition, activities related with construction and maintenance of infrastructure (road and firebreak) have been computed within the system boundaries (SS5).

<Figure 2 around here>

Soil preparation - SS1 (0 year): this stage involves soil treatment related operations, such as pest control with insecticides (sulfluramide-ant bait application), chemical weeding with herbicides (glyphosate application), lowering stumps waste scattering, subsoiling and mineral fertilization (application of urea and ammonium sulphate as N-based fertilizers, potassium chloride as K-based fertilizer and superphosphate as P-based fertilizer).

Seedlings plantation – SS2 (0 year): this stage consists on planting pine seedlings (at a rate of 1,750 seedlings per ha) together with corresponding irrigation. In addition, seedlings distribution to the stand and re-plantation process at a rate of 200 seedlings per ha were included in this stage. Seedling production at ~~a~~an external nursery was ~~excluded from analysis due to lack of real and valuable data~~included within the system boundaries.

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Forest management – SS3 (0 -12th year): after planting, forest management related activities are carried out such as pest control (sulfluramide-ant bait), chemical weeding (glyphosate) and mineral fertilization with nitrogen (N) and potassium (K) based mineral fertilizers.

Forest harvesting – SS4 (12th year): after 12 years from soil preparation and seedlings planting, pine biomass is harvested. Forest harvesting stage consists of three main processes such as trees harvesting, extraction of roundwood from cutting area until roadside landing and finally, loading of the logs onto trucks.

Infrastructure establishment – SS5 (0 -12th year): this subsystem consists on road and firebreak building and maintenance related activities. These processes are performed as previous activity of soil preparation (SS1) and after the Forest management related processes (SS4).

As it can be seen in Figure 2, a number of ancillary processes were included within the system boundaries corresponding to the background system. Background system includes: i) the production of fossil fuels (diesel required for forest machinery), ii) the production of chemicals required in activities such as mineral fertilizers (urea, ammonium sulfate, potassium chloride and superphosphate), herbicides (glyphosate) and insecticide (sulfluramide-ant bait) as well as their transportation to the forest site. Regarding the transportation of roundwood from the forest road side to the final woody factory, it was excluded from the analysis since transport routes may be very different depending on the final use of the biomass.

Other issues such as the transport of forest workers, and delivery of forest machinery as well as transport of seedlings to the forest land, were also excluded due to the lack of available information and in line with similar LCA studies of forest systems. (Dias and Arroja, 2012). On the contrary, the production and maintenance of capital goods such as tractors, machinery and related implements, harvester and forwarder were computed within the system boundaries due to their large use.

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2.4 Description of case study

The plantation under assessment is located in Agudos city, state of São Paulo, Southeastern region of Brazil. It is interesting to study since Southern and Southeastern regions concentrate 84% of the total area planted with pine in the country. Climate conditions as well as the location of the main processing centers of this type of wood are the rationale of the interest of pine cultivation (ABRAF, 2013). Climate in Agudos city is humid, with average annual temperature of 21.8ºC (≈15.4ºC in the winter and 28.2ºC in the summer). The average annual rainfall is 1237 mm (CEPAGRI, 2015).

2.4.1 Description of the process

The soil preparation stage (SS1) consists in a set of operations dedicated to elevate or maintain the forest productivity level by the improvement of physical, chemical and biological properties of the soil (Sixel, 2009). The first process involved in soil preparation is the pest control, which aims to avoid the attack of ants by means the application of sulfluramide. After that, the control of the weeds development is performed in the cultivation area (chemical weeding process) by means of glyphosate application as herbicide. In this operation it is commonly used a tractor connected to a sprayer to pulverize the herbicide in the planting area. It is important to bear in mind that in this operation it is applied the 16% of the total amount of glyphosate supplied to the stand all over its life cycle. Lowering stumps is the next process carried out in the plantation. It aims to promote the lowering of the remaining stumps in the cultivated area, facilitating the realignment of tillage direction (Malinovski, 2011). Subsequent, it is performed the waste scattering operation, which consists on distributing the biomass waste such as leaves, bark or roots in the field by means of the use of a tractor with a "clean path" implemented. After that, the soil is revolved in the subsoiling operation. It consists on deep plowing (greater than 30 cm) by means of a subsoiler coupled to a tractor, as implement (Sixel, 2009). The final step in SS1 is the mineral fertilization, which aims to supply the required nutrients to the soil by means of the application of urea and ammonium sulphate, potassium chloride and superphosphate (Santos et al., 2007). In this step, it is applied the 20% and 40% of the total amount of N-based and K-based fertilizers, respectively, supplied to the pine stands. Tractors are used to carry out the fertilizing step.

Regarding the processes involved in the Seedling plantation stage (SS2), the plantation of seedlings is the first step. Pine seedlings are planted in by mechanical way using a tractor, which opens the holes with a ridger disk. However, the seedlings are introduced in the hole manually. Thereafter, the irrigation process is performed, which aims to provide the initial water requirements for the development of the plants. The irrigation is conducted by tanker trucks. The last operation included in SS2 is the re-planting step, which should be done around 15-45 days after the planting operation. Re-planting is the replacement of dead or damaged seedlings which can appear after planting process.

Subsequently, the Forest management stage (SS3) is carried out. The operations within this stage are: pest control, chemical weeding and mineral fertilization. These processes are similar to those performed in SS1. The application of herbicides and insecticides is important to ensure the cleanliness of the planted area with seedlings, allowing them to reach sufficient size to dominate the invasive vegetation and to resist the attack of ants (Silva et al., 2013). For the analyzed scenario in this study, the insecticide is applied in each year of the tree's life cycle, while the herbicide is applied only in the 1^{st}, 2^{nd}, 3^{rd}, 4^{th}, 8^{th}, 9^{th} and 10^{th} years. Regarding to mineral fertilization, it aims to supply the nutrients to the plant until the age that it is harvested. It is carried out in the years 1^{st}, 2^{nd}, 3^{rd}, 7^{th} and 8^{th}.

Finally, 12 years after planting, the trees are cut. The activities include in the Forest harvesting stage (SS4) are: harvesting, extraction and loading onto trucks. The trees are harvested by a harvester. This machine also removes the branches as well as part of the bark. The next operation is the roundwood extraction, which consist on removing logs from the cutting place to the roadside landing by means of a forwarding machine. Finally, the last process of the life cycle of Pine roundwood production is the loading of biomass onto trucks. These activities are conducted in 12^{th} year of the tree.

Concerning the Infrastructure establishment (SS5), it is related to road and firebreak building and maintenance. These processes are intended to facilitate exploration activities and are performed as preliminary service of SS1 and after SS4. In this stage, machineries such as motor grader, backhoe and tractor are essential and require large consumption of diesel.

A short description of machineries and tillage required in each forest stage and process is reported in Table 1.

<Table 1 around here>

2.5 Allocation

Allocation is one of the most critical issues in LCA studies (González-Garcia et al., 2014a). Allocation of environmental burdens is needed if a process causes several outputs or products, respectively. However, ISO 14040 and 14044 strongly recommended avoiding allocation if possible. In the current study, which a ~~gate~~cradle-to-forest gate analysis, allocation was not ‘required since the total wooden biomass produced (roundwood) is considered as a single product. Forest waste such as leaves and branches, generated from

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the processes performed in SS4 (harvesting, extraction and loading) are left in the plantation area to improve the quality of the soil and consequently to reduce further fertilizers requirement. Therefore, forest waste was not computed in this analysis.

2.6 Life Cycle Inventory data quality

The quality of Life Cycle Inventory (LCI) data managed is an important issue to be addressed in LCA study (ISO 14040, 2006). Real and characteristic primary data should be considered to obtain representative environmental results. In this study, only primary data were managed for the foreground system directly taken by means of direct interviews with forest workers.

Concerning the data related to the requirements of fossil fuels, herbicide, insecticide, fertilizers and seedlings as well as data concerning operating hours and input rates, they were obtained by on-site measurements in forest stands assessed in collaboration with forest workers.

The average productivity is around 40 m^3 of pine roundwood per ha and year (481,2 $m^3 \cdot ha^{-1}$ after 12 years) according to on-site measurements and in line with average data reported from ABRAF (2013).

All inputs to and outputs from the system ~~have~~ were calculated and allocated to the functional unit considering in this study, i.e., 1m^3 of log (ub). Inventory data corresponding to the production of the ancillary processes involved in the production of pine roundwood (i.e., fossil fuels, chemicals and machinery) were collected from available databases (i.e., ecoinvent ® database) (Wernet et al., 2016). In this sense, data related with the production of mineral fertilizers, herbicide and insecticide were taken from Althaus et al. (2007). Production of fossil fuels has been taken from Nemecek and Käggi (2007).

Average transport distances corresponding to the inputs delivery up to the forest area are presented in Table 2. It was assumed that all the transport activities are performed by trucks with a payload higher than 32 ton - EURO 5 category (Spielmann et al., 2007).

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<Table 2 around here>

With regard to maintenance of machines used in different forest operations involved in soil preparation, seedlings plantation, forest management and forest harvesting, it has been included within the system boundaries according to descriptions reported in Ecoinvent ® database version 3 (Wernet et al., 2016).

~~Seedlings~~Data regarding seedlings production were ~~excluded due to the lack of available data. The same approach was assumed~~taken from Aldentun (2002) in ~~previous LCA of forest systems (Dias and Arroja, 2012; Morales~~agreement with González-García et al~~., 2015~~. (2014a). Table 3 displays a summary of inventory data considered (primary data supplied by forest workers) corresponding to the pine stand under study.

<Table 3 around here>

Direct emissions into air and into water derived from the application of herbicide and insecticide have been estimated by means of the method reported by Jansma and Linders (1995). Emissions into air and water resulting from the application of urea were computed based on emission factors reported by IPCC (2006). Regarding phosphate emissions into water derived from P-based fertilizer application, were calculated in accordance with Rossier (1998). With regard to emissions from K-based fertilizer application, it has been assumed that no emissions are produced into the air, water or soil according to Silva et al. (2013).

Combustion emissions derived from diesel use in forest machines, as well as from transport activities related with inputs supply, were taken from Nemecek and Käggi (2007) and Spielmann et al. (2007), respectively.

~~**3 Environmental results**~~

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2.7. Life Cycle Assessment methodology

The assessment of environmental impacts associated with pine production system proposed was conducted considering characterization factors reported by ReCiPe Midpoint methodology (Goedkoop et al., 2009). Twelve impact categories were chosen for assessment: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), water depletion (WD) and fossil depletion (FD).

These impact categories were selected taking into account previous LCA studies of forest system (Arroja et al., 2006; González-García et al., 2014a; González-García et al., 2014b; Klein et al., 2015). Software SimaPro 8.0.5.3 has been used for the computational implementation of all the inventories (PRé Consultants, 2017).

3. Results and discussion

3.1. General results

The life cycle impact assessment (LCIA) step establishes links between the life cycle inventory results and potential environmental impacts (Puettmann et al., 2013). Figure 3 shows the contributions to the environmental profile corresponding to the industrial pine roundwood production in Brazil.

<Figure 3 around here>

According to Figure 3, Forest harvesting stage (SS4) is the most responsible of environmental burdens in nine categories under assessment with contributing ratios ranging from 21% to 76% depending on the category. Thus, this stage can be considered as environmental hotspot. The second largest contributor to the impacts is soil preparation stage (SS1) with ratios ranging from 8% to 37%, followed by forest management stage

(SS3), which is great contributor to FE (35%), due to mineral fertilization. A detailed description of the rationale behind these contributions is detailed below. Thus, Figure 4 displays detailed contributions to the environmental profile corresponding to Pine production in Brazil derived from processes of each stage.

<Figure 4 around here>

Soil preparation stage (SS1) reports an outstanding effect on the environmental profile associated with industrial pine roundwood production in Brazil. The processes that are part of this stage are: pest control, chemical weeding, lowering stumps, waste scattering, subsoiling and mineral fertilization. All these activities are mechanically performed by tractor connected with specific equipment (such as sprayer, roller, milling, etc.) required for each process. The main impact contributions associated to this stage are linked to FE, TET, FET and MET being mostly related to the use of chemical fertilizers in mineral fertilization process (Figure 4a). Production of superphosphate (P-based) fertilizer (background process), which is applied to the soil before planting, is the main responsible factor of contributions to these categories. Superphosphate manufacturing process involves remarkable phosphate based emissions contributing considerably to FE. Regarding FET and MET, emissions into the water derived from the use of sulfuric acid as raw material in the fertilizer production process are behind of its contribution. The emission of cypermetrin also derived from production of this fertilizer is the main responsible of contributions to TET.

Forest management stage (SS3) is the main responsible of contributions to FE with ratio of approximately 36% (Figure 3). Having a look into Figure 4c, contributions to the environmental profile from SS3 are totally associated with the application of chemicals, being chemical weeding process the environmental hotspot (around 46% of contributing ratio on average in all categories). The negative impact is mostly associated with the production of the glyphosate used as herbicide, which is applied on the soil to combat weeds.

Seedlings plantation stage (SS2) as well as Infrastructure establishment stage (SS5) report negligible contributions to the global environmental profile (see Figure 3). Assessing in more detail SS2, the planting process itself is the main responsible of contributions from SS2 with contributing ratios ranging from 43% to 60% as displayed in Figure 4b due to outstanding consumption of diesel.

Concerning Forest harvesting stage (SS4), trees harvesting and roundwood extraction from the cutting area to the roadside landing are carried out by means of huge machines such as the harvester and the forwarder, respectively, being thus environmental hotspots (Figure 4d). These machines report a significant consumption of diesel (585 and 340 $L \cdot ha^{-1}$, respectively). In fact, 80% of the total fuel requirement all over the life cycle of Pine roundwood production is associated with these two specific processes. Assessing in more detail contributions to the environmental profile from SS4, combustion emissions from diesel used by harvester and forwarder machines are the main responsible of contributions to CC, TA and POF being emission of CO_2, NO and NO_x into the atmosphere the responsible substances. Regarding to contributions to OD, WD and FD, the production of diesel (background process) is behind of contributions to these categories. Regarding the toxicity related categories, environmental impacts are associated with emission of hydrocarbons from background processes (diesel production and machinery production).

Finally, regarding to Infrastructure establishment (SS5), its contribution to the global environmental profile derived from the Pine roundwood production is negligible. In this stage, building and maintenance of the roads (during the plantation lifespan) is considered. The high frequency of road maintenance based activities contributes with major impacts on the evaluated categories (Figure 4e).

3.2. Discussion and comparison with previous studies

In this present study, LCA has been considered as environmental tool to quantify and identify environmental burdens related to industrial pine roundwood production in Brazil. The interest on this forest specie is due to its relevance in the forest economy of the country. Pine is the second most reforested specie and wooden biomass is used in multiple industrial applications. Regarding the forest management in the area under study, forest stands are mainly managed under intensive conditions.

Remarkable differences were identified between the subsystems considered in the forest system analyzed. They are mainly related to the high consumption of diesel by forest machinery in some activities (i.e., harvesting) and the use of agrochemicals to supply required nutrients for plants growing either in the preparation of the soil before planting or in the further soil maintenance.

As previously discussed, LCA was considered in numerous studies to determine environmental impacts derived from the operations carried out in different forest systems in many European countries such as France, Portugal, Italy, Germany, Sweden and Spain as well as in Chile. Regarding Brazil, the interest on identifying the environmental profile associated with forest biomass production was previously reported regarding Eucalyptus stands (Silva et al., 2013).

The most important subsystem in terms of environmental burdens is the Forest harvesting (SS4). This stage was identified as the most responsible in nine of twelve impact categories analyzed and it is related to requirement of diesel by forest machinery, which involves combustion emissions derived from diesel use as well as derived emissions from diesel production (background process). This stage is responsible for 61%, 68% and 76% of total CO_2, SO_2 and NMVOC emissions production all over the life cycle of the forest stand (12 years). Similar results were identified in related LCA studies of pine production in Europe (Dias and Arroja, 2012; González-García et al.; 2014a~~).~~), which will be analyzed in more detail below.

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Other related studies considering other forest species (Berg and Karjalainen, 2003; Michelsen et al., 2008; González-García et al., 2009a; 2009; Berg et al., 2012) also highlighted the outstanding contribution to the global environmental profile from activities related to biomass harvesting (that is, harvesting and forwarding).

Soil preparation subsystem is the second most important stage from an environmental approach with remarkable contributions in the impact categories analyzed (see Figure 3). The highest contributions are mainly identified in categories related with eutrophication and toxicity due to fertilization process. According to Sixel and Gomes (2008), the largest nutritional limitation in Brazilian soils is related to phosphorous and therefore, large amounts of P-based fertilizer must be supply in the stands. It is important to highlight that as difference to other fertilizers, superphosphate is only applied in the soil preparation stage.

~~The~~ Taking in mind the environmental results ~~of this~~obtained in the case study ~~were~~under assessment, they have been compared with ~~others in which were assessed in terms of LCA methodology, the~~ the ones available in the literature related to roundwood production ~~of Pine. For instance,~~(Dias and Arroja, 2012; Silva et al., 2013; González-García et al~~. (~~., 2014a) ~~quantified~~with the aim of identifying differences (or not) regarding the activities that play a key environmental role. However and as it is detailed below, no outstanding differences have been identified being harvesting and fertilization the contributing activities to the global environmental profiles.

González-García et al. (2014a) identified the environmental profile ~~of~~ associated with the production of maritime pine (*Pinus pinaster* Ait.) roundwood in France under two different management scenarios (i.e., intensive and extensive ~~scenarios). For all~~management regimes). In that study and regardless both the environmental categories ~~analyzed by the authors,~~ considered for assessment and scenario, the logging ~~stages, which involves final cutting with a harvester~~stage (including harvesting, forwarding and loading ~~of~~ the logs onto trucks at the roadside~~,~~), was identified as the ~~most~~main responsible of the environmental burdens with ratios ranging from 39% to 57~~%. Moreover, it~~ %, depending on the category. The rationale behind these results was ~~highlighted in the study that 71% of the total~~ linked to the associated large fuel requirement ~~all~~ (more than 70% of the total consumption over the life cycle of the plantation ~~is associated with these three processes. The second most~~

important stage from). In addition, the authors identified the fertilization as an environmental point of view identified by the authors was hotspot in intensive management regimes due to background processes associated with the production of superphosphatethe fertilizers and derived emissions from itstheir application in the intensive management scenario, with contributions until 28% in categories such as photochemical oxidants formation potential..

Similar results were also reportedIn the case of the analysis performed by Dias and Arroja (2012) in a previous study focused on the production of Maritime Pine in Portugal. Authors also found high values (97%) of total contribution to global warming comes from CO_2 emitted mainly during the forest operation stagemaritime pine roundwood in Portuguese stands, the authors also identified harvesting and fertilizing activities as environmental hotspots due to, respectively, the large fossil fuel combustion. It was also found that the application of requirements and diffuse emissions from P-containingbased fertilizer in the soil, originates P and PO_4^{3-} emissions on-site and during the production of the fertilizer, contributing with 28 and 35%, respectively, of the total impact in eutrophication categoryapplication.

Silva et al. (2013) assessed the potential environmental impacts of the production of Eucalyptus specie in Brazil. In order to identify the main hotspots, the authors used CML and USEtox methods. Results showed that the major impacts occurred in the forest management stage due to the application of fertilizers (mainly N-based) and herbicides (glyphosates) in the soil, while the second most responsible for potential impacts was the use of diesel in harvesting, processing, and transport of wood, i.e., in forest harvesting operations stage.

In fact, there are important differences between Pine and Eucalyptus cultivation. The first one is the period of rotation of theses specie. As the most of Eucalyptus planted in the country is destined to the production of pulp and paper, the trees are cutting with 6-7 years old with biomass yield of 45 m^3 ub ha^{-1}, while Pine logs are designated to production of wood based panels and cutting with 12 years old and 40.1 m^3 ub ha^{-1}. Therefore, the volume of Pine specie after the period rotation is higher than Eucalyptus, which requires a greater

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~~amount of diesel consumption by forest machinery.~~

~~The second important difference is related to the amount of fertilizers and herbicides used in the plantations of each specie. Eucalyptus specie requires more fertilizer and herbicides than Pine plantation, which is applied mainly during management stage, contributing with higher potential impacts in this category.~~

~~Planting stage led to negligible contributions to the categories analyzed. These contributions varied from 3% to 7% depending on the category.~~ Concerning the infrastructure establishment, an essential stage to facilitate the access of workers and machinery to the forest stands (Machado, 1989), its effect on the global environmental profile is also negligible in line with previous studies (Dias and Arroja, 2012; González-García et al., 2014a; 2014b).

5. Conclusions

In this study, the production of industrial pine roundwood in the Southeastern region of Brazil was assessed from an environmental point of view following the LCA approach. Comparison of the environmental profile with other studies available in the literature even of different forest species leads to the identification of harvesting operations and fertilization as environmental hotspots. ~~However~~These results suggest that both fossil fuel requirements in harvesting activities and fertilizers dose should be optimized to decrease the environmental impacts. Moreover, special attention must be paid to the system boundaries, assumptions and methodological issues, since can derive on uncertainty.

Results reported in this study could be useful in decision making strategies specifically in forest based industries with pine as main raw material.

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***Graphical Abstract**

Environmental Life Cycle Assessment of Industrial Pine roundwood production in Brazilian forests

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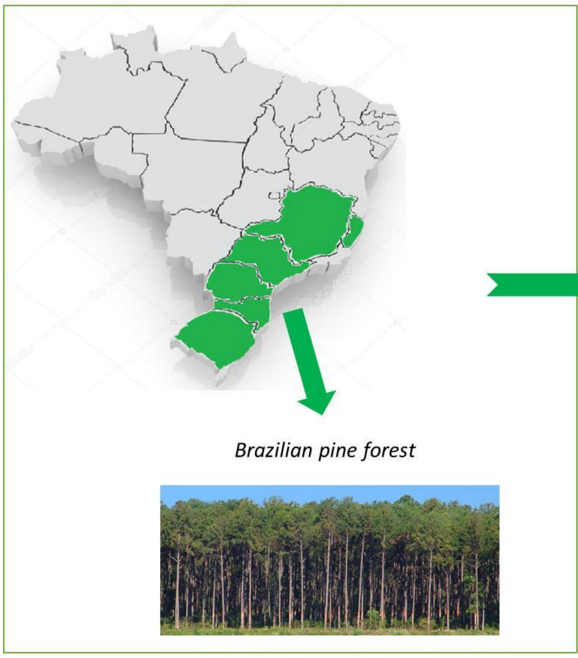

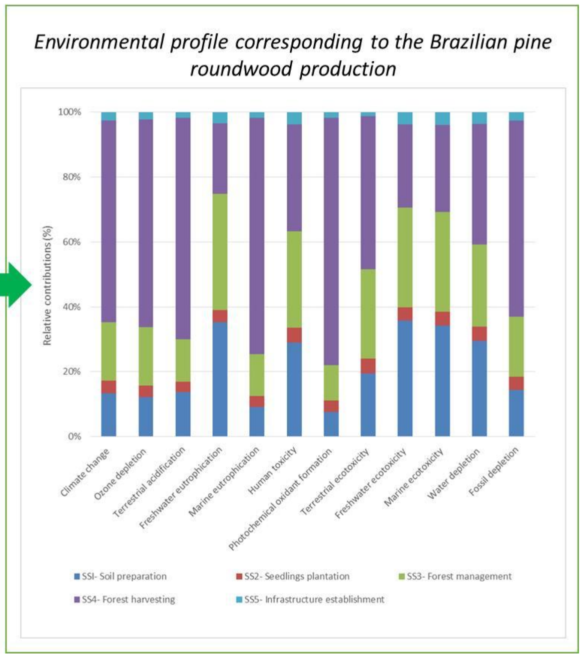

***Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

Environmental Life Cycle Assessment of Industrial Pine roundwood production in Brazilian forests

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Highlights

- ✓ A detailed environmental analysis of pine roundwood was performed
- ✓ Brazilian current forest practices were considered
- ✓ Forest harvesting related operations were identified as hotspot
- ✓ Diesel requirement and fertilizers application played a key role
- ✓ Optimization of forest practices is required to improve the environmental profile

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Abstract

Pine (*Pinus oocarpa*) wood has great economic importance in Brazil. Pine stands represent the second largest reforested area in the country due to their industrial interest. Combining the relevance of industrial pine stands in the country and corresponding environmental concerns, this current study aims to identify and quantify the environmental impacts derived from industrial pine roundwood production in Brazil. The environmental study was developed considering the Life Cycle Assessment (LCA) methodology according to ISO14040 framework. The study convers the life cycle of pine roundwood production from cradle-to-forest gate perspective and considers the current practices in the country. The production system was divided in five main stages: Soil preparation, Seedlings plantation, Forest management, Forest harvesting and Infrastructure establishment. The environmental profile was estimated considering characterization factors from the ReCiPe method, in terms of twelve impact categories. According to the results, Forest harvesting stage was identified as the environmental hotspot being the main responsible of contributions to nine impact categories under assessment with contributing ratios ranging from 21% (e.g., freshwater eutrophication) to 76% (e.g., photochemical oxidants formation). The high amount of fossil fuel required by heavy machinery used in the activities involved in this stage is behind this result. Soil preparation stage reported also an outstanding contribution in categories such as freshwater eutrophication (37%) and toxicity related categories (≈35%). The rationale behind these contributions is associated with the use of chemical fertilizers, mostly superphosphate. The identification of the environmental hotspots in forest biomass production can assist the Brazilian forest practitioners to improve the environmental profile by means of the optimization of forest practices.

Keywords: Brazil; Environmental profile; LCA; Forest system; *Pinus oocarpa*

1. Introduction

In Brazil, the forestry activities have great relevance not only due to the extensive forest cover that exists in the country but also because of their employment capacity and incomes generation within the sector. The last study performed by the Brazilian forest service (IBÁ, 2017) showed that approximately 60% of the Brazilian national territory (493.5 million ha) is covered by forest. Moreover, it was estimated that the forestry sector derived on 3.7 million direct and indirect jobs and the income generated by the sector was around 3 billion US dollars (IBÁ, 2017).

Regarding to the reforestation area in Brazil, it corresponds to 7.84 million ha, and of this total, around 20% corresponds to pine-based reforested stands. Pine is the second most important forest specie planted in the country, after Eucalyptus, being mostly destined to the production of cellulosic pulp (IBÁ, 2017). Throughout many years, different pine species originating from different countries all over the world were introduced in Brazil to produce the biomass used as raw material in wood industry for multiple applications (Shimizu, 2006). European pine such as *Pinus canariensis* was introduced in Brazil for silvicultural purposes in 1936 (Shimizu, 2006). American pine species such as *Pinus palustris*, *Pinus echinata*, *Pinus elliottii* and *Pinus taeda* were introduced by Forestry Service of São Paulo State (Shimizu, 2006) in 1948. *Pinus elliottii* and *Pinus taeda* stand out between others due to their fast growth in Southern and Southeastern Brazilian regions (Shimizu, 2006). The increase in the demand of wood derived into new pine-based plantations. As a result, new species started to be planted and commercialized such as *Pinus caribaea* and *Pinus oocarpa*, being the cultivation of the latter highlighted in the country due to its high potential growth in low fertility areas.

The forest area dedicated to pine stands in Brazil was around 1.5 million hectares in 2012 (ABRAF, 2013). Around 90% of this total area is concentrated in Southern regions mostly due to the climate and soil conditions. The State of Paraná leads the ranking of total planted area (39.7%), followed by Santa Catarina (34.5%), Rio Grande do Sul (10.5%) and

São Paulo (9.3%) as displayed in Figure 1 (ABRAF, 2013). Regarding the average production of pine roundwood in the country mostly dedicated to industrial use, it was around 47.6 million m³ in 2012 (ABRAF, 2013).

<Figure 1 around here>

After harvesting, the timber can be allocated to the laminating industry for plywood manufacturing (Iwakiri et al., 2005), to construction purposes (Zenid et al., 2009; Icimoto, 2012) or it can also be destined to the production of woody products such as pulp and paper (Morais et al., 2005), medium density fibreboards (Silva et al., 2014), sawn wood (Murara Junior et al., 2005) or furniture (Mattos et al., 2008). Moreover, woody residues from forest plantations and wood processing can be used as biomass for heat and energy generation (Cargnin, 2005).

In recent years, forest activities are receiving special attention concerning the quantification of their environmental profiles to be more competitive at global scale (González-García et al., 2014a). Life Cycle Assessment (LCA) is a standardized methodology that allows assessing environmental impacts associated to materials, products and services throughout their production systems, as well as it can support on decision-making strategies towards sustainability (Baumann and Tillman, 2004).

Numerous environmental studies are available in literature with the aim of identifying the environmental profiles of dedicated industrial forest systems by means of LCA methodology. Examples can be found in Finland and Sweden with regard to the production of Norway spruce and Scots pine (Berg and Karjalainen, 2003), Maritime pine in Portugal and France (Dias and Arroja, 2012; González-García et al., 2009b; González-García et al., 2014a; González-García et al., 2014b), eucalyptus in Portugal, Spain, Brazil and Chile (Dias et al., 2007; González-García et al., 2009a; Dias and Arroja, 2012; Silva et al., 2013; Morales et al., 2015), willow in Sweden (González-García et al., 2012a); poplar in Italy and Spain (Gasol et al., 2009; González-García et al., 2012b) and European beech in Germany (Berg et al., 2012).

Thus, having in mind the relevance of the production of pine biomass in Brazil as well as the increasing environmental concern mainly regarding greenhouse gases emission and climate change consequences, this study aims to identify and quantify environmental impacts derived from industrial production of pine roundwood in forest stands located in the Southeastern region of Brazil, following the LCA approach. To do so, current practices carried out in Brazilian stands were considered and assessed in detail. *Pinus oocarpa* was chosen as the target species due to its great economic relevance in the country and because its management is considered representative for other species of pine planted in Brazil.

2. Methodology

2.1 Goal and scope definition

The main goal of this research paper is to identify the environmental profile associated with industrial pine plantations located in the Southeastern region of Brazil that is, the most productive areas. The study covers the whole life cycle of pine (*Pinus oocarpa*) roundwood production system from a cradle-to-forest gate perspective, i.e, from the extraction of the raw materials to the loading of the logs onto trucks ready to be delivered to woody industries. The environmental assessment was performed following the ISO 14040 (2006) standard.

The Southeastern region of Brazil is composed by three states (Rio Grande do Sul, Santa Catarina and Paraná). It is an important industrial pole with regard to timber production and woody products, such as wood based panels, furniture, pulp and paper, resin and sawn wood (ABRAF, 2013). Furthermore, around 90% of the total pine biomass produced in the country derives from that region (ABRAF, 2013). Figure 1 shows the main areas of forest pine plantations in the country. The wooden biomass obtained from the forest scenario under analysis is dedicated to the mentioned industrial uses so high quality logs are not required.

2.2 Functional unit

Firstly, as reported in ISO 14040 and 14044 standards (ISO 14040, 2006; ISO 14044, 2006), the functional unit must be defined since it will provide the reference flow to which all the inputs to and outputs from the forest production system will be referred (ISO 14040, 2006). According to literature, one of the most common functional units considered in previous LCA studies of forest systems is referred to the volume of harvested wood under bark (ub) since it is also used by industrial practitioners (Berg and Lindholm, 2005; Dias and Arroja, 2012, González-García et al., 2009a; González-García et al., 2014a, Michelsen et al., 2008). Therefore, one cubic meter ub of pine roundwood ready to be delivered to woody industries for further applications was considered in this study to report the environmental impacts. The typical basic-density of the specie analyzed is around 400 $kg \cdot m^{-3}$.

2.3 System boundaries

All the activities performed in the forest pine stands were considered and analyzed in detail. The average lifespan, which includes from the forest site preparation up to roundwood loading onto trucks at forest road site, are 12 years. As displayed in Figure 2, all the forest activities were classified in four main stages or subsystems: Soil preparation (SS1), Seedlings plantation (SS2), Forest management (SS3) and Forest harvesting (SS4). In addition, activities related with construction and maintenance of infrastructure (road and firebreak) have been computed within the system boundaries (SS5).

<Figure 2 around here>

Soil preparation - SS1 (0 year): this stage involves soil treatment related operations, such as pest control with insecticides (sulfluramide-ant bait application), chemical weeding with herbicides (glyphosate application), lowering stumps waste scattering, subsoiling and mineral fertilization (application of urea and ammonium sulphate as N-based fertilizers, potassium chloride as K-based fertilizer and superphosphate as P-based fertilizer).

Seedlings plantation – SS2 (0 year): this stage consists on planting pine seedlings (at a rate of 1,750 seedlings per ha) together with corresponding irrigation. In addition, seedlings distribution to the stand and re-plantation process at a rate of 200 seedlings per ha were included in this stage. Seedling production at an external nursery was included within the system boundaries.

Forest management – SS3 (0 -12th year): after planting, forest management related activities are carried out such as pest control (sulfluramide-ant bait), chemical weeding (glyphosate) and mineral fertilization with nitrogen (N) and potassium (K) based mineral fertilizers.

Forest harvesting – SS4 (12th year): after 12 years from soil preparation and seedlings planting, pine biomass is harvested. Forest harvesting stage consists of three main processes such as trees harvesting, extraction of roundwood from cutting area until roadside landing and finally, loading of the logs onto trucks.

Infrastructure establishment – SS5 (0 -12th year): this subsystem consists on road and firebreak building and maintenance related activities. These processes are performed as previous activity of soil preparation (SS1) and after the Forest management related processes (SS4).

As it can be seen in Figure 2, a number of ancillary processes were included within the system boundaries corresponding to the background system. Background system includes: i) the production of fossil fuels (diesel required for forest machinery), ii) the production of chemicals required in activities such as mineral fertilizers (urea, ammonium sulfate, potassium chloride and superphosphate), herbicides (glyphosate) and insecticide (sulfluramide-ant bait) as well as their transportation to the forest site. Regarding the transportation of roundwood from the forest road side to the final woody factory, it was excluded from the analysis since transport routes may be very different depending on the final use of the biomass.

Other issues such as the transport of forest workers and delivery of forest machinery were also excluded due to the lack of available information and in line with similar LCA studies of forest systems (Dias and Arroja, 2012). On the contrary, the production and maintenance of capital goods such as tractors, machinery and related implements, harvester and forwarder were computed within the system boundaries due to their large use.

2.4 Description of case study

The plantation under assessment is located in Agudos city, state of São Paulo, Southeastern region of Brazil. It is interesting to study since Southern and Southeastern regions concentrate 84% of the total area planted with pine in the country. Climate conditions as well as the location of the main processing centers of this type of wood are the rationale of the interest of pine cultivation (ABRAF, 2013). Climate in Agudos city is humid, with average annual temperature of 21.8ºC (≈15.4ºC in the winter and 28.2ºC in the summer). The average annual rainfall is 1237 mm (CEPAGRI, 2015).

2.4.1 Description of the process

The soil preparation stage (SS1) consists in a set of operations dedicated to elevate or maintain the forest productivity level by the improvement of physical, chemical and biological properties of the soil (Sixel, 2009). The first process involved in soil preparation is the pest control, which aims to avoid the attack of ants by means the application of sulfluramide. After that, the control of the weeds development is performed in the cultivation area (chemical weeding process) by means of glyphosate application as herbicide. In this operation it is commonly used a tractor connected to a sprayer to pulverize the herbicide in the planting area. It is important to bear in mind that in this operation it is applied the 16% of the total amount of glyphosate supplied to the stand all over its life cycle. Lowering stumps is the next process carried out in the plantation. It aims to promote the lowering of the remaining stumps in the cultivated area, facilitating the realignment of tillage direction

(Malinovski, 2011). Subsequent, it is performed the waste scattering operation, which consists on distributing the biomass waste such as leaves, bark or roots in the field by means of the use of a tractor with a "clean path" implemented. After that, the soil is revolved in the subsoiling operation. It consists on deep plowing (greater than 30 cm) by means of a subsoiler coupled to a tractor, as implement (Sixel, 2009). The final step in SS1 is the mineral fertilization, which aims to supply the required nutrients to the soil by means of the application of urea and ammonium sulphate, potassium chloride and superphosphate (Santos et al., 2007). In this step, it is applied the 20% and 40% of the total amount of N-based and K-based fertilizers, respectively, supplied to the pine stands. Tractors are used to carry out the fertilizing step.

Regarding the processes involved in the Seedling plantation stage (SS2), the plantation of seedlings is the first step. Pine seedlings are planted in by mechanical way using a tractor, which opens the holes with a ridger disk. However, the seedlings are introduced in the hole manually. Thereafter, the irrigation process is performed, which aims to provide the initial water requirements for the development of the plants. The irrigation is conducted by tanker trucks. The last operation included in SS2 is the re-planting step, which should be done around 15-45 days after the planting operation. Re-planting is the replacement of dead or damaged seedlings which can appear after planting process.

Subsequently, the Forest management stage (SS3) is carried out. The operations within this stage are: pest control, chemical weeding and mineral fertilization. These processes are similar to those performed in SS1. The application of herbicides and insecticides is important to ensure the cleanliness of the planted area with seedlings, allowing them to reach sufficient size to dominate the invasive vegetation and to resist the attack of ants (Silva et al., 2013). For the analyzed scenario in this study, the insecticide is applied in each year of the tree's life cycle, while the herbicide is applied only in the 1st, 2nd, 3rd, 4th, 8th, 9th and 10th years. Regarding to mineral fertilization, it aims to supply the nutrients to the plant until the age that it is harvested. It is carried out in the years 1st, 2nd, 3rd, 7th and 8th.

Finally, 12 years after planting, the trees are cut. The activities include in the Forest harvesting stage (SS4) are: harvesting, extraction and loading onto trucks. The trees are harvested by a harvester. This machine also removes the branches as well as part of the bark. The next operation is the roundwood extraction, which consist on removing logs from the cutting place to the roadside landing by means of a forwarding machine. Finally, the last process of the life cycle of Pine roundwood production is the loading of biomass onto trucks. These activities are conducted in 12th year of the tree.

Concerning the Infrastructure establishment (SS5), it is related to road and firebreak building and maintenance. These processes are intended to facilitate exploration activities and are performed as preliminary service of SS1 and after SS4. In this stage, machineries such as motor grader, backhoe and tractor are essential and require large consumption of diesel.

A short description of machineries and tillage required in each forest stage and process is reported in Table 1.

<Table 1 around here>

2.5 Allocation

Allocation is one of the most critical issues in LCA studies (González-Garcia et al., 2014a). Allocation of environmental burdens is needed if a process causes several outputs or products, respectively. However, ISO 14040 and 14044 strongly recommended avoiding allocation if possible. In the current study, which a cradle-to-forest gate analysis, allocation was not ‘required since the total wooden biomass produced (roundwood) is considered as a single product. Forest waste such as leaves and branches, generated from the processes performed in SS4 (harvesting, extraction and loading) are left in the plantation area to improve the quality of the soil and consequently to reduce further fertilizers requirement. Therefore, forest waste was not computed in this analysis.

2.6 Life Cycle Inventory data quality

The quality of Life Cycle Inventory (LCI) data managed is an important issue to be addressed in LCA study (ISO 14040, 2006). Real and characteristic primary data should be considered to obtain representative environmental results. In this study, only primary data were managed for the foreground system directly taken by means of direct interviews with forest workers.

Concerning the data related to the requirements of fossil fuels, herbicide, insecticide, fertilizers and seedlings as well as data concerning operating hours and input rates, they were obtained by on-site measurements in forest stands assessed in collaboration with forest workers.

The average productivity is around 40 m^3 of pine roundwood per ha and year (481,2 $m^3 \cdot ha^{-1}$ after 12 years) according to on-site measurements and in line with average data reported from ABRAF (2013).

All inputs to and outputs from the system were calculated and allocated to the functional unit considering in this study, i.e., 1m^3 of log (ub). Inventory data corresponding to the production of the ancillary processes involved in the production of pine roundwood (i.e., fossil fuels, chemicals and machinery) were collected from available databases (i.e., ecoinvent ® database) (Wernet et al., 2016). In this sense, data related with the production of mineral fertilizers, herbicide and insecticide were taken from Althaus et al. (2007). Production of fossil fuels has been taken from Nemecek and Käggi (2007).

Average transport distances corresponding to the inputs delivery up to the forest area are presented in Table 2. It was assumed that all the transport activities are performed by trucks with a payload higher than 32 ton - EURO 5 category (Spielmann et al., 2007).

<Table 2 around here>

With regard to maintenance of machines used in different forest operations involved in soil preparation, seedlings plantation, forest management and forest harvesting, it has been included within the system boundaries according to descriptions reported in Ecoinvent ® database version 3 (Wernet et al., 2016).

Data regarding seedlings production were taken from Aldentun (2002) in agreement with González-García et al. (2014a). Table 3 displays a summary of inventory data considered (primary data supplied by forest workers) corresponding to the pine stand under study.

<Table 3 around here>

Direct emissions into air and into water derived from the application of herbicide and insecticide have been estimated by means of the method reported by Jansma and Linders (1995). Emissions into air and water resulting from the application of urea were computed based on emission factors reported by IPCC (2006). Regarding phosphate emissions into water derived from P-based fertilizer application, were calculated in accordance with Rossier (1998). With regard to emissions from K-based fertilizer application, it has been assumed that no emissions are produced into the air, water or soil according to Silva et al. (2013).

Combustion emissions derived from diesel use in forest machines, as well as from transport activities related with inputs supply, were taken from Nemecek and Käggi (2007) and Spielmann et al. (2007), respectively.

2.7. Life Cycle Assessment methodology

The assessment of environmental impacts associated with pine production system proposed was conducted considering characterization factors reported by ReCiPe Midpoint methodology (Goedkoop et al., 2009). Twelve impact categories were chosen for assessment: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), water depletion (WD) and fossil depletion (FD).

These impact categories were selected taking into account previous LCA studies of forest system (Arroja et al., 2006; González-García et al., 2014a; González-García et al., 2014b; Klein et al., 2015). Software SimaPro 8.0.5.3 has been used for the computational implementation of all the inventories (PRé Consultants, 2017).

3. Results and discussion

3.1. General results

The life cycle impact assessment (LCIA) step establishes links between the life cycle inventory results and potential environmental impacts (Puettmann et al., 2013). Figure 3 shows the contributions to the environmental profile corresponding to the industrial pine roundwood production in Brazil.

<Figure 3 around here>

According to Figure 3, Forest harvesting stage (SS4) is the most responsible of environmental burdens in nine categories under assessment with contributing ratios ranging from 21% to 76% depending on the category. Thus, this stage can be considered as environmental hotspot. The second largest contributor to the impacts is soil preparation stage (SS1) with ratios ranging from 8% to 37%, followed by forest management stage (SS3), which is great contributor to FE (35%), due to mineral fertilization. A detailed description of the rationale behind these contributions is detailed below. Thus, Figure 4 displays detailed contributions to the environmental profile corresponding to Pine production in Brazil derived from processes of each stage.

<Figure 4 around here>

Soil preparation stage (SS1) reports an outstanding effect on the environmental profile associated with industrial pine roundwood production in Brazil. The processes that are part of this stage are: pest control, chemical weeding, lowering stumps, waste scattering, subsoiling and mineral fertilization. All these activities are mechanically performed by tractor connected with specific equipment (such as sprayer, roller, milling, etc.) required for each process. The main impact contributions associated to this stage are linked to FE, TET, FET and MET being mostly related to the use of chemical fertilizers in mineral fertilization process (Figure 4a). Production of superphosphate (P-based) fertilizer (background process), which is applied to the soil before planting, is the main responsible factor of contributions to these categories. Superphosphate manufacturing process involves remarkable phosphate based emissions contributing considerably to FE. Regarding FET and MET, emissions into the water derived from the use of sulfuric acid as raw material in the fertilizer production process are behind of its contribution. The emission of cypermetrin also derived from production of this fertilizer is the main responsible of contributions to TET.

Forest management stage (SS3) is the main responsible of contributions to FE with ratio of approximately 36% (Figure 3). Having a look into Figure 4c, contributions to the environmental profile from SS3 are totally associated with the application of chemicals, being chemical weeding process the environmental hotspot (around 46% of contributing ratio on average in all categories). The negative impact is mostly associated with the production of the glyphosate used as herbicide, which is applied on the soil to combat weeds.

Seedlings plantation stage (SS2) as well as Infrastructure establishment stage (SS5) report negligible contributions to the global environmental profile (see Figure 3). Assessing in more detail SS2, the planting process itself is the main responsible of contributions from SS2 with contributing ratios ranging from 43% to 60% as displayed in Figure 4b due to outstanding consumption of diesel.

Concerning Forest harvesting stage (SS4), trees harvesting and roundwood extraction from the cutting area to the roadside landing are carried out by means of huge machines such as the harvester and the forwarder, respectively, being thus environmental hotspots (Figure 4d). These machines report a significant consumption of diesel (585 and 340 $L \cdot ha^{-1}$, respectively). In fact, 80% of the total fuel requirement all over the life cycle of Pine roundwood production is associated with these two specific processes. Assessing in more detail contributions to the environmental profile from SS4, combustion emissions from diesel used by harvester and forwarder machines are the main responsible of contributions to CC, TA and POF being emission of CO_2, NO and NO_x into the atmosphere the responsible substances. Regarding to contributions to OD, WD and FD, the production of diesel (background process) is behind of contributions to these categories. Regarding the toxicity related categories, environmental impacts are associated with emission of hydrocarbons from background processes (diesel production and machinery production).

Finally, regarding to Infrastructure establishment (SS5), its contribution to the global environmental profile derived from the Pine roundwood production is negligible. In this stage, building and maintenance of the roads (during the plantation lifespan) is considered. The high frequency of road maintenance based activities contributes with major impacts on the evaluated categories (Figure 4e).

3.2. Discussion and comparison with previous studies

In this present study, LCA has been considered as environmental tool to quantify and identify environmental burdens related to industrial pine roundwood production in Brazil. The interest on this forest specie is due to its relevance in the forest economy of the country. Pine is the second most reforested specie and wooden biomass is used in multiple industrial applications. Regarding the forest management in the area under study, forest stands are mainly managed under intensive conditions.

Remarkable differences were identified between the subsystems considered in the forest system analyzed. They are mainly related to the high consumption of diesel by forest machinery in some activities (i.e., harvesting) and the use of agrochemicals to supply required nutrients for plants growing either in the preparation of the soil before planting or in the further soil maintenance.

As previously discussed, LCA was considered in numerous studies to determine environmental impacts derived from the operations carried out in different forest systems in many European countries such as France, Portugal, Italy, Germany, Sweden and Spain as well as in Chile. Regarding Brazil, the interest on identifying the environmental profile associated with forest biomass production was previously reported regarding Eucalyptus stands (Silva et al., 2013).

The most important subsystem in terms of environmental burdens is the Forest harvesting (SS4). This stage was identified as the most responsible in nine of twelve impact categories analyzed and it is related to requirement of diesel by forest machinery, which involves combustion emissions derived from diesel use as well as derived emissions from diesel production (background process). This stage is responsible for 61%, 68% and 76% of total CO_2, SO_2 and NMVOC emissions production all over the life cycle of the forest stand (12 years). Similar results were identified in related LCA studies of pine production in Europe (Dias and Arroja, 2012; González-García et al.; 2014a), which will be analyzed in more detail below.

Other related studies considering other forest species (Berg and Karjalainen, 2003; Michelsen et al., 2008; González-García et al., 2009a; 2009; Berg et al., 2012) also highlighted the outstanding contribution to the global environmental profile from activities related to biomass harvesting (that is, harvesting and forwarding).

Soil preparation subsystem is the second most important stage from an environmental approach with remarkable contributions in the impact categories analyzed (see Figure 3). The highest contributions are mainly identified in categories related with eutrophication and toxicity due to fertilization process. According to Sixel and Gomes (2008), the largest nutritional limitation in Brazilian soils is related to phosphorous and therefore, large amounts of P-based fertilizer must be supply in the stands. It is important to highlight that as difference to other fertilizers, superphosphate is only applied in the soil preparation stage.

Taking in mind the environmental results obtained in the case study under assessment, they have been compared with the ones available in the literature related to roundwood production (Dias and Arroja, 2012; Silva et al., 2013; González-García et al., 2014a) with the aim of identifying differences (or not) regarding the activities that play a key environmental role. However and as it is detailed below, no outstanding differences have been identified being harvesting and fertilization the contributing activities to the global environmental profiles.

González-García et al. (2014a) identified the environmental profile associated with the production of maritime pine (*Pinus pinaster* Ait.) roundwood in France under two different management scenarios (i.e., intensive and extensive management regimes). In that study and regardless both the environmental categories considered for assessment and scenario, the logging stage (including harvesting, forwarding and loading the logs onto trucks at the roadside) was identified as the main responsible of the environmental burdens with ratios ranging from 39% to 57%, depending on the category. The rationale behind these results was linked to the associated large fuel requirement (more than 70% of the total consumption over the life cycle of the plantation). In addition, the authors identified the fertilization as an environmental hotspot in intensive management regimes due to background processes associated with the production of the fertilizers and derived emissions from their application.

In the case of the analysis performed by Dias and Arroja (2012) focused on the production of maritime pine roundwood in Portuguese stands, the authors also identified harvesting and fertilizing activities as environmental hotspots due to, respectively, the large fossil fuel requirements and diffuse emissions from P-based fertilizer application.

Concerning the infrastructure establishment, an essential stage to facilitate the access of workers and machinery to the forest stands (Machado, 1989), its effect on the global environmental profile is also negligible in line with previous studies (Dias and Arroja, 2012; González-García et al., 2014a; 2014b).

5. Conclusions

In this study, the production of industrial pine roundwood in the Southeastern region of Brazil was assessed from an environmental point of view following the LCA approach. Comparison of the environmental profile with other studies available in the literature even of different forest species leads to the identification of harvesting operations and fertilization as environmental hotspots. These results suggest that both fossil fuel requirements in harvesting activities and fertilizers dose should be optimized to decrease the environmental impacts. Moreover, special attention must be paid to the system boundaries, assumptions and methodological issues, since can derive on uncertainty.

Results reported in this study could be useful in decision making strategies specifically in forest based industries with pine as main raw material.

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Table 1. Description of processes carried out in a representative industrial pine wood stand in Brazil

Subsystem	Operation	Year	Machinery	Weight (kg) & Power (kW)	Implement	Weight (kg)	Operating rate (h·ha^{-1})	Diesel consumption (L·ha^{-1})
Soil preparation	Subsoiling	0	Tractor	8,568 kg 107.7 kw	Plower	2,000	1.8	9
	Pest control[a]	0	Tractor	8,568 kg 107.7 kw	Sprayer	230	2.3	4
	Chemical weeding[b]	0	Tractor	8,568 kg 107.7 kw	Sprayer	230	2.3	3.6
	Lowering stumps	0	Tractor	8,568 kg 107.7 kw	Milling	-	0.2	0.9
	Waste scattering	0	Tractor	8,568 kg 107.7 kw	Roller	4,700	3.2	11
	Mineral fertilization[c]	0	Tractor	8,568 kg 107.7 kw	Sprayer	230	2.0	3.5
Seedlings plantation	Planting[d]	0	Truck	8,030 kg 191.2 kw	-	-	3.3	3.2
		0	Tractor	8,568 kg 107.7 kw	Furrower	190	0.5	2.5
	Irrigation	0	Tractor	8,568 kg 107.7 kw	Tanker truck	640	1.2	5.7
	Re-plantation[e]	0	Tractor	8,568 kg 107.7 kw	Furrower	190	0.3	1.3
Forest management	Chemical weeding[f]	0-12	Truck	8,030 kg 191.2 kw	Tanker truck	-	17	34
	Pest control[g]	0-11	Tractor	8,568 kg 107.7 kw	-		12	25
	Mineral fertilization[h]	0-11	Tractor	8,568 kg 107.7 kw	Sprayer	230	13	24
Forest harvesting	Harvesting	11	Harvester	28,725 kg 219 kW	Tracer	1400	24	585
	Extraction	11	Forwarder	19,500 kg 160 kW	-	-	16	340
	Loading onto trucks	11	Bulldozer	23,530 kg 110.0 kW	-	-	6	115
Infrastructure establishment	Roads building and maintenance	0	Crawler Tractor	7,795 kg 55.2 kw	Blade	-	0.53	0.3
		0	Motor grader	13,032 kg 93 kw	-	-	0.5	1.8
		0	Backhoe	10,200 kg 58 kw	-	-	0.9	3.5

[a]5 kg·ha-1 of Sulfluramide based ant bait; [b] 2 kg·ha-1 of glyphosate; [c] 672g·ha^{-1} of urea, 1.5 kg·ha^{-1} of ammonium sulfate, 36 kg·ha^{-1} of superphosphate and 12.5 kg·ha^{-1}of potassium chloride; [d] Planting of 1,750 seedlings per ha; [e] Re-planting of 200 seedlings per ha; [f]11 kg·ha^{-1} of glyphosate; [g]26.6 kg·ha^{-1} Sulfluramide-ant bait; [h] 9.48 kg·ha^{-1} of urea, 3.2 kg·ha^{-1} of ammonium sulfate, 74.9 kg·ha^{-1} of superphosphate and 24.5 kg·ha^{-1}of potassium chloride

Table 2. Average transport distances corresponding to the inputs' delivery up to the forest site

Inputs	**Distance (km)**
Urea	2117
Ammonium sulfate	2389
Superphosphate	2173
Potassium chloride	2634
Glyphosate	2403
Sulfluramide-ant bait	566

Table 3. Summarized inventory data corresponding to 1 m³ under bark (ub) of pine roundwood production at forest stand

	Quantity	Unit
INPUTS FROM TECHNOSPHERE		
Materials		
Seedlings	15	units of plants
Herbicide		
Glyphosate	26	g
Insecticide		
Sulfluramide-ant bait	82	g
Fertilizers		
Urea	21	g
Ammonium sulfate	10	g
Superphosphate	225	g
Potassium chloride	76	g
Fossil fuel		
Diesel	234	g
Transport		
Truck	280	t·km
OUTPUTS TO TECHNOSPHERE		
Product		
Pine logs	1	m³ ub
OUTPUTS TO ENVIRONMENT		
Emissions into air		
from diesel combustion		
NMVOC	10	g
NO_x	83	g
CO	25	g
CO_2	5	kg
SO_2	4	g
CH_4	3	g
Benzene	4	g
Particles	13	g
Cadmium	10	g
Chromium	10	g
Copper	10	g
Dinitrogenmonoxide	3	g
Nickel	10	g
Zinc	10	g
Benzo(a) pyrene	4	g
PAH[a]	6	g
Heat	70	kg
Ammonia	3	g
Selenium	10	g
from fertilizers application		
Urea	67	g
from herbicide application		
Glyphosate	14	g
Emissions into soil		
from herbicide application		
Glyphosate	119	g
Emissions into water		
from herbicide application		
Glyphosate	14	g
from fertilizers application		
Sulfate leaching	27	g
Phosphate	0.73	g

[a]polycyclic aromatic hydrocarbons

Table 4: Potential environmental profile per 1 m^3 ub of pine roundwood production in Brazil. Acronyms: SS1: Soil preparation; SS2- Seedlings plantation; SS3- Forest management; SS4- Forest harvesting; SS5- Infrastructure establishment; CC- Climate Change; OD –Ozone Depletion, TA- Terrestrial Acidification, FE- Freshwater Eutrophication, ME- Marine Eutrophication, HT- Human Toxicity, POF- Photochemical Oxidants Formation, TET- Terrestrial Ecotoxicity, FET- Freshwater Ecotoxicity, MET- Marine Ecotoxicity; WD- Water Depletion; FD- Fossil Depletion.

Impact category	**Unit**	**SS1**	**SS2**	**SS3**	**SS4**	**SS5**	**Total**
CC	kg CO_2eq	1.17	$3.43\cdot10^{-1}$	1.53	5.28	$2.14\cdot10^{-1}$	8.54
OD	kg CFC-11eq	$1.67\cdot10^{-7}$	$4.56\cdot10^{-8}$	$2.32\cdot10^{-7}$	$8.2\cdot10^{-7}$	$2.94\cdot10^{-8}$	$1.30\cdot10^{-6}$
TA	kg SO_2eq	$9.15\cdot10^{-3}$	$2.18\cdot10^{-3}$	$8.50\cdot10^{-3}$	$4.46\cdot10^{-2}$	$1.13\cdot10^{-3}$	$6.55\cdot10^{-2}$
FE	kg P eq	$7.75\cdot10^{-4}$	$7.53\cdot10^{-5}$	$7.30\cdot10^{-4}$	$4.40\cdot10^{-4}$	$6.92\cdot10^{-5}$	$2.09\cdot10^{-3}$
ME	kg N eq	$3.54\cdot10^{-4}$	$1.26\cdot10^{-4}$	$4.83\cdot10^{-4}$	$2.71\cdot10^{-3}$	$6.31\cdot10^{-5}$	$3.73\cdot10^{-3}$
HT	kg 1,4-DB eq	$7.22\cdot10^{-1}$	$1.14\cdot10^{-1}$	$7.18\cdot10^{-1}$	$7.97\cdot10^{-1}$	$9.27\cdot10^{-2}$	2.44
POF	kg NMVOC	$7.76\cdot10^{-3}$	$3.67\cdot10^{-3}$	$1.10\cdot10^{-2}$	$7.70\cdot10^{-2}$	$1.70\cdot10^{-3}$	$1.01\cdot10^{-1}$
TET	kg 1,4-DB eq	$2.29\cdot10^{-4}$	$4.95\cdot10^{-5}$	$2.97\cdot10^{-4}$	$5.10\cdot10^{-4}$	$1.29\cdot10^{-5}$	$1.10\cdot10^{-3}$
FET	kg 1,4-DB eq	$2.25\cdot10^{-2}$	$2.51\cdot10^{-3}$	$1.87\cdot10^{-2}$	$1.56\cdot10^{-2}$	$2.34\cdot10^{-3}$	$6.16\cdot10^{-2}$
MET	kg 1,4-DB eq	$2.16\cdot10^{-2}$	$2.62\cdot10^{-3}$	$1.88\cdot10^{-2}$	$1.64\cdot10^{-2}$	$2.40\cdot10^{-3}$	$6.18\cdot10^{-2}$
WD	dm^3	10.2	1.47	8.25	12.2	1.16	33.3
FD	kg oil eq	$4.30\cdot10^{-1}$	$1.15\cdot10^{-1}$	$5.32\cdot10^{-1}$	1.74	$7.55\cdot10^{-2}$	2.89

Figure 1.Area and distribution of pine forest plantations throughout Brazil (ABRAF, 2013). Acronyms: AP- Amapá; TO- Tocantins; BA- Bahia; MG- Minas Gerais; GO- Goiás; MS- Mato Grasso do Sul; ES- Espírito Santo; SP- São Paulo; PR- Paraná; SC- Santa Catarina; RS- Rio Grande do Sul.

Figure 2. Flowchart and system boundaries corresponding to the Brazilian pine roundwood production system. Subsystem acronyms: SS1- Soil preparation; SS2- Seedlings plantation; SS3- Forest management; SS4- Forest harvesting; SS5- Infrastructure establishment.

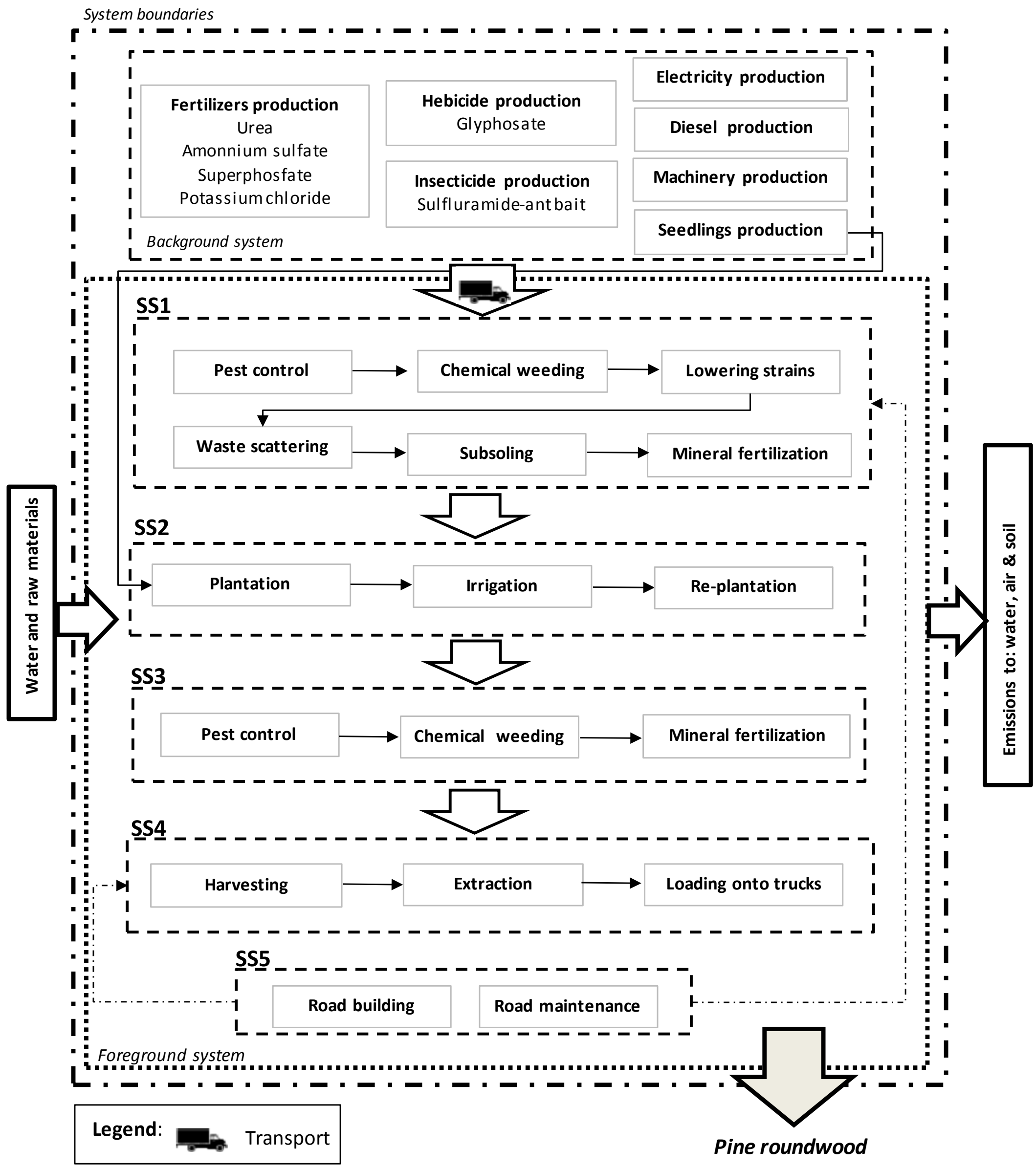


Figure 3.Contributions to the environmental profile corresponding to the Brazilian pine roundwood production system considering current forest practices. Acronyms: SS1: Soil preparation; SS2- Seedlings plantation;SS3- Forest management; SS4- Forest harvesting; SS5- Infrastructure establishment; CC- Climate Change; OD – Ozone Depletion, TA- Terrestrial Acidification, FE- Freshwater Eutrophication, ME- Marine Eutrophication, HT- Human Toxicity, POF- Photochemical Oxidants Formation, TET- Terrestrial Ecotoxicity, FET- Freshwater Ecotoxicity, MET- Marine Ecotoxicity; WD- Water Depletion; FD- Fossil Depletion.

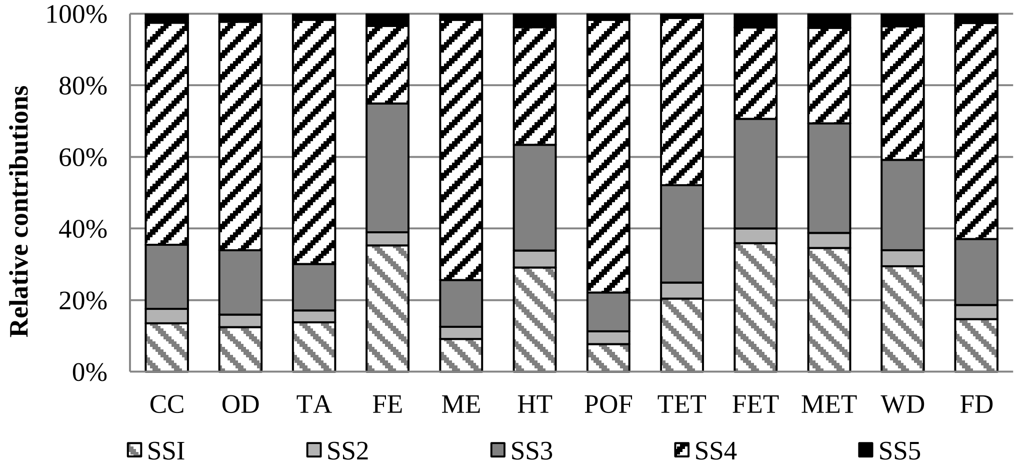


Figure 4. Distribution of impacts per processes involved in each subsystem. a) Soil preparation (SS1); b) Seedlings plantation (SS2); c) Forest management (SS3); d) Forest harvesting (SS4); e) Infrastructure establishment (SS5). Acronyms: CC- Climate Change; OD - Ozone Depletion, TA- Terrestrial Acidification, FE- Freshwater Eutrophication, ME- Marine Eutrophication, HT- Human Toxicity, POF- Photochemical Oxidants Formation, TET- Terrestrial Ecotoxicity, FET- Freshwater Ecotoxicity, MET- Marine Ecotoxicity; WD- Water Depletion; FD- Fossil Depletion.

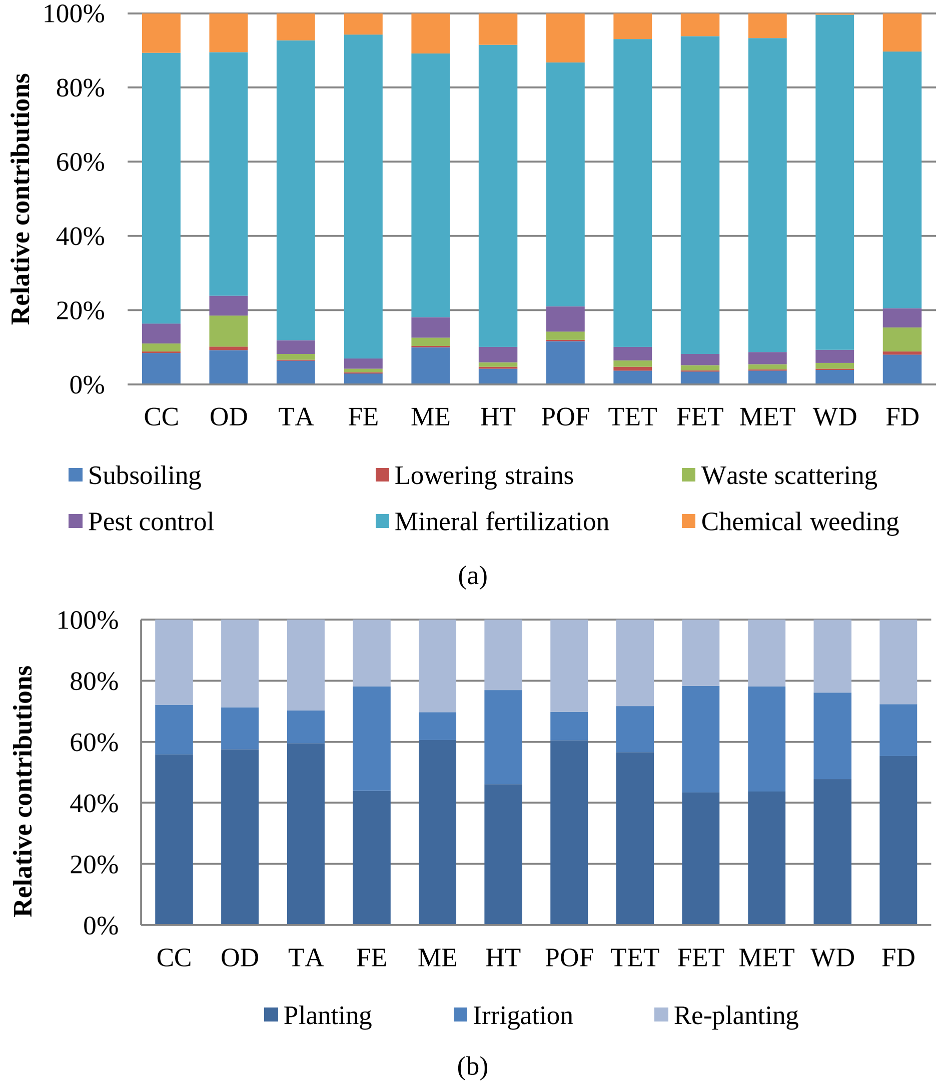
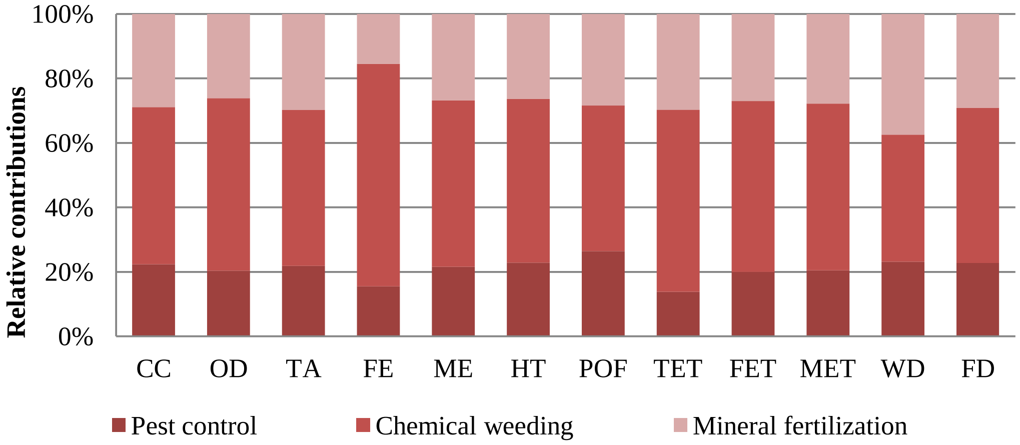
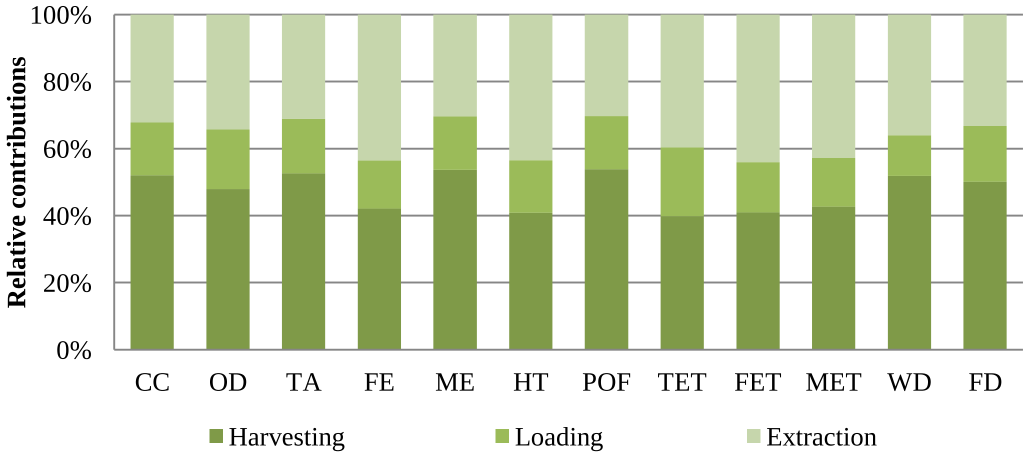


Figure 4 (cont.).Distribution of impacts per processes involved in each subsystem. a) Soil preparation (SS1); b) Seedlings plantation (SS2); c) Forest management (SS3); d) Forest harvesting (SS4); e) Infrastructure establishment (SS5). Acronyms: CC- Climate Change; OD –Ozone Depletion, TA- Terrestrial Acidification, FE- Freshwater Eutrophication, ME- Marine Eutrophication, HT- Human Toxicity, POF- Photochemical Oxidants Formation, TET- Terrestrial Ecotoxicity, FET- Freshwater Ecotoxicity, MET- Marine Ecotoxicity; WD- Water Depletion; FD- Fossil Depletion.

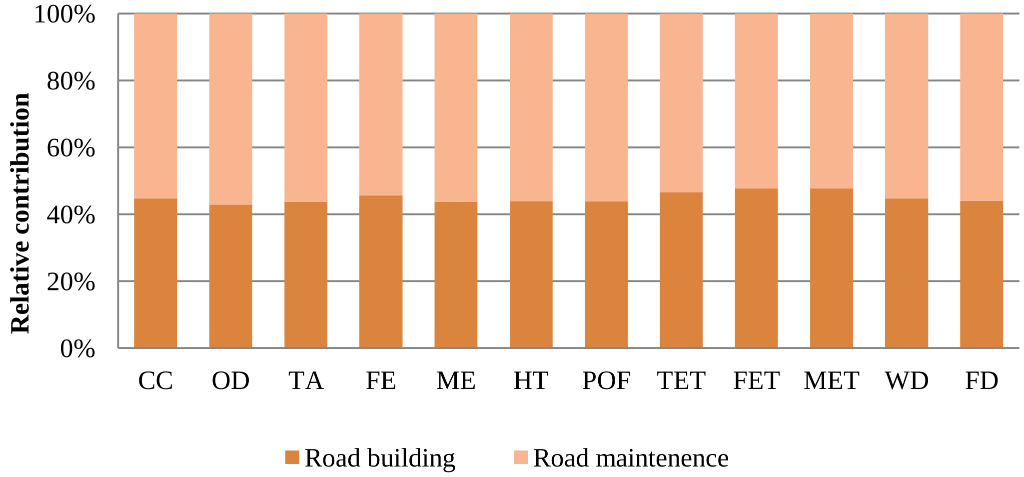


(c)



(d)

Figure 4 (cont.). Distribution of impacts per processes involved in each subsystem. a) Soil preparation (SS1); b) Seedlings plantation (SS2); c) Forest management (SS3); d) Forest harvesting (SS4); e) Infrastructure establishment (SS5). Acronyms: CC- Climate Change; OD –Ozone Depletion, TA- Terrestrial Acidification, FE- Freshwater Eutrophication, ME- Marine Eutrophication, HT- Human Toxicity, POF- Photochemical Oxidants Formation, TET- Terrestrial Ecotoxicity, FET- Freshwater Ecotoxicity, MET- Marine Ecotoxicity; WD- Water Depletion; FD- Fossil Depletion.



(e)