Journal of Sustainable Forestry

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/wjsf20

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To cite this article: José Ferreira, Dennis Jones, Bruno Esteves, Luisa Cruz-Lopes, Helena Pereira & Idalina Domingos (2021) Life Cycle Assessment of Maritime Pine Wood: A Portuguese Case Study, Journal of Sustainable Forestry, 40:5, 431-445, DOI: 10.1080/10549811.2020.1768871

To link to this article: https://doi.org/10.1080/10549811.2020.1768871

JOURNAL OF SUSTAINABLE FORESTRY
2021, VOL. 40, NO. 5, 431–445
https://doi.org/10.1080/10549811.2020.1768871

Life Cycle Assessment of Maritime Pine Wood: A Portuguese Case Study

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ABSTRACT
Life Cycle Assessment has become one of the most recognized and internationally accepted method for examining the environmental performance of forest products and processes. The main aim of this study was to evaluate the potential environmental impact associated with different commercial outputs of maritime pine wood (round, industrial, and residual) produced in the Portuguese forest under natural regeneration. Identifying the hotspots in the life cycle (cradle-to-gate) of each sort of maritime pine was another objective of the study. SimaPro software was used for this study, whilst the CML-IA (baseline) method was chosen to assess the environmental impacts. The study showed that round wood presented the highest values in all impact categories and industrial wood presented the lowest values except in photochemical oxidation where residual wood was the best co-product when economic allocation is chosen. The major hot spots appeared to be the felling and hauling processes due to fossil fuel combustion in the chainsaw and forwarder, respectively. The co-product that should be more environmentally friendly considerably depends on the allocation procedure chosen.

KEYWORDS
Industrial wood; life cycle assessment; maritime pine wood; residual wood; round wood

Introduction

The heightened awareness of the importance of environmental protection and the possible impacts associated with the manufacture and consumption of products has realized an interest in the development of methods to better comprehend and reduce these impacts (ISO & International Standard Organisation, 2006a). One of the most recognized and internationally accepted methods for examining the environmental performance of products and processes is Life Cycle Assessment (LCA) (Heijungs & Guinée, 2012). LCA can be seen as a business decision support tool related to sustainable consumption and production (Wolf et al., 2012) and help to promote "greener" products and the use of "greener" processes (EPA, 2006). The life-cycle concept, such as the most commonly used "cradle-to-grave" approach, has influenced and shaped many methods and techniques to calculate, assess, and improve the environmental performance of products and production systems (Fava et al., 1991; Vigon et al., 1993).

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Supplemental data for this article can be accessed here.

LCA methodology has been applied in many sectors, particularly in the forest sector, as a direct consequence of recognition of its importance as a decision-making support tool. Among areas where LCA has been applied are forestry and forest production (González-García et al., 2009; Karjalainen et al., 2001; Michelsen et al., 2008), buildings or building materials and component combinations (Yuan & Guo, 2017), wood and wood products (J Ferreira et al., 2016, 2018b; Höglmeier et al., 2014; Mahalle et al., 2014; Silva et al., 2014; Suter et al., 2017), the timber industry (Eshun et al., 2010) and wood for energy production (J Ferreira et al., 2018a, 2014; Muazu Rukayya et al., 2017; Pergola et al., 2018). LCA was applied to quantify the environmental profiles of maritime pine round wood production in Portugal and France by González-García et al. (2014), though this was undertaken using the ReCiPe impact assessment method. A recent state of the art of existing LCA study of forest production was carried out by Klein et al. (2015), whereby the authors analyzed 22 different peer-reviewed studies, 4 original reports, and 2 databases. The main finding from their literature review is that the system boundaries, functional units or allocation assumptions and methods differed from study to study which can difficult the comparisons between them.

Forests are critical for human livelihood due to the wide range of products (wood and others) and the amount of money generated by forest industry sector, essential ecosystem services they provide (such as preventing soil erosion and protecting biodiversity), as well as providing space for recreation, etc. (European Union, 2017; FAO, 2012). It is estimated that the total area of the world's forests in 2005 is 3.8 billion hectares, or 30% of the global land area (FAO, 2012). The European Union holds approximately 5% of the world's forests and overall area is slowly increasing. It has been estimated that the world's forests have stored about 2.4 Gigatonnes of carbon every year between 1990 and 2007 which clearly demonstrate the key role that forests and forest products play in carbon storage (FAO, 2012). Such facts demonstrate why forests are at the heart of the transition to low-carbon economies as demonstrated by the majority of the Paris Agreement's (United Nations, 2015) signatories, whereby forests in their Intended Nationally Determined Contributions were included as a viable means for mitigating climate change.

According to the FAO's forest products statistics (FAO, 2016), global industrial round wood production (all round wood used for any purpose other than energy) amounted to 1874 million m^3 in 2016, of which 590 million m^3 (32%) were produced in Europe (including the Russian Federation). This is an increase of 2.6% compared to 2015 and 5.9% compared to the level in 2012. Similarly, for 2016, global wood fuel production (round wood that is used as fuel for cooking, heating or power production, as well as wood used to make charcoal and pellets) amounted to 1 863 million m^3 which is a minor increase from 2012 and from 2015 (less than 1%). In the same period, wood fuel production increased 5% in Europe.

The preliminary results of the 6th National Forest Inventory (ICNF, 2013) estimated the total area of Continental Portugal forests in 2010 at 3.15 Million hectares or 35.4% of the total land area. The area occupied by coniferous species in 2010 corresponded to 31% of the Portuguese forest, with the remaining 69% occupied by hardwoods. Maritime pine (*Pinus pinaster* Ait.) with a land occupation of 714 thousand ha, represented 23% of the total forest area, 74% of total coniferous growth, and was the third most common species produced in the country (ICNF, 2013). The same study revealed that maritime pine domain had a net loss (−27%) of forest area between 1995 and 2010.

Overall, the forest sector was one of the main sectors in the Portuguese economy in 2015 (ICNF, 2018). The different forest products are of enormous importance in the national trade balance (10% exports and 4% imports). The net exports have been growing since 2009, with a surplus of €2.5 billion in 2015. The Gross Value Added (GVA) of forest-based industries represented more than €3 billion, in 2014, corresponding to 15% of industrial GVA and 2% of national GVA and Gross Domestic Product (GDP). The forestry sector is also responsible for the creation of approximately 92 thousand jobs, of which almost 25 thousand correspond to jobs in the primary sector and forest-based manufacturing industries.

There are continual changes to how society perceives these valuable forest resource, particularly their importance for human well-being and ecosystem health. The main aim of this work was to assess the potential life cycle environmental impact associated with different types of maritime pine wood products coming from the Portuguese forest and identifying the hotspots.

Materials and methods

The LCA study was performed with the methodology recommended in the ISO 14040 (ISO & International Standard Organisation, 2006a) and 14044 (ISO & International Standard Organisation, 2006c) standards. It was divided into four phases: goal definition – which defines the aim and scope of the study as well as the functional unit; inventory analysis – which lists emissions of pollutants into air, water and soil, solid wastes and consumption of resources per functional unit; impact assessment – which assesses the environmental impact of the pollutants emitted throughout the life cycle; and interpretation of results in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope.

A forest management model adopted in this study for maritime pine stands, under natural regeneration (typical for 80% of the Portuguese conditions) was adapted from AIFF (2013). According to this model, clearing operation using a rotary mower takes place between the 3rd and 5th years; the manual pruning is carried out between the 4th and 10th years; the first and second thinning using a chainsaw and a forwarder occur between the 15th and 20th years and between the 25th and 30th years, respectively; the final cut using a chainsaw and a forwarder takes place at the 35th year (minimum age).

The model used for wood production in Portuguese maritime pine stands was adapted from a DGRF report (DGRF, 2006). According to this model, wood production has the following destination: 3.4×10^6 $m^3.year^{-1}$ for sawmill with a price of €40 per m^3; 1.4×10^6 $m^3.year^{-1}$ for chipping with a price of €25 per m^3; and 0.2×10^6 $m^3.year^{-1}$ for biomass for energy with a price of €20 per m^3.

For this study, the following assumptions were taken into account: wood production for sawmill, chipping, and biomass for energy are equivalent to round wood, industrial wood, and residual wood, respectively. Round wood is defined in this study as wood with a log diameter $d > 14$ centimeters, whilst industrial wood has a log diameter between 7 and 14 centimeters and residual wood has a log diameter $d < 7$ centimeters, along with materials from branches and tops of trees.

Goal and scope of the study

The main aim of the study was, as mentioned before, to assess the potential life cycle environmental impact associated with the production of different sorts of maritime pine (*Pinus pinaster* Ait.) wood (round, industrial, and residual) in the Portuguese forest, under natural regeneration, reflecting 80% of the Portuguese conditions (AIFF, 2013). Another objective of the study was concerned with identifying the environmental hot-spots in the product systems within this study.

Function of the system and functional unit

The function of the system being studied is to harvest and produce maritime pine wood for different uses: round wood is mainly used in the sawmill industry; industrial wood is used in paper or wood fiber industries; and residual wood is mainly used as fuel wood.

Since the volume remains more or less constant with changing water content, the functional unit in this study is given as 1 m^3 under bark (ub) of green wood (recently harvested wood) with a moisture content of 45%. The choice of this functional unit is in agreement with other wood systems studied via LCA (González-García et al., 2009; Klein et al., 2015; May et al., 2012; Werner et al., 2007) and recommended in PCR 2012:01 v2.2 (EPD International, 2017).

System boundary

Figure 1 is a simplified way of showing the system boundary for the product system being studied.

The modules included in the boundaries were related to natural regeneration within wood production whereby:

Maritime pine standing in forest – this is used to account for the land on which trees grow and for the CO_2 assimilated by the trees;

Infrastructure establishment: road maintenance – this refers to the forest road maintenance with a motor grader;

Forest processes: clearing (mowing) refers to the use of a rotary mower pulled by a tractor to cut above-ground vegetation;

Pruning – refers to the removal of side branches with the object of reducing the number of significant knots in the timber being formed that will affect the visual grading properties of the material (carried out manually); and

Thinning/final cut – that consists of two processes – the felling process comprising cuts made either in the immature stand to improve the average form of the remaining trees or in the mature stand at final harvesting, respectively, and the subsequent hauling process of the usable wood to the nearest forest road. For round wood production, the mature tree is cut and debranched with a chainsaw, loaded, and moved by a forwarder to the forest road. Residual wood (branches, small trees from thinning) and industrial wood (immature trees) are harvested with chainsaws, cut into suitable pieces, and then loaded and moved by a forwarder to the forest road.

Allocation procedure

Because the process “thinning/final cutting” is a multi-output process, the allocation of the burdens to the different outputs is necessary and was based on the economic return of co-products (May et al., 2012; Tucker et al., 2009; Werner et al., 2007). This procedure is recommended in PCR 2012:01 v2.2 (EPD International, 2017) when the difference in revenue of co-products is more than 25%. In this study, the difference in revenue of round wood and residual wood is 50%. Based on the wood production model previously mentioned 77.7% of the burdens were allocated to round wood, 20% to industrial wood,

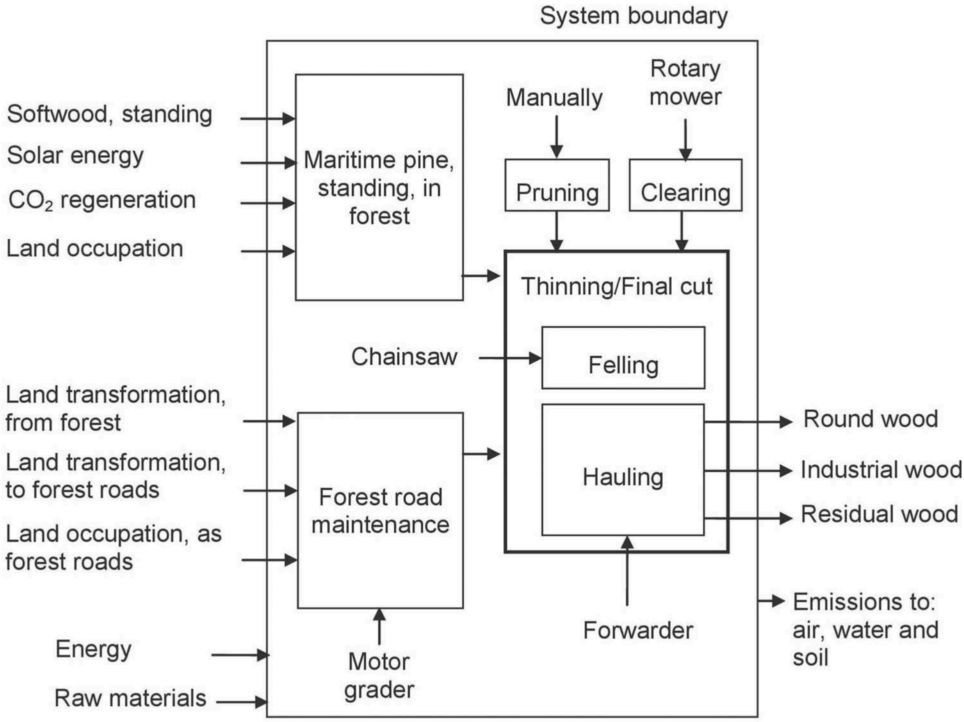

Figure 1. Cradle-to-gate product system for commercial outputs of Portuguese maritime pine wood under natural regeneration.

and 2.3% to residual wood. As the economic allocation cannot take into account the mass and energy balance of the products, correcting modules were defined in order to add or subtract the CO_2 uptake based on the resource, energy source (wood, solar, etc.) and the level of consumption from nature. The following correction factors were calculated (see Tab. S1): –0.143 m^{-3} for round wood; 0.286 m^{-3} for industrial wood; and 0.429 m^{-3} for residual wood. A negative correction meant deducting the final amount of wood by the value of the correction factor.

Since the allocation approach can have a strong effect on the results, a sensitivity analysis was also proposed considering volume allocations between the co-products, in order to identify differences on the environmental profile.

Inventory analysis

The life cycle inventory analysis and, subsequently, the life cycle impact assessment was performed using the SimaPro 8.5.2 (PRé Consultante, 2018) software and associated databases and methods.

Data type/data collection

Most datasets for the products and processes included in the system boundaries were based on reports of national offices (DGRF, 2006; DNGF, 2010) and industry associations (AIFF, 2013). The temporal and geographical representativeness of data is 2005 and

Continental Portugal, respectively. Background data were taken from the ecoinvent database (Werner et al., 2007) and adapted to Portuguese conditions as described in the following paragraphs.

According to the 5th National Forest Inventory (DNGF, 2010), in 2005, Portuguese maritime pine stands occupied 795489 ha, stored a total volume of 85.756 × 10^6 m^3, representing a total biomass of 49.690 × 10^6 ton, a total carbon of 24.845 × 10^6 ton and a $CO_{2equivalent}$ of 91.098 × 10^6 ton. Based on these figures, the Portuguese maritime pine stands are considered to provide a yield of 108 m^3 ha^{-1}, a specific weight (density) of 0.579 $t.m^{-3}$, a carbon content of 50%, and a moisture content of u = 45% (based on a specific weight of 400 kg/m^3 dried matter (Lousada et al., 2008)). This information along with other datasets are essential to achieving the Inventory Table.

Firstly, the land use for wood production and the flows within the forest process "maritime pine, standing, in forest" were adapted from Werner et al. (2007) and calculated according to information and assumptions given in Table 1 and Table 2, respectively. Despite the fact that forests and forest roads are multifunctional, through the provision of

Table 1. Land use for Portuguese maritime pine production and forest processes.

Nr.	Portuguese maritime pine	Mean value	Units	Source
1	Yield (including forest roads and 10% of bark)	108	m^3/ha	DNGF, 2010
2	Time from tree regeneration to final harvesting	35	years	AIFF, 2013
3	Forest road length	71.3	m/ha	Faias et al., 2007
4	Forest road width	3.50	m	IC-EQUAL, 2007
5	Forest road area	249.55	m^2/ha	Calculated[a]
6	Yield (including forest roads)	0.0108	m^3/m^2	Calculated[b]
7	Yield (excluding forest roads)	0.0111	m^3/m^2	Calculated[c]
8	Land use forest	90.3	m^2/m^3	Calculated[d]
9	Land use forest roads	2.31	m^2/m^3	Calculated[e]
10	Land occupation forest	3161	$m^2.yr/m^3$	Calculated[f]
11	Land occupation forest roads	80.9	$m^2.yr/m^3$	Calculated[g]

[a]Forest road area = (Forest road length x Forest road width)
[b]Yield (including forest roads) = Yield (including forest roads and 10% of bark)/10000 m^2
[c]Yield (excluding forest roads) = Yield (including forest roads and 10% of bark)/(10000 m^2 – Forest road area)
[d]Land use forest = Yield (excluding forest roads)$^{-1}$
[e]Land use forest roads = Forest road area/Yield (including forest roads and 10% of bark)
[f]Land occupation forest = Land use forest x Time from planting trees to final harvesting
[g]Land occupation forest roads = Land use forest roads x Time from planting trees to final harvesting

Table 2. Flows for "Maritime pine, standing, in forest".

Inputs from nature	Remarks	Units	Mean value	Source
Wood, soft, standing	Including bark (10%)	m^3	1.1	
Solar energy	Equals to gross calorific value of maritime pine	MJ	8976	Calculated[a]
CO_2 regenerativ	Mass of CO_2 sequestered	Kg	807	Calculated[b]
Transformation, from forest, extensive	90.3 (Table 1, Nr. 8) x 1.10	m^2	99.3	Calculated
Transformation, to forest, intensive	Equal to "Transformation, from forest, extensive"	m^2	99.3	-
Land occupation forest	3161 (Table 1, Nr. 10) x 1.10	m^2. yr	3477	Calculated
Output: Maritime pine, standing, in forest	Under bark	m^3	1.0	

[a]Equals to gross calorific value of maritime pine (20.4 MJ/Kg dry matter) (Frischknecht et al., 2007) x dried matter (400 Kg/m^3) (Lousada et al., 2008) x 1.1 m^3
[b]Equals m_{dry} of timber (1.1 x 400) x percentage of carbon in dry matter, for timber (0,5) x molecular mass of CO_2 (44)/ atomic mass of carbon (12)

mushrooms and aromatic production, biodiversity, protection against soil erosion, etc., for this study the total forest area is allocated solely to wood production.

Then, the infrastructure establishment comprising "Forest road maintenance" was adapted from Werner et al. (2007) too and calculated according to information and remarks given in Table 1 and assuming that road maintenance is undertaken every 5 years (7 times over 35 years) using an industrial tractor equipped with a front blade (motor grader), providing an effective work time of 0.6 $h.ha^{-1}$, a fuel (diesel oil) consumption of 14 $l.h^{-1}$ with a net calorific value of 36.83 $MJ.l^{-1}$ (Dias et al., 2007). The inputs achieved for this process were: 22 MJ of energy used in the motor grader; 2.54 m^2 of land transformation from forest to forest roads; and 89 $m^2.yr$ of land occupation as forest roads, per 1 m^3 of wood under bark as output.

Finally, the flows within the process "Thinning/final cutting" are represented in Tab. S2. As previously indicated, two machines were used for this operation: a chainsaw with an effective work time of 0.24 $h.m^{-3}$ (u.b.) using gasoline as fuel and a forwarder with an effective work time of 0.08 $h.m^{-3}$ (u.b.) and fuel (diesel oil) consumption of 12 $l.h^{-1}$ (Dias et al., 2007). According to Dias et al. (2007), the clearing (mowing) operation was normally undertaken using a rotary mower pulled by a tractor, with an effective work time of 4.5 $h.ha^{-1}$ and a fuel (diesel oil) consumption of 8 $l.h^{-1}$. The forwarder's values were related to round wood and industrial wood. For residual wood (biomass for energy), the forwarder productivity was considered to be 5.4 $t.h^{-1}$ and a fuel (diesel oil) consumption of 12.5 $l.h^{-1}$ (Silva, 2009), meaning an effective work time of 0.119 $h.m^{-3}$ (u.b.) $(5.4/0.579\text{ (density)})*0.9)^{-1}$. The results were used to obtain the inventory table.

A moisture content (u = 45%) was assumed for all outputs because this is the value considered for maritime pine stands in forest as mentioned before. The moisture content is necessary within the inventory for determining the transport of products or calculating the heating value.

The inventory tables

The results presented in Tab. S2 were entered into the software SimaPro 8.5.2 (PRé Consultante, 2017) in order to perform the data tables for the production of 1 m^3 of different sorts of maritime pine: round, industrial, and residual wood. The results of the calculations are presented in Table 3 and they take into account the allocation based in economic value of the outputs and 10% of bark as previously described. The inventory tables are not presented here because they have hundreds of lines (substances).

Table 3. The inventory table results for 1 m^3 round, industrial and residual maritime pine wood at forest road.

Inputs from technosphere (per 1 m^3 of each sort of wood, under bark)	Units	Round wood	Industrial wood	Residual wood
Maritime pine, standing, in forest	m^3	1.143	0.714	0.575
Forest road maintenance (motor grader)	m^3	1.143	0.714	0.575
Clearing (rotary mower)	MJ	15.4 3	9.6 4	7.76
Felling (chainsaw)	H	0.274	0.17 1	0.138
Hauling (forwarder)	MJ	39.69	24.81	54.75
Pine, allocation correction	m^3	−0.157	0.314	0.471
Output: (under bark)	m^3	1.0	1.0	1.0

Life cycle impact assessment (LCIA)

The method chosen for determining the environmental impact assessment was CML-IA (baseline) V 3.05/World 2000, which uses the problem-oriented (midpoint) approach (Guinée et al., 2002; PRé Consultante, 2017). The impact categories addressed were: abiotic depletion (AD); abiotic depletion (fossil fuels) (AD(FF)); global warming (GWP100a) (GW); ozone layer depletion (ODP) (OD); human toxicity (HT); fresh water aquatic ecotoxicity (FWET); marine aquatic ecotoxicity (MAET); terrestrial ecotoxicity (TET); photochemical oxidation (PO); acidification (AC); eutrophication (EU). This LCIA method was chosen because it is the method required within the European standard EN 15804:2012+ A1:2013 (CEN, 2013) for environmental product declarations (EPD) of construction products.

Results and discussion

Reference scenario

The life cycle impact assessment (LCIA) results (characterization) for different sorts of maritime pine under natural regeneration, at forest road, using CML-IA (baseline) method are presented in Table 4 and Figure 2.

According to Figure 2(a) and (b), for both round wood and industrial wood the felling process using a chainsaw (gasoline) was the main contributor (38–88%) to the categories AD, HT, FWET, TET, and PO while the remaining categories (AD-FF, GW, OD, MAET, AC, and EU) were mainly affected (37–41%) by the hauling process using a forwarder (diesel oil). For these co-products the forest road maintenance using a motor grader (diesel oil) presented the highest contribution (28%) to the acidification and the lowest contribution (4%) to the PO. The clearing process using a rotary mower (diesel oil) played a similar role but with lower contribution (17%) in acidification and in PO (2%).

For residual wood, the hauling process was the main contributor (45–68%) in all categories except in PO, where the felling process (79%) was mainly responsible (Figure 2c). These two processes (together) play a major role in all impact categories (74–94%) while the forest road maintenance and clearing processes play a minor role (6–26%).

Table 4. Impact assessment results for 1 m^3 (under bark) of different sorts of maritime pine, at forest road, using CML-IA baseline method.

Impact category	Units	Round wood	Industrial wood	Residual wood
Abiotic depletion	mg Sb eq	2.2	1.4	1.6
Abiotic depletion (fossil fuels)	MJ	134.2	83.8	111.7
Global warming (GWP100a)	kg CO_2 eq	8.9	5.5	7.7
Ozone layer depletion (ODP)	mg CFC-11[a] eq	1.2	0.8	1.0
Human toxicity	kg 1,4-DB[b] eq	1.15	0.72	0.89
Fresh water aquatic ecotox.	kg 1,4-DB eq	0.69	0.43	0.49
Marine aquatic ecotoxicity	kg 1,4-DB eq	1108	692	916
Terrestrial ecotoxicity	g 1,4-DB eq	10.1	6.3	7.6
Photochemical oxidation	g C_2H_4 eq	11.7	7.3	6.5
Acidification	g SO_2 eq	63.1	39.4	56.2
Eutrophication	g $PO_{4\,-}$ eq	16.2	10.1	13.8

[a]CFC-11: chlorofluorocarbon; [b]1,4-DCB: 1,4 dichlorobenzene

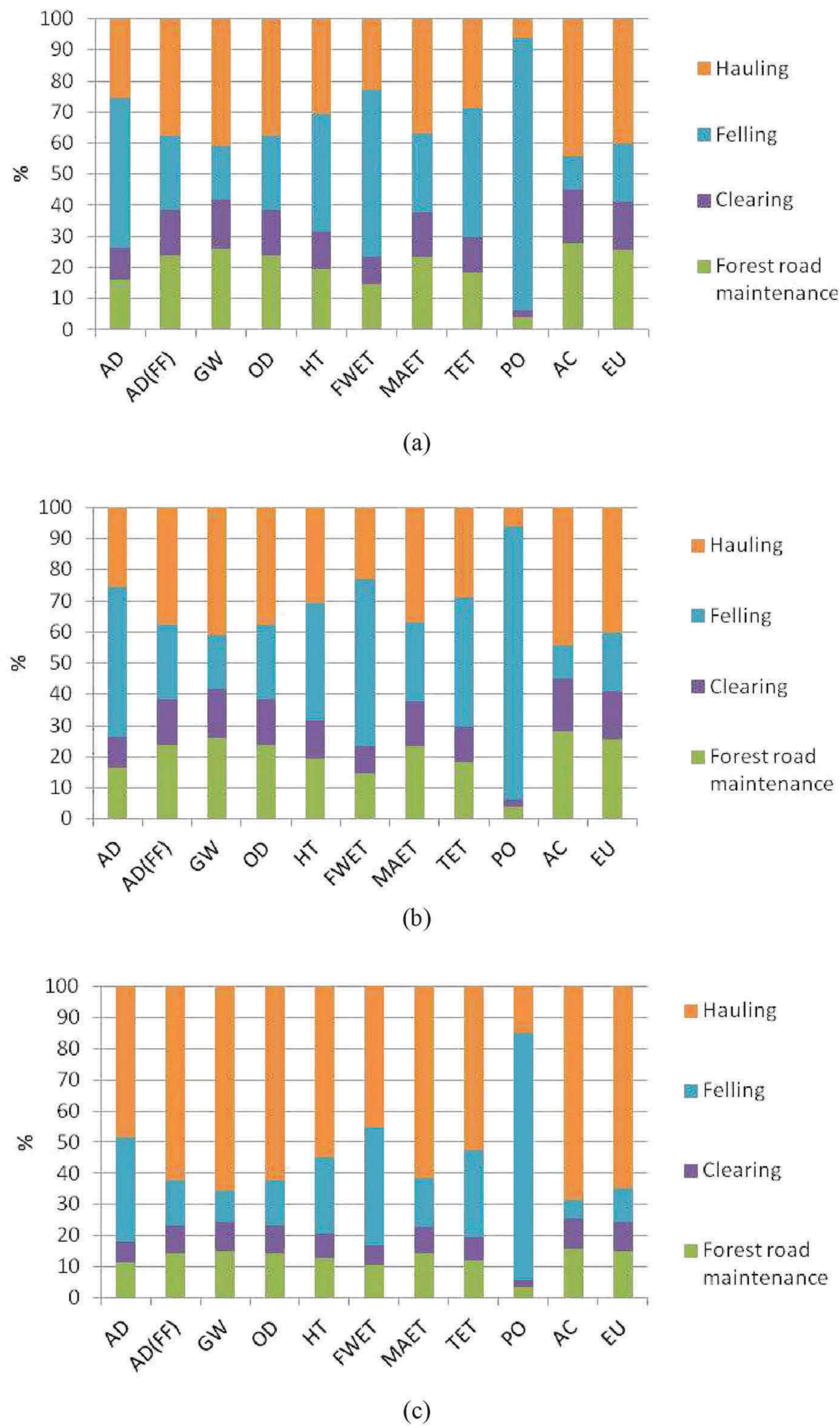

Figure 2. Relative contribution of each process to the environmental results of maritime pine. (a) round wood; (b) industrial wood; (c) residual wood. Acronyms: AD (abiotic depletion); AD(FF) (abiotic depletion (fossil fuels)); GW (global warming (GWP100a)); OD (ozone layer depletion (ODP)); HT (human toxicity); FWET (fresh water aquatic ecotoxicity); MAET (marine aquatic ecotoxicity); TET (terrestrial ecotoxicity); PO (photochemical oxidation); AC (acidification); EU (eutrophication).

In terms of AD, the metals (mainly chromium, nickel, and molybdenum) used in manufacturing of the chainsaw were responsible for 48% of this impact category followed by the forwarder (26%) and motor grader (16%).

The fuel (mainly crude oil) used in forwarder contributed to about 38% for AD(FF) followed by that used in chainsaw and motor grader that contributed with about 24% each.

The carbon dioxide (fossil) emitted into the air was responsible for 95% of GW where the forwarder contributed 42% followed by the motor grader (27%) and the rotary mower (16%).

Halon 1301 emissions into the air were responsible for 98% of OD emitted mainly from the use of the forwarder (38%), the chainsaw, and the motor grader (24% each).

The use of the chainsaw contributed 38% of HT mainly due to emissions of chromium VI in air (62%) followed by those from the forwarder (31%) mainly due to emissions of chromium VI in air and selenium in water. The total chromium VI emissions into the air contributed 42% of HT while barium emission in water was responsible for 10% and nitrogen oxides in air for 9% of this impact category.

FWET was mainly due to emissions of the metolachlor into the soil (34%) followed by the nickel emissions to the water (30%). The chainsaw was the most responsible for those metolachlor´s emissions and the emissions of nickel were mainly caused by the chainsaw (30%) and by the forwarder (35%).

Emissions of beryllium into the water represented the higher contribution (28%) for MAET followed by hydrogen fluoride emissions into the air (25%) and barium and nickel emissions into the water (14% and 13%, respectively). The forwarder emissions contributed 37% for this category while the emissions of the chainsaw represented 25% and the motor grader 23%, respectively.

TET was mainly due to emissions of the mercury into the air (46%) followed by the chromium VI emissions to the soil (12%). The chainsaw and the forwarder were the main contributors for this category with 42% and 29%, respectively.

Carbon monoxide (fossil) emitted into the air contributed 90% to the PO almost due to the chainsaw emissions (94%).

About 71% of the AC was due to the emissions into the air of nitrogen oxides while 28% was due to sulfur dioxide. The major contributors were the forwarder (44%) followed by the motor grader (28%) and the rotary mower (17%) respectively.

About 72% of the EU was due to the emissions into the air of nitrogen oxides while emissions into the water by nitrates and phosphates represented 11% and 9%, respectively. The major contributors were the forwarder (40%) followed by the motor grader (25%) and the rotary mower (19%).

Sensitivity analysis

A sensitivity analysis was performed to identify the influence of the allocation procedure on the environmental profiles.

The environmental profiles changed considerably when the volume-based allocation was considered instead of the economic-based method as shown in Table S3. The round wood and industrial wood present the same values for all impact categories because they share all processes including the hauling process. Residual wood presents the highest values in all impact categories which were expectable and attributed to the highest fuel consumed in the hauling (forwarder) operation as registered in Table S3. Regardless of the category, the environmental profile of the round wood is about 12% better and the industrial wood about 41% worse if the volume allocation is used instead of economic allocation. For residual wood the environmental profile is worse, varying between 23% in AC to 63% in PO.

Discussion

The results obtained in this study for global warming, photochemical oxidant formation, acidification, and eutrophication varied between the values found by Dias and Arroja (2012) for high- and low-intensive management scenarios of maritime pine in Portugal. However, in this study, a natural regeneration model was adopted that carried out two more operations (road maintenance and clearing) and one less (loading onto truck) than the low-intensive management scenario and five less operations (cleaning, loading onto truck, road building, firebreak building, and firebreak maintenance) than the high-intensive management scenario adopted in that study. The allocation method and the CML method versions used in both studies were different too. In this study, the allocation method adopted was based in the economic value of the co-products, while in the previous study all the burdens were allocated to the round wood and none of them were allocated to the industrial and residual wood. Land occupation was included in this study while it was not taken into account in the previous work.

Other study concerned round wood and focused on the same environmental impact categories in forest operations in Scandinavia (Michelsen et al., 2008), which reported that the largest impacts were associated with the logging (felling) and forwarding operations. For logging (felling) operations, impact category results in this current study were lower (15–-68%) and for forwarding operation, results herein were lower in PO (93%) and GW (22%) and higher in AC (21%) and EU (30%). However, the characterization factors of that study (Michelsen et al., 2008) were taken from a different version (V 2.03) of the CML (baseline) method which may at least partly explain the difference from results of the current study.

The results presented in this study are limited to the different types of maritime pine wood products from the Portuguese forest, based on natural regeneration, and the data are representative for the year 2005.

Conclusions

This study proposed to determine the environmental impacts of maritime pine wood production in the Portuguese forest. Three co-products were produced: round wood; industrial wood; and residual wood.

Based on the most common forest practices carried out nowadays in Portugal a management model based on natural regeneration was proposed, reflecting 80% of the Portuguese conditions.

The environmental profiles considerably altered when the allocation procedures changed from economic value to the volume of the co-products. If an economic-based allocation is, round wood presented the highest values in all impact categories and industrial wood presented the lowest values except in photochemical oxidation, where residual wood presented the lower value. Otherwise, if a volume-based allocation was considered, the residual wood presented the highest values in all impact categories.

The major hot spots appeared to be the felling and hauling processes due to fossil fuel combustion in the chainsaw and forwarder, respectively.

Finally, comparison with other environmental studies of maritime pine or other forest species led to differences on the environmental results due to differences on the assumptions and methodological issues.

Acknowledgments

This work is financed by national funds through FCT - Fundação para a Ciência e Tecnologia, I.P., under the project UIDB/00681/2020. Furthermore, we would like to thank the Instituto Politécnico de Viseu and CERNAS for their support.

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