



The influence of forest management systems on the environmental impacts for Douglas-fir production in France



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HIGHLIGHTS

- Two different forest management scenarios (intensive and extensive) were assessed.
- Thinning steps due to the use of large machines are the environmental key factors.
- Minor differences were identified comparing the results with other forest studies.

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ABSTRACT

The environmental wood profile, all over its life cycle, is a subject of interest for industries within the forest sector. Douglas-fir is a wood species with multiple applications and high productivity. In Europe, France is the country with the largest area dedicated to the cultivation of this tree species.

This study aims to quantify the Douglas-fir forestry environmental impacts under different management practices performed in France. This study presents detailed life cycle inventories of both intensive and extensive scenarios, including all the processes from site preparation to logging activities.

The results showed that stand establishment operations, tending and logging were the main stages responsible for the environmental impacts in both scenarios. The requirement of numerous thinning steps prior to the final cutting, which require machines with large fuel consumption, also had a negative influence. The logging stage, which includes the final cutting and the corresponding forwarding and loading onto trucks, also accounted for a significant contribution to all the categories. When the environmental results were compared with other life cycle studies on pine, eucalyptus and spruce, similar trends were identified in spite of the different management practices (low or high intensive scenarios), system boundaries and forest systems intensity (frequency of activities) considered.

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1. Introduction

Forests produce wood, a renewable raw material with multiple uses and applications. European wood production in 2011 reached 687.7 million m³, of which 73% was industrial roundwood to produce paper, furniture or building materials while 13% was used for heating and cooking (FAO, 2012). The three most important European countries

in terms of wood production are Sweden (72.1 Mm³), Germany (56.1 Mm³) and France (53.5 Mm³).

The Kyoto Protocol has promoted the forest relevance to mitigate climate change and to balance greenhouse gas (GHG) emissions (UNFCCC, 1997; Briceño-Elizondo et al., 2006). However, the forest systems management involves other environmental effects which occur during their life cycle. In this sense, the forest sector has paid special attention to provide information on environmental performance in order to be competitive, especially in some European countries such as Norway (Michelsen et al., 2008). Examples of environmental impacts derived from wood production are changes in the organic carbon content in the soil (Milà I Canals et al., 2007), eutrophication and climate change. Eutrophication is related to nutrient release (NH₃ and N₂O) associated with mineral fertilizing (Seppala et al., 1998; Sonne, 2006; Dias

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et al., 2007). Climate change is mainly associated with greenhouse gases emissions derived from the fossil fuel use in forest machines (González-García et al., 2012).

Numerous studies have been performed concerning the environmental burdens identification and quantification derived from forest management activities in countries with an extended tradition in the forest sector such as Scots pine and Norway spruce in Sweden, Finland and Norway (Berg, 1997; Berg and Karjalainen, 2003; Berg and Lindholm, 2005; González-García et al., 2009a; Berg and Karjalainen, 2003; Michelsen et al., 2008) or maritime pine and eucalyptus in Portugal and Spain (Dias et al., 2007; Dias and Arroja, 2012; González-García et al., 2009b). In these reports, representative plantations dedicated to wood production for industrial applications (energy, paper or boards) were assessed in detail. However, no detailed environmental studies have been performed for forest operations in France despite its importance for European wood production.

Douglas-fir (*Pseudotsuga menziesii*) is one of the premier timber trees in the world. It is a forest species naturally occurring in the west coast of North America (Hermann and Lavender, 1999; Sonne, 2006) although it has been extended geographically in many temperate regions of Australia, New Zealand and South America and it is expected to continue spreading due to climate change (Hermann and Lavender, 1999). Douglas-fir has been introduced in Europe, becoming one of the most important species due to the favorable site conditions in Scotland, Denmark and Germany (Hermann and Lavender, 1999).

Douglas-fir forests have increased in importance in recent years for two main reasons: high productivity (Heidingsfelder and Knoke, 2004) and physiological adaptability (Albrecht et al., in press). Douglas-fir wood presents very good mechanical and processing properties, being considered as a suitable raw material for outdoor elements with good dimensional stability, moderate resistance to fungal decay, low treatability and maneuverability in stages of drying, cutting and assembling (Kutnik et al., 2011). Moreover, this type of wood can be used in construction materials which are not treated with wood preservatives (Hans Sauter, 2008). Nowadays, Douglas-fir is discussed as an alternative to other economically important coniferous species such as Norway spruce. The reason is that Norway spruce is facing reduced vitality and a significant reduction in area due to difficulties in coping with increasing temperatures (Spiecker et al., 1996). The impacts and effects of climate change (rising atmospheric CO₂ concentration, higher temperature, flooding, droughts, etc.) on European forests are currently affecting tree species growth and distribution but also soil matter decomposition (AGRI-2007-G4-06, 2008).

Currently, the European countries with the highest number of Douglas-fir plantations are France, Germany, United Kingdom and the Netherlands (Hermann and Lavender, 1999). Among the different varieties, the coastal kind is preferred to the interior one in European forestry since it has higher growth rates although it presents lower

drought tolerance and is affected by late frosts (Hermann and Lavender, 1999; Reyer et al., 2010). The purpose of this study was to evaluate the environmental impacts associated with Douglas-fir wood production in France by using the Life Cycle Assessment (LCA) methodology, from a cradle-to-gate perspective (i.e. from the extraction of the raw materials to the loading of the logs onto trucks). The choice of Douglas-fir as the target species also offered the possibility of analyzing its cultivation under different management regimes.

2. Materials and methods

LCA is a methodology used to evaluate the environmental burdens associated with a product (process or activity) by identifying natural resources consumption and emissions associated with its entire life cycle and to identify and propose improvement opportunities for a better environmental performance (ISO 14044, 2006).

2.1. Case studies

Two Douglas-fir scenarios located in France were assessed from a cradle-to-gate perspective: an intensive management (IS) and an extensive management scenario (ES). Differences between scenarios lie on the application or absence of agro-chemicals (fertilizers and herbicides), forest processes repetition intensity (e.g. thinning activities) and pruning stages, which imply different biomass yield and lifespan (47 years for IS and 60 years for ES). Both plantations are located in the same French region, the Grand Massif Central, which includes, among others, the regions of Auvergne-Limousin and Bourgogne (Fig. 1). On average, this region has a semi-oceanic climate with continental influence, especially in the North-east zone. Trees are exposed to the best precipitation conditions with an average rainfall of more than 1000 mm/yr and average temperatures ranging from 10 °C to 12 °C. French Douglas-fir forest is young, since 87% of the stands do not exceed 40 years old. From a general point of view, difficulties in selling the first thinning have led to dense Douglas-fir plantations in many cases.

2.2. Functional unit

According to the different forest management practices, the lifespan per rotation varies to the scenarios under study. ES produces around 1133 m³ of wooden biomass per 1 ha and rotation (60 years). IS produces approximately the same biomass amount after 47 years. Therefore, in this study the assessment and comparisons were based on a single Douglas-fir rotation under extensive conditions (60 years), which should be equivalent to 1.3 Douglas-fir rotations under an intensive regime.



Fig. 1. French Douglas-fir plantation in the Grand Massif Central (South-central France) under study.

The wooden biomass presents an average basic density (weight of dry wood divided by the volume of green wood) of 425 kg/m³, an average green density of 773 kg/m³ and an average moisture content of 45%.

Other LCA studies carried out in Europe for other forest systems (e.g. maritime pine, eucalyptus or spruce) have proposed the use of different functional units; i.e. m³ of fresh wood under bark (ub), and an approach which excludes the bark from the assessment (Berg and Lindholm, 2005; Michelsen et al., 2008; González-García et al., 2009a; Dias and Arroja, 2012). In this case, with the objective of comparing the environmental profiles to the ES and IS scenarios with different forest studies, the environmental profiles will also be referred to m³ of fresh wooden biomass under bark (m³ ub). Based on the study conditions, the average bark content is around 13% from the total wooden biomass harvested (percentage in volume).

2.3. Description of forest systems: extensive and intensive management scenarios of Douglas-fir in France

In this LCA study, all the forest activities or processes involved throughout the forest system life cycle, starting from soil treatment to wood delivery until roadside were considered. Thus, the forest systems were divided in three main stages:

- Stage 1: Site preparation stage including clearing, soil scarification and agrochemicals (fertilizers and herbicides) application.

- Stage 2: Stand establishment and tending stage including planting, mechanical weed control, pruning, thinning, forwarding and loading onto trucks.
- Stage 3: Logging stage including final cutting, forwarding and loading onto trucks.

A graphical description of the systems under study is detailed in Fig. 2a (ES) and b (IS).

The scenarios under assessment correspond to two different French Douglas-fir forest management scenarios. The proposal of both scenarios is based on the fact that French silviculture of this species can be extremely variable due to certain factors, such as forest managers and silvicultural practices that change over time. Consequently, it is not possible to propose an average silviculture scheme. The yield for each French silviculture scenario was simulated using the SimCoP software (Ottorini, 1995). This software contains a model that determines the growth of Douglas-fir plantations (foliar volume and annual volume increment of stems). Both scenarios were built according to suggestions and guidelines from the French forest office (Angelier, 2007) and from Le Douglas AFOCEL (Bailly and de Champs, 1997), both compiling the different silviculture practices in France.

2.3.1. Extensive management Scenario (ES)

As previously reported, the forest systems were assessed from a cradle-to-gate perspective; i.e., from the raw material production to

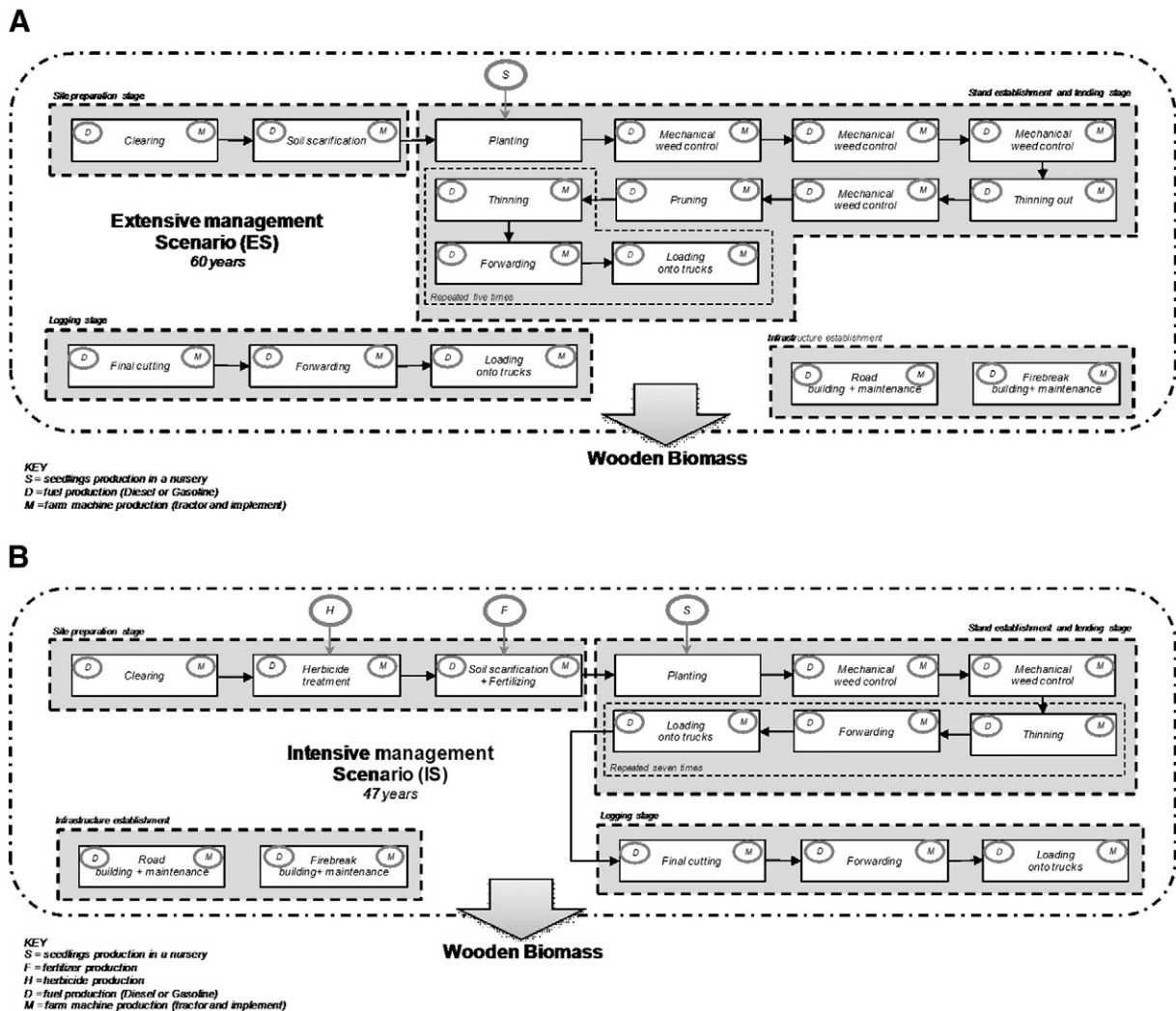


Fig. 2. A. Douglas-fir plantation System boundaries scheme for one rotation over (60 years) under extensive management conditions (ES). B. Douglas-fir plantation system boundaries scheme, over one rotation (47 years) under intensive management conditions. (IS).

wooden biomass transportation to the forest roadside. Table 1 displays the agricultural activities included in the life cycle and corresponding years of activity.

Before planting, soil is plowed over and refined (with a rotary mower) in order to remove the undesirable vegetation, which will facilitate the subsequent soil scarification and planting. It will also reduce the competition for space, light, moisture and nutrients with seedlings. Soil scarification allows breaking up the forest floor to improve conditions for tree planting. This is done through plowing

(depth of 30 cm), which is then turned over to the soil's upper layer to keep the land leveled, avoiding ridges and furrows. Planting is manually carried out at a density of 1100 seedlings/ha. One year after planting (1st year), mechanical weed control is performed combining a rotary harrow and a manual brush cutter. This activity is performed in order to remove the unwanted vegetation in young stands, facilitating the pruning and thinning out subsequent steps. It is repeated up to 3 times (years 3, 9 and 12). Douglas-fir plantations under extensive management do not require fertilizers application or irrigation. The

Table 1
Shows forest operations, timeline, machine specifications and fossil fuel requirements for Douglas-fir extensive management scenario (ES) over one rotation (lifespan 60 years). Total biomass yield of 1133 m³/ha.

Stage	Operation	Time (year)	Machine (A)	Tillage (B)		Operating rate (h/(ha · yr))	A + B	Comments
			Weight (kg) & power (kW)	Weight (kg)			Fuel diesel (lubricating oil) (kg/(ha · yr))	
Site preparation	Clearing ^a	0	5000 kg 66 kW	Mower	1800	1.7	24.0 (0.042)	
	Soil scarification	0	5000 kg 88 kW	Moldboard plough	2000	2.25	39.0 (0.14)	
Stand establishment and tending	Planting ^b	0	–	–	–	17.5	–	1100 seedlings/ha
	Mechanical weed control	1	5000 kg 66 kW	Rotary harrow + manual brush cutter	1800	0.8	11 (0.042)	
	Mechanical weed control	3	5000 kg 66 kW	Rotary harrow + manual brush cutter	1800	0.8	11 (0.042)	
	Mechanical weed control	9	5000 kg 66 kW	Rotary harrow + manual brush cutter	1800	0.8	11 (0.042)	
	Thinning out ^c	9	–	Brushcutter	–	–	–	Biomass yield: 5 m ³ /ha
	Mechanical weed control	12	5000 kg 66 kW	Rotary harrow + manual brush cutter	1800	0.8	11 (0.042)	
	Pruning ^c	12	–	Pruning saw	7.0	22.5	19.8 (0.99)	
	1st Thinning	15	12,500 kg 85 kW ^d	–	–	5.4	76 (5.1)	Biomass yield: 32 m ³ /ha
	Forwarding	15	16,000 kg 105 kW ^e	–	–	5.4	69 (2.1)	
	Log loading onto trucks	15	5300 kg 105 kW	Crane	–	0.6	5.0 (0.25)	
	2nd Thinning	22	12,500 kg 85 kW ^d	–	–	6.9	106 (7.4)	Biomass yield: 60 m ³ /ha
	Forwarding	22	16,000 kg 105 kW ^e	–	–	6.9	96 (2.9)	
	Log loading onto trucks	22	5300 kg 105 kW	Crane	–	0.8	7.0 (0.35)	
	3rd Thinning	30	12,500 kg 85 kW ^d	–	–	7.1	128 (8.9)	Biomass yield: 74 m ³ /ha
	Forwarding	30	16,000 kg 105 kW ^e	–	–	7.1	116 (3.5)	
	Log loading onto trucks	30	5300 kg 105 kW	Crane	–	1.0	8.4 (0.42)	
	4th Thinning	39	19,000 kg 170 kW ^d	–	–	6.0	110 (5.4)	Biomass yield: 71 m ³ /ha
	Forwarding	39	16,000 kg 105 kW ^e	–	–	7.3	119 (3.6)	
	Log loading onto trucks	39	5300 kg 105 kW	Crane	–	1.0	8.6 (0.43)	
	5th Thinning ^b	49	–	Chain saw	7.0	13.6	12 (6.3)	Biomass yield: 72 m ³ /ha
	Forwarding	49	14,000 kg 150 kW ^f	–	–	6.8	109 (1.1)	
	Log loading onto trucks	49	5300 kg 105 kW	Crane	–	0.97	8.1 (0.41)	
Logging	Final cutting ^b	60	–	–	Chain saw	159.2	140 (71.9)	Biomass yield: 819 m ³ /ha
	Forwarding	60	14,000 kg 150 kW ^f	–	–	79.6	1248 (12.8)	
	Log loading onto trucks	60	5300 kg 105 kW	Crane	–	11.1	93.6 (4.68)	

^a Cut-over clearing.

^b Manual.

^c Gasoline consumption.

^d Combine harvester.

^e Forwarder.

^f Skidder.

plantation is thinned-out (also known as precommercial thinning) with a brush cutter in year 9, turning the average harvested trees diameter to 7 cm ($\sim 5 \text{ m}^3$ biomass harvested). This forest activity tries to reduce the number of trees in young stands and it is carried out before the removed stems are large enough to have commercial value. After that, pruning (180 trees/ha) is manually performed with a pruning saw (year 12th) in order to remove side branches to reduce the number of knots in the timber. The biomass amount pruned (leaves and branches) was not considered in this study due to the lack of information. Typically, it is left over on the soil contributing to improve its quality. Douglas-fir plantation requires up to five thinnings, which are repeated at different stand ages in years 15 (DBH¹ of 17 cm), 22 (DBH of 25 cm), 30 (DBH of 34 cm), 39 (DBH of 43 cm) and 49 (DBH of 48 cm). The thinning step consists of cutting some trees in an immature stand in order to increase the average diameter of the remaining trees. The first four thinnings are carried out with a combined harvester and roundwood extraction is accomplished with a forwarder. The last thinning is manual with a chain saw and logs are extracted with a skidder. The logs are finally loaded onto trucks on the roadside with a crane connected to the extraction equipment. The lifespan is estimated to be 60 years (DBH of 58 cm) under extensive management regime. The final cutting is also manually performed with a chain saw and the log extraction is made by a skidder. The corresponding annual average wood volume increase (including thinned and final felled biomass) under extensive conditions is $18.8 \text{ m}^3/(\text{ha} \cdot \text{yr})$, which is in agreement with the biomass yield reported by Ponette et al. (2001) for Douglas-fir stands in France: $17.9 \text{ m}^3/(\text{ha} \cdot \text{yr})$.

2.3.2. Intensive management Scenario (IS)

Table 2 displays the forest operations covered in the IS, showing the differences that can be identified in comparison to the extensive scenario. The field is firstly cleared away, treated with an herbicide (1.6 kg glyphosate/ha) and ploughed (depth of 45 cm), while fertilizing is simultaneously performed. Fertilization is carried out by applying a rate of 80 kg P_2O_5 /ha as triple superphosphate. After that, the planting of 2000 seedlings/ha is manually performed. Weed control is carried out mechanically in the 1st and 3rd years from the plantation in contrast to the FES scenario, where this process is repeated four times. The three thinning in the young stand is repeated seven times: years 13 (DBH of 11 cm), 17 (DBH of 14 cm), 21 (DBH of 18 cm), 25 (DBH of 22 cm), 30 (DBH of 26 cm), 36 (DBH of 31 cm) and 43 (DBH of 35 cm) and final cutting at the end of its lifespan (DBH of 42 cm), which is approximately 47 years. The average yield under intensive management conditions is 1034, which corresponds to $22 \text{ m}^3/(\text{ha} \cdot \text{yr})$.

The capital goods production such as tractors, tillage machines, harvesters, chain saws and saws, forwarders and skidders were included within the system boundaries. Secondary wood haulage from the forest roadside to the end-point was not considered since transport routes may be very different depending on the biomass final use. Other minor issues such as workers transport, forest machines and materials (agrochemicals, diesel, gasoline and lubricant oil) including the forest land and the infrastructure establishment (road and firebreak building and maintenance) were excluded due to the lack of available information (Dias and Arroja, 2012).

2.4. Life cycle inventory

Primary and site-specific inventory data (operating hours, input rates and specification concerning equipments) for each scenario under assessment are given in Tables 1 and 2 (Ottorini, 1995; Bailly and de Champs, 1997; ASAE standards, 1999; Athanassiadis et al., 1999; ASAE standards, 2003; Klvac et al., 2003).

Forest systems were assumed to be in steady state concerning carbon stocks and management operations, in agreement with previous LCA forest systems studies available in literature (Seppala et al., 1998; Sonne, 2006; May et al., 2012). Therefore, it was considered that there is no change in the nutrients availability and water, land use and soil organic matter stocks over the steady state. The uptake of CO_2 by the biomass growth was considered equal to the amount of CO_2 released to the environment after wood oxidation at the end of its life cycle (Dias and Arroja, 2012).

Inventory data concerning the production of agrochemicals (specific for the intensive scenario) such as herbicide (glyphosate) and fertilizer (triple superphosphate) were taken from the ecoinvent database (Althaus et al., 2007). The phosphate based fertilizers application involves phosphate emissions to water. This emission was estimated according to the emission rate proposed by Rossier (1998), which is 0.01 kg/kg of applied P.

Gaseous emissions from fossil fuels combustion (diesel and/or gasoline) in forest machines (tractors, harvesters, forwarders and skidders) were taken into account using the combustion factors reported by the ecoinvent database (Nemecek and Käggi, 2007; Spielmann et al., 2007).

Concerning the capital goods, a detailed description of activities (tractors, harvesters, forwarders and skidders) and tillage (mower, plough, rotary harrow, brush cutter and saw) assigned to each forest activity per rotation is presented in Tables 3 and 4.

2.5. Allocation procedure

In a multi-functional system, the ISO 14044 (2006) standard recommends avoiding allocation whenever possible either through processes subdivision or by expanding the system boundary including the additional functions related to them. In this cradle-to-gate analysis, the total wooden biomass produced was considered as a single product, including the biomass from all thinning and final cutting steps, since both can be used for energy or industrial applications. Therefore, an allocation procedure was not required. The remaining biomass generated in the pruning steps (such as leaves and branches) was not computed in the analysis as co-products since they remain in the plantation, contributing to improve soil quality.

3. Environmental results

The environmental profile for both scenarios performed using the ReCiPe Midpoint method version 1.05 (Goedkoop et al., 2012). This midpoint methodology was used to understand the impacts complexity for air, water and soil for both Douglas-fir biomass production systems. This method transforms the list of inventory data collected throughout the production systems life cycle into a number of indicator scores (Tables 1–4). These indicator scores express the relative severity on an environmental impact category. In this study, the analysis for each forest system was calculated in terms of ten impact categories: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), photochemical oxidant formation (POF), agricultural land occupation (ALO), water depletion (WD), mineral resource depletion (MRD) and fossil fuel depletion (FD).

The LCA software SimaPro v7.3.3 (PRÉ Consultants, 2012) was used to construct the LCA model and undertake the impact assessment calculations. Table 5 displays the impacts for all the environmental impact categories for each forest system under study per functional unit.

3.1. General results

According to Table 5, there are large variations in all impact categories between the Douglas-fir scenarios, being the wooden biomass

¹ DBH = Diameter at Breast Height.

Table 2
Shows forest operations, timeline, machine specifications and fossil fuel requirements for Douglas-fir Intensive management Scenario (IS) over one rotation (lifespan 47 years). Total biomass yield of 1034 m³/ha.

Stage	Operation	Time (year)	Machine (A)	Tillage (B)		Operating rate (h/(ha · yr))	A + B	Comments
			Weight (kg) & power (kW)	Weight (kg)	Fuel diesel (lubricating oil) (kg/(ha · yr))			
Site preparation	Clearing ^a	0	5000 kg 66 kW	Mower	1800	1.7	24.0 (0.042)	
	Herbiciding	0	5000 kg 37 kW	Spraying machine	700	0.5	4 (0.019)	1.6 kg glyphosate/ha
	Soil scarification ^b	0	5000 kg 88 kW	Moldboard plough	2000	2.25	39.0 (0.14)	80 kg P ₂ O ₅ /ha
Stand establishment and tending	Planting ^c	0	–	–	–	28.0	–	2000 seedlings/ha
	Mechanical weed control	1	5000 kg 66 kW	Rotary harrow + manual brush cutter	1800	0.8	11 (0.042)	
	Mechanical weed control	3	5000 kg 66 kW	Rotary harrow + manual brush cutter	1800	0.8	11 (0.042)	
	1st Thinning ^d	13	12,500 kg 85 kW	–	–	2.7	36.9 (1.9)	Biomass yield: 30 m ³ /ha
	Forwarding ^e	13	16,000 kg 105 kW	–	–	2.7	35 (1.0)	
	Log loading onto trucks	13	5300 kg 105 kW	Crane	–	0.3	2.5 (0.13)	
	2nd Thinning ^d	17	12,500 kg 85 kW	–	–	2.1	30 (2.1)	Biomass yield: 24 m ³ /ha
	Forwarding ^e	17	16,000 kg 105 kW	–	–	2.1	27 (0.8)	
	Log loading onto trucks	17	5300 kg 105 kW	Crane	–	0.2	2.0 (0.10)	
	3rd Thinning ^d	21	12,500 kg 85 kW	–	–	5.0	70 (0.8)	Biomass yield: 55 m ³ /ha
	Forwarding ^e	21	16,000 kg 105 kW	–	–	5.0	64 (1.9)	
	Log loading onto trucks	21	5300 kg 105 kW	Crane	–	0.6	4.6 (0.23)	
	4th Thinning ^d	25	12,500 kg 85 kW	–	–	4.7	66 (4.6)	Biomass yield: 51 m ³ /ha
	Forwarding ^e	25	16,000 kg 105 kW	–	–	4.7	60 (1.8)	
	Log loading onto trucks	25	5300 kg 105 kW	Crane	–	0.5	4.3 (0.21)	
	5th Thinning ^d	30	12,500 kg 85 kW	–	7.0	7.2	111 (7.7)	Biomass yield: 86 m ³ /ha
	Forwarding ^e	30	16,000 kg 105 kW	–	–	7.2	101 (3.0)	
	Log loading onto trucks	30	5300 kg 105 kW	Crane	–	0.9	7.2 (0.36)	
	6th Thinning ^d	36	12,500 kg 85 kW	–	7.0	4.7	66 (4.6)	Biomass yield: 51 m ³ /ha
	Forwarding ^e	36	16,000 kg 105 kW	–	–	4.7	60 (1.8)	
	Log loading onto trucks	36	5300 kg 105 kW	Crane	–	0.5	4.3 (0.21)	
	7th Thinning ^d	43	12,500 kg 85 kW	–	7.0	12.0	215 (15)	Biomass yield: 168 m ³ /ha
	Forwarding ^e	43	17,000 kg 150 kW	–	–	10	116 (3.9)	
	Log loading onto trucks	43	5300 kg 105 kW	Crane	–	1.7	14.1 (0.7)	
Logging	Final cutting ^d	47	19,000 kg 170 kW	–	–	33.5	613 (30)	Biomass yield: 569 m ³ /ha
	Forwarding ^e	47	17,000 kg 150 kW	–	–	33.5	394 (13.3)	
	Log loading onto trucks	47	5300 kg 105 kW	Crane	–	5.7	47.8 (2.4)	

^a Cut-over clearing.

^b Including fertilising.

^c Manual.

^d Combine harvester.

^e Forwarder.

production under intensive management conditions the worst option. These differences can be attributed to two main factors: the forest management intensity due to the fact that the intensive regime requires agrochemicals application (herbicide and fertilizer) as well as more thinning and forwarding steps which involve the use of large machines

as well as the biomass yield, which is ~14% lower for the ES than for the IS considering the same lifespan (60 years). Below a short description of the contributions to each impact category for the forest scenarios under assessment is presented. The corresponding contributions are depicted in Fig. 3.

Table 3

Shows machine and tillage requirements per processes involved in the Douglas-fir plantation under extensive management regime (over one rotation – 60 years).

Stage	Operation	Time (year)	Tractor (kg)	Tillage (kg)
Site preparation	Clearing	0	1.18	4.08
	Soil scarification	0	1.56	9.38
Stand establishment and tending	Planting	0	–	–
	Mechanical weed control	1	0.56	4.00
	Mechanical weed control	3	0.56	4.00
	Mechanical weed control	9	0.56	4.00
	Thinning out	9	n.a.	n.a.
	Mechanical weed control	12	0.56	4.00
	Pruning	12	–	0.063
	1st Thinning	15	9.64	–
	Forwarding	15	9.09	–
	Log loading onto trucks	15	0.44	1.12
	2nd Thinning	22	12.32	–
	Forwarding	22	11.62	–
	Log loading onto trucks	22	0.59	1.58
	3rd Thinning	30	12.68	–
	Forwarding	30	11.96	–
	Log loading onto trucks	30	0.74	1.90
	4th Thinning	39	12.0	–
	Forwarding	39	12.29	–
	Log loading onto trucks	39	0.74	1.94
	5th Thinning	49	–	0.038
Logging	Forwarding	49	10.02	–
	Log loading onto trucks	49	0.71	1.84
	Harvesting	60	–	0.446
	Forwarding	60	117.3	–
	Log loading onto trucks	60	8.17	21.2

3.1.1. Climate Change (CC)

In this impact category, the results are expressed in kg CO₂ equivalent, using the characterization factors proposed by the IPCC report (2007) in a 100 year timeframe. In this impact category, greenhouse gases emissions derived from forest activities are quantified. The stand establishment and tending stage presents the largest contribution in all scenarios: IS (51%) and ES (48%).

3.1.2. Ozone Depletion (OD)

This category accounts for the stratospheric ozone layer destruction by anthropogenic emissions of ozone depleting substances, which contain chlorine or bromine atoms. The values are reported in terms of kg CFC-11 (trichlorofluoromethane). In the ES, the logging is the stage with the highest contribution (48%), while both the stand establishment and tending stage (51%) are very relevant in the IS.

3.1.3. Terrestrial Acidification (TA)

Changes in soil acidity due to inorganic acidifying substance emissions such as sulfates, nitrates and phosphates to air are assessed in this impact category, expressing the results in kg SO₂ equivalent. The logging stage is the main responsible for acidifying emissions (47% of total) in the ES while the stand establishment and tending stage in the IS (50%).

3.1.4. Freshwater eutrophication (FE) and Marine eutrophication (ME)

Eutrophication consists on the nutrient enrichment for the aquatic environment as a result of human activities. Nutrients such as N and P are considered here since they are limiting the aquatic biomass yield (e.g. phytoplankton). The ReCiPe method considers two types of eutrophication depending on if the nutrient enrichment is in freshwater (FE) or seawater (ME) since both of them present different limiting nutrients. Eutrophication in freshwater level is measured by phosphorous enrichment (kg P eq) and in seawater by nitrogen enrichment (kg N eq). According to Table 5, the intensive scenario presents the largest contributions to FE and ME in comparison to the extensive one. The stand establishment and tending is the stage with the highest contribution to

Table 4

Shows machine and tillage requirements per processes involved in the Douglas-fir plantation under intensive management regime (over one rotation – 47 years).

Stage	Operation	Time (year)	Tractor (kg)	Tillage (kg)
Site preparation	Clearing	0	1.21	3.06
	Herbicide	0	0.22	0.35
Stand establishment and tending	Soil scarification	0	1.61	4.50
	Planting	0	–	–
	Mechanical weed control	1	0.56	4.00
	Mechanical weed control	3	0.56	4.00
	1st Thinning	13	26.0	–
	Forwarding	13	28.8	–
	Log loading onto trucks	13	0.13	0.56
	2nd Thinning	17	21.2	–
	Forwarding	17	22.4	–
	Log loading onto trucks	17	0.11	0.45
	3rd Thinning	21	48.1	–
	Forwarding	21	53.3	–
	Log loading onto trucks	21	0.24	1.03
	4th Thinning	25	45.2	–
	Forwarding	25	50.1	–
	Log loading onto trucks	25	0.22	0.95
	5th Thinning	30	69.2	–
	Forwarding	30	76.8	–
	Log loading onto trucks	30	0.37	1.61
	6th Thinning	36	45.2	–
Logging	Forwarding	36	50.1	–
	Log loading onto trucks	36	0.22	0.95
	7th Thinning	43	115.4	–
	Forwarding	43	113.3	–
	Log loading onto trucks	43	0.72	3.14
	Final cutting	47	489.6	–
	Forwarding	47	379.7	–
	Log loading onto trucks	47	2.44	10.64

FE regardless of the scenario (Fig. 3): IS (44%) and ES (76%). Regarding the ME, the stand establishment and tending accounts for 50% of the total contributions to this category in the IS. For the ES, the logging stage is the hot spot with a contribution of 48% of the total impact.

3.1.5. Photochemical Oxidant Formation (POF)

This impact category quantifies the air pollutants formed by the action that sunlight has on nitrogen and hydrocarbon oxides. The results are expressed in kg NMVOC eq. According to the results displayed in Fig. 3, the contributing stages are the stand establishment and tending in the IS (51%) and logging in the ES (51%).

3.1.6. Agricultural Land Occupation (ALO)

This impact category represents the land requirements the systems evaluated need, for a limited period of time, through their entire

Table 5

Impact assessment results for the scenarios under assessment and per functional unit (1 rotation of Douglas-fir under an extensive regime).

Impact category	Unit	ES	IS
Climate Change (CC)	t CO ₂ eq	10.71	23.99
Ozone Depletion (OD)	g CFC-11 ^a eq	1.46	2.89
Terrestrial Acidification (TA)	kg SO ₂ eq	66.63	138.45
Freshwater Eutrophication (FE)	kg P eq	2.18	9.90
Marine Eutrophication (ME)	kg N eq	3.79	7.52
Photochemical Oxidant Formation (POF)	kg NMVOC ^b	115.90	208.88
Agricultural Land Occupation (ALO)	m ² · yr	71.72	248.78
Water Depletion (WD)	dm ³	29.06	115.39
Mineral Resource Depletion (MRD)	t Fe eq	2.07	7.70
Fossil fuel Depletion (FD)	t oil ^c eq	3.85	8.40
Wooden biomass production	m ³	1133	1320

^a CFC-11: Chlorofluorocarbon.

^b NMVOC: Non Methane Volatile Organic Carbon compound.

^c Oil crude feedstock (42 MJ/kg).

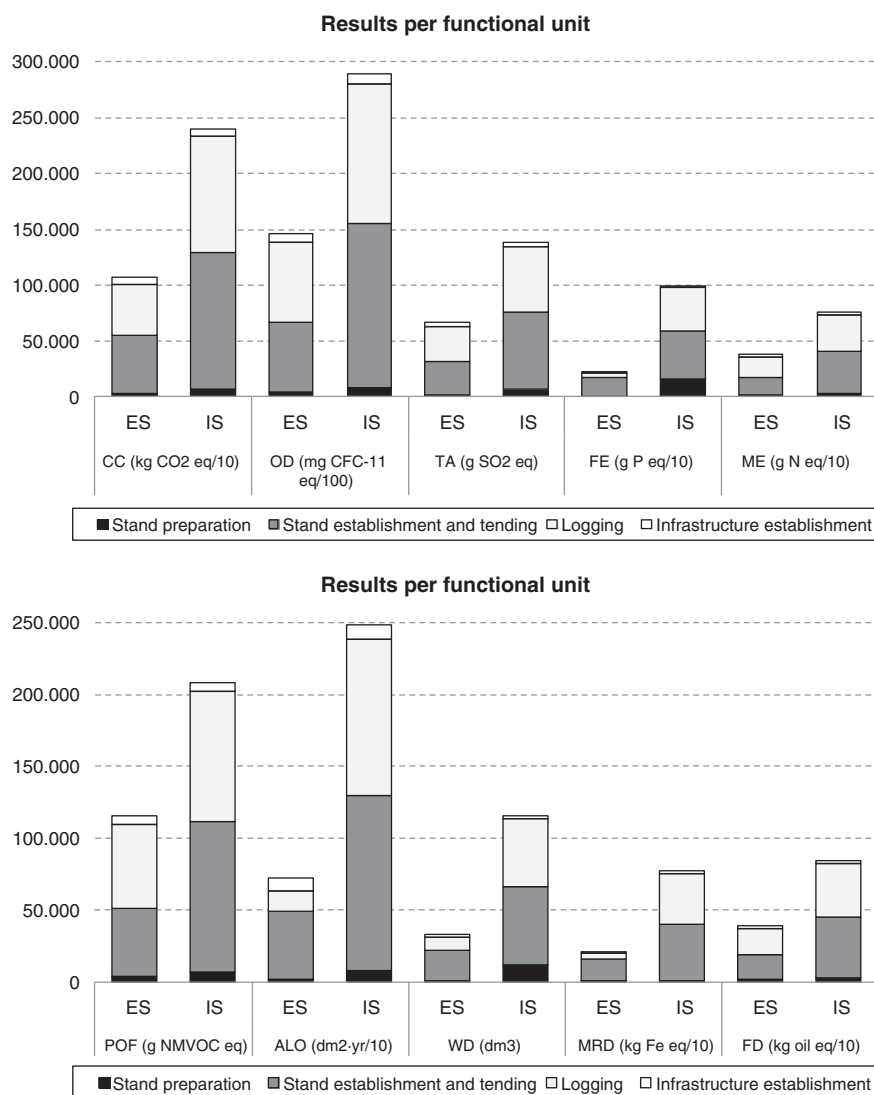


Fig. 3. Contributions from the different stages involved in Douglas-fir life cycle scenarios under assessment. ES = Extensive Scenario; IS = Intensive Scenario. CC = Climate Change; OD = Ozone Depletion; TA = Terrestrial Acidification; FE = Freshwater Eutrophication; ME = Marine Eutrophication; POF = Photochemical Oxidant Formation; ALO = Agricultural Land Occupation; WD = Water Depletion; MRD = Mineral Resource Depletion; FD = Fossil fuel Depletion.

life cycle. Therefore, the results are calculated on the basis of the area altered or required to produce a certain wooden biomass amount (1133 m³ and 1320 m³ on IS and ES respectively) for a restoration time of 60 yr. In this study, the same period of time to compare both sown fields (i.e. 60 years) was considered; that is, one rotation under extensive conditions and 1.3 rotations under intensive conditions. Therefore, the contributions to ALO are higher for the IS since a greater land area is required for the same period of time (Fig. 3). Stand establishment and tending is once again the stage with the highest contribution to ALO (49% for IS and 66% for ES).

3.1.7. Water Depletion (WD)

This impact category expresses the water amount consumed by the systems, being studied through their entire life cycle. This category is really interesting especially in forest systems due to the fact that water is a scarce resource and extracting it could cause significant damages to different ecosystems. According to the results (Fig. 3), water requirement is higher in the IS than in the ES. The same trend is observed in this category in comparison with the previous ones, being the stand establishment and tending stage the responsible for the higher contributions to this category (47% in IS and 64% in ES).

3.1.8. Mineral Resource Depletion (MRD)

Mineral consumption, which naturally occurs by geological processes, is measured here, being the results expressed in terms of kg Fe eq. The IS scenario required more minerals per functional unit than the ES (7.70 t Fe eq vs 2.07 t Fe eq). The stand establishment and tending stage is the most important contributor to this category regardless of the scenario (73% and 51% respectively for ES and IS).

3.1.9. Fossil fuel Depletion (FD)

This impact category assesses the non-renewable resources requirements which contain hydrocarbons such as fuel oil, coal, etc. The results are expressed in kg of crude oil with an energy content of 42 MJ per kg. The stand establishment and tending are responsible for the highest fossil fuel requirement through their entire life cycle regardless of the Douglas-fir production scenario 51% and 47% of total for IS and ES respectively (Fig. 3).

3.2. Assessment per scenarios

3.2.1. Intensive management scenario

This scenario presented the worst results in all the categories in comparison with the extensive one. The contributions to the different

categories were 45–78% higher in the IS than in the ES depending on the category. These large differences per functional unit (one rotation under extensive conditions, i.e. 60 years) were mainly due to the forest management conditions, which can be explained based on the fact that approximately the same amount of wooden biomass per ha is produced in a shorter time period. The intensive scenario is a highly mechanized forest system, which requires a dosage of fertilizers and herbicides. In this case, up to seven highly mechanized thinning steps are performed; in contrast, only five steps are carried out in the extensive scenario. As a consequence, the tree's quality and growth are increased, especially in terms of diameter. In addition, trees from extensive management conditions grow much faster than those from the intensive scenario.

According to Table 2 and Fig. 2b, the stand establishment stage includes the following forest processes performed between years 0 and 43 of their lifespan: planting (also seedlings production), mechanical weed control, thinning, and thinned wooden biomass forwarding and loading onto trucks. All these activities except planting are mechanized with large gears (tractors, harvesters and forwarders) and repeated several times per rotation. That is the reason behind the large contribution to the global environmental profile associated with this stage (Fig. 3). The contributions from stand and tending stages range from 44% to 51% depending on the impact category. Therefore, this stage involves higher energy requirements (4.26 t crude oil per functional unit – 3.28 t crude oil per ha) and combustion emissions than the other stages.

Concerning the contributions from the processes involved in this stage, each thinning process entails both forwarding and loading onto trucks. Therefore, these three activities have been included in a global “thinning step”, which is repeated seven times. According to the results displayed in Fig. 4, the main environmental hot spots are the thinning steps (mainly, thinning and forwarding), specifically the last thinning procedure carried out in the year 43 (~38% of contributions from this stage).

The diesel requirement and operation hours in the different thinning steps depend on the log's size. According to Michelsen et al. (2008), large sized logs require less fuel per m³ of roundwood in activities such as harvesting, forwarding and loading than small sized logs. In our study, a similar trend in terms of operation hours (h/m³) and diesel consumption (kg/m³) was observed. The high contribution showed in Fig. 4 by the 5th and 7th thinning steps is associated with the biomass thinned volume (86 and 168 m³ respectively).

Regarding the second most important stage in terms of environmental impact, the logging stage (39–46%) entails the final cutting process as well as the corresponding felled roundwood truck forwarding and loading. Final cutting and forwarding are the main hot spots, being responsible for ~98% of contributions to the environmental impact associated with this stage.

Concerning the site preparation stage, it is important in terms of FE (16%) since this stage involves not only forest processes such as cleaning, agrochemicals application (and its corresponding diffuse emissions) and soil scarification, but also the fertilizer production and herbicide applied. According to the results, the most important process involved in this stage is the herbicide production (glyphosate).

3.2.2. Extensive management scenario

The Douglas-fir production under extensive management conditions (ES) showed a better environmental profile than the intensive scenario in all the categories under study. The main differences between both scenarios (both located in the same French region) are related to the agrochemicals application and the number of forest activities during the forest management (stand establishment and tending stage). On the contrary, this system presents more mechanical weed controls (four steps in comparison with two in the IS), thinning out and pruning of young stands and lower biomass yield referred to the timeframe considered (60 years): 1133 m³/ha in the ES vs 1320 m³/ha in the IS.

In this Douglas-fir production system, the stand establishment and tending is again the main responsible for the environmental profile in almost all the categories (except in OD, POF, TA and ME where the logging stage prevails).

Fig. 5 displays the contributions from the processes involved in this stage to each impact category. According to the results shown in the figure, the 3rd and 4th thinning steps are the main hot spots due to the processed roundwood volume: 74 and 71 m³/ha, respectively. The last thinning step sums up to 72 m³/ha, the felling is carried out with chainsaws instead of harvesters. The use of chainsaws involves longer working periods to cut down the same biomass amount (e.g. 13.6 h vs 6.0 h per ha for the 5th and 4th thinning process respectively) but a lower fossil fuel requirement (0.17 kg/m³ of gasoline in the 5th thinning vs 1.55 kg/m³ of diesel in the 4th thinning). Moreover, there are also differences concerning the combustion emissions derived from the use of either diesel or gasoline. There is an increase of CO emissions to the environment due to the chainsaw use.

Concerning the logging stage, the forwarding process is the hot spot with contributions up to 88%, mainly due to the large diesel consumption in comparison with the final cutting process (it is performed with chainsaws) and the felled roundwood truck loading.

4. Discussion

This study aims to identify and calculate the environmental impacts caused by Douglas-fir roundwood production in different forest management scenarios in France, the most important European country in terms of Douglas-fir plantations.

The environmental results displayed in Table 5 and Figs. 3–5 show a wide range of variations in all the categories under study when different management scenarios (different operations and fossil fuel requirements) and productivities are considered for the same period of time (60 years).

To date, there were no studies in which all the Douglas-fir roundwood production environmental impacts were identified in spite of its interest as a tree species with high biomass yield and physiological adaptability. Only one study has been found in literature that focused on the quantification of GHGs from Douglas-fir plantations in the Pacific Northwest under different management practices (Sonne, 2006). Sonne's study could be considered a Douglas-fir plantation representative in the USA, as it considered 408 different regimes, including differences on e.g. fertilization, thinning and herbicide treatments (Sonne, 2006).

The results reported in our study could be considered a Douglas-fir silviculture representative in Europe due to its relevance in France. In addition, this study is one of the most comprehensive studies in terms of accounting energy use in the different forestry activities.

There are numerous studies where forest systems were assessed using the LCA methodology but focused on the most common European species: maritime pine and eucalypt in Portugal (Dias et al., 2007; Dias and Arroja, 2012), spruce and pine in Finland, Sweden and Norway (Berg and Karjalainen, 2003; González-García et al., 2009a; Michelsen et al., 2008) or eucalyptus in Spain (González-García et al., 2009a, 2009b). There is poor consistency between them as different system boundaries, assumptions, functional units and characterization factors can be found between the mentioned published studies. However, similar results or trends have been identified between them and this study, which will be discussed below.

Ponette et al. (2001) studied the aboveground biomass production and nutrient content in five Douglas-fir stands located in France. According to this study, common French plantations present a planting density of 1100 seedlings per ha and require six thinning steps being the final cutting at 61 years and the average biomass yield of 17.9 m³/(ha · yr). These values are close to those for the extensive scenario (ES) assessed here (Table 1): the same seedlings density, plantation lifespan and number of thinning steps, although only slight differences in the biomass yield were observed: 18.9 m³/(ha · yr).

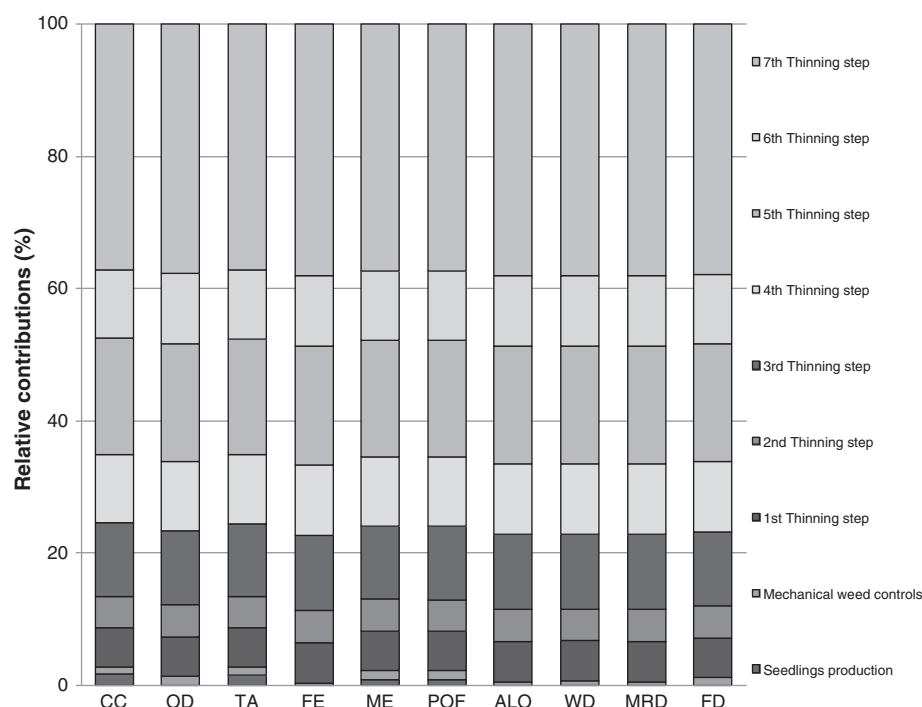


Fig. 4. Contributions to each impact category from the different processes involved in the Stand establishment and tending stage in the Douglas-fir production scenario under intensive management conditions (IS). Each thinning step entails 3 processes: thinning + forwarding + loading onto trucks. CC = Climate Change; OD = Ozone Depletion; TA = Terrestrial Acidification; FE = Freshwater Eutrophication; ME = Marine Eutrophication; POF = Photochemical Oxidant Formation; ALO = Agricultural Land Occupation; WD = Water Depletion; MRD = Mineral Resource Depletion; FD = Fossil fuel Depletion.

Large differences were found for the intensive scenario (IS, Table 2) with 2000 seedlings per ha, up to seven thinning steps, final cutting after 47 years and biomass yield of $21.5 \text{ m}^3/(\text{ha} \cdot \text{yr})$. This higher yield per ha and shorter lifespan are attributed to the management practices carried out in the plantation, paying special attention to:

- The stand preparation stage: glyphosate and triple superphosphate are applied to promote tree growth as well as the higher number of seedlings planted per ha.
- The stand establishment and tending: thinning process entails the tree cutting of immature stands in order to accelerate their growth

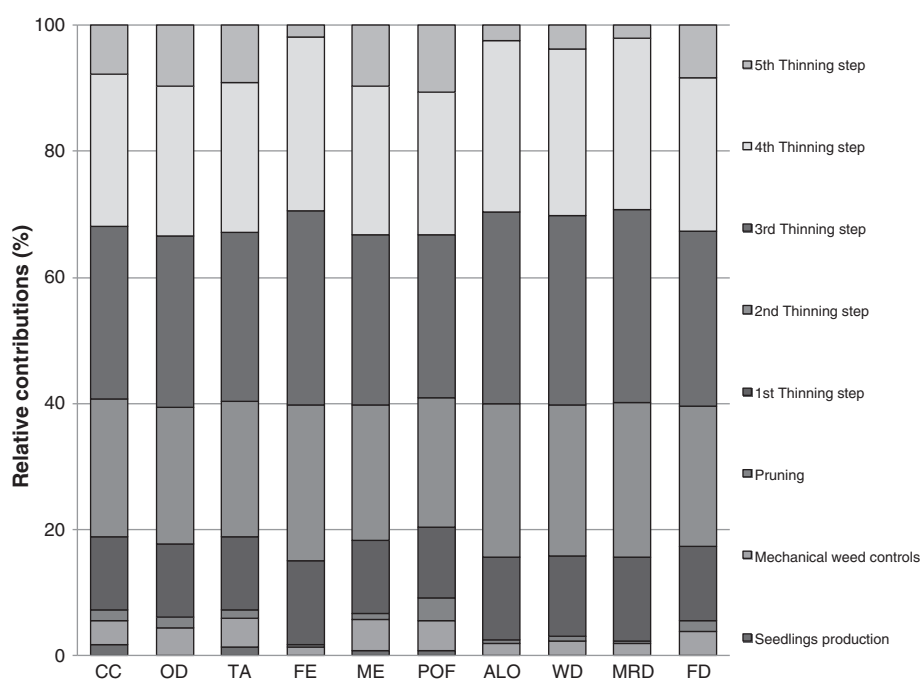


Fig. 5. Contributions to each impact category from the different processes involved in the Stand establishment and tending stage in the Douglas-fir production scenario under extensive management conditions (ES). Each thinning step entails 3 processes: thinning + forwarding + loading onto trucks. CC = Climate Change; OD = Ozone Depletion; TA = Terrestrial Acidification; FE = Freshwater Eutrophication; ME = Marine Eutrophication; POF = Photochemical Oxidant Formation; ALO = Agricultural Land Occupation; WD = Water Depletion; MRD = Mineral Resource Depletion; FD = Fossil fuel Depletion.

in diameter and to improve the quality and growth of the remaining trees.

4.1. Influence of the functional unit

Numerous authors have considered in their evaluations 1 m³ of fresh roundwood under bark (González-García et al., 2009a, 2009b; Dias and Arroja, 2012) as the functional unit to represent the environmental results. In these studies, the environmental impacts were allocated to the m³ of wood excluding bark content. The bark content in wood is variable and it depends on the DBH range and the forest species.

In our study, the functional unit was considerably different since it was based on one Douglas-fir rotation under extensive management conditions (ES) i.e. 60 years. The consideration for this functional unit was based on the large lifespan difference between the cultivation under extensive and intensive conditions. In this sense, 1.3 Douglas-fir rotations in intensive conditions take place per 1 rotation under extensive conditions. The wooden biomass production is also different: 1133 m³/ha in the ES vs 1320 m³/ha in the IS.

If the environmental results for Douglas-fir are compared with the ones characteristic of other European species, the comparison in terms of m³ under bark (m³ub) may be required. The average wooden biomass' bark content harvested throughout the Douglas-fir life cycle is around 13%.

However, another important issue to take into account when forest systems are compared is the system boundaries description. Processes such as seedlings production, biomass haulage harvested to the final user, production and road maintenance and artificial fires or the workers transportation to the forest could either be included or not (Berg and Lindholm, 2005; Dias et al., 2007; Michelsen et al., 2008; González-García et al., 2009a, 2009b; Dias and Arroja, 2012). Thinning processes were also excluded from the assessment performed by Dias and Arroja (2012) due to the lack of data despite their potential weight in case these activities are mechanically performed.

The environmental comparison between the Douglas-fir biomass productions in France with other forest species shows a number of similar issues among the different studies. Forest activities which require the use of large machines such as final cutting and forwarding are common environmental hot spots due to their fossil fuel consumption (diesel and lubricant) and the corresponding nitrogen oxides, carbon dioxide, sulfur oxides and hydrocarbon emissions from fossil fuel combustion. Thus, the logging stage was identified as the main responsible in tree species such as pine and spruce (Berg and Karjalainen, 2003; Michelsen et al., 2008; González-García et al., 2009a, 2009b) and maritime pine and eucalyptus (González-García et al., 2009b; Dias and Arroja, 2012).

While the thinning steps in the Douglas-fir scenarios significantly contribute to the environmental impact, this fact has not been identified in other reports where thinning steps were excluded from the assessment or they were not required as observed in the eucalyptus silviculture.

Fertilizing, another hot spot that involves the mineral fertilizers production and application with the corresponding pollutants emission (ammonia, nitrogen oxides and nitrate leaching), was also considered a hot spot in other forest related systems (González-García et al., 2009a, 2009b; Dias and Arroja, 2012).

In terms of absolute values, it is possible to compare the environmental profiles according to three impact categories: climate change, acidification and fossil energy requirements. In our study, climate change accounts for 10.9 kg CO₂ eq/m³ ub of Douglas-fir under the extensive scenario (ES) and 20.5 kg CO₂ eq/m³ ub under the intensive one. The potential climate change for other forest species presents a wide range of results, which depend on the forest species and the management scenario. Dias and Arroja (2012) reported 4.8–12.2 kg CO₂ eq/m³ ub for maritime pine and 8.3–18.5 kg CO₂ eq/m³ ub for

eucalyptus production in Portugal. The variations depend on the forest management conditions intensity performed in both plantations and according to the authors, differences in the environmental profile could be higher than 200% (Dias and Arroja, 2012). González-García et al. (2009b) reported emissions of 35.5 kg CO₂ eq/m³ ub for eucalyptus production in Spain and 36.1 kg CO₂ eq/m³ ub for spruce production in Sweden. Michelsen et al. (2008) also reported a value of 25.0 kg CO₂ eq/m³ ub for spruce production in Norway. However, these high values are considerably affected by the wood distribution to the final users within the system boundaries, which adds up to 60% of total potential climate change. If this last stage was excluded from the assessment, similar results should be achieved.

Concerning acidification, our results reported values of 67.6 and 118 g SO₂ eq/m³ ub for ES and IS respectively. Dias and Arroja (2012) reported lower values for maritime pine scenarios in Portugal (30–80 g SO₂ eq/m³ ub) and extremely variable results for the eucalyptus scenarios ranging from 50 to 230 g SO₂ eq/m³ ub. The large differences in the eucalyptus results are mainly attributed to the management scenarios intensity. Stand tending operations under intensive management conditions present a remarkable contribution in terms of acidification. It is mainly due to the fertilization process which releases significant amounts of ammonia (~60% of the acidification impact). On the contrary, under low intensive conditions, the main responsible is the logging related activities. These large differences have not been reported for the maritime pine because this species does not require the application of nitrogen based fertilizers. Michelsen et al. (2008) reported 110 g SO₂ eq/m³ ub for spruce roundwood production in Norway, from which 35% derived from road transport.

Despite the differences related to the forest activities intensity, system boundaries and fossil fuel requirements, pine, eucalyptus and Douglas-fir stands require more mechanical forest activities than spruce, all of them being in the same range.

Concerning fossil energy requirement, Douglas-fir scenarios required 164 and 300 MJ/m³ ub for the extensive and intensive scenarios respectively. Very large differences were identified in the literature regarding this category. Dias et al. (2007) reported 135 and 169 MJ/m³ ub for conventional pine and eucalypt plantations in Portugal. González-García et al. (2009a, 2009b) estimated a requirement of 269 MJ/m³ ub for eucalyptus in Spain. Berg and Lindholm (2005) reported 82 MJ/m³ ub for softwood (spruce and pine) plantations in Sweden. According to literature, these large differences should depend on the log size (smaller logs would require higher fuel consumption), the forest management intensity scenarios and the forest operations efficiency.

According to the comparison with other LCA forest system studies such as pine, eucalyptus and spruce, slight differences are evidenced despite different management practices (low or high intensive scenarios), system boundaries and forest systems intensity (frequency of activities).

If 1 m³ of harvested biomass (including bark) is considered as the functional unit, it could be possible to compare our results in terms of CC with Douglas-fir plantations' results reported by Sonne (2006). These authors indicated that 14.8 kg CO₂ eq/m³ and 13.1 kg CO₂ eq/m³ should be the average GHG emissions derived from Douglas-fir plantations in USA when the final cutting is performed at 50 and 60 years respectively. In our study, the CC accounts for 18.2 kg CO₂ eq/m³ and 9.5 kg CO₂ eq/m³ for intensive (47 years) and extensive (60 years) regimes. These slight differences in GHG emissions are mainly affected by differences in the characterization factors, biomass yield, system boundaries and databases. However, it is important to remark that harvesting events (thinning processes and final cutting) have been identified in both studies as the major responsible contributors for environmental profiles due to the derived combustion emissions.

5. Conclusions

Douglas-fir is a potential softwood forest species with multiple industrial applications, which makes it an interesting source to obtain

wooden biomass. Nowadays, its cultivation is not as extended in Europe as other forest species but it is very common in France and Germany, being France the most important European country in terms of Douglas-fir plantations. This study assessed the environmental impacts associated with Douglas-fir cultivation in France under two management scenarios. The results achieved in this study show that the stand establishment and tending and logging stages were the main sources for environmental impacts. Numerous thinning steps are performed before the final cutting regardless of the scenario. Thinning steps require large machines (combine harvesters and forwarders) with a high fuel requirement and considerably affect the environmental results. The logging stage (final cutting and the corresponding forwarding and loading onto trucks) also accounts for a remarkable contribution to all the categories in both management scenarios. Finally, and according to the results, it is important to highlight that the biomass productivity increase does not compensate the environmental impact.

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