Delving the environmental impact of roundwood production from poplar plantations

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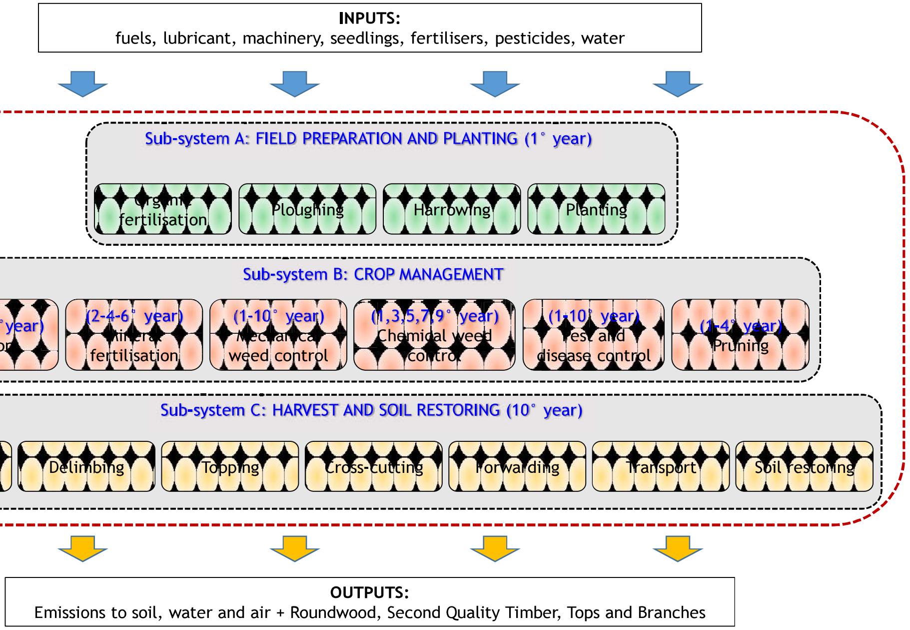
***Graphical Abstract**

AIM

- → To quantify the environmental load associated with the production of roundwood from planted poplar plantation in Italy
- → Two different harvesting systems (Baseline **BS** – with harvester and Alternative – **AS** with chainsaw) were considered

FUNCTIONAL UNIT

1 ton of roundwood



INPUTS:
fuels, lubricant, machinery, seedlings, fertilisers, pesticides, water

Sub-system A: FIELD PREPARATION AND PLANTING (1° year)

- Organic fertilisation
- Ploughing
- Harrowing
- Planting

Sub-system B: CROP MANAGEMENT

- (1,2,5,8,10° year) Irrigation
- (2-4-6° year) Mineral fertilisation
- (1-10° year) Mechanical weed control
- (1,3,5,7,9° year) Chemical weed control
- (1-10° year) Pest and disease control
- (1-4° year) Pruning

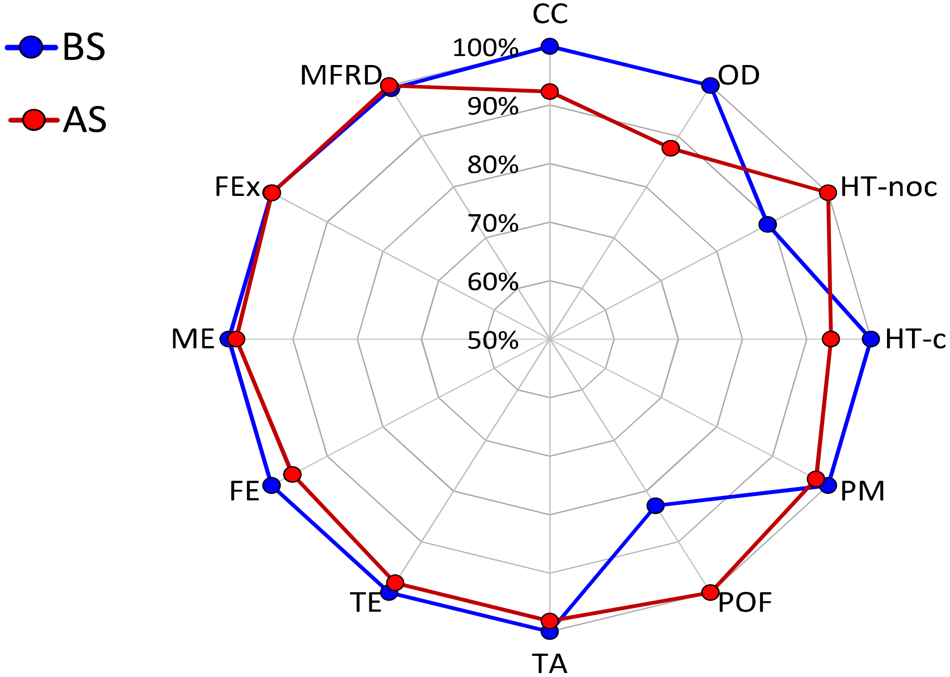
Sub-system C: HARVEST AND SOIL RESTORING (10° year)

- Felling
- Delimbing
- Topping
- Cross-cutting
- Forwarding
- Transport
- Soil restoring

OUTPUTS:
Emissions to soil, water and air + Roundwood, Second Quality Timber, Tops and Branches

RESULTS

AS (felling delimbing and cross cutting carried out using chainsaw) performs better respect to **BS** (harvester) for all impact categories except than for HT-noc and POF (due to fuel and vegetable oil consumption).



Climate change (CC), Ozone depletion (OD), Particulate matter formation (PM), Human toxicity-no cancer effect (HTnoc), Human toxicity- cancer effect (HTc), Photochemical ozone formation (POF), Terrestrial acidification (TA), Terrestrial eutrophication (TE), Freshwater eutrophication (FE), Marine eutrophication (ME), Freshwater ecotoxicity (FEx), Mineral and fossil resource depletion (MFRD)

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Abstract

The environmental impact of timber production from poplar plantation was evaluated by means of Life Cycle Assessment (LCA) using an attributional approach. A comparison was performed between a baseline scenario and an alternative one in which different harvesting operations were identified. An economic allocation was adopted to solve the multi-functionality of the studied process, by taking into account the price of the main product and of co-products. Sensitivity analysis was performed on alternative mass allocation and yield variations that derive from using high sustainability plants or from climate stress. A different characterization method was also analyzed.

Among the different field operations, crop management involves a higher impact respect to field preparation-planting and harvesting-soil restoring. Emissions related to fertilizers' applications are the main responsible for acidification, eutrophications and particular matter formation. The results show that the modelling of the environmental impact of timber production is robust. The alternative scenario resulted better than baseline for all impact categories (impact reduction ranging from 0.1% to 12.4%), except for HT-noc (+12.2%) and POF (+20.6%), due to fuel and oil consumption in the chainsaw used for harvesting.

In the next years, introducing high-sustainability clones (characterized by higher yield and higher resistance to pests and drought) could be an effective way for reducing the environmental impact of poplar roundwood production.

Keywords: Life Cycle Assessment, Harvesting solutions, Mechanization, Poplar, Timber, Italy.

1 Introduction

European consumption of wood-based products has reached record levels in recent years, mostly driven by the market demand from the "end-use" sectors of residential construction, furniture, cabinets, flooring and mouldings (Gonzalez Garcia et al., 2011a). Among the wood-based products, timber derives from roundwood and is commonly associated with building and construction materials, as well as with many common aspects of today's world.

Roundwood derives from forestry activities and from dedicated plantations and, among these lasts, poplar plantations play the main role (FAO, 2016). In 2016, the area dedicated to traditional planted poplar plantations was 31.4 Mha, of which Canada (21.8 Mha) and China (8.5 Mha) are the countries with the highest dedicated area (FAO, 2016). Worldwide, 18.3 million ha (58%) are managed for multi-purposes, 9.4 million ha (30%) are planted primarily for wood production, 2.9 million ha (9%) for environmental protection and 0.9 million ha (3%) are managed for biomass production for fuelwood. In the same year, wood removal worldwide accounted for 12.2 million m^3 of roundwood.

According to the International Poplar Commissions (FAO, 2016), the proportion of end-use products from planted poplars was particle/fibre board (51%), plywood (17%), veneer (16%), wood pulp (6%), sawn wood (5%), wood chips (4%) and logs/pulp logs and fuelwood (1%). In Europe, the most important countries for poplar production are France (0.2 Mha), Spain and Turkey (0.1 Mha), followed by Italy. In Italy, the area dedicated to traditional poplar cultivation is continuously decreasing (about 50,000 ha in 2016) due to competition with other more profitable agricultural crops and with more competitive poplar products imported from other countries (Pra and Pettenella, 2017). As a reaction to this state, the Italian poplar sector has launched a number of research programs to develop innovative uses for Poplars and to create new clones with high resilience to salinity, drought and pests (Rosso et al., 2013; Pra and Pettenella, 2017). The new Poplar varieties were selected by public and private organisations for their fast growth capabilities and positive tolerance to disease/pest, which results in increased productivity and reduced economic and energetic costs compared to the traditional "I-214" clone.

In Italy, the traditional poplar cultivation for plywood production is mainly located in the Po Valley Regions (Nervo et al., 2011). It is based on ten-years cycles and achieves high productivity and good wood quality, with wood production remaining the main purpose.

Besides these traditional poplar plantations (TPP), in the last 30 years, about 6,500 ha of poplar Short Rotation Forestry (SRF) (also called Short Rotation Coppice – SRC) have been planted in Northern Italy. SRC plantations are cultivations of woody crops (poplar, willow, black locust, and other fast-growth species) characterized by short cutting cycles (1, 2, or 5-6 years), high plant density (from 1,000 to 12,000 trees per hectare), and a crop cycle ranging from 10 to 15 years, over which several harvests take place. Despite the possibility of growing different species, in Italy, SRC is mainly carried out with poplar clones (Manzone et al., 2014; Bacenetti et al., 2016). Although both cultivation systems are poliannual, between SRF and TPP there are several differences, among which the most important relate to crop management, number of harvests and cultivation purpose. Thus, differently from SRF, plants in TPP are felled only once at the end of the cycle, the main product is timber (for wood pulp, pallets, plywood and furniture) and the need to produce good quality timber involves intensive pest and pathogens controls. Finally, only top and branches can be used for energy purposes.

Regarding electricity production from renewable sources, Italian producers benefit of a specific subsidy framework and the Feed-in-Tariff (FiT) is granted to "renewable electric energy". Specifically for electricity from biomass, higher FiTs are foreseen when biomass is a by-product instead of a specifically produced one. In this context, wood chips produced by chipping tops and branches of TPP allow to get the highest FiT, whereas wood chips from SRF determine a lower tariff because SRF is considered a dedicated crop (MISE, 2012).

Over the years, increasing attention has been paid to the environmental consequences related to agricultural productions and processing. Besides this, consumer awareness about this issue has grown and the demand for "environmentally friendly" products has increased (Gonzalez-Garcia et at., 2009a; 2010a; Galli et al., 2017). Within this framework, in order to evaluate the environmental impact of products or services, the Life Cycle Assessment (LCA) method has been more and more applied (Curran, 1996). LCA is a holistic approach that uses a systematic set of procedures to convert inputs and outputs of materials and energy of a process into environmental impact. In this context, some LCA studies evaluated the environmental impact of plywood production (Puettmann and Wilson, 2007; Wilson and Sakimoto, 2007; Pommier et al., 2016), furniture (Gamage et al., 2008; Gonzalez-Garcia et at., 2011c) and other wood-products (Lippke et al., 2004; Asif et al., 2007; Perez-Garcia et al., 2007; Gonzalez-Garcia et at., 2009b; Gonzalez-Garcia et at., 2011a and 2011b; Ramesh et al., 2010; Basbagill et al., 2013). Nevertheless, all of them focus on the processing phase, while seldom the attention is paid to the production of raw materials (i.e. roundwood). Moreover, despite the importance of poplar timber to produce pulpwood, plywood and furniture, there are no studies evaluating the environmental impact of timber production from TPP.

The aim of this study is to analyse the environmental impact of timber poplar production in Italy. To this purpose, the LCA approach was applied, the environmental hotspots (i.e. processes mainly responsible for the environmental impact) were identified and two scenarios involving different harvesting solutions were compared.

2 Materials and methods

The environmental impacts of poplar timber were estimated using the LCA method by following ISO 14040/44 recommendations (ISO, 2006a; b). The Standards ISO

14040/44 involve defining goal and scope, functional unit and system boundary, collecting inventory data, assessing the environmental impacts and interpreting results. The attributional approach was used to model the poplar production process. This approach, differently from the consequential one, is commonly used to study the life cycle of a product as it is, based on collected average data and without considering market effects or any influence external to the system boundary (United Nations Environment Programme; 2011). Thus, the inventory data were attributed to the functional unit of the product system in accordance with a normative rule, and evaluating the environmental burdens directly linked to timber production. The goal of the LCA study, data and assumptions are discussed below.

2.1 Goal and scope definition

The goal of this study is to quantify the environmental load associated with the production of roundwood from planted poplar plantations in Italy.

Poplar cultivation practice is quite standardized in its traditional conformation; in particular, guidelines for integrated (Allegro et al., 2014; Regione Lombardia, 2017) and sustainable production practices were developed to help farmers achieving high yields and good quality products, and minimizing the environmental impact of this production system.

The research questions in this study are as follows:

- How much is the environmental impact related to the production of 1 t of poplar timber in plantations managed according to the guidelines for integrated production?
- What are the processes mainly responsible for this impact?
- Can the impact of poplar timber be reduced?

The outcomes of this study will be useful for:

- LCA practitioners involved in sectors in which poplar timber is used as raw material;

- technicians and farmers' associations that are interested in identifying, from an environmental point of view, the most critical production steps and possible alternative solutions with regard to different harvesting;
- policymakers, as a starting point for the development of a subsidy framework (into the Common Agricultural Policy program) able to modulate grants according to the environmental performances of different cultivation practices.

2.2 Description of crop cultivation

Poplar cultivation practice follows the principles of integrated agriculture (Regione Lombardia, 2017) and shows a 10-years long crop cycle that includes several operations. For the analysis in this study, these operations were divided into three subsystems:

Subsystem A: field preparation and plantation. Organic fertilization with manure is carried out at the beginning of the crop cycle. After, primary tillage is performed with a moldboard plow (45 cm deep) and secondary tillage is carried out with a rotary harrow (10 cm deep). At planting, using a soil drill machine, 2-years-old seedlings (280 seedlings/ha) are planted with a 6-meters distance on the row and between rows.

Subsystem B: crop management. This subsystem aims to assure a regular plants' growth and the production of good quality timber. Irrigation is carried out the first two years (1,000 m^3/ha each) and one year every three years in the following growing seasons (1,200 m^3/ha). Mineral fertilization takes place 3 times: the first intervention involves the application of NPK fertilizers, while the other two are carried out using only nitrogen fertilizers. Weed control involves both mechanical and chemical interventions, in which the first involves one intervention per year with a disc harrow in the inter-row, and the second foresees five applications of herbicide. Finally, pest and disease control involves numerous applications of insecticide and one of fungicide. Pruning is carried out by different operators using a lifting basket and takes place 5 times.

Subsystem C: harvesting and soil restoring. Felling and first processing of plants are performed using a harvester: the plant is felled, the top and branches are eliminated, and cross-cutting is carried out. At the harvest, the average plant diameter at 1.30 m height ranges from 30 to 32 cm and the average tree mass is 0.60 t; 0.35 t is first quality roundwood (58.4%), 0.14 t is timber for pallets production (23.3%) and 0.11 t (18.3%) is plant top and branches. Felling, delimbing, topping and cross-cutting are followed by forwarding and by timber transport to the storage point. Soil restoring involves the chopping of plant stumps and is carried out using a forestry shredder.

2.3 Functional unit

Among the steps defined by the ISO standards, the selection of the functional unit (FU) is crucial to allow fair comparison with previous studies. The FU is the quantified performance of a product system and is used as reference unit in an LCA.

In this study, according to previous LCA studies for wood products (Asif et al., 2007; Puettmann and Wilson, 2007; Gonzalez-Garcia et at., 2009c; Pierobon et al., 2015; Proto et al., 2017; Bernardi et al., 2018) and agricultural systems (Nikkah et al., 2017; Schmidt Rivera et al., 2017; Vázquez-Rowe et al., 2017; Firouzi et al., 2018), 1 t of poplar timber as roundwood was selected as FU.

2.4 System boundary

The system boundary of the traditional poplar plantation (TPP) is reported in **Figure 1**.

The system boundary was defined with a "cradle to farm gate" perspective and, consequently, the life cycle of each agricultural process was included within the system boundary. More in details, the following activities were included: raw materials extraction (e.g., fuels, metals and minerals), manufacture of the agricultural production factors (e.g., seedlings, fertilizers, pesticides, agricultural machines and infrastructures), use of agricultural inputs and related emissions to the environment (fertilizer and diesel fuel emissions and tire abrasion emissions), maintenance and final disposal of tractors, operative machines and infrastructures.

Concerning the emissions related to crop cultivation, different emission sources were considered: those from N and P compounds that are related to ammonia volatilization, denitrification, nitrogen leaching and runoff, as well as emissions related to fuel combustion. According to previous studies (Gonzalez-Garcia et al., 2009 a,b; Manzone et al., 2014; Bacenetti et al., 2018b), no change in the soil organic carbon content was considered.

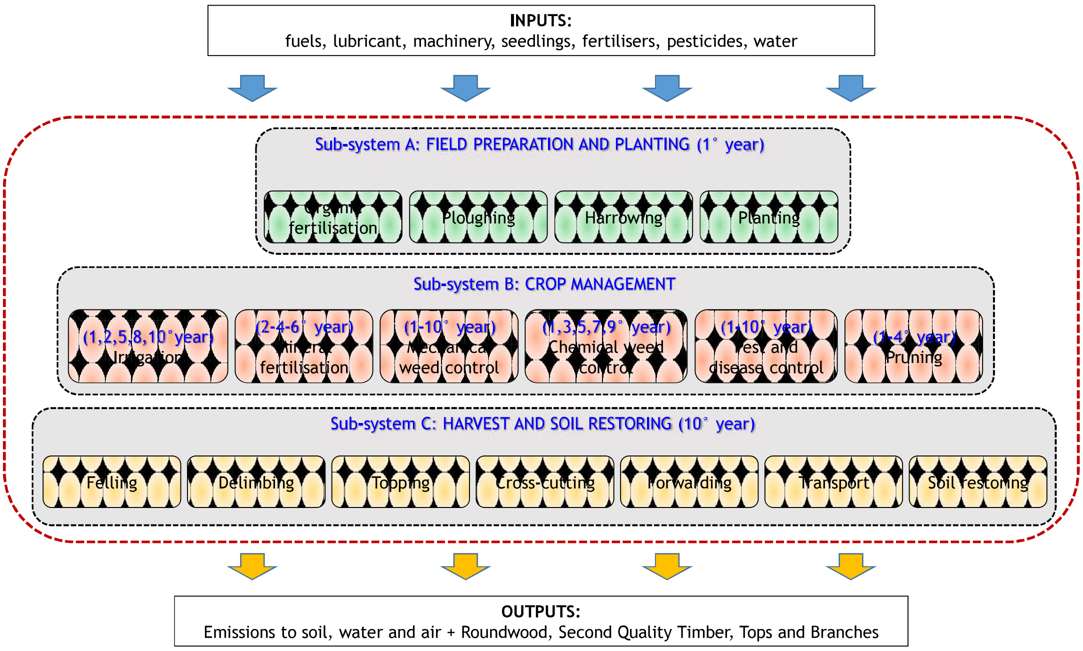

Figure 1 – System boundary for the TPP.

2.4.1 Alternative scenario

Over the years several studies focused on timber harvesting showed that the use of harvester for felling and first processing of trees can involve soil disturbance and soil damage due to compaction (Reisinger et al., 1988), reduced water drainage with increase run-off of nutrients (Williamson et al., 2000) and erosion (Zabowiski et al, 1994; Sun et al., 2001), disturbance of wildlife (Petranka et al., 1993) and, when the harvesting takes place in arable soil, increased fuel consumption for soil restoring (Soane and Van Ouwerkerk, 1995; Lovarelli and Bacenetti, 2017b). For this reason, an alternative scenario was considered for harvesting and felling and first processing of plants to study if improvements to these aspects could be achieved. Respect to the Baseline Scenario (BS), where these operations are carried out by the harvester, in the Alternative Scenario (AS), felling and first processing (top and branches elimination and trunk sectioning) are performed by operators equipped by chainsaw. In addition, although other studies are available in literature, for this study the increase in fuel consumption during soil restoration was not assessed due to lack of data.

2.5 Inventory

Primary inventory data regarding crop cultivation were collected by means of surveys at farm and questionnaires with the farmer. On the selected farm, poplar cultivation is carried out following the guidelines for integrated poplar production in Northern Italy (Regione Lombardia, 2017). Specifically, a data sheet for the questionnaire was developed, which includes the following sections:

- Section 1 – Cultivation practice: includes information about timing and number of repetitions of the field operations;
- Section 2 – Field operations: includes, for each field operation, information about operative machines (size, mass, length and width, required power, age, annual average working time, life span) and tractors (power, mass, exhaust gases emissions stage, age, annual working time, life span);
- Section 3 – Inputs: includes information about the production factors consumed (fuel, pesticides, fertilizers, etc.). Diesel fuel consumption was directly measured with the "full-tank method" (Lovarelli et al., 2016) during surveys on fields.

The amounts of tractors and agricultural equipment depleted for each field operation were calculated considering the annual working time and the physical and economic life span. According to Lovarelli and Bacenetti (2017a), physical life span (h) was considered equal to 12,000 h for tractors; 2,000 h for plow, harrow, seeder and fertilizer spreader and 3,000 h for farm trailers. Concerning the economic life span (years), 12 years were taken into account for tractors, farm trailers and spreader; 8 years for plow, harrow, fertilizer spreader and seeder (Bodria et al., 2006, Bacenetti et al., 2018b). **Table 1** reports the main inventory data adopted in the analysis.

Table 1 – Processes involved in the poplar cultivation in the two evaluated scenarios (SC): Baseline (BS) and Alternative (AS)

Subsystem	**SC**	**Field Operation**	**Rep**[a]	**Operative machine**	**Tractor**		**Fuel Cons.**[b]	**Input**		**Time**
					kW	**kg**	**kg ha^{-1}**	**Product**	**Amount (ha^{-1})**	**h/ha**
A - Field preparation and planting	BS & AS	Organic fertilisation	1	Spreader	100	5600	35	cattle manure	50 t	2.2
		Ploughing	1	Plough	110	6050	19			1.1
		Harrowing	1	Rotary harrow	90	5050	15			1.7
		Planting	1	Auger	70	3900	17	2-years seedling	280	5.5
B - Crop management	BS & AS	Irrigation	5	Pump	70	3900	18	Water	1000 m^3/ha 1st and 2nd year; 1200 m^3/ha one year every three	3.0
		Mineral fertilization	3	Fertilizer spreader	90	5050	6	Urea superphosphate KCl	495 kg 250kg 290 kg	0.4
		Mechanical weed control	3 x 10	Disc harrow	90	5050	11			2.0
		Chemical weed control	5	Sprayer	90	5050	8	Glyphosate	4.5 dm^3	0.30
		Pest and disease control	2 x 10	Sprayer	90	5050	8	Pyretroid-comp. Fungicide	4.8 dm^3 18.0 dm^3	0.30
		Pruning	5	Lifting baskets	70	3900	4			13.0
C - Harvest and soil restoring	BS	Felling, delimbing, topping and cross-cutting	1	Harvester	335	15500	90	Roundwood 2nd quality timber Tops & Branches	135 t 54 t 40.5 t	10.5
	AS		1	Chainsaw		7	32.1 [c] 16.0 [d]			109.5
	BS	Forwarding	1	Forwarder	90	5050	92			7.0
	AS		1	Tractor with winch			172			15.9
	BS & AS	Transport	1	Trailer	90	5050	54			7.5
	BS & AS	Soil restoring	1	Forestry shredder	110	6050	40			8.0

[a] Repetitions; [b] Fuel consumption; [c] Petrol two-stroke blend; [d] vegetable oil

Concerning the background data, information about the production of seeds, diesel fuel, urea, pesticides, tractors and agricultural machines was retrieved from the Ecoinvent Database v.3 (Weidema et al., 2013).

The emissions related to fertilizer applications (nitrate leaching, ammonia volatilization and nitrous oxide from denitrification) were evaluated according to Brentrup et al. (2000) and Prahsun (2006). More in detail, following Brentrup et al. (2000) NH_3 volatilization, emissions of N_2O and NO_3 leaching were assessed considering soil characteristics (texture, pH, cation-exchange capacity), climate (temperature, wind, precipitation) and type of fertilizers. Phosphate emissions were calculated considering leaching to groundwater (assessed with a factor of 0.06 kg P·ha^{1}·year^{-1}) and runoff to surface water (evaluated considering 0.175 kg P·ha^{-1}·year^{-1} as emission factor) (Prahsun, 2006). Due to the presence of herbaceous cover on the soil, phosphate emissions through erosion to surface waters were considered negligible (Zuazo et al., 2009).

2.6 Allocation

Besides roundwood, poplar plantations produce as co-products: (i) second quality timber, which is usually used for pallets production, and (ii) tops and branches usually used for energy purposes after the production of wood chips by chipping. Consistently with other LCA studies facing multi-functionality in agriculture (e.g., Schmidt Rivera et al. (2017) for grain and straw in barley cultivation; Bacenetti et al. (2017) for biodiesel and press cake from camelina and linseed; and Tricase et al., (2018) for cereals), an economic-based allocation method was implemented. **Table 2** reports the market prices and the allocation factors considered for the co-products.

Table 2 - Prices and economic allocation factors

Parameter	Value
Average Roundwood price[a]	130 €/t
Average second quality timber price[a]	45 €/t

Average tops and branches price[a]	25 €/t
Allocation factor Roundwood	84%
Allocation factor second quality timber	12%
Allocation factor tops and branches	5%

[a] Camera di Commercio di Alessandria (2018).

2.7 Life Cycle Impact Assessment (LCIA)

During LCIA, inventory data are converted into a reduced number of environmental indicators using specific characterization factors. In this study, the ILCD (International Reference Life Cycle Data System) midpoint method (ILCD, 2011) was used, which is the LCIA method endorsed by the European Commission. The following impact categories were evaluated:

- Climate Change (CC, expressed as kg CO_2 eq.),
- Ozone Depletion (OD, expressed as kg CFC-11 eq.),
- Particulate Matter Formation (PM, expressed as kg PM2.5 eq),
- Human Toxicity–No Cancer Effect (HTnoc, expressed as CTUh),
- Human Toxicity–Cancer Effect (HTC, expressed as CTUh),
- Photochemical Ozone Formation (POF, expressed as kg NMVOC eq.),
- Terrestrial Acidification (TA, expressed as molc H+ eq.),
- Terrestrial Eutrophication (TE, expressed as molc N eq.),
- Freshwater Eutrophication (FE expressed as kg P eq.),
- Marine Eutrophication (ME, expressed as kg N eq.),
- Freshwater Ecotoxicity (FEx, expressed as CTUe),
- Mineral and Fossil Resource Depletion (MFRD, expressed as kg Sb eq.).

3 Results and Discussion

3.1 Baseline scenario

Table 3 reports the environmental impact of poplar roundwood production in the baseline scenario (BS).

The relative contributions to the impact of each input and output are shown in Figure 2. Emissions from the application of fertilizers represent the hotspot process in TA, TE and ME, with a contribution greater than 80% (i.e. 80%, 83% and 86%, respectively for TA, TE and ME). More in details, ammonia volatilization affects TA and, secondarily, ME. Also nitrate leaching affects ME, while phosphate run-off increases FE. The emissions related to fertilizing are also hotspot for CC (31%, mainly due to the emissions of dinitrogen oxide) and for PM (49%, due to the emission of ammonia that is the main precursor of secondary inorganic aerosol).

Table 3 – Absolute results for the FU (1 t of roundwood) in BS

Impact category	**Unit**	**Score**
CC	kg CO_2 eq	59.17
OD	mg CFC-11 eq	6.34
HT-noc	CTUh	$4.16 \cdot 10^{-5}$
HT-c	CTUh	$2.52 \cdot 10^{-6}$
PM	kg PM2.5 eq	6.96
POF	kg NMVOC eq	0.318
TA	molc H+ eq	1.922
TE	molc N eq	8.296
FE	g P eq	9.088
ME	kg N eq	1.046
FEx	CTUe	7726.8
MFRD	g Sb eq	6.81

Among the different field operations:

- Field preparation and planting are always responsible for less than 2% of the impact, except for CC (4.1%), OD (5.3%), HT-noc (9.3%), HT-c (5.6%) and POF (8.2%). For these field operations, the impact is due to fuel consumption and to the related emissions from the exhausts pipeline. Although the impact of these operations is limited, it should be considered that they are carried out only once during the crop cycle;
- Crop management is a hotspot for 6 of the 12 evaluated impact categories. It contributes with 28% to CC (due to the emissions of CO_2 from diesel

combustion), 35% to OD (due to the consumption of diesel), 69% to HT-noc, 48% to HT-c and 51% to POF (due to the emissions of exhaust gases pollutants from the tractor engine);

- Harvesting and soil restoring, although carried out only once over the crop cycle, are responsible for more than 10% of the impact on CC (19%), OD (30%), HT-noc (13%), HT-c (15%) and POF (26%), while they have a minor role (<7%) for the other 6 impact categories.

The production of fertilizers contributes considerably to the environmental impact of:

- OD (26%) and HT-c (28%), mainly due to the energy consumption for N-fertilizer production,
- PM (25%) and FE (66%), due to the emissions of N-oxides and ammonia during nitrogen fertilizer manufacturing;
- MFRD (73%), due to the high energy-consumptive processes required to produce mineral fertilizers.

Emissions due to the application of pesticides are hotspot for FEx (98%), whereas they do not contribute to the other impact categories.

Finally, the consumption of other production factors (seedlings and pesticides) only slightly affects the environmental impact categories and shows a contribution to the total impact always lower than 5%.

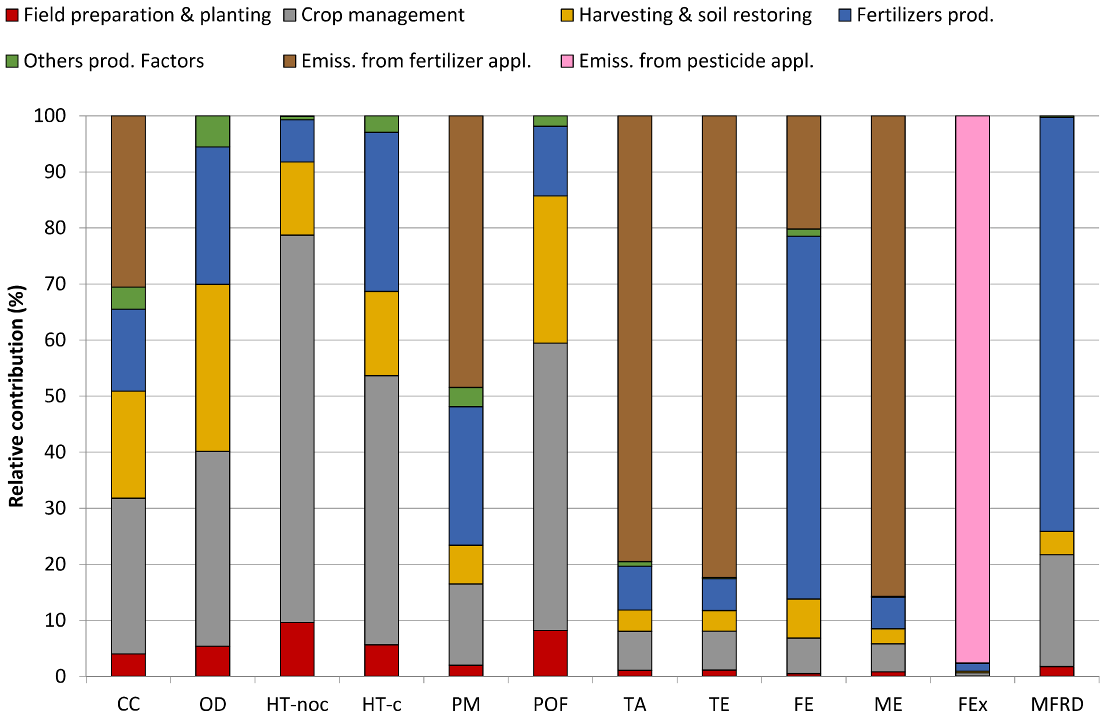

Figure 2 – Hotspots identification for BS scenario

3.2 Alternative scenario and comparison between BS and AS

Figure 3 identifies the environmental hotspots for AS. Respect to BS, the differences refer to harvesting and soil restoring. In fact, although the contribution of these operations is lower in respect to the one of crop management and is higher in respect to field preparation and planting, there are variations among impact categories. Harvesting and soil restoring in AS are important contributors for HT-noc (22% compared to 13% in BS) and POF (38% compared to 28% in BS) and this is mainly due to the consumption of fuels and vegetable oil in the chainsaw that is adopted for felling, topping, delimbing and cross-cutting.

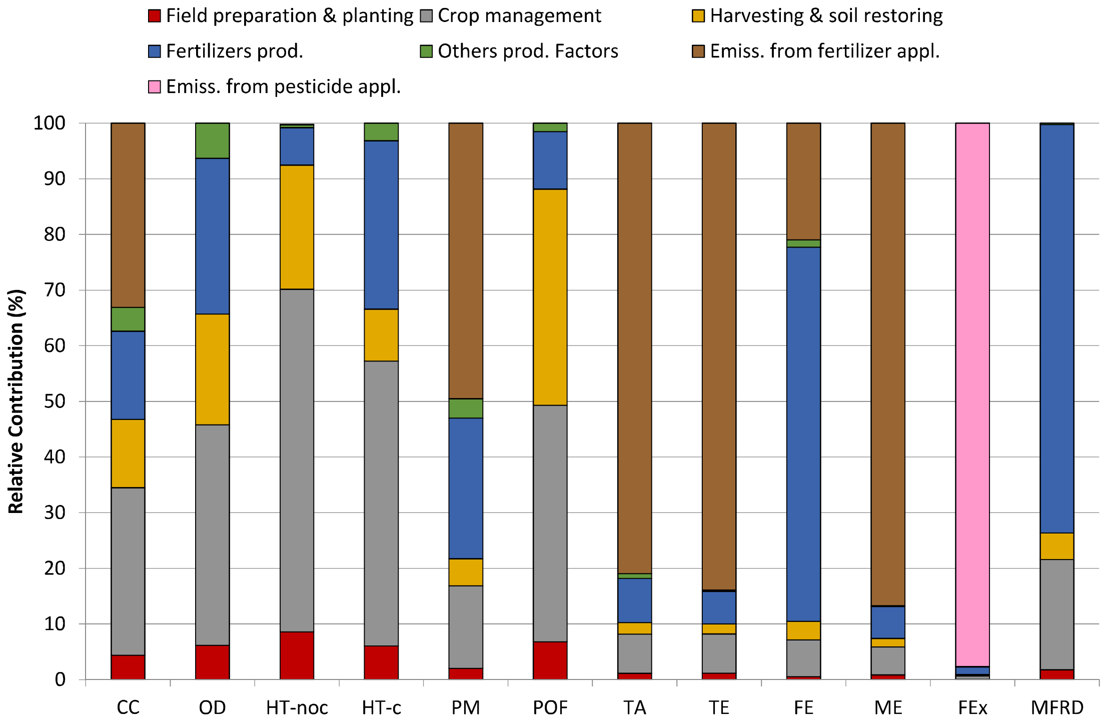

Figure 3 – Processes contribution for AS

Table 4 reports the absolute impact for AS and the impact variation between the two scenarios, while **Figure 4** shows the relative comparison. For 9 of the 12 evaluated categories, AS performs the best, with an environmental impact reduction ranging from -0.1% in FEx to -7.7% in CC, while for the remaining 3 (HT-noc, POF and MFRD) the alternative mechanization of felling, topping, delimbing and cross-cutting involves an impact increase ranging from 0.6% for MFRD to 20.6% for POF. The impact categories mostly affected by changes in the mechanization of harvesting are those mostly related to fuel consumption. In AS, CC and OD are reduced because, globally, a lower amount of fuel is consumed while POF and HT-noc increase considerably mainly because of the emissions of non-methane volatile organic compounds (NMVOC) related to the consumption of petrol two-stroke blend and vegetable oil instead of diesel.

The two scenarios show similar results for all the impact categories affected by emissions of N and P compounds in the atmosphere (e.g., TA, TE and ME) because emissions are related to the application of fertilizers that is the same in the two scenarios.

Table 4 – Environmental results for AS: Absolute impacts and variation respect to BS.

Impact category	**AS**	**Variation respect to BS**
CC	54.59 kg CO2 eq	-7.7%
OD	5.56 mg CFC-11 eq	-12.4%
HT-noc	$4.67 \cdot 10^{-5}$ CTUh	+12.2%
HT-c	$2.36 \cdot 10^{-6}$ CTUh	-6.2%
PM	68.13 g PM2.5 eq	-2.2%
POF	0.384 kg NMVOC eq	+20.6%
TA	1.888 molc H+ eq	-1.8%
TE	8.137 molc N eq	-1.9%
FE	8.75 g P eq	-3.7%
ME	1.033 kg N eq	-1.2%
FEx	7721 CTUe	-0.1%
MFRD	6.85 g Sb eq	+0.6%

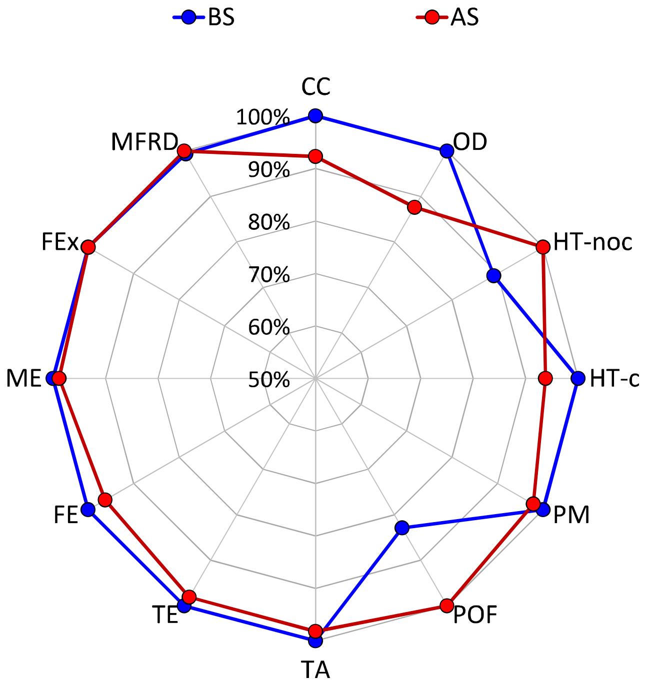

Figure 4 – Relative comparison between the two scenarios

3.3 Sensitivity and uncertainty analysis

To test the robustness of the achieved environmental results, a sensitivity analysis and uncertainty analysis were carried out.

3.3.1 Sensitivity analysis

A sensitivity analysis was realized to investigate the effect of key parameters, assumptions and methodological choices of the study. Thus, the following aspects were considered for BS:

- the biomass yield. Since in recent years have been developed new "highly sustainable" poplar clones characterized by high resistance to drought and pests and diseases (Allegro et al., 2014), a 25% increase in biomass yield was considered. However, climatic conditions (e.g., severe drought, especially in the first growing seasons), presence of insects (e.g., *Chrysomela populi* L. and *Saperda carcharias* L.) and fungi's (*Marssonina brunnea*) attacks cause a possible sensible slowdown of the growth, for which a yield reduction of 25% was also considered. As a consequence to yield changes, a reasonable variation in the working time of harvesting and forwarding was taken into account. According to Cielo et al. (2002) and Verani and Sperandio (2003), during harvesting and forwarding of poplar plantation, 20% of the working time is "dead time". Consequently, for these operations the increase of working time was considered proportional to the yield increase with the exclusion of increases in "dead time";
- The allocation method. A mass-based allocation method was evaluated instead of the economic one. Based on the mass of co-products – roundwood, second quality timber, tops and branches - the following allocation factors were used: 58.9% for roundwood, 23.5% for timber for pallets and 17.6% for tops and branches. Although not suitable for differentiating the co-products according to their value and their different uses, the mass-based allocation is not affected by price variability.

The results of the sensitivity analysis are reported in **Table 5**. Yield variation deeply affects all impact categories. Nevertheless, the impact categories mainly related to the emissions of N and P compounds (i.e. PM, TA, TE, FE, ME) and of active ingredients from pesticides (FEx) show the biggest variations. For the other impact categories (CC, OD, HT-noc, HT-c, POF and MFRD), yield changes entail smaller variations because harvesting operations are directly affected by the increase or decrease of the produced biomass. For this reason, with lower or higher yields, the environmental impact increases or decreases less respect to the other categories. When yield is reduced, N and P compounds and active ingredients are still applied, so their contribution plays a higher role, while the harvesting is more restrained due to the lower biomass to harvest. On the opposite, when yield increases, harvesting operations increase in time and inputs used, therefore, the related reduction in environmental impact is lower.

Finally, when the mass-based allocation is used instead of the economic one, all impact categories are deeply affected. Although expected, the outcome of the sensitivity analysis highlights the importance of the allocation choice in the definition of the environmental load of roundwood. Noya et al. (2015), Renzulli et al. (2015), Schmidt Rivera et al. (2017), Tricase et al (2017) and Rugani et al. (2015) previously obtained similar results.

Table 5 – Results of the sensitivity analysis for yield and allocation method: Impact variation respect to BS

Impact category	Yield		MASS ALLOC.
	LOW	HIGH	
CC	20.7%	-17.2%	-34.6%
OD	18.2%	-15.5%	-34.6%
HT-noc	22.0%	-17.7%	-34.6%
HT-c	21.5%	-17.5%	-34.6%
PM	23.5%	-19.0%	-34.6%
POF	19.4%	-16.3%	-34.6%

TA	24.2%	-19.5%	-34.6%
TE	24.2%	-19.5%	-34.6%
FE	23.3%	-18.9%	-34.6%
ME	24.4%	-19.6%	-34.6%
FEx	24.9%	-20.0%	-34.6%
MFRD	24.0%	-19.3%	-34.6%

Concerning the comparison between the two scenarios, a different characterization method was used for the impact assessment. Instead of the ILCD midpoint method (ILCD, 2011), the ReCiPe Midpoint (H) 1.12 method (Goedkoop et al. 2013) was considered.

Table 6 reports the environmental results for the two scenarios when the Recipe LCIA method is used. Although a direct comparison between the environmental results between the two LCIA methods cannot always be drawn due to the assessment of different impact categories and due to the use of different units of measure, when the two scenarios are compared, similar results can be observed independently from the LCIA method. More in detail, except for ME, for the other impact categories the two LCIA methods provide univocal results for the identification of the best/worst scenario.

Table 6 – Absolute and relative results for the two scenarios with Recipe LCIA method

Impact category	**Absolute results**		**Relative comparison**	
	BS	**AS**	**BS**	**AS**
Climate change	67.284 kg CO_2 eq	63.244 kg CO_2 eq	100	94.0
Ozone depletion	6.39 mg CFC^{-11} eq	5.61 mg CFC^{-11} eq	100	87.8
Terrestrial acidification	1.543 kg SO_2 eq	1.517 kg SO_2 eq	100	98.3
Freshwater eutrophication	8.204 g P eq	7.865 g P eq	100	95.9
Marine eutrophication	0.971 kg N eq	0.973 kg N eq	99.9	100
Human toxicity	7.907 kg 1,4-DB eq	7.717 kg 1,4-DB eq	100	97.6
Photochemical oxidant form.	0.326 kg NMVOC	0.403 kg NMVOC	80.9	100
Particulate matter formation	0.299 kg PM10 eq	0.287 kg PM10 eq	100	96.1
Freshwater ecotoxicity	4.450 kg 1,4-DB eq	4.438 kg 1,4-DB eq	100	99.7
Metal depletion	6.059 kg Fe eq	5.798 kg Fe eq	100	95.7
Fossil depletion	14.783 kg oil eq	13.222 kg oil eq	100	89.5

Note: Only the impact categories assessing similar environmental impact to the ILCD method are reported

3.3.2 Uncertainty analysis

An uncertainty analysis was run on scenarios BS and AS using the Monte Carlo technique (1,000 iterations and a confidence interval of 95%) to test the robustness of the results. **Figure 5** reports the outcomes of such analysis. The bars on the left represent the probability that the environmental impact of AS is lower than the one of BS while the bars on the right mean the opposite (i.e. the environmental impact of poplar production in AS is higher than the one in BS).

The results show that the modelling of the environmental impact of timber production is robust, thus outcomes are trustworthy. Except for FEx and OD, for all the other evaluated impact categories there is a reduced uncertainty level. In particular, for 7 of the 12 impact categories, BS has a higher impact than AS with a level of statistical significance higher than 99%; similarly, the level of statistical significance related to the case that BS has a lower impact than AS is almost 100% for POF and HT-noc. The level of statistical significance is lower than 90% only for OD (BS > AS, with a level of statistical significance of 88%) and MFRD (AS> BS with level of statistical significance of 84%) Thus, these results show that the uncertainty due to selection of the data source, model imprecision and variability of data does not significantly affect the results.

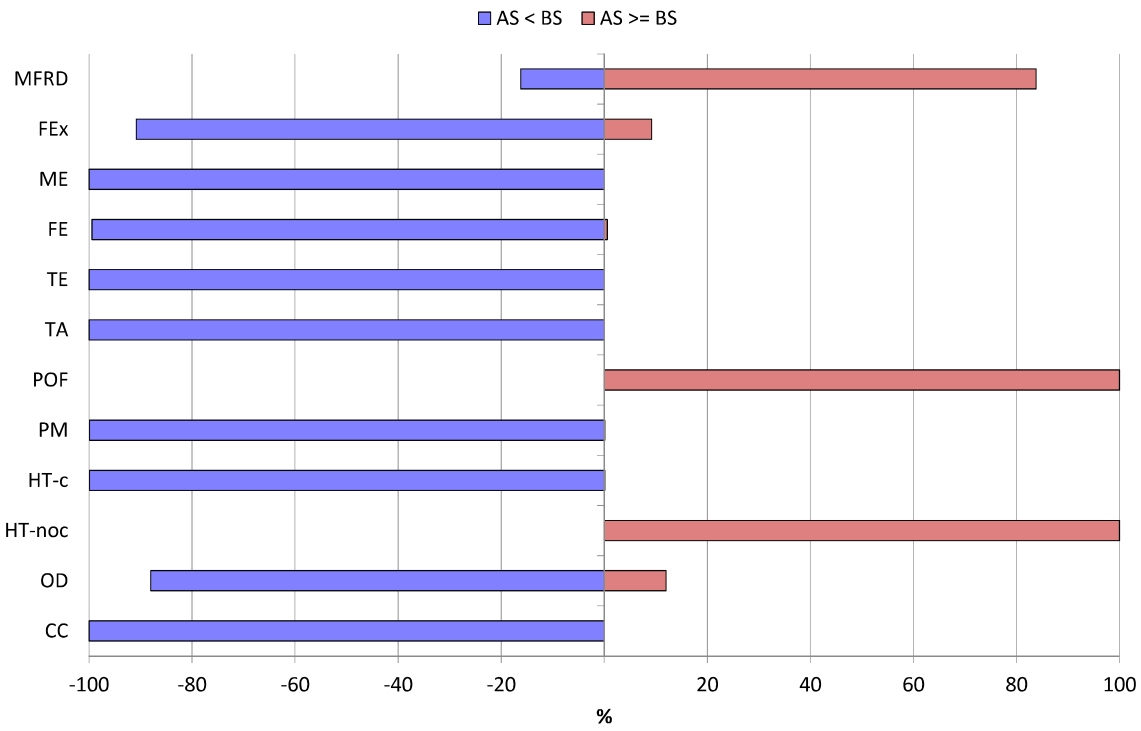

Figure 5 – Results of the uncertainty analysis.

4 Conclusions

Roundwood can be produced from forestry activities as well as from dedicated plantations. In this study, the environmental impact of timber production from poplar plantation was evaluated by means of LCA using an attributional approach and a "from cradle to gate" perspective. Among the different field operations, crop management involves a higher impact respect to field preparation-planting and harvesting-soil restoring. The emissions related to fertilizers applications are the main responsible for acidification, eutrophications and particular matter formation. The comparison between the two harvesting solutions shows that the alternative scenario (felling delimbing and cross cutting carried out using chainsaw instead of harvester) resulted better for all impact categories (impact reduction ranging from 0.1% to 12.4%), except for HT-noc (+12.2%) and POF (+20.6%), due to fuel and vegetable oil consumption.

Although the production of timber from poplar plantations is responsible of negative environmental impacts, in the next years, the introduction of high-sustainability clones (characterized by higher yield and higher resistance to pests and drought) could be particularly interesting for reducing the environmental impact of poplar roundwood production. Moreover, they could represent a valid solution for policymakers interested in supporting poplar production chains and in increasing poplar cultivated area.

The outcomes of this study can be useful for the development of a subsidy framework related to the environmental performances by comparing the impact of poplar timber with the ones of timber from other species and because, by identifying the main environmental hotspots, the most effective mitigation solutions can be designed and subsidized.

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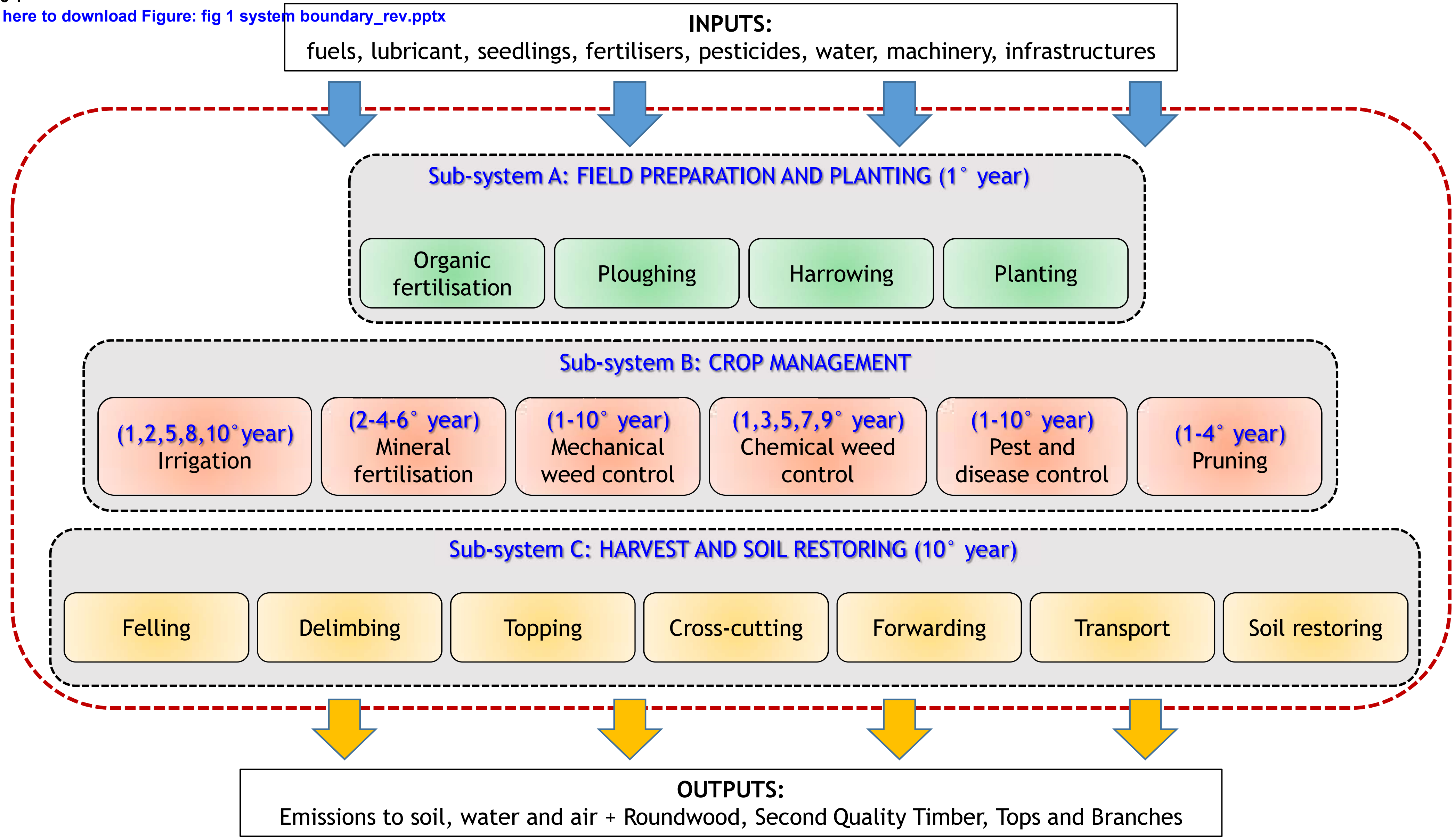
TABLES

Table 1 - Processes involved in the poplar cultivation in the two evaluated scenarios (SC): Baseline (BS) and Alternative (AS)

Subsystem	SC	Field Operation	Repetition	Operative machine	Tractor		Fuel Cons.	Input		Time
					kW	kg	kg·ha^{-1}	Product	Amount (·ha^{-1})	h/ha
A - Field preparation and planting	BS & AS	Organic fertilisation	1	Spreader	100	5600	35	cattle manure	50 t	2.2
		Ploughing	1	Plough	110	6050	19			1.1
		Harrowing	1	Rotary harrow	90	5050	15			1.7
		Planting	1	Auger	70	3900	17	2-years seedling	280	5.5
B - Crop management	BS & AS	Irrigation	5	Pump	70	3900	18	Water	1000 m^3/ha 1st and 2nd year; 1200 m^3/ha one year every three	3.0
		Mineral fertilization	3	Fertilizer spreader	90	5050	6	Urea superphosphate Potassium chloride	495 kg 250kg 290 kg	0.4
		Mechanical weed control	3 x 10	Disc harrow	90	5050	11			2.0
		Chemical Weed control	5	Sprayer	90	5050	8	Glyphosate	4.5 dm^3	0.30
		Pest and Disease control	2 x 10	Sprayer	90	5050	8	Pyretroid-comp. Fungicide	4.8 dm^3 18.0 dm^3	0.30
		Pruning	5	lifting baskets	70	3900	4			2.0-4.0
C - Harvest and soil restoring	BS	Felling, delimbing, topping and cross-cutting	1	Harvester	335	15500	90	Roundwood 2nd quality timber Tops & Branches	135 t 54 t 40.5 t	10.5
	AS		1	Chainsaw		7	32.1 [a] 16.0 [b]			109.5
	BS	Forwarding	1	Forwarder	90	5050	92			7.0
	AS		1	Tractor with winch			172			15.9
	BS & AS	Transport	1	Trailer	90	5050	54			7.5
	BS & AS	Soil restoring	1	Forestry shredder	110	6050	40			8.0

[a] Petrol two-stroke blend [b] vegetable oil

Figure 1


INPUTS:
fuels, lubricant, seedlings, fertilisers, pesticides, water, machinery, infrastructures
Sub-system A: FIELD PREPARATION AND PLANTING (1° year)
Organic fertilisation
Ploughing
Harrowing
Planting
Sub-system B: CROP MANAGEMENT
(1,2,5,8,10°year) Irrigation
(2-4-6° year) Mineral fertilisation
(1-10° year) Mechanical weed control
(1,3,5,7,9° year) Chemical weed control
(1-10° year) Pest and disease control
(1-4° year) Pruning
Sub-system C: HARVEST AND SOIL RESTORING (10° year)
Felling
Delimbing
Topping
Cross-cutting
Forwarding
Transport
Soil restoring
OUTPUTS:
Emissions to soil, water and air + Roundwood, Second Quality Timber, Tops and Branches