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# Roundwood and bioenergy production from forestry: environmental impact assessment considering different logging systems

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## ABSTRACT

The aim of this paper is to analyse the environmental performances of three different extraction systems for forestry considering three different scenarios concerning the valorisation of forest residuals are analysed.

The compared tree extraction systems are characterized by felling and processing performed with chainsaw and three different extraction methods: i) by farm tractor equipped with a winch; ii) by skidder and iii) by cable crane. The “Full Tree System” was adopted for all the felling sites; trees were felled and transported to roadside with branches and top intact. For wood chips produced from branches and tops, different scenarios were considered: heat and electricity generation and substitution of wood-chip production.

To evaluate the environmental performance the Life Cycle Assessment (LCA) approach was applied. The selected functional unit (FU) is 1 $m^3$ of roundwood; the system boundary involves all the operations carried out in forestry (felling, bunching, extraction, processing, chipping of forest residuals), the transport of the produced wood chips and all the related inputs and emissions. A comparison with previously carried out studies in similar geographic areas were performed.

The study's outcomes show how, the environmental results among the different logging systems are not univocal and the best logging system depends on the considered impact category. Though cable yarder is recognised as an extraction method able of reducing the physical impacts on residual stand (wounding) and soil (disturbance and compaction), for 10 of the 12 impact categories evaluated in this study, achieves the worst performances. The logging systems in which the extraction is performed using the tractor and the skidder show the best performance for 6 of the 12 evaluated impact categories. Finally, regarding wood residues utilisation and the impact of particulate matter formation, the energetic valorisation of wood chips does not involve any benefit but involves a worsening of the environmental performances due to wood combustion emissions.

**KEYWORDS**

Forestry; Life cycle assessment; renewable energy, cable yarder, skidder, mechanisation.

## 1. INTRODUCTION

Forests and wood represent a basis for economic, environmental and social stability in rural areas (Tam et al., 2017; Siebert et al., 2017; Zambon et al., 2016). Wood harvesting has always represented one of the most important management interventions, not only in meeting production objectives but also in shaping the composition (biodiversity, etc.) for the future of forests; additionally, several techniques have been developed during the last fifty years to increase operator productivity, work qualifications and occupational safety (Klein et al., 2016; Winter and Brambach, 2011). All forest operations, especially logging or timber harvesting, have environmental impacts (Putz et al., 2000; Brunori et al., 2016). Commonly, three harvesting methods are applied: full-tree, tree-length, and cut-to-length. With full-tree system trees are felled and transported to roadside with branches and top intact trees are processed at roadside or hauled as full trees to central processing yards or the mill. In the tree-length system trees are felled, delimbed and topped in the cut-over; delimbing and topping can occur at the stump area or at a point before roadside. The other method is the cut-to-length (shortwood), in which trees are felled, delimbed and bucked to various assortments directly in the stump area. In addition to the target product, the applicability of each system depends on several variables related to stand characteristics (such as stocking density, average tree volume or thinning intensity) and to every single tree characteristics (volume, height, tree form, branch size and state of pruning) or terrain (slope, soil or state of roughness) (Monarca et al., 2011; Balimunsi et al., 2012). Efficiency and functionality of a particular harvesting system depends on a number of features. The economic benefits can be evaluated by indicators such as labour productivity and costs; environmental indicators can include soil damage (trail depth or degree of soil compaction) (Deconchat, 2010; Gondard et al., 2003), damage to undergrowth or remaining trees, etc. (Syunev et al., 2009). In many industrialised European countries, full mechanised cut-to-length wood harvesting methods have become widely used in Sweden (ca. 98%), Ireland (ca. 95%) and Finland (ca. 91%) compared to motor-manual harvesting (Karjalainen et al. 2001). In Italy, where landscape morphology is highly irregular, many operators resort the full tree system for trees with small and medium diameter using farm tractors equipped with forestry winches (Marchi et al., 2014), cable crane (Zimbalatti and Proto, 2009; Proto and Zimbalatti, 2016), skidder and forwarder (Macrì et al., 2016).

Similarly to economic aspects, each harvesting system is responsible for a different environmental impact depending on machine productivity and site characteristics (Morrison and Golden, 2017; Lovarelli and Bacenetti, 2017a). Nevertheless, until now, only few studies have considered a full set of environmental impacts for the logging systems (Gonzalez-Garcia et al., 2009; Valente et al., 2011, Laschi et al., 2016; De la Fuente et al 2017); furthermore, differently from those studies, in this evaluation particular attention has been paid to Mediterranean areas and to the valorisation of wood by-products (Proto et al., 2017).

During last decades, to evaluate the environmental impact of agricultural systems, the Life Cycle Assessment (LCA) approach has been more and more widely employed. This method aims to analyse products, processes or services from an environmental perspective (ISO, 2006a, ISO, 2006b). Over the years, LCA has been applied to evaluate different renewable energy sources such as firewood (White et al., 2005; Pierobon et al., 2015), wood chips from forestry (Dias, 2014; Rafael et al., 2016) and Short Rotation Coppice (González-García et al., 2012; Bacenetti et al., 2016a), pellet (Magelli et al., 2009; Fantozzi and Buratti, 2010) and biogas from agricultural biomass (Bacenetti al., 2016b; Lijó et al., 2014a; Lijó et al., 2014b) and waste (Lijó et al., 2017).

In this context, the aim of this paper is to analyse the environmental performances of three different extraction systems. In addition, three different alternative scenarios (AS) concerning the valorisation of forest residuals are analysed.

## 2. MATERIALS AND METHODS

### 2.1 Goal and scope definition

The goal of this study is to assess the environmental impact of three logging system solutions, each of which is composed of different operations. The selected harvesting solutions are typical for slopes and rough forestry and are called "full tree system – F.T.S." because they foresee the extraction of whole tree after felling. The considered forests are chestnut (*Castanea sativa*) at high forest, at an altitude of 1,050 m a.l.s for site A, 900 m a.l.s in B and 750 m a.l.s in site C. The studies were conducted in selective felling sites, on an area of 8 ha with N-W exposition in site A, 14 ha with S-W exposition in site B and 11 ha with N-E exposition in site C, respectively. The forests in the three sites are classified as I class for roughness, while the slope is between II and III class (20/60%) in according to UK Forestry Commission (1995).

The research questions can be summarised as follows:

1) What is the environmental impact of different logging systems?
2) Which processes are mainly responsible for this impact? How can this impact be reduced?
3) Which is the best valorisation for the wood chips produced from residual biomass?

The outcomes of this study can be useful for forestry operators, farmers associations and stakeholders involved in forestry management as well as for technicians and decision makers to support the development of a specific subsidy framework and choice of logging operations or different wood chips utilisation pathways with the lowest environmental impact. Though related to forestry operations carried out in Southern Italy, the achieved results can be up-scaled to other geographic forestry areas (e.g., Central and Eastern European Countries; Mediterranean Basin) with similar characteristics in terms of productivity, slopes and road network.

### 2.2 Functional unit

The functional unit (FU) provides the reference to which all other data in the environmental assessment are normalised. Several functional units (FUs) can be selected; the FU most used for the analysis of agricultural systems are: the mass of product, the area, the produced energy, the product's energy content and the product's volume (Renzulli et al., 2015). Mass-based FU is prevalent in LCA studies of agricultural systems (Noya et al., 2015;

Schmidt et al., 2017). Nevertheless, in forestry sector, the most frequently used unit of measure is the volume of produced wood. For this reason, in this study, the selected FU is 1 $m^3$ of roundwood. With respect to the mass, the volume of wood is less affected by moisture content.

## 2.3 Case study and system description

"Full Tree System" (F.T.S) method was adopted for all felling sites; this means that trees were felled and moved to roadside with branches and top.

The three sites cover an area of 33 hectares (8, 14 and 11 ha for Site A, B and C, respectively); the same workers were employed maintaining the same function. Among sites, there are differences concerning slope, number of trees per hectare and tree volume. **Table 1** reports the main characteristics of the three sites.

**Table 1 –** around here

The three similar harvesting systems (F.T.S) are composed of different logging operations: felling, bunching, extraction, tree processing and forest residuals chipping.

Although characterised by different productivity depending on site-specific conditions (e.g. slope and number of trees per hectare), felling is the same in the three sites, and it is carried out by two workers equipped with chainsaws. The three systems differ only in extraction method:

- in logging system 1 (LS1) a farm tractor equipped with a winch performs the bunching (during which the trees are grouped) before the extraction (during which the tree grouped are moved to roadside);
- in logging system 2 (LS2), bunching and extraction are carried out using a skidder;
- in logging system 3 (LS3), bunching does not take place because the trees are extracted by a cable crane.

After extraction, a further processing of trees is carried out (delimbing and cross-cutting) by two workers equipped with chainsaw. More in details, trees were cross-cut in different measures to obtain roundwood: 4 m (Ø 0.15-0.20 m), 6 m (Ø 0.21 - 0.30 m) and 8 m (Ø > 0.31m). The forest residuals available after processing are chipped using a motorised chipper to produce chips wood for energy purpose.

### 2.4 System boundary

The system boundary involves all the operations carried out in forestry (felling, bunching, extraction, processing and chipping) as well as the transport of chips wood and all of the related inputs (diesel fuel, lubricating oil and capital goods such as chainsaws, tractors, skidders and cable yarders) and emissions.

Therefore, raw materials extraction and transport (e.g., fossil fuels and minerals) and manufacture (e.g., chainsaws, tractors, skidders, cable cranes and other equipment), use (diesel fuel consumption and derived combustion and tyre abrasion emissions), maintenance and final disposal of machines were considered.

Each logging system generates two different products: roundwood (main product) and wood chips (coproduct). To solve the multifunctionality issue instead of allocation, different scenarios were analysed:

- Alternative Scenario 1 (AS1) in which the coproduct is transported 50 km to be used in a small-scale domestic boiler (< 50 kW) to produce thermal energy, which supplies energy requirements of single house. The produced heat is supposed to substitute thermal energy production from natural gas in domestic boilers;
- Alternative Scenario 2 (AS2) where wood chips is transported for 150 km to be used in a medium-size (15-20 MW) power generation plant to produce electricity. The produced electric energy substitutes an equal amount of electricity produced according to the Italian energy source mix;

- Alternative Scenario 3 (AS3), in this case no hypothesis regarding the final destination of the coproduct is drawn, and the produced wood chips are supposed to replace the production of wood chips from other sources. Consequently, environmental credits related to the coproduct's production is equal to the environmental impact of wood chip production from another source.

**Figure 1** around here

### 2.5 Life Cycle Inventory

Inventory data concerning logging operations performed in the three logging systems were collected in three different sites in Southern Italy (Calabria Region) by means of measurements; these data refer to working times, machine productivity (PMH), total volume extracted and fuels consumption.

According to Harstela (1993), productivity is the ratio between output (volume of wood) and input (time). In this study, time was measured using the repetition-timing method to determine the total yarding cycle time (Spinelli and Magagnotti 2012; Nikooy et al. 2013). Each work cycle was divided into work elements and classified as productive time or delay time, following the terminology suggested by the IUFRO Working Group (Bjorhedenet al. 1995) and timed using a digital chronometer (i.e. 1 min = 100 unit), Tag-HeuerMicrosplit™.

The extraction cycle for site A (Tractor + Winch) and B (Skidder + Winch) was divided into several elements (Spinelli and Hartsough 2001, Wang et al. 2004):

- Travel unloaded: begins when skidder leaves the landing area and ends when the machine stops in stump area;
- Release and hooking: begins when the worker has just grabbed the cable, sets the choker on the log about 0.5 -1.0 m away from the log end and ends when operator starts winching;

- Winching: begins when the driver starts to winch and ends when logs arrive in the rear part of the machine;
- Travel loaded: begins when the machine moves to landing and ends when it reaches the landing;
- Unhooking begins when the machine reaches landing and ends when the load is unhooked.

In the third site (Cable Crane), the cycle time was determined by using stopwatches for each individual cycle, where the productive time was separated from delay time, as well as by identifying the variables that were most likely to affect the time consumption (Balimunsi et al., 2012). Seven yarding elements were identified and timed to determine the total cycle time (Huyler and Ledoux, 1997; Proto et al., 2016):

- Outhaul Empty: Begins when the operator is ready to move carriage from landing out to choke setter and ends when the choke setter touches the choke.

Hook descent: Begins when the operator locks the carriage and begins to release the hook, and it ends when the operator starts to connect with the load.

Lateral Out: Begins at the end of outhaul empty and ends when the choke setter is ready to hook a turn (choke setter's forward motion has stopped and is ready to begin setting the chokers).

Hookup: Begins at the end of lateral out and ends when the choke setter has completed hooking the chokers and signals to begin yarding.

Lateral in: Begins at the end of hookup and ends when the turn is pulled up to the carriage and the carriage begins to move up the corridor.

In haul: Begins at the end of lateral in and ends when the turn has reached the position on the deck where it can be directly unhooked at the landing.

Unhook begins at the end of in haul when the carriage passes over the tripblock and ends when the chokers have returned to the carriage.

Trees in each site (A, B and C) were counted, while the volume of each tree was calculated based on Smalian’s formula by multiplying the average cross-sectional area of stem by stem length (Macrì et al. 2016).

All hours needed to harvest this area were monitored by two operators. One hundred cycles were monitored per site, covering 1-1.5 ha for both sites. The total measured volume was 185 m3 in A, 210 in B and 220 in site C, respectively.

Diesel fuel consumption was measured by evaluating the volume of fuel used to fill up fuel tanks to the brim, working time for felling, bunching and wood extraction were directly measured on forestry.

**Table 2 – 3 – 4** report the main technical and operational parameters measured during tests in the three sites for felling, bunching and extraction, respectively. Total volume extracted was 1392, 2520, and 2460 $m^{3}\cdot$ in site A, B and C, respectively.

**Table 2- 3 - 4** around here

The processing is carried out by means of chainsaw in all the LS but, considering the different characteristics of the three sites, diverse productivity and, consequently, dissimilar material consumptions are achieved:

- fuel (mixture and oil) consumption for processing is equal to 0.33 kg/$m^3$, 0.70 kg/$m^3$ and 0.37 kg/$m^3$ in LS1, LS2 and LS3, respectively;
- lubricant (vegetable oil) consumption is 0.17 kg/$m^3$, 0.35 kg/$m^3$ and 0.18 kg/$m^3$ in LS1, LS2 and LS3, respectively;
- amount of equipment(chainsaw) consumed is equal to 0.56 kg/$m^3$, 0.97 kg/$m^3$ and 0.76 g/$m^3$ in LS1, LS2 and LS3, respectively.

For what concerns chipping, the motorised chipper has an engine power of 571 kW and an hourly fuel consumption of about 96 kg/h of diesel that corresponds to an average specific fuel consumption of 0.48 kg/$m^3$ of roundwood. Working time was equal to 1.39, 2.52

and 2.64 for site 1, 2 and 3, respectively while the chips production was equal to 34.8, 36.0 and 38.1 m$^3$/ha (loose chips) for LS1, LS2 and LS3, respectively.

Concerning the alternative scenarios (AS):

- A moisture content of 35% and a lower heating value of 18.81 MJ/kg of dry matter (equal to 11.43 MJ/kg wet basis) were considered. Moisture content of biomass was determined according to the European Standard CEN/TS 14774-2;
- Transport of wood chips in AS1 and AS2 takes place with EURO 3 trucks with a load capacity of 32 metric tons;
- For AS1, a biomass loss of 10% and a thermal efficiency equal to 80% for small-scale boiler were considered according to Caserini et al. (2010) and Colantoni et al. (2016);
- For AS2, a biomass loss of 20% and, considering a Rankine Cycle, a biomass-to-electricity efficiency equal to 18% for medium-size power generation plant were considered (Fiala, 2012);
- For AS3, the wood chips production from a mix of hardwood and softwood in Europe was considered to quantify the environmental credits.

Considering that, maintenance and depreciation costs of capital equipment represent a substantial part of the product's price; the impact of capital goods was included in the analysis (Weidema et al., 2013; Lovarelli and Bacenetti, 2017b). Therefore, for all the logging systems, the indirect environmental burdens of tractors, skidders, cable cranes and other equipment such as chainsaws and winches were included too.

Background data for production of fuel, lubricant, tractor and other equipment as well as data regarding the environmental impacts related to wood chips combustion for heat and electricity production were retrieved from the Ecoinvent database v.3 (Weidema et al., 2013). **Table 5** reports the Ecoinvent database processes involved in the inventory.

**Table 5** – Around here

## 2.6 Life Cycle Impact Assessment (LCIA)

The characterisation factors reported by ILCD method were used (Wolf et al., 2012). Twelve impact potentials were evaluated: climate change (CC), ozone depletion (OD), human toxicity, non-cancer effects (HTnoc); human toxicity, cancer effects (HTc); particulate matter (PM), photochemical ozone formation (POF), acidification (TA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FEx) and mineral, fossil and renewable resource depletion (MFRD).

## 3. RESULTS

For each scenario and for each impact category the environmental results depend on the balance between impacts (generated environmental burdens) and credits (avoided environmental burdens). The impact arises from the sum of the environmental load of logging operations (felling, bunching, extraction, processing and chipping), transport of wood chips and, in AS1 and AS2, heat and electricity generation while the credits stem from the production of heat, electricity and wood chips in LS1, LS2 and LS3, respectively. Consequently, when the impact category score is negative (below zero), credits are higher than impacts and completely offset the latter.

## 3.1 Climate Change (CC)

**Figure 2** shows the results for CC impact category. The score for this impact category ranges from -24.09 kg $CO_2eq/m^3$ to +12.00 kg $CO_2eq/m^3$. The best performances are achieved for AS1, in which wood chip are used to produce heat while the worst in AS3. Also AS2 (electricity production from wood chips) achieves environmental benefits, though to a lesser extent than AS1. The credits arising from heat (in AS1) and electricity (in AS2) completely offset environmental impacts related to different logging operations; on the contrary, in AS3, the credits for avoiding wood chips production are lower compared with generated impacts.

Differences among scenarios are greater than the ones among logging systems. LS1 achieves the better performances but, LS2 (+1.32 kg $CO_2eq/m^3$) and LS3 (+2.06 kg $CO_2eq/m^3$) are comparable. These differences depend completely on differences in logging operations impacts. In LS1 and LS2, the logging operations with the highest environmental impact are bunching (28.9-33.1% of total impact in LS1 and 26.9-31.0% of total impact in LS2 of total impact) and extraction (26.1-29.9% of total impact in LS1 and 25.8- 29.7% of total impact in LS2), while in LS3, extraction is different (61.5-69.3% of total impact). In particular, in LS3, the extraction impact is higher than the sum of bunching and extraction in LS1 and LS2. In all the logging systems, felling is responsible for 6.7-9.3% of the impact, and processing is responsible for 3.6-7.2%.

In AS1, the heat generation in small-scale boiler is responsible for a non-negligible impact (1.73 kg $CO_2eq/m^3$, corresponding to 12.7% of impact), mainly due to the combustion emissions. In AS2, chips burning in the medium-size plant represents a little share of the impact (0.36 kg $CO_2eq/m^3$, corresponding to 2.7% of impact); in respect to the impact related to heat generation, this impact is lower because the plant is equipped with filter and devices for treatment of combustion gases.

**Figure 2** around here

### 3.2 Ozone depletion (OD)

For this impact category, despite credits, all of AS and LS, the environmental score is higher than zero.

The best logging system is LS2 where bunching and extraction are carried out using the skidder, while LS3 is the worst and shows the highest impact. The results for OD are strongly affected by diesel and petrol consumption during logging operations. Considering this, LS2 is the logging system with lowest diesel consumption (1.70 kg of $/m^3$ in respect to 1.92, and 2.53 for LS2 and LS3, respectively).

Among the different scenarios, though credits for electricity production are higher than that for heat production, the best performances are achieved in AS1 and not in AS2 since heat generation has a lower impact than electricity production. AS1 shows better performances (0.056-0.272 mg CFC-11 eq /m$^3$) than AS2 (1.753-1.969 mg CFC-11 eq /m$^3$) and AS3 (1.622-1.933 mg CFC-11 eq /m$^3$). Among different LS, LS3 shows the worst result.

**Figure 3** around here

### 3.3 Human toxicity, non-cancer effects (HTnoc) and cancer effects (HTc)

**Figure 4** and **Figure 5** show the results for human toxicity related impact categories. Among the different LS, the best logging system is:

- LS2 followed by LS1 (+3-8%) and LS3 (+17-40%) for HTnoc;
- LS1, followed by LS2 and LS3, for HTc.

LS3 has the higher impact because, as for other impact categories previously discussed, the impact of extraction is higher than the sum of bunching and extraction in LS1 and LS2. For HTnoc, the differences among logging systems are mainly related to fuel consumption and derived combustion emissions while for HTc the amount of machines consumed is the main responsible.

Both for HTnoc and HTc, the scenario in which wood chips are used to heat production in small-scale boiler (AS1) shows, by far, the worst performance. This is due to:

- For HTnoc to ash production and to the emissions related to biomass combustion;
- For HTc, to the production of the domestic boiler and to combustion emissions.

In particular, for HTnoc, all of the scenarios show a score > 0 but in AS1 the environmental impact is twice than of AS2 and AS3. For HTc, in LS1, credits arising from electricity production from a renewable source are higher than impacts, consequently the process results in an environmental benefit (-0.121 and -0.033 CTUhx10$^{-6}$/m$^3$ for LS1 and LS2, respectively).

**Figure 4 - 5** around here

## 3.4 Particulate matter (PM)

For PM, the differences among different logging systems are negligible; LS1 shows a slightly better environmental performance, while LS2 the worst (**Figure 6**). Regarding the comparison among scenarios, in AS1, the results are dominated by the emissions related to woody chips combustions (mainly particulates and nitrogen oxides in the air) and the impact is 45 times higher than in AS2 and 64 times higher than in AS3.

**Figure 6** around here

## 3.5 Photochemical ozone formation (POF)

For this impact category, the environmental score is > 0 for all of the logging systems and all of the scenarios and ranges from 117.2 g non-methane volatile organic compounds (NMVOC) eq/m$^3$ in LS1 and AS1 to 249.3 g NMVOC eq/m$^3$ in LS3 and AS1 (**Figure 7**). In particular, among logging systems, LS1 achieves the lowest environmental impact followed by LS3 (+25-36%) and LS2 (+36-51%). Among different logging operations, felling is the main responsible for POF (57, 56 and 53 g NMVOC/m$^3$ in LS1, LS2 and LS3, respectively); this is due to the emissions in atmosphere related to the chainsaw fuels (petrol and vegetable oil) combustion in the chainsaw and, in particular, to the NMVOC[1] emissions.

The combustion of wood chips for energy purpose is responsible for 39-46% of environmental load in AS1 (heat production) and for 13-17% in AS2 (electricity production). Consequently, the best scenario is AS3, where wood chips are directly credited and where no energy production is considered.

**Figure 7** around here

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[1] Amount of NMVOC emissions that are not inventoried as individual substances based on total NMVOC emissions of 26% of carbon content and based on a C content of petrol of 0.857 kg C/kg and excluding PAH, which are inventoried separately.

### 3.6 Terrestrial acidification (TA)

LS1 has the lowest environmental impact, while LS3 shows the worst performance; among the varying logging systems, the main differences are due to processing (higher in LS2) and to extraction (higher in LS3). Felling is responsible for < 10% of total impact in all of the logging systems while bunching ranges from 11% to 32%, extraction from 11% to 68% (higher value in LS3), processing from 2% to 7% and chipping from 6% to 17%. When wood chips are used to produce energy, the combustion emissions are the main hotspot. More in details:

- In AS1, TE production from wood chips represents from 59% (in LS3) to 63% (in LS1) of total impact mainly due to emissions in air of nitrogen oxides and ammonia;
- In AS2, the impact for electricity production represents from 38% (in LS3) to 41% (in LS1) of total impact due to emissions in the air, in particular, of nitrogen oxides and sulphur dioxide.

Among different scenarios, only AS1 involves environmental benefits (from -0.017 to -0.016 molc H+ eq/m$^3$) thanks to avoided thermal energy production from natural gas. In AS2, credits for electricity production are almost equal to total impact and, consequently, the result is slightly above zero. AS3 shows the worst performances because the credit for wood chips production represents only 16% of total impact.

**Figure 8** around here

### 3.7 Terrestrial eutrophication (TE)

For all logging systems and AS, the TE's environmental impact is > 0 (**Figure 9**). There are small differences among logging systems; LS1 has the lower impact, followed by LS2 (+2-5%) and LS3 (+5-11%) mainly due to the lower consumption of petrol and lubricants. As for other impact categories, felling is responsible for a small share of environmental impact (<7%) while the most impacting logging operations are bunching (in LS1 and LS2) and extraction (in LS3).

The results among the different scenarios vary widely. AS3 shows the lowest impact followed by AS2 (+77-93%) and AS1 (+235-283%). The combustion emissions from small-scale boiler in AS1 and medium-size plant for electricity production (AS2) deeply affect the environmental performance. Credits for TE and EE production - arising from the avoided production of heat (from natural gas in a domestic boiler) and electricity (from Italian electric sources mix) - are lower than the impact generated by the use of wood chips for energy purposes. From an environmental point of view, the valorisation of wood chips does not involve any benefit but a worsening of the environmental performances.

**Figure 9** around here

## 3.8 Freshwater (FE) and marine (ME) eutrophication

**Figure 10** and **11** reports the results for FE and ME. For both impact categories, LS1 is the best followed by LS3 (+12-18% for FE and +6-11% for ME) and LS2 (+11-17% for FE and +3-7% for ME).

As for TE, FE and ME, the impact of thermal energy production from wood chips is considerably higher than the credit granted for the substitution of heat production from natural gas; consequently, AS1 results in the worst scenario. AS2 shows the best results because the credits related to electricity production (-2.83 g P/ $m^3$ for FE and g P/$m^3$ for ME) completely offset the environmental burdens due to logging operations and wood chips- electricity conversion .

**Figure 10-11** around here

## 3.9 Freshwater ecotoxicity (FEx)

LS1 shows the lowest impact followed by LS2 and LS3. In LS2, bunching is the main aspects responsible for the impact while, in LS3, it is extraction (**Figure 12**). Among scenarios - thanks to credits for electricity production - AS2 shows the best results, followed by AS3, while, AS1 is the worst due to emissions related to biomass combustion. As for TE, FE and ME, the heat production in a small-scale domestic boiler increases the environmental impact when also considering the substitution of thermal energy production from natural gas.

**Figure 12** around here

### 3.10 Mineral, fossil and renewable resource depletion (MFRD)

MFRD always shows a score > 0. The lowest impact is achieved with the LS1 and with heat production (LS1 and AS1), while the highest is in LS2 and AS2 (**Figure 13**).

This impact category strongly depends on the amount of machines virtually consumed and, consequently, on their mass, lifespan and annual working time. Bunching (in LS1 and LS2) and extraction (in all of the logging systems and in LS3 in particular) are, by far, the two logging operations with the highest impact on MFRD, while felling, processing and chipping play a minor roles. Wood chips transport cannot be neglected above all for AS2, where the transport distances are longer.

**Figure 13** around here

## 4. DISCUSSION

### 4.1 Comparison among the harvesting systems

The study' outcomes highlight how, among different logging systems, the environmental results are not univocal and how the best logging system depends on the considered impact category.

**Table 6** reports the comparison among different LS taking into account only logging operations and, in particular, felling, bunching, extraction and processing. LS3, which uses a cable yarder for extraction, shows the worst performance for 10 of the 12 evaluated impact categories;

for HT-noc and HT-c in particular the impact is considerably higher with respect to the other logging systems. LS1 and LS2 show the best performance for 6 impact categories.

With regards to the results for different logging systems, it should be considered that, in respect to previously conducted studies (Deconchat, 2001; Gondard et al., 2003; Spinelli et al., 2010) focused on physical impacts on wounding and soil (disturbance and compaction), this LCA study focuses on inputs and outputs related to the evaluated logging systems. It should be considered that cable yarder is recognised as an extraction method able to reduce the negative effects of wounding and soil disturbance and compaction. However, these potential benefits were not taken into account during this evaluation because they can be appreciated only with long-term studies.

A limited number of LCA studies was carried out in the same geographical areas (Mediterranean forestry). The comparison among achieved results is made difficult due to different assumptions and dissimilar system boundaries. Furthermore, not always the same environmental impacts are evaluated. Lanschi et al. (2016) for logging operations carried out in Toscana with a harvesting system similar to LS1 (but considering also the transport of the wood) found a CC of 12.64 and 16.72 kg CO2eq/t for flat/low steep' terrain and steep/very steep terrain, respectively.

## 4.2 Comparison among the alternative scenarios

Regarding different scenarios on the valorisation of wood chips produced from residual biomass, the achieved results clearly highlighted that, although the production of energy from renewable sources allows avoiding the production of the same energy from fossil fuels, the environmental benefits cannot be taken for granted. In particular, for impact categories such as HT-noc, HT-c, PM, POF, TE, FE, ME and FEx, the production of heat from wood chips combustion in a small-scale domestic boiler worsens the environmental results because the related impact is higher with respect to the avoided process (heat production from natural gas).

**Table 6** – around here

### 4.3 Environmental hotspots for logging operations

For each logging operation, the environmental load is due to consumption of fuel (petrol, diesel), lubricants (vegetable oil for chainsaws and fossil lubricating oil for tractors, skidders and cable yarders), machines (chainsaws, tractors, skidders and cable yarders) and other equipment (e.g., cable for forestry operations). It is also due to the emissions into the environment. Among different logging operations and the different impact categories, the role of these items shows a huge variation:

- Fuel consumption[2] is, for all logging operations: (i) the main responsible for OD (with a share of environmental load ranging from 92% to 95%) and (ii) an important contributor of PM, TA, HT-c and FE (about 28-32% for bunching and extraction where diesel is consumed and about 20-45% in felling and processing where petrol is used), for POF (20%) and CC (10-17%) while for other impact categories its role is negligible (<5%);
- Lubricant consumption[3] plays a relevant role for felling and processing (e.g., from 33% to 52% for CC, HT-noc, PM, TA and TE and >80% for FE, ME, FEx and MFRD mainly due to palm tree oil production) when vegetable oil is consumed while is negligible (<1% in all of the evaluated impact categories) in bunching and extraction where fossil lubricant is consumed in the diesel engines;
- amount of machinery virtually consumed cannot be neglected, it is the main responsible of: (i) MFRD (for bunching, 95% and 90% in LS1 and LS2, respectively and, for extraction, 96%, 91% and 90% in LS1, LS2 and LS3, respectively); (ii) HT-c (for bunching, 78% in LS2 and, for extraction, in 60%, 47% and 68% in LS1, LS2 and LS3, respectively); (iii) FE (for bunching, 80% in LS2 and, for extraction, in 67%, 78% and 50% in LS1, LS2 and LS3, respectively) and (iv) FEx (for bunching, 92% in LS2 and, for

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[2] The impact for fuel consumption arises from the environmental load related to diesel and petrol production

[3] As for the fuels, also for lubricants the environmental impact is related to their production

extraction, in 37%, 92% and 81% in LS1, LS2 and LS3, respectively). For MFRD, this impact depends on mine operations, while for HT-c, FE and FEx, it is related to the disposal of waste arising from mine operations. For felling and processing, logging operations carried out by workers equipped with chainsaw, the consumption of chainsaw is responsible for a small impact (<1%) on all the of evaluated impact categories except for HT-c and FE (2-3%)

- Use of cables during bunching in LS1 and LS2 and during extraction in all of the logging systems involves its substitution after every 2 years with an environmental impact negligible for all of the impact categories except for HT-c (mainly due to ferrochromium and unalloyed steel production) and FE (mainly due to mining activities). In particular, for HT-c in LS3, the impact for the production of cable used during logging operations represents about 45% of the environmental load.
- Emissions related to fuel combustion in the chainsaw, tractor, skidder and cable yarder engines play a different role between the operations where petrol and vegetable oil are used (felling and processing) and the operations in which diesel and fossil lubricant (bunching and extraction) are consumed. For felling and processing, the emissions related to fuel combustion are the main hotspots for POF (>95%), these play a relevant role also for FE and CC (about 40%). Regarding the logging operations carried out using machines equipped with a diesel engine, the combustion emissions are the main hotspots for HT-noc (98%), CC (85%), TE (84%), ME (77%) and POF (73%).

## 5. CONCLUSIONS

Using the LCA approach, this study evaluated the environmental impact of three different wood harvesting technologies in Southern Italy (Calabria Region) and considered different alternative scenarios for the valorisation of wood chips produced as by-product. Among different logging systems, the environmental results are not univocal. The identification of the best system depends on the considered impact category. Though cable yarder is recognised as the extraction method best able to reduce physical impacts on residual stand (wounding) and soil (disturbance and compaction) and though their use is typically carried out on steep slopes and other rough terrain, cable yarder shows the highest environmental impact on all impact categories (except for POF). However, tractor and skidder use achieves better environmental performances. Extraction is the logging operation responsible for the main share of the environmental impact, while felling and processing carried out with chainsaw involve a lower environmental impact. The use of skidder, though characterised by higher hourly diesel consumption, shows a lower environmental impact with respect to the use of cable crane, thanks to the skidder's higher productivity. Considering that the three logging systems can operate in areas characterised by different slopes and road networks, the productivity increase is the best solution to achieve impact reductions for all of the evaluated logging systems.

In regards to what concerns the energetic valorisation of wood chips produced by branches and tree tops, the production of thermal energy and electricity involves environmental benefits for impact categories, such as climate change, terrestrial acidification and mineral and fossil resource depletion. On the other hand, wood chips utilisation for energy production worsens the results for the impact categories affected by combustion emissions (e.g., particulate matter formation, ozone depletion, terrestrial and freshwater eutrophication, freshwater ecotoxicity). This worsening is usually higher for heat production, which takes place in domestic small size boiler not equipped with specific devices for exhaust gas treatment and cleaning. In this regard, future research should consider the possibility of using the energy produced by the wood chips to substitute heat and electricity from other fossil fuel sources (e.g., carbon, LPG and diesel).

## ACKNOWLEDGEMENTS

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## REFERENCES

Bacenetti J., Bergante S., Facciotto G., Fiala M. (2016). Woody biofuel production from short rotation coppice in Italy: Environmental-impact assessment of different species and crop Management, Biomass & Bioenergy, 94, 209-219.

Bacenetti, J., Sala, C., Fusi, A., Fiala, M., 2016. Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more environmentally sustainable. Applied Energy; 179, 669-686.

Bjorheden, R., Apel, K., Shiba, M., Thompson, M.A., 1995. IUFRO forest work study nomenclature. Garpenberg: Department of Operational Efficiency, Swedish University of Agricultural Science. 16 pp.

Brunori, A., Sdringola, P., Dini, F., Ilarioni, L., Nasini, L., Regni, L., Proietti, P., Proietti, S., Vitone, A., Pelleri, F., 2016. Carbon balance and Life Cycle Assessment in an oak plantation for mined area reclamation. Journal of Cleaner Production; 144, 69-78.

Caserini, S., Livio, S., Giugliano, M., Grosso, M., Rigamonti, L., 2010. LCA of domestic and centralized biomass combustion: The case of Lombardy (Italy). Biomass and Bioenergy; 34: 474–82.

Colantoni, A., Evic, N., Retschitzegger, S., Proto, A.R., Gallucci, F., Monarca, D., 2016. Characterization of biochars produced from pyrolysis of pelletized agricultural residues. Renewable & Sustainable Energy Reviews; 64: 187-194.

de la Fuente, T., Athanassiadis, D., González-García, S., Nordfjell, T., 2017. Cradle-to-gate life cycle assessment of forest supply chains: Comparison of Canadian and Swedish case studies. Journal of Cleaner Production; 143, 866-881.

Deconchat, M., 2001. Effets des techniques d'exploitation forestiêre sur l'état de surface du sol. Annals of Forest Science 58: 653-661.

Fantozzi, F., Buratti, C., 2010. Life cycle assessment of biomass chains: Wood pellet from short rotation coppice using data measured on a real plant. Biomass and Bioenergy, 34(12), 1796-1804.

Gondard, H., Romane, F., Aronson, J., Shater, Z., 2003 Impact of soil surface disturbances on functional group diversity after clear-cutting in Aleppo pine (*Pinus halepensis*) forests in southern France. Forest Ecology and Management 180: 165-174.

González-García, S., Bacenetti, J., Murphy, R., Fiala, M., 2012. Present and future environmental impact of poplar cultivation in Po valley (Italy) under different crop management systems. Journal of Cleaner Production; 26: 56-66.

Harstela, P., 1993: Works studies in forestry. Silva Carelica n°25 - Joensuu University Library, Finland, p. 135.

ISO, 2006a, ISO 14040. Environmental management - Life cycle assessment - Principles and framework. International Organization for Standardization, Geneva.

ISO, 2006b, ISO 14044. Environmental management - Life cycle assessment - Requirements and guidelines. International Organization for Standardization, Geneva.

Karjalainen, T., Zimmer, B., Berg, S., Welling, J., Schwaiger, H., Finér, L., Cortijo, P., 2001. Energy, carbon and other material flows in the Life Cycle Assessment of forestry and forest products. Achievements of the working group 1 of the COST action E9. European Forest Institute, Torikatu, Finland.

Klein, D., Wolf, C., Schulz, C., Weber-Blaschke, G. 2016. Environmental impacts of various biomass supply chains for the provision of raw wood in Bavaria, Germany, with focus on climate change. Science of the Total Environment, 539, 45-60.

Laschi, A., Marchi, E., González-García, S., 2016. Forest operations in coppice: Environmental assessment of two different logging methods. Science of the Total Environment, 562, 493-503.

Lijó, L., González-García, S., Bacenetti, J., Fiala, M., Feijoo, G., Lema, J.M., Moreira, M.T., 2014. Life Cycle Assessment of electricity production in Italy form anaerobic co-digestion of pig slurry and energy crops. Renewable Energy; 68: 625-35.

Lijó, L., González-García, S., Bacenetti, J., Fiala, M., Feijoo, G., Moreira, M.T., 2014. Assuring the sustainable production of biogas from anaerobic mono-digestion. Journal of Cleaner Production; 72: 23-34.

Lijó, L., Lorenzo-Toja, Y., González-García, S., Bacenetti, J., Negri, M., Moreira, M. T. 2017. Eco-efficiency assessment of farm-scaled biogas plants. Bioresource Technology.

Lovarelli, D., Bacenetti, J. (2017). Seedbed preparation for arable crops: environmental impact of alternative mechanical solutions. Soil Tillage Research (in press, accepted manuscript).

Lovarelli, D., Bacenetti, J., 2017. Bridging the gap between reliable data collection and the environmental impact for mechanised field operations. Biosystems Engineering, 160, 109-123.

Magelli, F., Boucher, K., Bi, H. T., Melin, S., Bonoli, A., 2009. An environmental impact assessment of exported wood pellets from Canada to Europe. Biomass and Bioenergy, 33(3), 434-441.

Marchi, E., Picchio, R., Spinelli, R., Verani, S., Venanzi, R., Certini, G., 2014. Environmental impact assessment of different logging methods in pine forests thinning. Ecological Engineering, 70, 429–436.

Monarca, D., Cecchini, M., Colantoni, A., 2011. Plant for the production of chips and pellet: technical and economic aspects of a case study in the central Italy. In: (a cura di): © Springer-Verlag Berlin Heidelberg 2011, In: Computational Science and Its Applications. Santander (Spain), June 20-23, 2011. doi: 10.1700/978-3-642-21898-9.

Morrison, B., Golden, J.S., 2017. Life cycle assessment of co-firing coal and wood pellets in the Southeastern United States. Journal of Cleaner Production, 150, 188-196.

Huyler, N. K., LeDoux, C.B., 1997. Cycle-Time Equation for the Koller K300 Cable Yarder Operating on Steep Slopes in the Northeast. Forest Service Northeastern Forest Experiment Station Research Paper NE-70

Nikooy, M., Esmailnezhad, A., Naghdi, R., 2013: Productivity and cost analysis of skidding with Timberjack 450C in forest plantations in Shafaroud watershed, Iran. Journal of Forest Science, 59, p. 261–266.

Noya, I., González-García, S., Bacenetti, J., Arroja, L., Moreira M.T., 2015. Comparative life cycle assessment of three representative feed cereals production in the Po Valley (Italy). J Clean Prod. 99, 250-265

Pierobon, F., Zanetti, M., Grigolato, S., Sgarbossa, A., Anfodillo, T., Cavalli, R., 2015. Life cycle environmental impact of firewood production – A case study in Italy. Applied Energy, 150: 185–95.

Proto, A.R., Zimbalatti, G., 2016. Firewood cable extraction in the southern Mediterranean area of Italy. Forest Science and Technology, Vol. 12(1), 16-23.

Proto, A.R., Skoupy, A., Macrì, G., Zimbalatti, G., 2016. Time consumption and productivity of a medium size mobile tower yarder in downhill and uphill configurations: a case study in Czech Republic. Journal of Agricultural Engineering Vol XLVII:551, 217-221.

Proto, A.R., Macrì, G., Bernardini, V., Russo, D., Zimbalatti, G., 2017. Acoustic evaluation of wood quality with a non-destructive method in standing trees: a first survey in Italy. iForest, 10: 700-706

Putz, F.E., Redford, K.H., Robinson, J.G., Fimbel, R., Blate, G.M., 2000. Biodiversity conservation in the context of tropical forest management. World Bank Environment Department paper No. 75, Washington, DC. 80pp.

Rafael, S., Tarelho, L., Monteiro, A., Sá, E., Miranda, A. I., Borrego, C., Lopes, M., 2015. Impact of forest biomass residues to the energy supply chain on regional air quality. Science of the Total Environment, 505, 640-648.

Renzulli, P.A., Bacenetti, J., Benedetto, G., Fusi, A., Ioppolo G., Niero, M., Proto, M., Salomone, R., Sica, D., Supino, S., 2015. Life cycle assessment in the cereal and derived products sector. In: Notarnicola, B., Salomone, R., Petti, L., Renzulli, P.A., Roma, R., Cerrutti, A.K. (Eds.), Life Cycle Assessment in the Agri-Food Sector. Case Studies, Methodological Issues and Best Practices. Springer; pp. 185–250.

Schmidt Rivera, X.C., Bacenetti, J., Fusi, A., Niero, M., 2017. The influence of fertiliser and pesticide emissions model on life cycle assessment of agricultural products: The case of Danish and Italian barley. Sci Total Environ. 592, 745-757.

Siebert, A., Bezama, A., O'Keeffe, S., Thrän, D., 2017. Social life cycle assessment indices and indicators to monitor the social implications of wood-based products. Journal of Cleaner Production (doi.org/10.1016/j.jclepro.2017.02.146).

Spinelli, R., Hartsough, B., 2001: A chipping survey in Italy. CNR-IRL Contributi Scientifici – Pratici XLI, Firenze, p.112.

Spinelli, R., Magagnotti, N., Nati, C. 2010 Benchmarking the impact of traditional small-scale logging systems used in Mediterranean forestry. Forest Ecology and Management, 260 (11): 1997-2001.

Spinelli, R., Magagnotti. N., 2012: Wood Extraction with Farm Tractor and Sulky: Estimating Productivity, Cost and Energy Consumption. Small-scale Forestry - Springer, 11, p. 73-85.

Tam, V. W., Senaratne, S., Le, K. N., Shen, L. Y., Perica, J., Illankoon, I. C. S., 2017. Life-cycle cost analysis of green-building implementation using timber applications. Journal of Cleaner Production, 147, 458-469.

UK Forestry Commission (1995) Terrain classification. Technical Note 16/95, p. 5

Valente, C., Spinelli, R., Hillring, B. G., 2011. LCA of environmental and socio-economic impacts related to wood energy production in alpine conditions: Valle di Fiemme (Italy). Journal of Cleaner Production, 19(17), 1931-1938.

Wang, J., Long, C., McNeel, J., Baumgras, J., 2004: Productivity and cost of manual felling and cable skidding in central Appalachian hardwood forests. Forest Product Journal, 54, p. 45–51.

Weidema, B.P., Bauer. C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C.O., Wernet, G., 2013. Overview and methodology. Data quality guideline for the ecoinvent database version 3. Ecoinvent Report 1(v3). St. Gallen: The Ecoinvent Centre.

White, M. K., Gower, S. T., Ahl, D. E., 2005. Life cycle inventories of roundwood production in northern Wisconsin: Inputs into an industrial forest carbon budget. Forest Ecology and Management, 219(1), 13-28.

Winter, S., Brambach, F., 2011. Determination of a common forest life cycle assessment method for biodiversity evaluation. Forest Ecology and Management, 262(12), 2120-2132.

Wolf, M.A., Pant, R., Chomkhamsri, K., Sala S., Pennington, D., 2012. ILCD Handbook- Towards more sustainable production and consumption for a resource efficient Europe. JRC Reference Report.

Wolf, C., Klein, D., Richter, K., Weber-Blaschke, G., 2016. Mitigating environmental impacts through the energetic use of wood: Regional displacement factors generated by means of substituting non-wood heating systems. Science of the Total Environment, 569, 395-403.

Zambon, I., Colosimo, F., Monarca, D., Cecchini, M., Gallucci, F., Proto A.R, Lord R., Colantoni, A., 2016. An Innovative Agro-Forestry Supply Chain for Residual Biomass: Physicochemical Characterisation of Biochar from Olive and Hazelnut Pellets. Energies; 9: 1-11.

Zimbalatti, G., Proto, A.R., 2009. Cable logging opportunities for firewood in Calabrian forests. Biosystems Engineering 102, 63–68.

## FIGURE

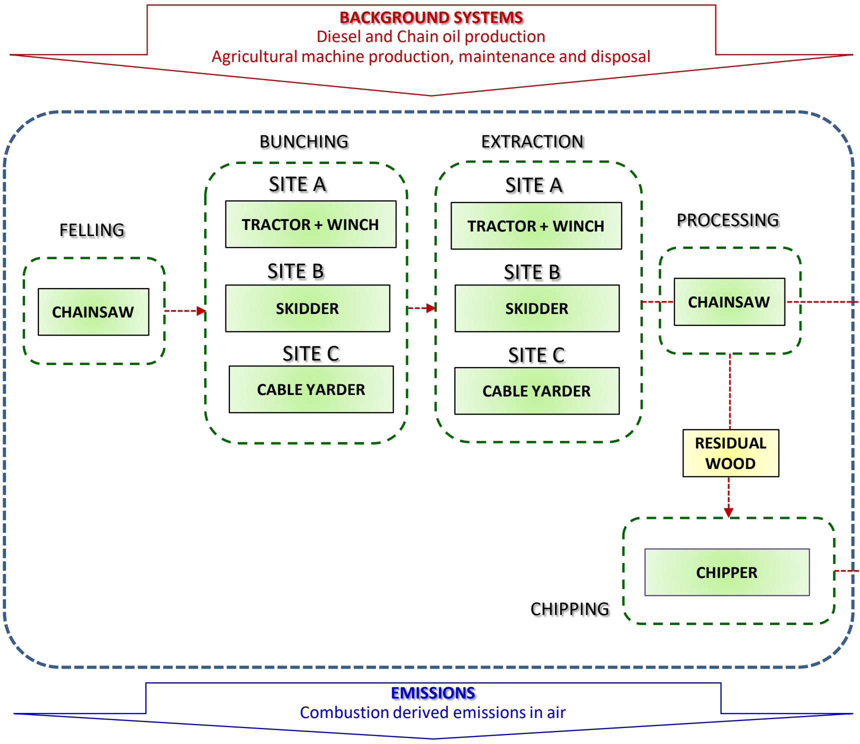


**Figure 1** – System boundary of the different logging systems (LS)

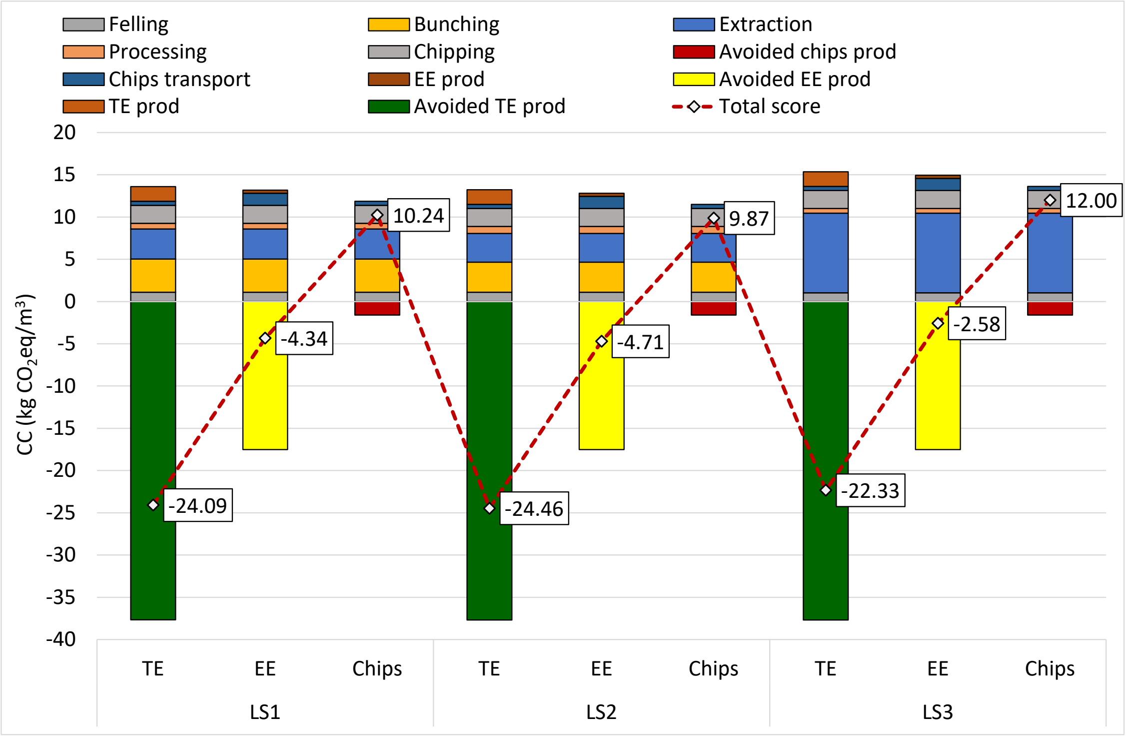


**Figure 2** – Environmental impact and hotspot identification for CC

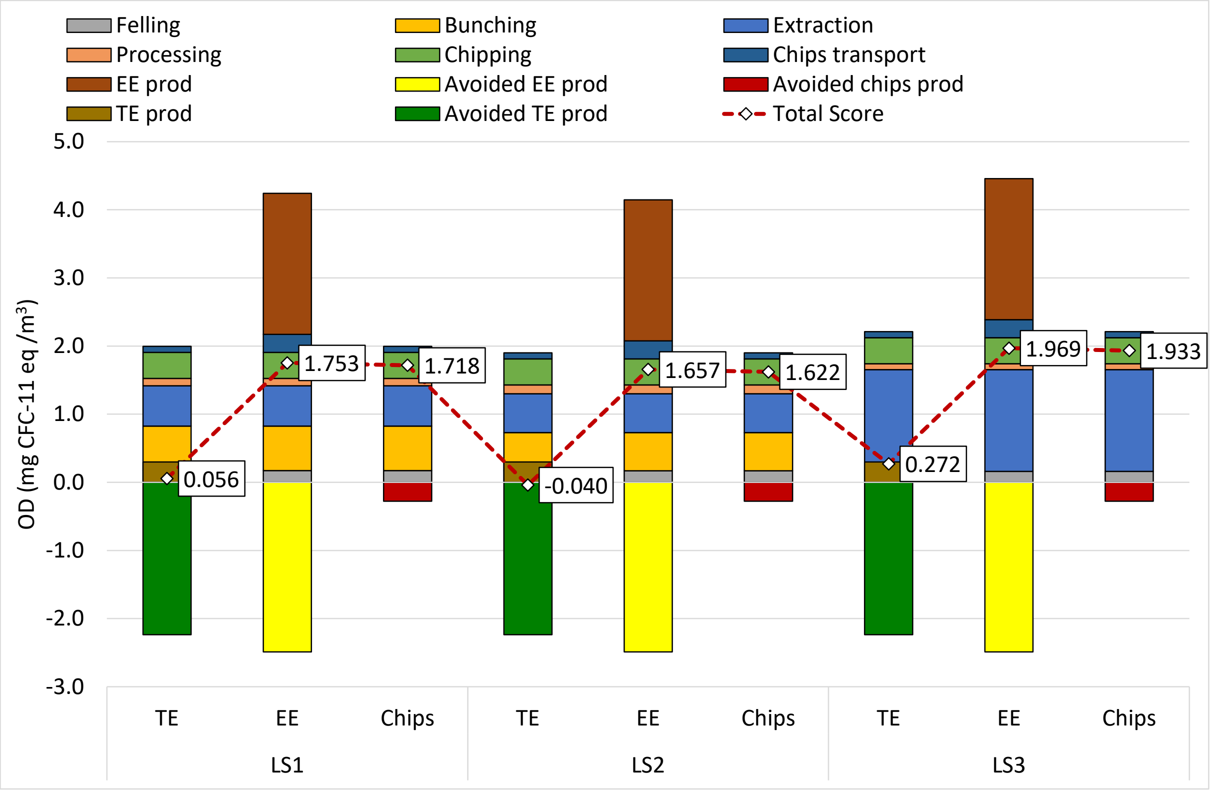


**Figure 3** – Environmental impact and hotspot identification for OD

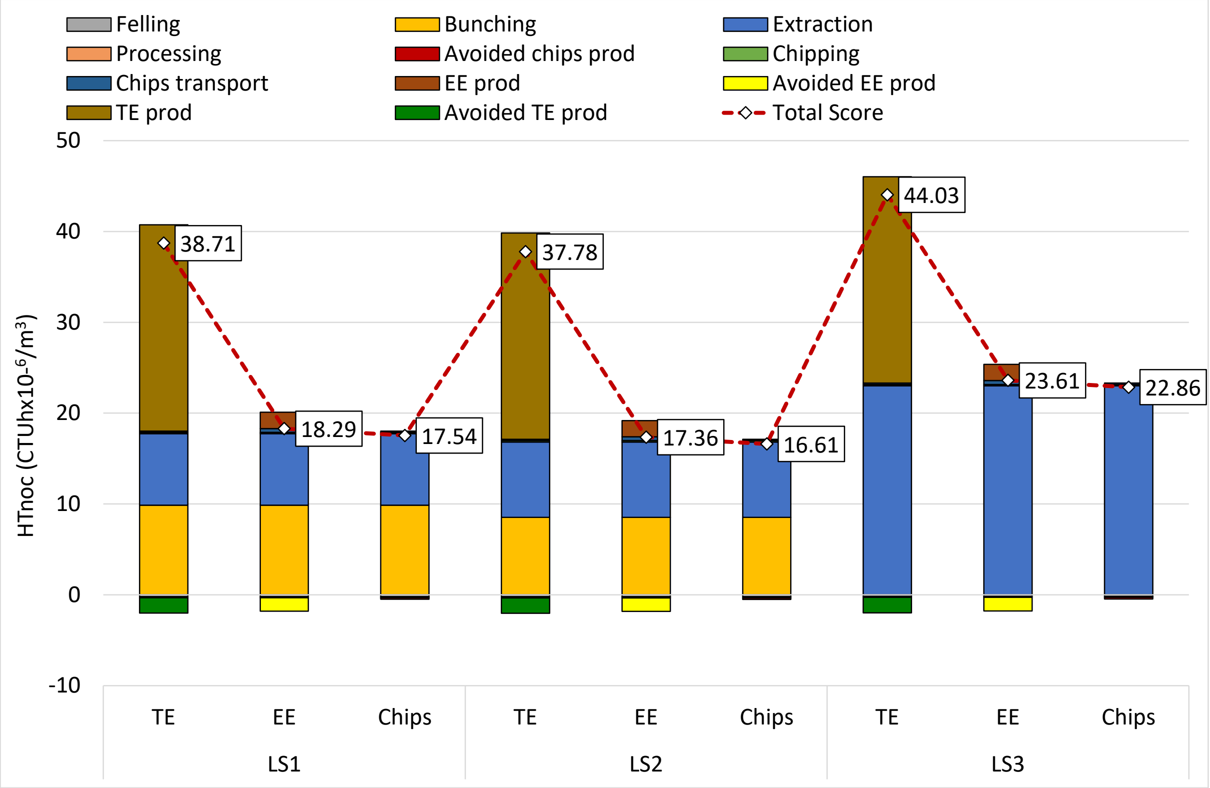


**Figure 4 -** Environmental impact and hotspot identification for HTnoc

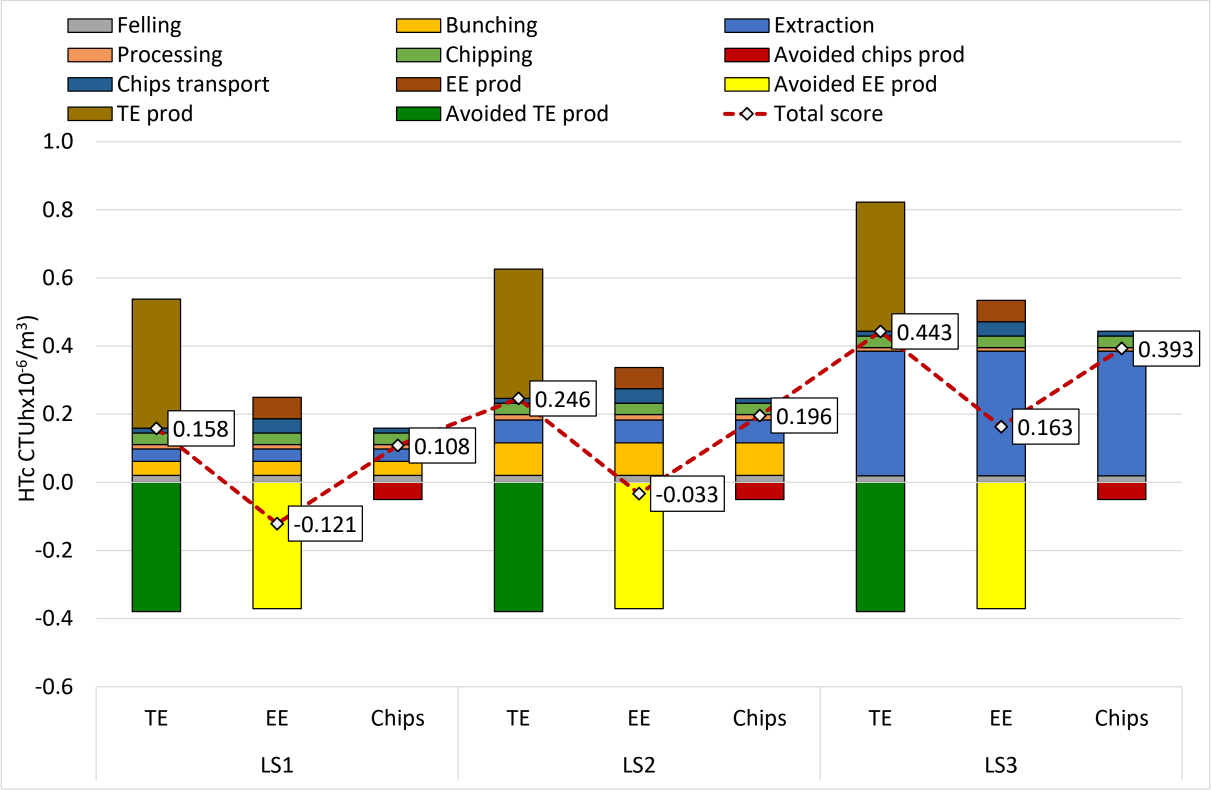


**Figure 5 -** Environmental impact and hotspot identification for HT-c

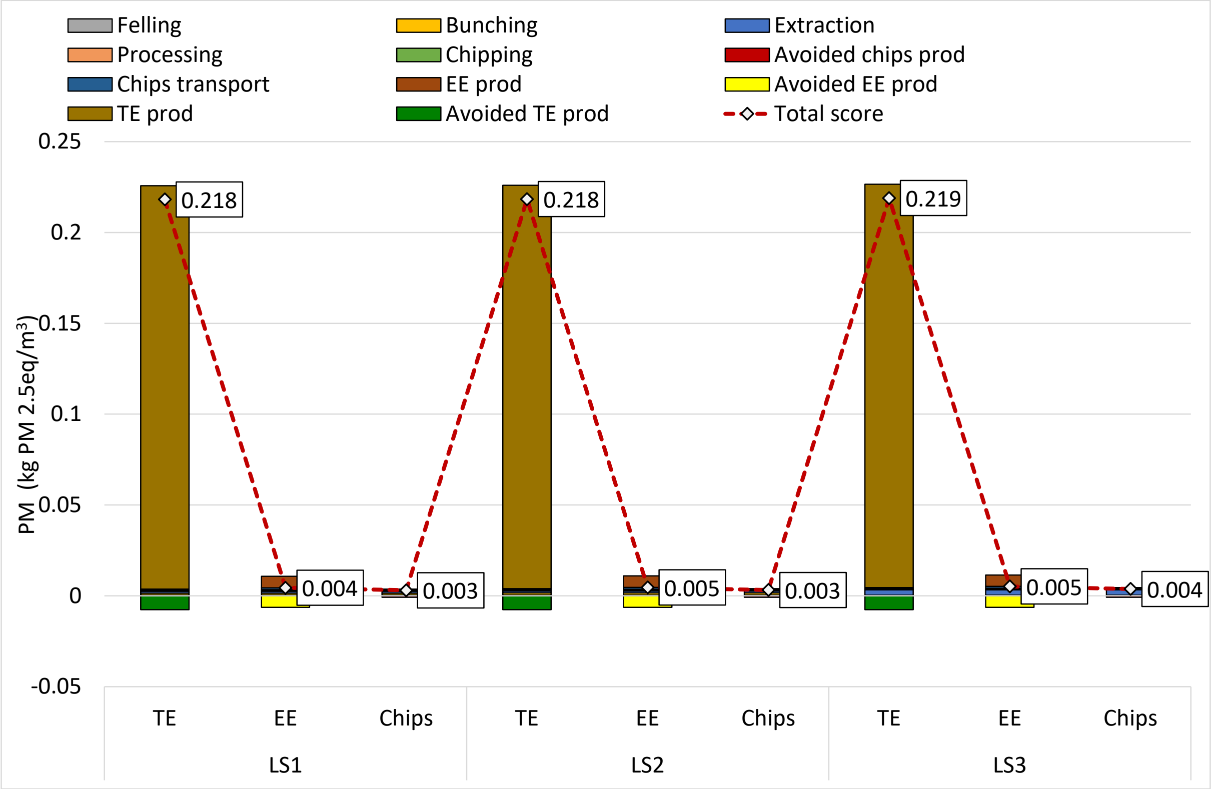


**Figure 6 -** Environmental impact and hotspot identification for PM

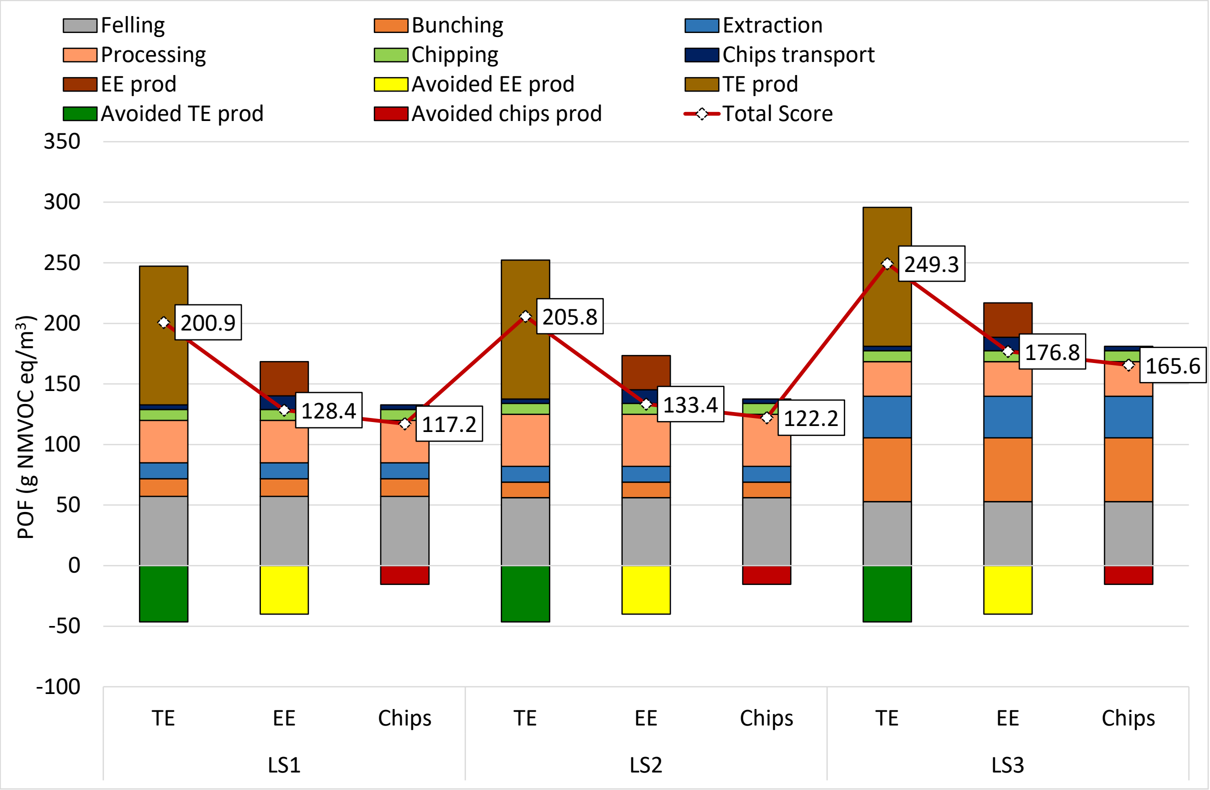


**Figure 7 -** Environmental impact and hotspot identification for POF

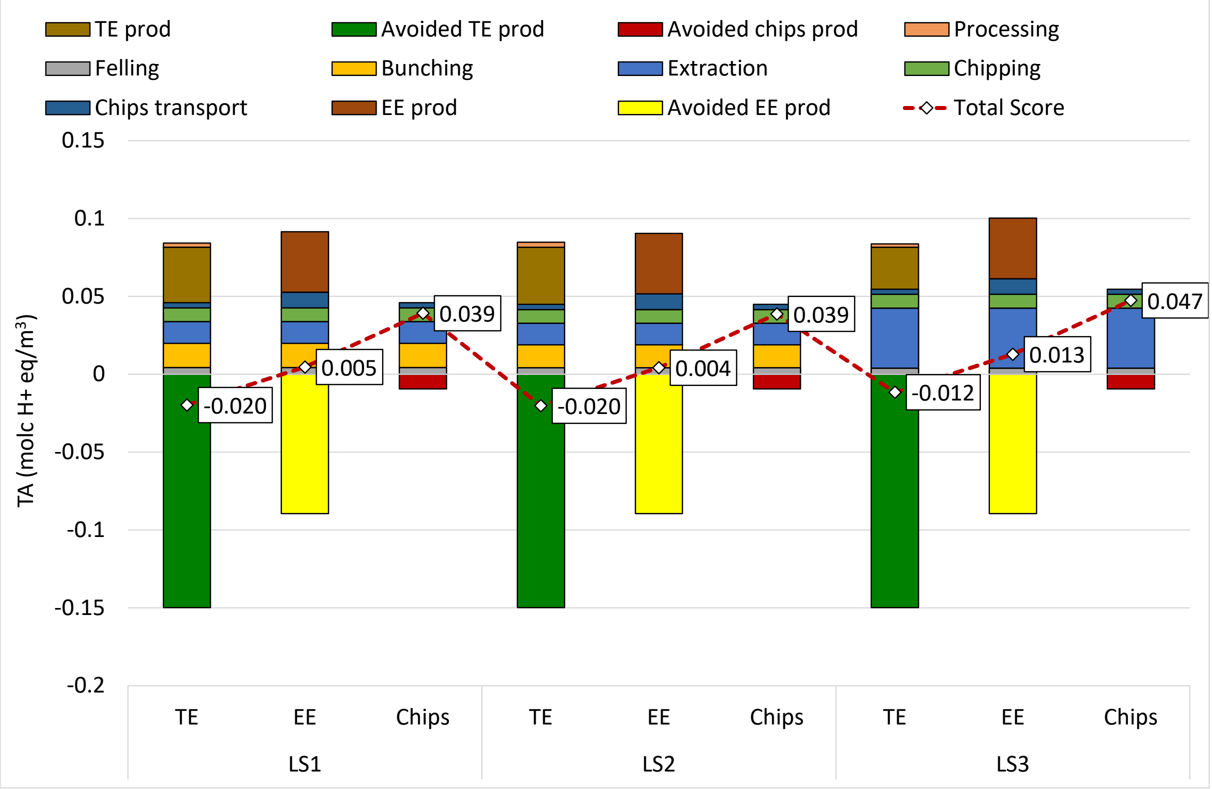


**Figure 8 -** Environmental impact and hotspot identification for TA

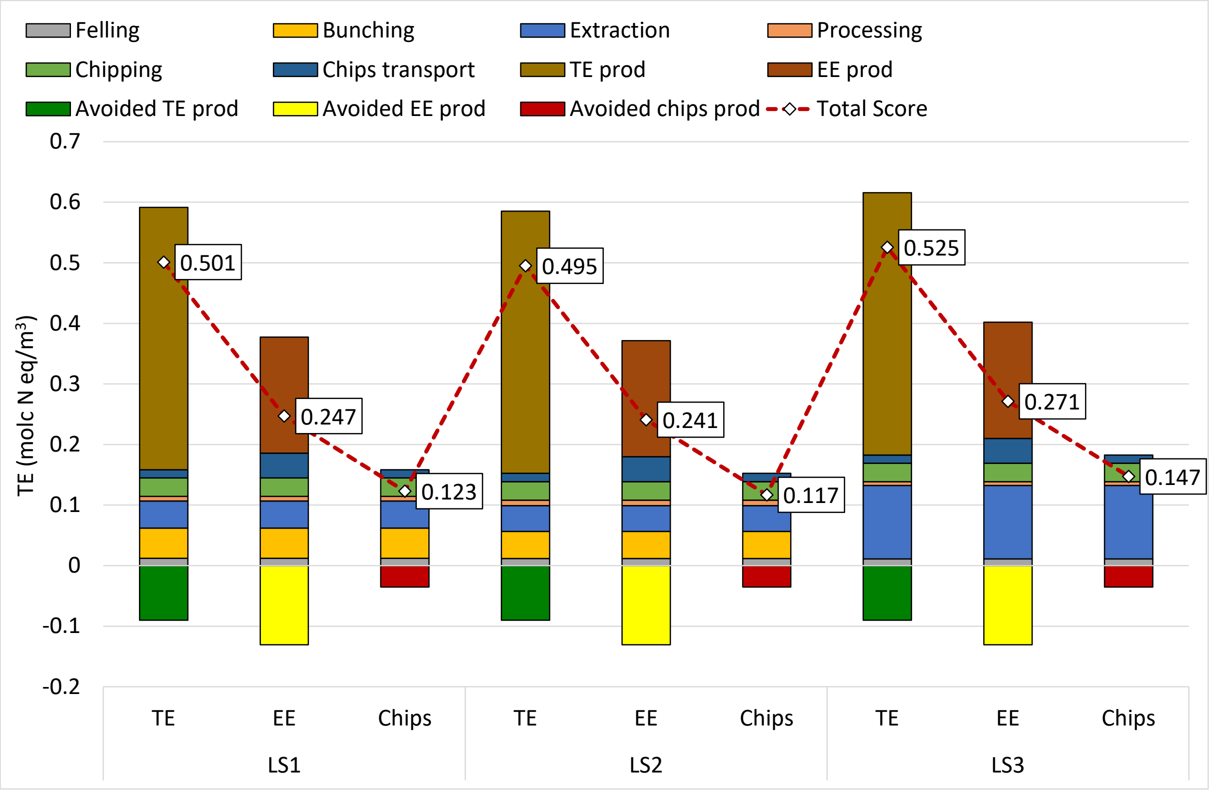


**Figure 9 -** Environmental impact and hotspot identification for TE

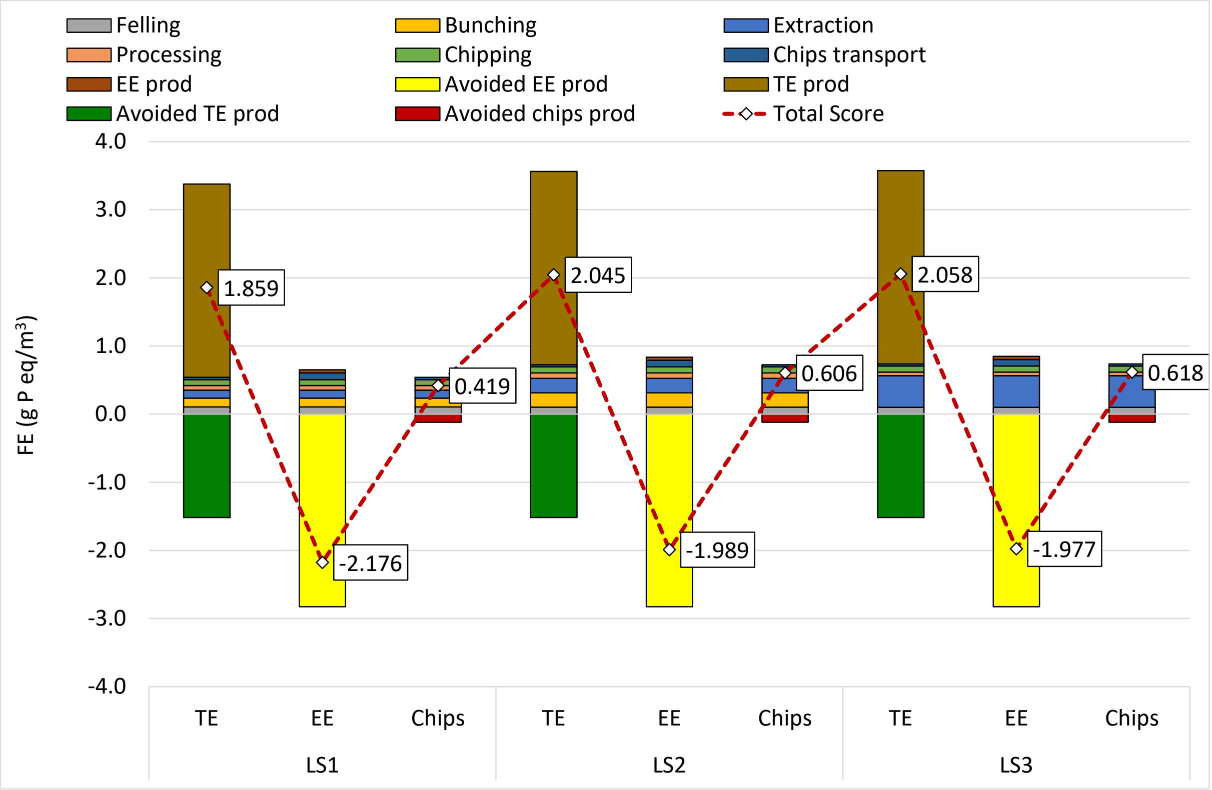
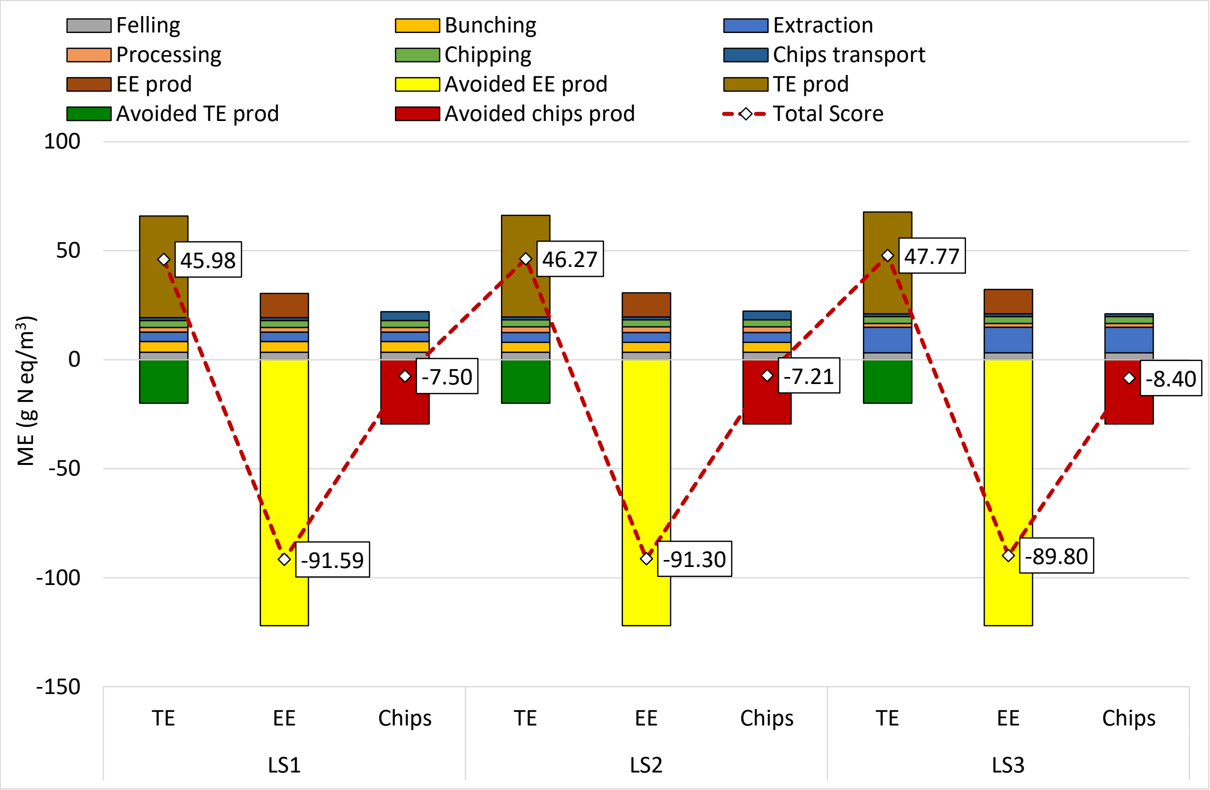
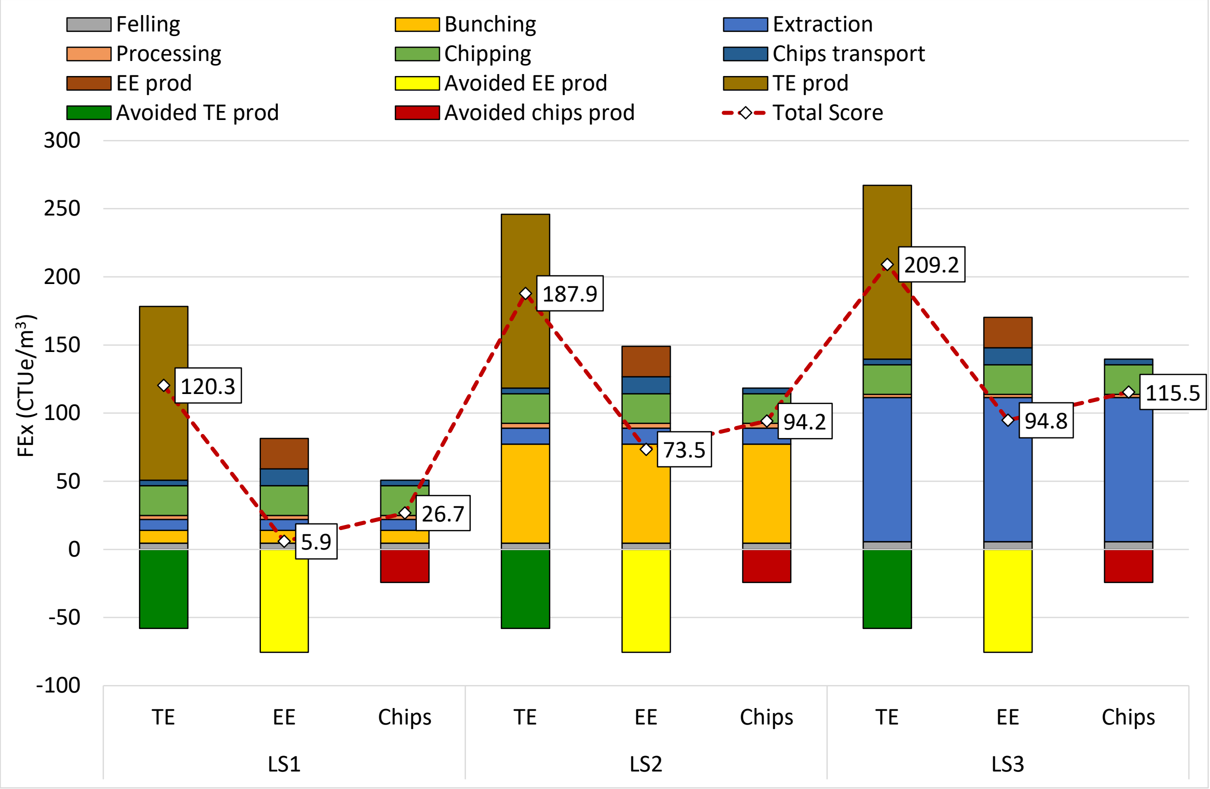


**Figure 10 -** Environmental impact and hotspot identification for FE

22 

23 **Figure 11 -** Environmental impact and hotspot identification for ME

24 

25 **Figure 12 -** Environmental impact and hotspot identification for FEx

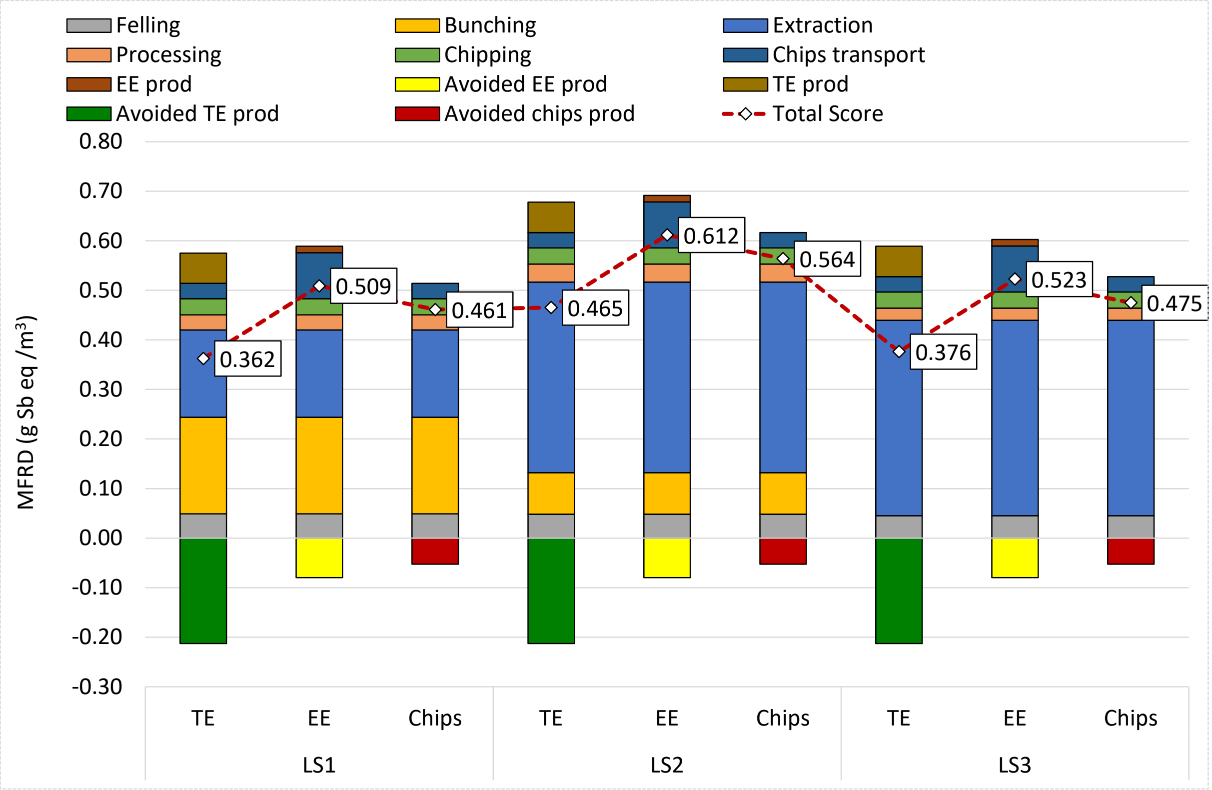


**Figure 13 -** Environmental impact and hotspot identification for MFRD

# TABLE

**Table 1 –** Main characteristics of the three experimental sites

| Characteristics | Unit | Site A | Site B | Site C |
|---|---|---|---|---|
| Harvesting system | - | Tractor + Winch | Skidder + Winch | Cable Crane |
| Location | - | Brognaturo | Fabrizia | Cardinale |
| Prevalent Specie | - | Chestnut | Chestnut | Chestnut |
| Government | - | High forest | High forest | High forest |
| Altitude | m a.m.s.l. | 1050 | 980 | 750 |
| Stand Density | plants/ha | 870 | 900 | 1200 |
| Total Volume | m³/ha | 670 | 720 | 700 |
| Number of tree | tree/ha | 261 | 270 | 360 |
| Three average diameter | cm | 35/36 | 38/40 | 30 |
| Three average volume | m³ | 0.65 | 0.75 | 0.4 |
| Slope Min | % | 15 | 20 | 40 |
| Slope Max | % | 45 | 65 | 80 |
| Slope medium | % | 30 | 43 | 60 |
| Roughness | - | Medium | Medium | Medium |
| Height tree | m | 24 | 22 | 21 |
| Total area | ha | 8 | 14 | 11 |
| Total Tree | plants | 2088 | 3780 | 3960 |
| Total volume extracted | m³ | 1392 | 2520 | 2640 |
| Volume per ha | m³/ha | 174 | 180 | 240 |

**Table 2 –** Main inventory data for felling operation

| Parameter | Unit | Harvesting system | | |
|---|---|---|---|---|
| | | **1** | **2** | **3** |
| Workers | N | 2 | 2 | 2 |
| Productivity | $m^3$/h | 8 | 9.4 | 6.4 |
| Machine | - | Chainsaw | | |
| Two-stroke blend hourly cons. | kg/h | 1.0 | 1.2 | 0.8 |
| Vegetable oil hourly cons. | kg/h | 0.5 | 0.6 | 0.4 |
| Two-stroke blend consumption | kg/$m^3$ | 0.222 | 0.218 | 0.205 |
| Vegetable oil consumption | kg/$m^3$ | 0.111 | 0.109 | 0.103 |
| Mass chainsaw | kg | 5 | 5 | 5 |
| Life span | year | 3 | 3 | 3 |
| Economic duration | h | 3000 | 3000 | 3000 |
| Annual use[1] | day/year | 180 | 180 | 180 |
| | h/year | 1440 | 1440 | 1440 |
| Amount of machine consumed | g/$m^3$ | 0.1286 | 0.1052 | 0.1484 |

[1] Considering to 8 h/day

**Table 3 –** Main inventory data for bunching operation

| **Parameter** | **Unit** | Harvesting system | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Workers | N | 3 | 3 | n/a |
| Productivity | m$^3$/h | 14.1 | 21.6 | |
| Machine | - | Tractor | Skidder | |
| Power | kW | 74 | 110 | |
| Machine mass | Tons | 4.16 | 12.16 | |
| Life span machine | Years | 15 | 15 | |
| Economic duration | h | 12000 | 10000 | |
| Engine load | % | 80% | 60% | |
| Minimum specific fuel consumption | g/kWh | 240 | 240 | |
| Specific fuel consumption | g/kWh | 241.7 | 283.3 | |
| Hourly fuel consumption | kg/h | 14.306 | 18.699 | |
| Diesel fuel consumption | kg/m$^3$ | 1.015 | 0.866 | |
| Lubricant consumption | kg/m$^3$ | 0.004 | 0.003 | |
| Amount of machine consumed[2] | g/m$^3$ | 24.6 | 56.3 | |
| Cable mass | kg | 37 | 108 | |
| Life span cable | year | 2 | 2 | |
| Nominal Pulling Force of Winch | kN | 53 | 193 | |
| Pulling Cable | mm | 8 | 15.8 | |
| Drum capacity | m | 90 | 80 | |
| Amount of cable consumed | g/m$^3$ | 3.1 | 7.2 | |

[1] Considering to 8 h/day

[2] Considering 200 and 160 days/year (corresponding to 1600 and 1280 h/year) for the tractor (LS1) and the skidder (LS2), respectively.

**Table 4 –** Main inventory data for extraction operation

| Parameter | Unit | Harvesting system | | |
|---|---|---|---|---|
| | | **1** | **2** | **3** |
| Workers | N | 3 | 3 | 3 |
| Productivity | $m^3/h$ | 15.6 | 25.5 | 6.9 |
| Machine | - | Tractor | Skidder | Cable crane |
| Amount of machine consumed | $g/m^3$ | 22.22 | 47.69 | 86.96 |
| Engine load | % | 80% | 80% | 80% |
| Specific diesel fuel consumption | g/kWh | 241.664 | 241.664 | 241.664 |
| Hourly diesel fuel consumption | kg/h | 14.306 | 21.266 | 16.240 |
| Diesel fuel consumption | $kg/m^3$ | 0.917 | 0.834 | 2.354 |
| Lubricant consumption | $kg/m^3$ | 0.004 | 0.003 | 0.009 |
| Cable mass | kg/100m | 41 | 135 | 135 |
| | Kg | 37 | 108 | 1890 |
| Life span cable | year | 2 | 2 | 2 |
| Amount of cable consumed[2] | $g/m^3$ | 2.8 | 6.1 | 12.7 |

[1] Considering to 8 h/day

[2] Considering 200, 160 and 135 days/year corresponding to 1600, 1280 and 1080 h/year for the tractor (LS1), the skidder (LS2) and the cable crane (LS3), respectively.

**Table 5** – Processes retrieved from the database

| INPUT or OUTPUT | ECOINVENT PROCESS |
|---|---|
| Fuel for chainsaw | Petrol, two-stroke blend {GLO}\| market for \| Alloc Def, U |
| Lubricant for chainsaw | Vegetable oil, refined {GLO}\| market for \| Alloc Def, U |
| Fuel for tractor, skidder and cable yarder | Diesel {CH}\| market for \| Alloc Rec, U |
| Lubricant for tractor, skidder and cable yarder | Lubricating oil {RER}\| production \| Alloc Def, U |
| Chainsaw for felling, bunching and processing | Power saw, without catalytic converter {RER}\| production \| Alloc Def, U |
| Tractor for bunching and extraction in LS1 | Tractor, 4-wheel, agricultural {CH}\| production \| Alloc Def, U |
| Skidder for bunching and extraction in LS2 | Skidder {GLO}\| production 12 ton, 130 kW \| Alloc Def, U |
| Cable yarder for bunching and extraction in LS3 | Mobile cable yarder, trailer-mounted \|13.5 tom - 175 kW \| {GLO}\| Alloc Def, U |
| Cable for bunching (LS1 and LS2) and extraction in (LS1, LS2 and LS3) | Cable for forestry operation {GLO} |
| Impact of chips wood utilisation in small-scale domestic boiler[1] | Heat production, central or small-scale {RER}\| hardwood chips from forest, at furnace 50kW \| |
| Credit for heat production from wood chips | Heat, central or small-scale, natural gas {Europe without Switzerland}\| market for heat, central or small-scale, natural gas \| Alloc Def, U |
| Impact of chips wood utilisation in medium-size power generation plant[1] | Electricity, high voltage {CH}\| heat and power co-generation, wood chips |
| Credit for electricity production from wood chips | Electricity, medium voltage {IT}\| market for \| Alloc Def, U |
| Credit for wood chips production | Wood chipping, chipper, mobile, diesel, at forest road {RER}\| wood chipping, mobile chipper, at forest road |

[1] The plants (small-scale boiler for heat and medium-size power generation plant for electricity) consume the wood chips produced in the different LS, the Ecoinvent process has been modified for what concerns the consumed biomass.

The acronyms GLO (global), CH (Switzerland), IT (Italy) and RER (Europe) indicate the geographic area to which the process is referred

**Table 6** – Impact and relative comparison of the different logging systems (chipping, chip-wood transport and biomass valorisation are excluded)

| Impact Category | Absolute value | | | | Relative comparison | | |
|---|---|---|---|---|---|---|---|
| | **Unit** | **LS1** | **LS2** | **LS3** | **LS1** | **LS2** | **LS3** |
| CC | kg $CO_2$ eq | 9.26 | 8.88 | 11.02 | 84% | 81% | 100% |
| OD | g CFC-11 eq | 1.526 | 1.396 | 1.741 | 88% | 80% | 100% |
| HT-noc | CTUhx$10^6$ | 17.42 | 16.40 | 22.73 | 77% | 72% | 100% |
| HT-c | CTUhx$10^6$ | 0.111 | 0.217 | 0.396 | 28% | 55% | 100% |
| PM | kg PM2.5 eq | 0.003 | 0.003 | 0.004 | 79% | 85% | 100% |
| POF | g NMVOC eq | 119.9 | 124.2 | 115.6 | 97% | 100% | 93% |
| TA | molc H+ eq | 0.036 | 0.036 | 0.045 | 82% | 81% | 100% |
| TE | molc N eq | 0.114 | 0.108 | 0.139 | 82% | 78% | 100% |
| FE | g P eq | 0.420 | 0.578 | 0.618 | 68% | 93% | 100% |
| ME | g N eq | 14.82 | 14.93 | 16.60 | 89% | 90% | 100% |
| FEx | CTUe | 24.93 | 145.28 | 112.31 | 17% | 100% | 77% |
| MFRD | g Sb eq | 0.450 | 0.243 | 0.464 | 97% | 52% | 100% |

For the relative comparison, "Conditional formatting" was applied: the red represents the higher impacts while more the cell gets greener more the impact is lower