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1 **Roundwood and bioenergy production from forestry: environmental impact**  
2 **assessment considering different logging systems**

3

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11

12 **ABSTRACT**

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

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

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

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

38

39 **KEYWORDS**

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

41

## 42 1. INTRODUCTION

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

69 medium diameter using farm tractors equipped with forestry winches (Marchi et al., 2014), cable  
70 crane (Zimbalatti and Proto, 2009; Proto and Zimbalatti, 2016), skidder and forwarder (Macri et al.,  
71 2016).

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

79 During last decades, to evaluate the environmental impact of agricultural systems, the Life  
80 Cycle Assessment (LCA) approach has been more and more widely employed. This method aims  
81 to analyse products, processes or services from an environmental perspective (ISO, 2006a, ISO,  
82 2006b). Over the years, LCA has been applied to evaluate different renewable energy sources  
83 such as firewood (White et al., 2005; Pierobon et al., 2015), wood chips from forestry (Dias, 2014;  
84 Rafael et al., 2016) and Short Rotation Coppice (González-García et al., 2012; Bacenetti et al.,  
85 2016a), pellet (Magelli et al., 2009; Fantozzi and Buratti, 2010) and biogas from agricultural biomass  
86 (Bacenetti et al., 2016b; Lijó et al., 2014a; Lijó et al., 2014b) and waste (Lijó et al., 2017).

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

90

91

## 92 **2. MATERIALS AND METHODS**

### 93 **2.1 Goal and scope definition**

94 The goal of this study is to assess the environmental impact of three logging system  
95 solutions, each of which is composed of different operations. The selected harvesting solutions

96 are typical for slopes and rough forestry and are called “full tree system – F.T.S.” because they  
97 foresee the extraction of whole tree after felling. The considered forests are chestnut (*Castanea*  
98 *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  
99 site C. The studies were conducted in selective felling sites, on an area of 8 ha with N-W  
100 exposition in site A, 14 ha with S-W exposition in site B and 11 ha with N-E exposition in site C,  
101 respectively. The forests in the three sites are classified as I class for roughness, while the slope  
102 is between II and III class (20/60%) in according to UK Forestry Commission (1995).

103 The research questions can be summarised as follows:

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

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

116

## 117 **2.2 Functional unit**

118 The functional unit (FU) provides the reference to which all other data in the  
119 environmental assessment are normalised. Several functional units (FUs) can be selected; the  
120 FU most used for the analysis of agricultural systems are: the mass of product, the area, the  
121 produced energy, the product’s energy content and the product’s volume (Renzulli et al.,  
122 2015). Mass-based FU is prevalent in LCA studies of agricultural systems (Noya et al., 2015;

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

126

## 127 2.3 Case study and system description

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

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

134

135 [Table 1 – around here](#)

136

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

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

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

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

154

## 155 **2.4 System boundary**

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

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

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

167 - Alternative Scenario 1 (AS1) in which the coproduct is transported 50 km to be used in a small-  
168 scale domestic boiler (< 50 kW) to produce thermal energy, which supplies energy  
169 requirements of single house. The produced heat is supposed to substitute thermal energy  
170 production from natural gas in domestic boilers;

171 - Alternative Scenario 2 (AS2) where wood chips is transported for 150 km to be used in a  
172 medium-size (15-20 MW) power generation plant to produce electricity. The produced electric  
173 energy substitutes an equal amount of electricity produced according to the Italian energy  
174 source mix;

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

180

181 **Figure 1** around here

182

## 183 **2.5 Life Cycle Inventory**

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

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

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

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

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

207 In the third site (Cable Crane), the cycle time was determined by using stopwatches for  
208 each individual cycle, where the productive time was separated from delay time, as well as by  
209 identifying the variables that were most likely to affect the time consumption (Balimunsi et al.,  
210 2012). Seven yarding elements were identified and timed to determine the total cycle time (Huyler  
211 and Ledoux, 1997; Proto et al., 2016):

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

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

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

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

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

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

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

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

230 All hours needed to harvest this area were monitored by two operators. One hundred  
231 cycles were monitored per site, covering 1-1.5 ha for both sites. The total measured volume  
232 was 185 m<sup>3</sup> in A, 210 in B and 220 in site C, respectively.

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

236 [Table 2 – 3 – 4](#) report the main technical and operational parameters measured during  
237 tests in the three sites for felling, bunching and extraction, respectively. Total volume extracted  
238 was 1392, 2520, and 2460 m<sup>3</sup>. in site A, B and C, respectively.

239

240 [Table 2- 3 - 4 around here](#)

241

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

- 245 - fuel (mixture and oil) consumption for processing is equal to 0.33 kg/m<sup>3</sup>, 0.70 kg/m<sup>3</sup>  
246 and 0.37 kg/m<sup>3</sup> in LS1, LS2 and LS3, respectively;
- 247 - lubricant (vegetable oil) consumption is 0.17 kg/m<sup>3</sup>, 0.35 kg/m<sup>3</sup> and 0.18 kg/m<sup>3</sup> in  
248 LS1, LS2 and LS3, respectively;
- 249 - amount of equipment(chainsaw) consumed is equal to 0.56 kg/m<sup>3</sup>, 0.97 kg/m<sup>3</sup> and  
250 0.76 g/m<sup>3</sup> in LS1, LS2 and LS3, respectively.

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

254 and 2.64 for site 1, 2 and 3, respectively while the chips production was equal to 34.8, 36.0 and  
255 38.1 m<sup>3</sup>/ha (loose chips) for LS1, LS2 and LS3, respectively.

256 Concerning the alternative scenarios (AS):

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

269

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

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

279

280 [Table 5 – Around here](#)

281

## 282 2.6 Life Cycle Impact Assessment (LCIA)

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

289

## 290 3. RESULTS

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

299

### 300 3.1 Climate Change (CC)

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

308 Differences among scenarios are greater than the ones among logging systems. LS1  
309 achieves the better performances but, LS2 (+1.32 kg CO<sub>2</sub>eq/m<sup>3</sup>) and LS3 (+2.06 kg CO<sub>2</sub>eq/m<sup>3</sup>)  
310 are comparable. These differences depend completely on differences in logging operations  
311 impacts. In LS1 and LS2, the logging operations with the highest environmental impact are  
312 bunching (28.9-33.1% of total impact in LS1 and 26.9-31.0% of total impact in LS2 of total impact)  
313 and extraction (26.1-29.9% of total impact in LS1 and 25.8- 29.7% of total impact in LS2), while in  
314 LS3, extraction is different (61.5-69.3% of total impact). In particular, in LS3, the extraction impact is  
315 higher than the sum of bunching and extraction in LS1 and LS2. In all the logging systems, felling is  
316 responsible for 6.7-9.3% of the impact, and processing is responsible for 3.6-7.2%.

317 In AS1, the heat generation in small-scale boiler is responsible for a non-negligible impact  
318 (1.73 kg CO<sub>2</sub>eq/m<sup>3</sup>, corresponding to 12.7% of impact), mainly due to the combustion emissions.  
319 In AS2, chips burning in the medium-size plant represents a little share of the impact (0.36 kg  
320 CO<sub>2</sub>eq/m<sup>3</sup>, corresponding to 2.7% of impact); in respect to the impact related to heat generation,  
321 this impact is lower because the plant is equipped with filter and devices for treatment of  
322 combustion gases.

323

324 **Figure 2** around here

325

### 326 **3.2 Ozone depletion (OD)**

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

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

334 Among the different scenarios, though credits for electricity production are higher than  
335 that for heat production, the best performances are achieved in AS1 and not in AS2 since heat  
336 generation has a lower impact than electricity production. AS1 shows better performances (0.056-  
337 0.272 mg CFC-11 eq /m<sup>3</sup>) than AS2 (1.753-1.969 mg CFC-11 eq /m<sup>3</sup>) and AS3 (1.622-1.933 mg CFC-  
338 11 eq /m<sup>3</sup>). Among different LS, LS3 shows the worst result.

339

340 **Figure 3** around here

341

### 342 **3.3 Human toxicity, non-cancer effects (HTnoc) and cancer effects (HTc)**

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

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

346 - LS1, followed by LS2 and LS3, for HTc.

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

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

353 - For HTnoc to ash production and to the emissions related to biomass combustion;

354 - For HTc, to the production of the domestic boiler and to combustion emissions.

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

359

360 **Figure 4 - 5** around here

361

### 362 3.4 Particulate matter (PM)

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

368

369 [Figure 6 around here](#)

370

### 371 3.5 Photochemical ozone formation (POF)

372 For this impact category, the environmental score is > 0 for all of the logging systems and  
373 all of the scenarios and ranges from 117.2 g non-methane volatile organic compounds (NMVOC)  
374 eq/m<sup>3</sup> in LS1 and AS1 to 249.3 g NMVOC eq/m<sup>3</sup> in LS3 and AS1 (Figure 7). In particular, among  
375 logging systems, LS1 achieves the lowest environmental impact followed by LS3 (+25-36%) and LS2  
376 (+36-51%). Among different logging operations, felling is the main responsible for POF (57, 56 and  
377 53 g NMVOC/m<sup>3</sup> in LS1, LS2 and LS3, respectively); this is due to the emissions in atmosphere related  
378 to the chainsaw fuels (petrol and vegetable oil) combustion in the chainsaw and, in particular, to  
379 the NMVOC<sup>1</sup> emissions.

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

384

385 [Figure 7 around here](#)

---

<sup>1</sup> 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.

386

### 387 3.6 Terrestrial acidification (TA)

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

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

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

404

405 **Figure 8** around here

406

### 407 3.7 Terrestrial eutrophication (TE)

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

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

421

422 **Figure 9** around here

423

### 424 **3.8 Freshwater (FE) and marine (ME) eutrophication**

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

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

433

434 **Figure 10-11** around here

435

### 436 **3.9 Freshwater ecotoxicity (FEx)**

437 LS1 shows the lowest impact followed by LS2 and LS3. In LS2, bunching is the main aspects  
438 responsible for the impact while, in LS3, it is extraction (**Figure 12**). Among scenarios - thanks to  
439 credits for electricity production - AS2 shows the best results, followed by AS3, while, AS1 is the worst

440 due to emissions related to biomass combustion. As for TE, FE and ME, the heat production in a  
441 small-scale domestic boiler increases the environmental impact when also considering the  
442 substitution of thermal energy production from natural gas.

443

444 **Figure 12** around here

445

### 446 **3.10 Mineral, fossil and renewable resource depletion (MFRD)**

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

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

455

456 **Figure 13** around here

457

## 458 **4. DISCUSSION**

459

### 460 **4.1 Comparison among the harvesting systems**

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

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

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

469 With regards to the results for different logging systems, it should be considered that, in  
470 respect to previously conducted studies (Deconchat, 2001; Gondard et al., 2003; Spinelli et al.,  
471 2010) focused on physical impacts on wounding and soil (disturbance and compaction), this LCA  
472 study focuses on inputs and outputs related to the evaluated logging systems. It should be  
473 considered that cable yarder is recognised as an extraction method able to reduce the negative  
474 effects of wounding and soil disturbance and compaction. However, these potential benefits  
475 were not taken into account during this evaluation because they can be appreciated only with  
476 long-term studies.

477 A limited number of LCA studies was carried out in the same geographical areas  
478 (Mediterranean forestry). The comparison among achieved results is made difficult due to  
479 different assumptions and dissimilar system boundaries. Furthermore, not always the same  
480 environmental impacts are evaluated. Lanschi et al. (2016) for logging operations carried out in  
481 Toscana with a harvesting system similar to LS1 (but considering also the transport of the wood)  
482 found a CC of 12.64 and 16.72 kg CO<sub>2</sub>eq/t for flat/low steep' terrain and steep/very steep terrain,  
483 respectively.

484

#### 485 **4.2 Comparison among the alternative scenarios**

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

493

494 [Table 6 – around here](#)

495

### 496 **4.3 Environmental hotspots for logging operations**

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

- 503 - Fuel consumption<sup>2</sup> is, for all logging operations: (i) the main responsible for OD (with a  
504 share of environmental load ranging from 92% to 95%) and (ii) an important contributor  
505 of PM, TA, HT-c and FE (about 28-32% for bunching and extraction where diesel is  
506 consumed and about 20-45% in felling and processing where petrol is used), for POF  
507 (20%) and CC (10-17%) while for other impact categories its role is negligible (<5%);
- 508 - Lubricant consumption<sup>3</sup> plays a relevant role for felling and processing (e.g., from 33%  
509 to 52% for CC, HT-noc, PM, TA and TE and >80% for FE, ME, FEx and MFRD mainly due  
510 to palm tree oil production) when vegetable oil is consumed while is negligible (<1% in  
511 all of the evaluated impact categories) in bunching and extraction where fossil  
512 lubricant is consumed in the diesel engines;
- 513 - amount of machinery virtually consumed cannot be neglected, it is the main  
514 responsible of: (i) MFRD (for bunching, 95% and 90% in LS1 and LS2, respectively and,  
515 for extraction, 96%, 91% and 90% in LS1, LS2 and LS3, respectively); (ii) HT-c (for  
516 bunching, 78% in LS2 and, for extraction, in 60%, 47% and 68% in LS1, LS2 and LS3,  
517 respectively); (iii) FE (for bunching, 80% in LS2 and, for extraction, in 67%, 78% and 50%  
518 in LS1, LS2 and LS3, respectively) and (iv) FEx (for bunching, 92% in LS2 and, for

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<sup>2</sup> The impact for fuel consumption arises from the environmental load related to diesel and petrol production

<sup>3</sup> As for the fuels, also for lubricants the environmental impact is related to their production

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

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

539

## 540 **5. CONCLUSIONS**

541 Using the LCA approach, this study evaluated the environmental impact of three different  
542 wood harvesting technologies in Southern Italy (Calabria Region) and considered different  
543 alternative scenarios for the valorisation of wood chips produced as by-product. Among different  
544 logging systems, the environmental results are not univocal. The identification of the best system  
545 depends on the considered impact category. Though cable yarder is recognised as the

546 extraction method best able to reduce physical impacts on residual stand (wounding) and soil  
547 (disturbance and compaction) and though their use is typically carried out on steep slopes and  
548 other rough terrain, cable yarder shows the highest environmental impact on all impact  
549 categories (except for POF). However, tractor and skidder use achieves better environmental  
550 performances. Extraction is the logging operation responsible for the main share of the  
551 environmental impact, while felling and processing carried out with chainsaw involve a lower  
552 environmental impact. The use of skidder, though characterised by higher hourly diesel  
553 consumption, shows a lower environmental impact with respect to the use of cable crane, thanks  
554 to the skidder's higher productivity. Considering that the three logging systems can operate in  
555 areas characterised by different slopes and road networks, the productivity increase is the best  
556 solution to achieve impact reductions for all of the evaluated logging systems.

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

567

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573

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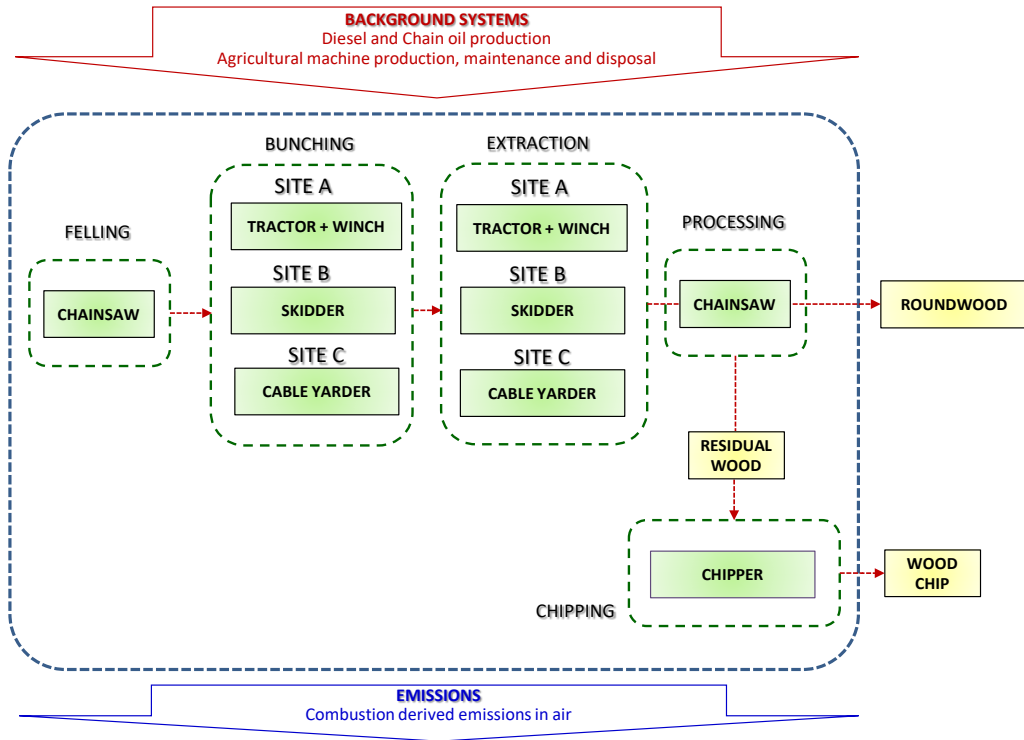
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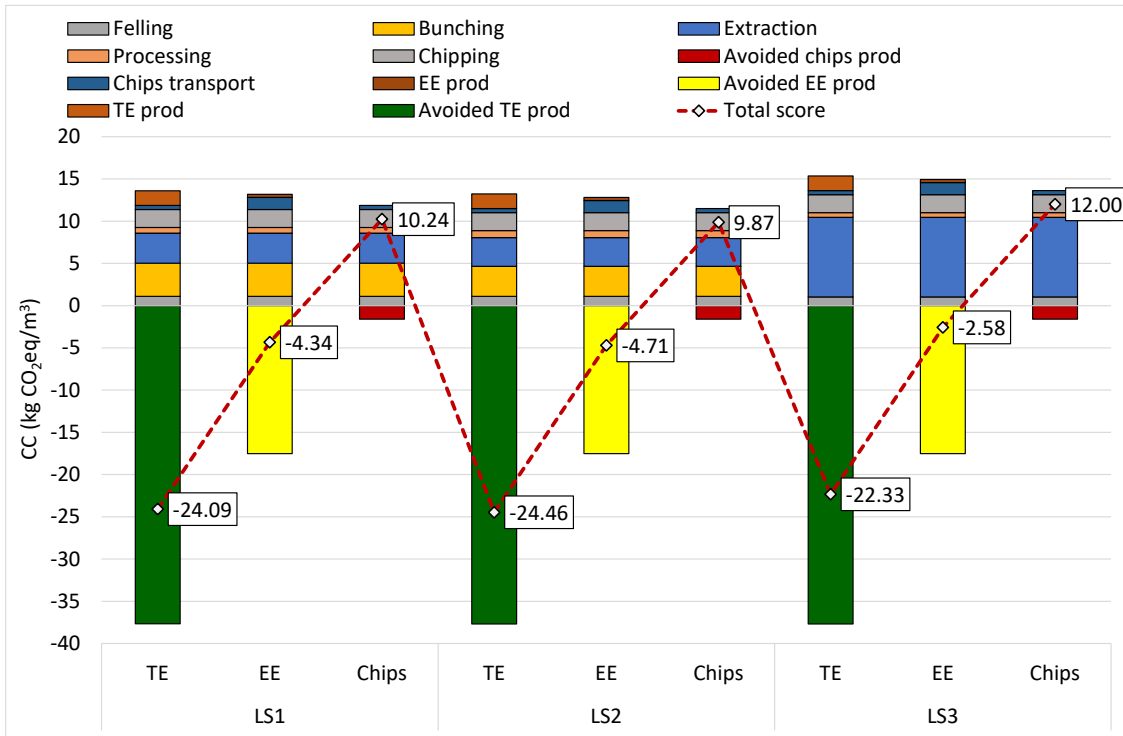
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**FIGURE**



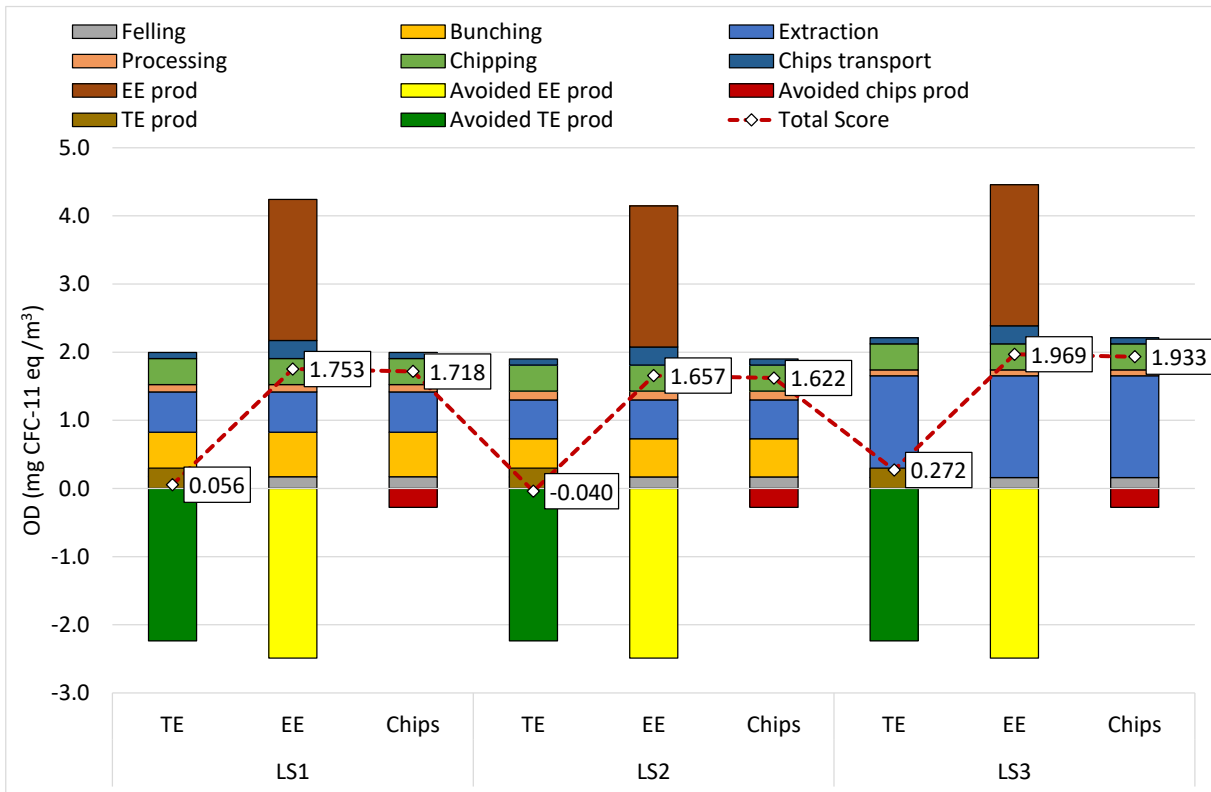
2

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



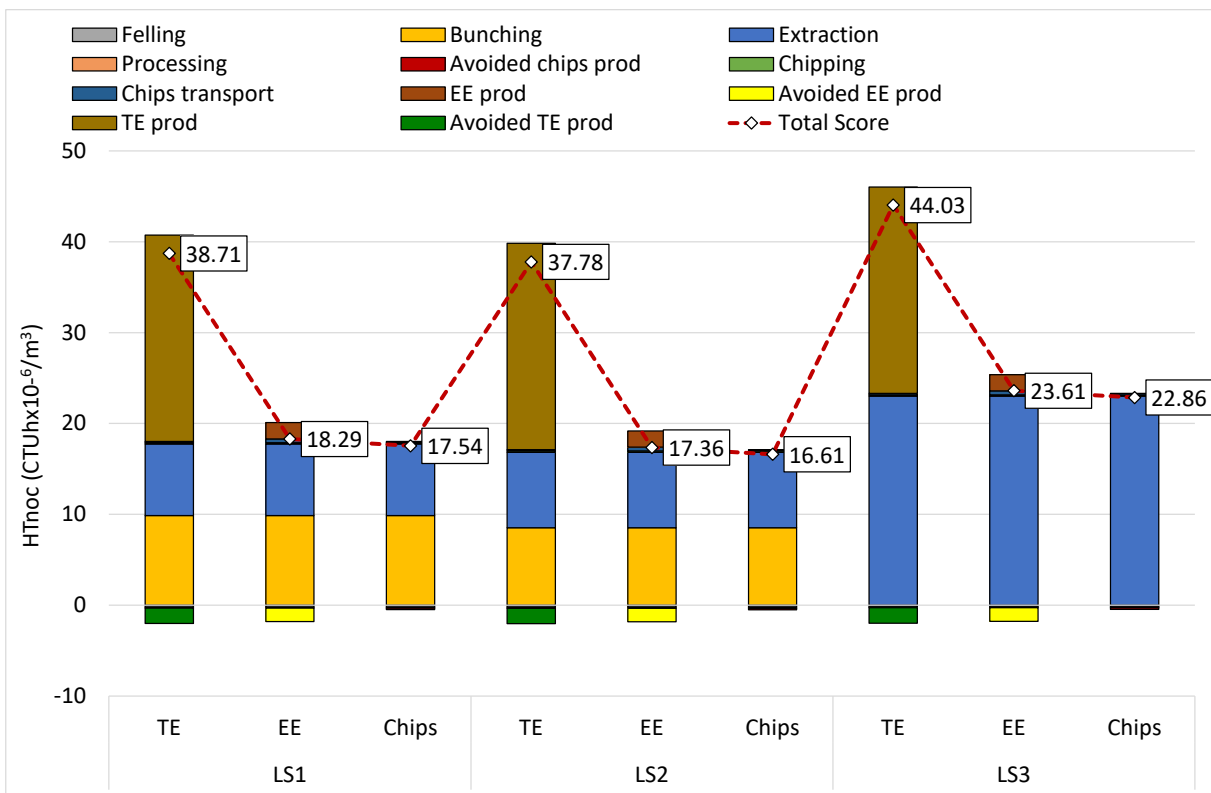
4

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



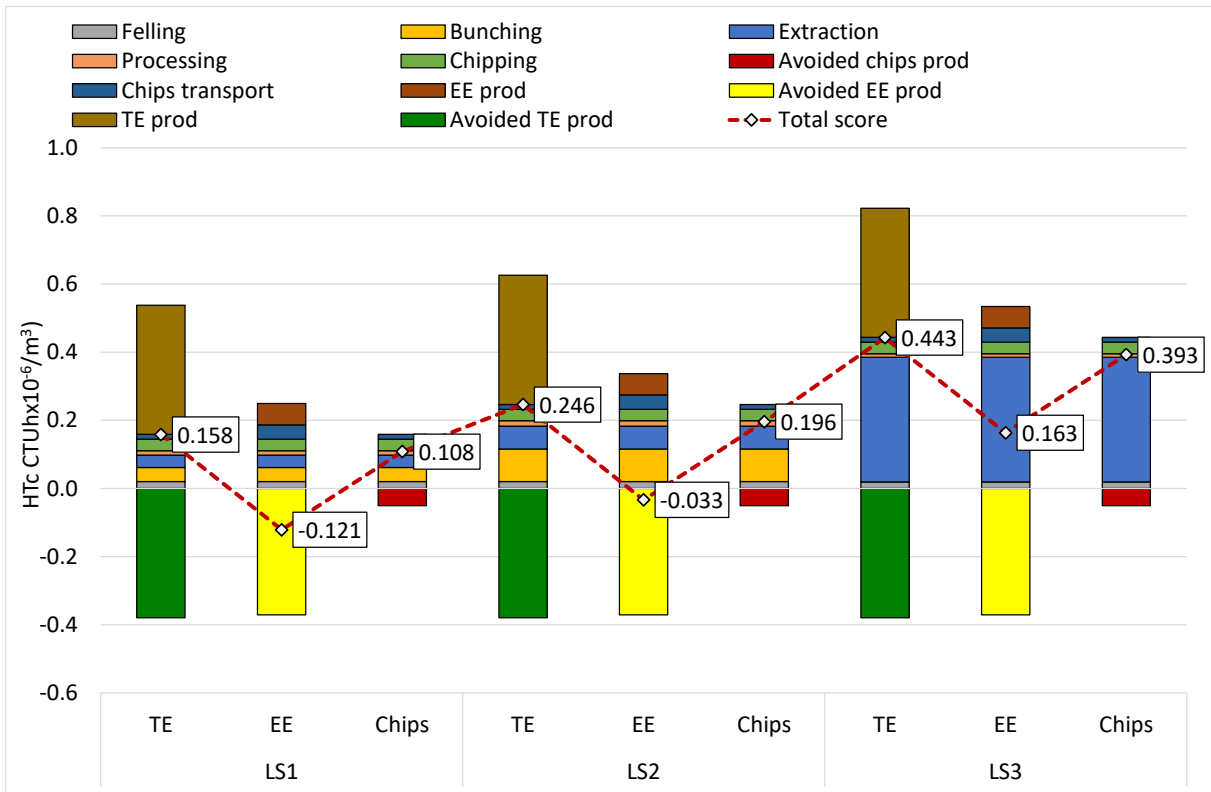
6

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



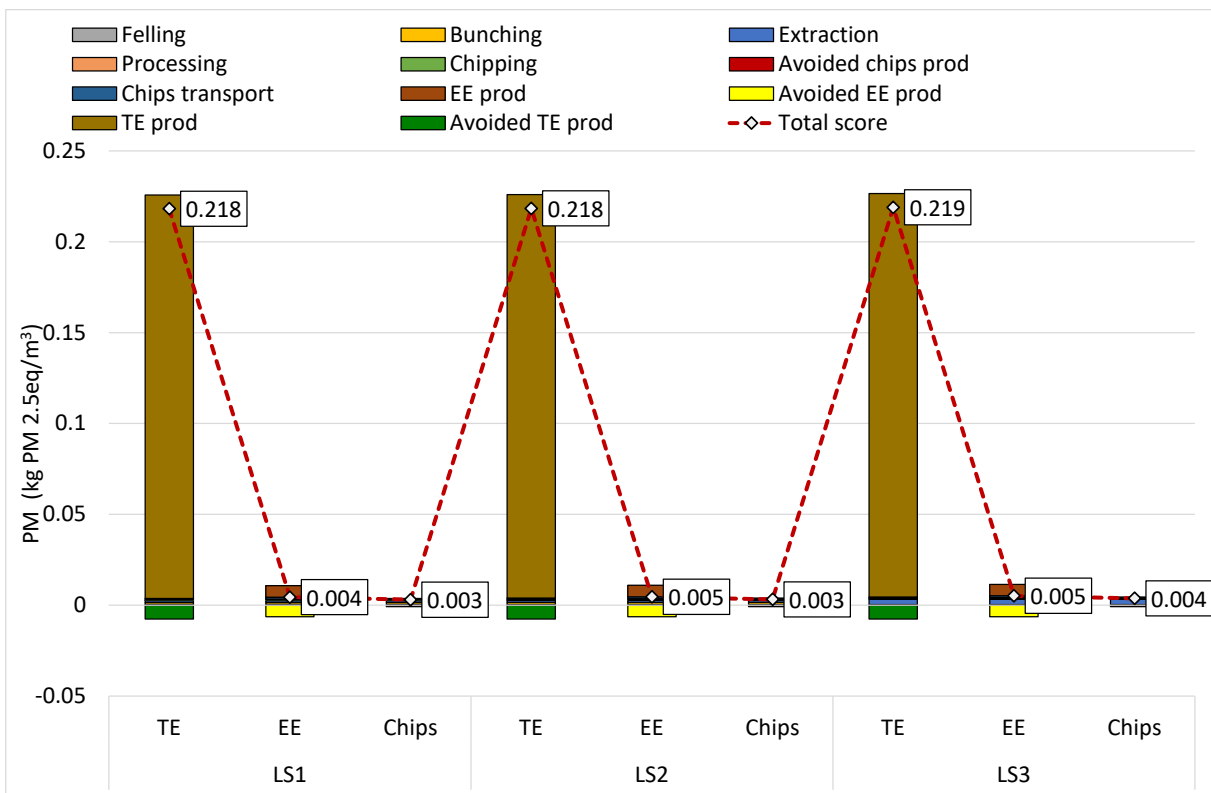
8

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



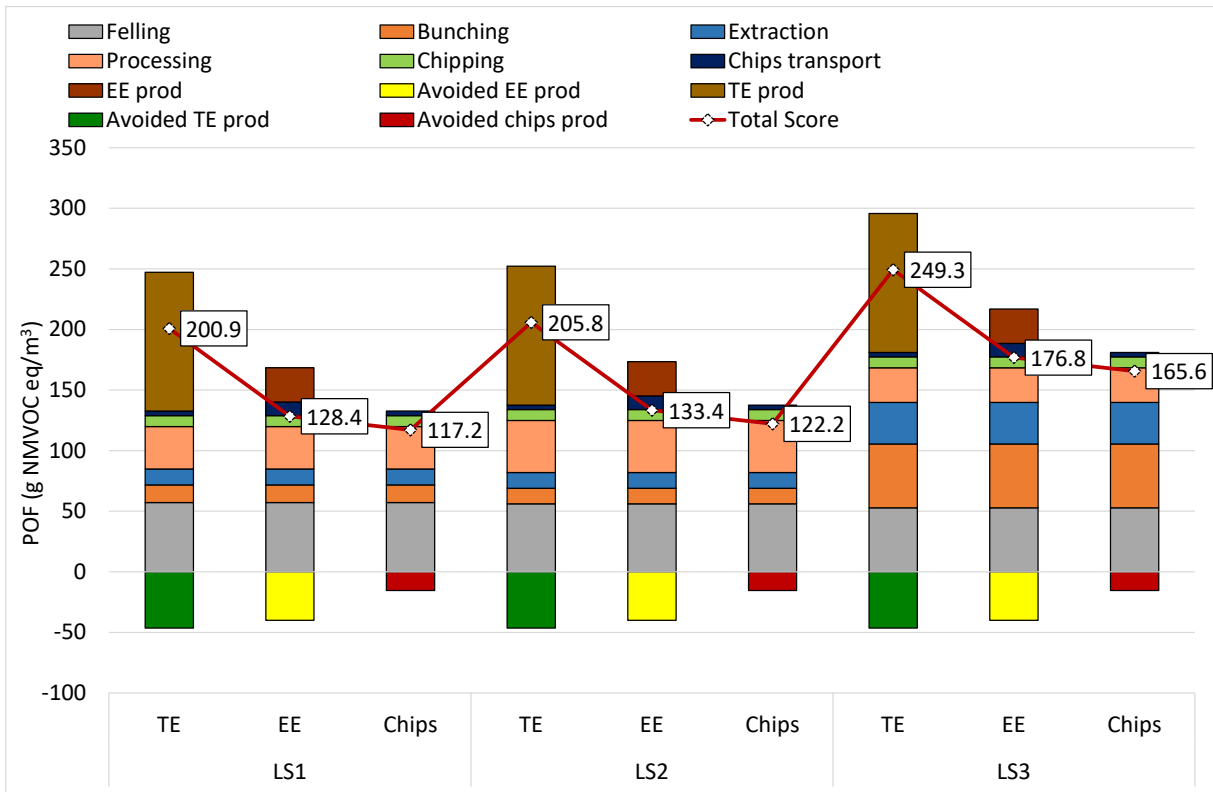
10

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



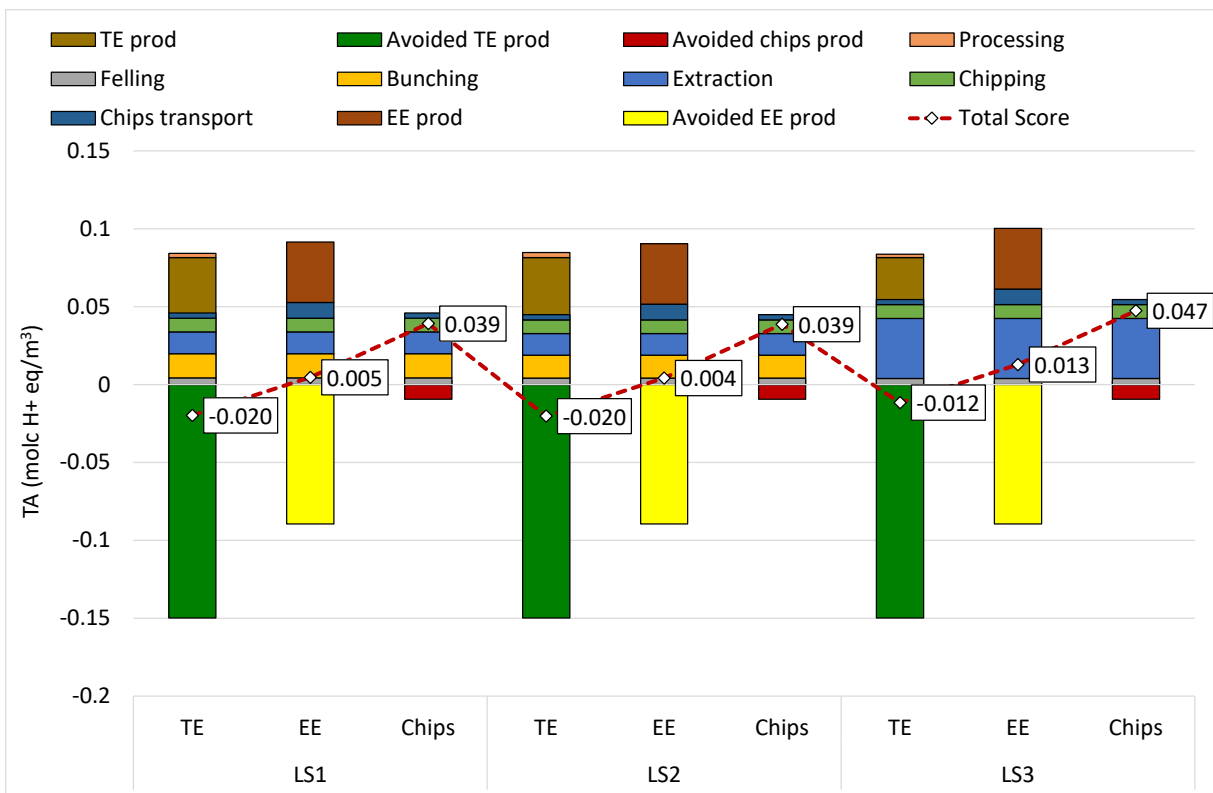
12

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



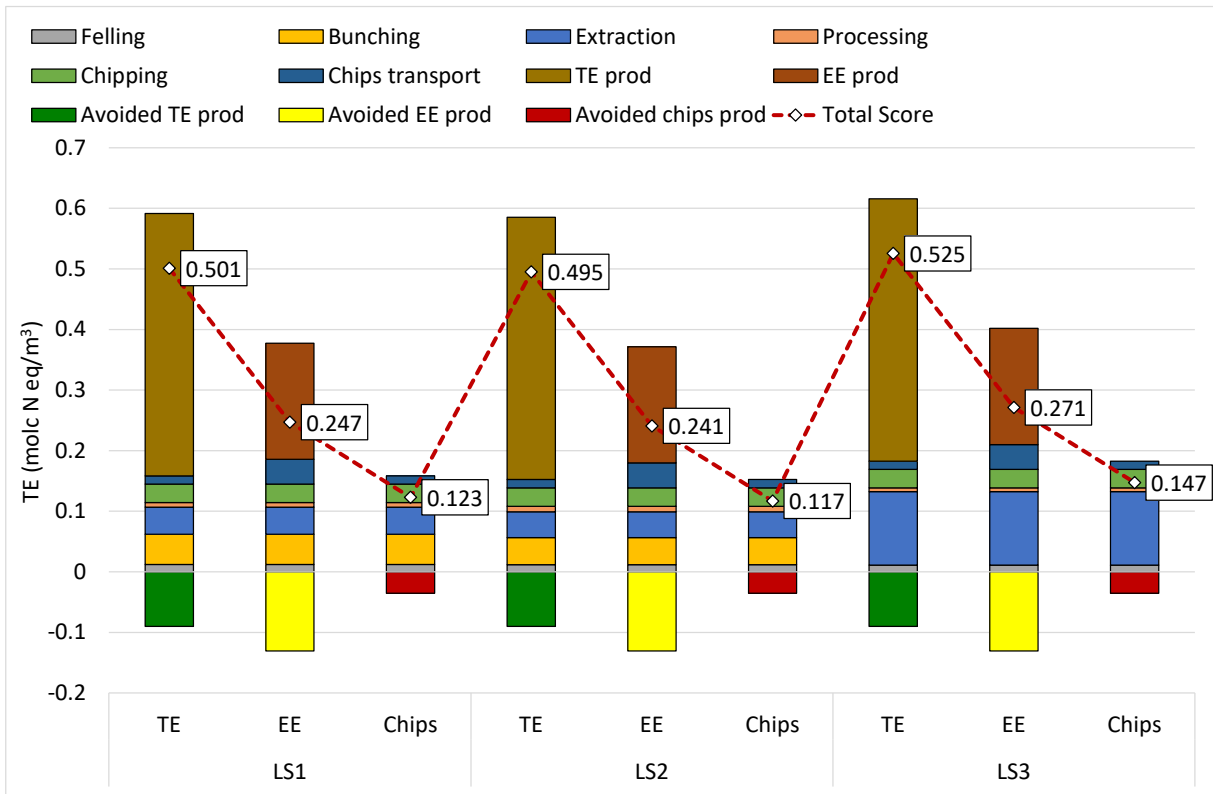
14

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



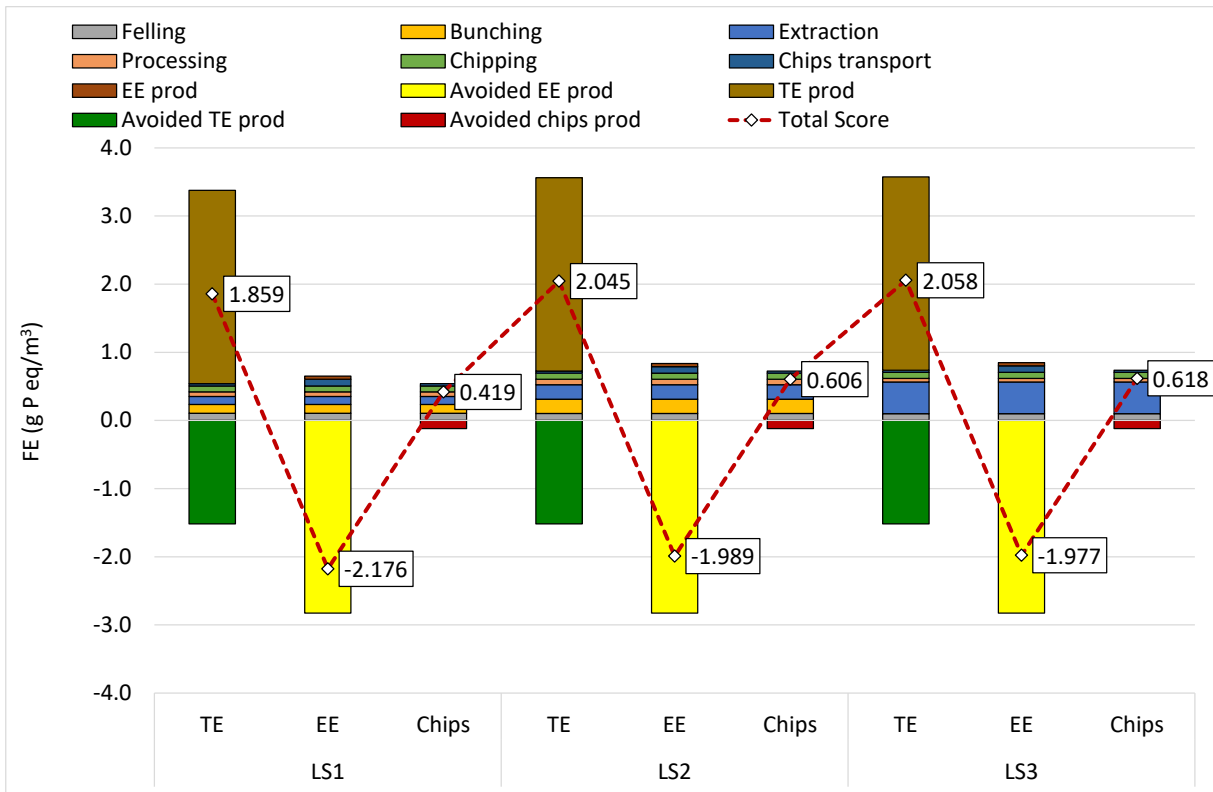
16

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



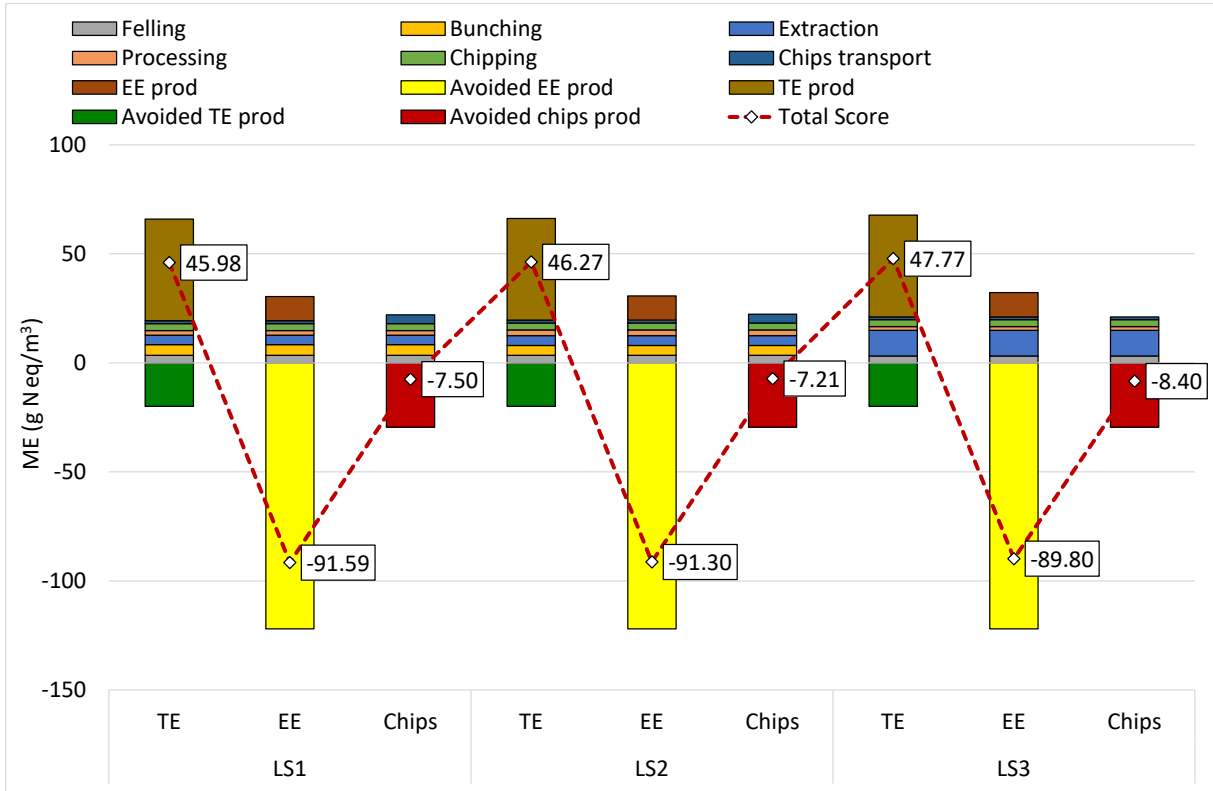
18

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



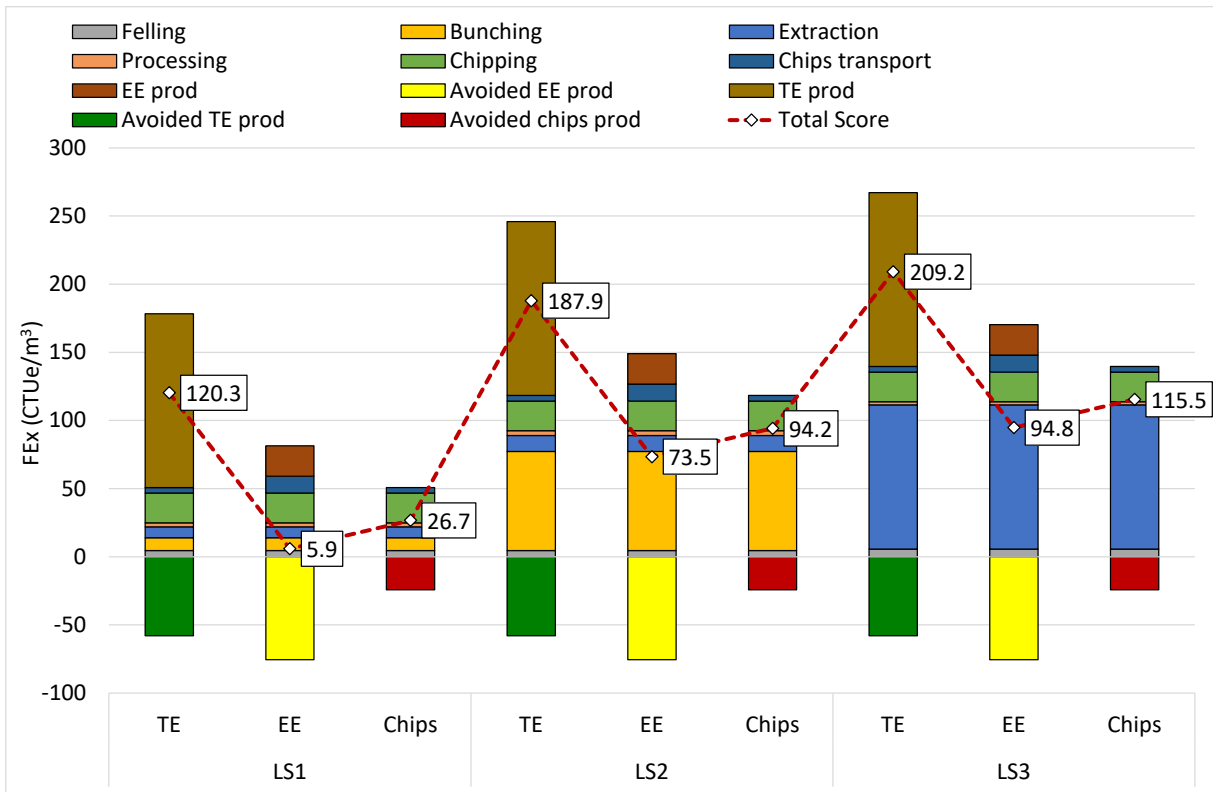
20

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



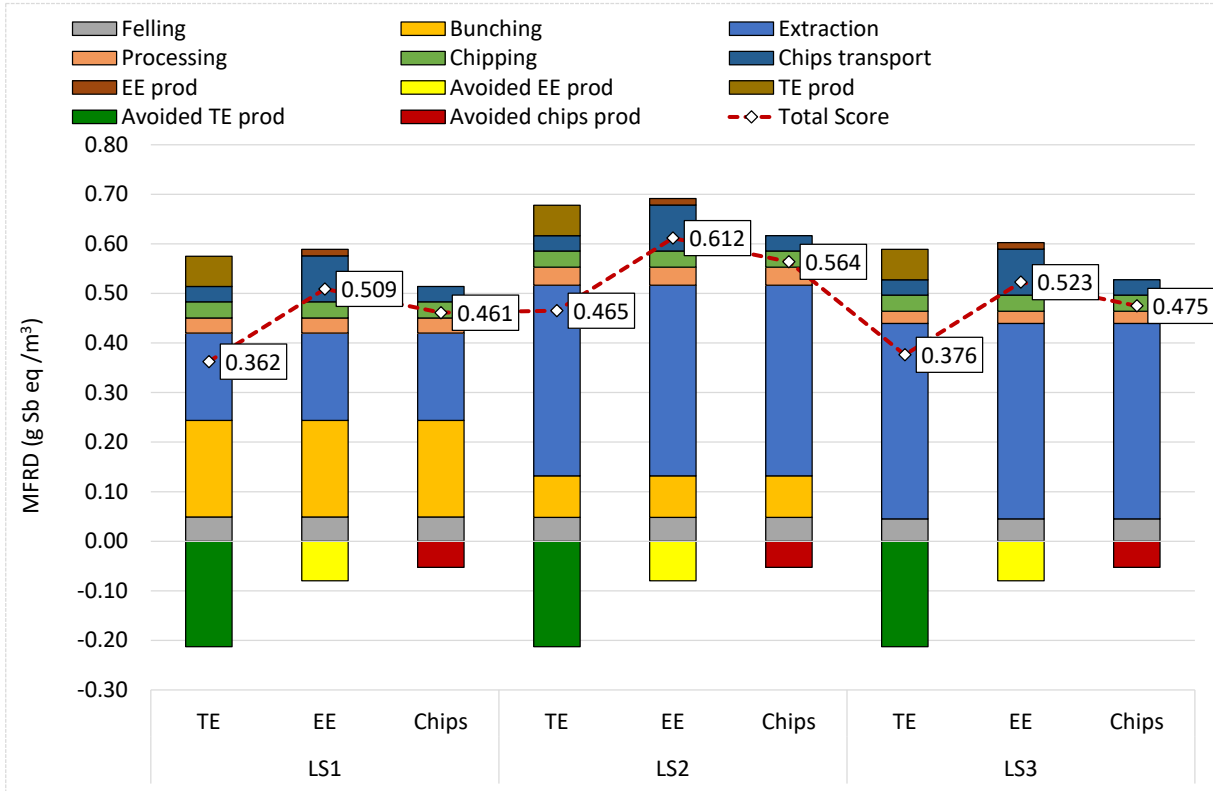
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23 **Figure 11 - Environmental impact and hotspot identification for ME**



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



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27 **Figure 13 - Environmental impact and hotspot identification for MIFRD**

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**TABLE**

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

<b>Characteristics</b>	<b>Unit</b>	<b>Site A</b>	<b>Site B</b>	<b>Site C</b>
Harvesting system	-	Tractor + Winch	Skidder + Winch	Cable Crane
Location	-	Brognauro	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	m <sup>3</sup> /ha	670	720	700
Number of tree	tree/ha	261	270	360
Three average diameter	cm	35/36	38/40	30
Three average volume	m <sup>3</sup>	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	m <sup>3</sup>	1392	2520	2640
Volume per ha	m <sup>3</sup> /ha	174	180	240

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

Parameter	Unit	Harvesting system		
		1	2	3
Workers	N	2	2	2
Productivity	m <sup>3</sup> /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 <sup>3</sup>	0.222	0.218	0.205
Vegetable oil consumption	kg/m <sup>3</sup>	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 <sup>1</sup>	day/year	180	180	180
	h/year	1440	1440	1440
Amount of machine consumed	g/m <sup>3</sup>	0.1286	0.1052	0.1484

8 <sup>1</sup> Considering to 8 h/day

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

Parameter	Unit	Harvesting system		
		1	2	3
Workers	N	3	3	n/a
Productivity	m <sup>3</sup> /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 <sup>3</sup>	1.015	0.866	
Lubricant consumption	kg/m <sup>3</sup>	0.004	0.003	
Amount of machine consumed <sup>2</sup>	g/m <sup>3</sup>	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 <sup>3</sup>	3.1	7.2	

12 <sup>1</sup> Considering to 8 h/day

13 <sup>2</sup> Considering 200 and 160 days/year (corresponding to 1600 and 1280 h/year) for the tractor  
 14 (LS1) and the skidder (LS2), respectively.

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

Parameter	Unit	Harvesting system		
		1	2	3
Workers	N	3	3	3
Productivity	m <sup>3</sup> /h	15.6	25.5	6.9
Machine	-	Tractor	Skidder	Cable crane
Amount of machine consumed	g/m <sup>3</sup>	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 <sup>3</sup>	0.917	0.834	2.354
Lubricant consumption	kg/m <sup>3</sup>	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 <sup>2</sup>	g/m <sup>3</sup>	2.8	6.1	12.7

19 <sup>1</sup> Considering to 8 h/day

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

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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 ton - 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 <sup>1</sup>	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 <sup>1</sup>	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

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

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

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

Impact Category	Absolute value				Relative comparison		
	Unit	LS1	LS2	LS3	LS1	LS2	LS3
CC	kg CO <sub>2</sub> 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	CTUhx10 <sup>6</sup>	17.42	16.40	22.73	77%	72%	100%
HT-c	CTUhx10 <sup>6</sup>	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%

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

38 impact is lower