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1 Energy and CO₂ emissions associated with mechanical planters used in 2 biomass plantations

3 4 5 **Abstract**

6 Until now, SRC has been studied from many points of view (economic sustainability,
7 environmental impact, harvesting systems, etc.), but few studies of the actual planting
8 operations have been carried out. The objective of this study was to evaluate the energy
9 input and CO₂ emission were evaluated during very Short Rotation Coppice (vSRC)
10 planting. The analysis was performed considering different planter types and tree
11 species (poplar, willow and black locust).

12 This work showed that the energy input and CO₂ emission of vSRC planting is linked to
13 different planter types and, consequently, to the type of planting material used (rods,
14 cuttings and rooting plants). Among the combinations tested, rods planters showed the
15 lowest value for energy consumption (356 MJ ha⁻¹) and CO₂ emission (31 kg ha⁻¹)
16 compared to universal planters type (1,028 MJ ha⁻¹ and 92 kg ha⁻¹). No difference
17 between tree species was observed in this experiment. Results highlighted that the
18 energy input required by the planting operation is only 1.7% of the total energy input of
19 the vSRC.

20 21 **Keywords**

22 Short Rotation Coppice, planters, productivity, fuel consumption, energy input, CO₂
23 emission

25 1. Introduction

26

27 In Europe, there are two different methods of SRC cultivation: very Short Rotation
28 Coppice (vSRC) with a very high density, from 5,500 to 14,000 plants per hectare, and
29 a harvesting cycle of 1-4 years, and Short Rotation Coppice (SRC) with a high density,
30 from 1,000 to 2,000 plants per hectare, and a harvesting cycle of 5-7 years [1].

31 In general, because the trees do not have a small diameter (>150 mm), the SRC with the
32 highest rotation time (5-7 years) offers woodchips of high quality, with a high fibre
33 content (85–90%) and a favourable particle-size distribution. On the contrary, vSRC
34 presents a high bark content ($>20\%$) [2-3] and occasionally a mediocre particle-size
35 distribution that is often too rich in ash ($>10\%$) [2, 4]. Nevertheless, farmers prefer the
36 vSRC cultivation model because it has a lower rotation period and allows for a more
37 rapid change of the tree culture in the case of poor economic benefits [5]. Furthermore,
38 its cultivation and harvest machines and methods are more familiar to farmers.

39

40 The main forestry species used in fast-growing wood crops for biomass production are
41 willows, poplars, eucalyptus and black locust [6-7]. Generally, the choice of the forestry
42 species is made as a function of the soil and landscape conditions where the SRC is
43 planted [8].

44

45 Over the years, many aspects of vSRC have been studied - economic sustainability [8],
46 environmental impact [9-10], and harvesting systems [11-12] - but SRC planting has not
47 been well studied [13]. In fact, the machines and implements used in planting operations
48 are adapted from other agricultural sectors (mainly the horticultural sector) or are only

49 prototypes [14-15]. Generally, the choice of planters is made on the basis of the tree
50 species used in vSRC because different tree species present a different planting material
51 (rods, cuttings, and rooting plants) and consequently require different types of planters.
52 In fact, in poplar and willow vSRC, it is possible to use cuttings and rods, while in black
53 locust and eucalyptus vSRC, only rooting plants can be used [13, 16].

54

55 Often, when an evaluation of the energy or of the environmental impact of biomass
56 plantations is performed, the average values are considered independently from the
57 planter types used [17]. However, this assumption is not completely correct because the
58 planter types both in the amount of power that they require and in their productivity
59 [16].

60

61 To improve the understanding of the energy consumption and CO₂ emission required in
62 the planting operation, the goal of this study is to evaluate the performance of six
63 different types of planters used in vSRC planting in order to show which one is
64 mechanically more efficient.

65

66 **2. Materials and methods**

67

68 In this experiment, different types of planters used in a vSRC plantation were tested.
69 Trials were performed using a “rod planter” (a machine that works only with rods, three
70 “cutting planters” (machines that work only with cuttings), and two “universal planters”
71 (machines that can work with both cuttings and rooting plants) (Table 1) [16]. In this
72 study, rod was considered a stem of at least 3 m length and 20 mm bottom diameter.

73

74 Because these planters have a large mass (approximately 600-700 kg) and size, they
75 require a tractor of adequate mass to guarantee longitudinal stability during manoeuvres.

76 In the test, each planter was coupled with a tractor with the minimum mass required to
77 guarantee longitudinal stability during the manoeuvres (Table 1). All of the tractors
78 chosen showed a nominal power of at least 44 kW.

79

80 The planters were tested the establishment of a very Short Rotation Coppice plantation
81 of hybrid poplar (*Populus x canadensis*), willow (*Salix*) and black locust (*Robinia*
82 *pseudoacacia*) because these species can be considered to be representative of the
83 planters used [16].

84

85 All of the planters were tested on sandy soil, with a moisture content between 8 and
86 10%. The tests were carried out in an area of 3 hectares, with plots that were 200 metres
87 in length and 150 meters in width. This area was a fenced ~~area~~ field in northwest Italy,
88 near the town of Alessadria (45° 8' 33" N; 8° 28' 11" E).

89

90 A starting plant density of 6,700 plants per hectare was adopted for all of the tree
91 species. The trials were carried out assuming a distance between rows of 3.00 metres
92 and a distance between plants of 0.50 metres [16].

93

94 All of the tests were performed under the same weather conditions (air temperature 9-11
95 C°, and relative humidity 69-73%) and lasted for 3 days. The planters were allotted by
96 random methods. Because the planters showed a different working width (3 and 6

97 metres as a function of the number of rows worked), each test consisted of five full runs
98 (1000 metres) carried out continuously (with four turns). For this reason, during data
99 analysis, a different surface worked by the planters was considered, which consisted of
100 3000 m² for planters equipped with only a planting device (one row) and 6000 m² for
101 planters that worked with two planting devices (two rows). The author considered a
102 distance of 1000 m to be sufficient to determine the fuel consumption and productivity
103 [15]. Each combination of planter and tree species was replicated three times, for a total
104 of 42 replications (black locust was planted only with the “universal planters”) (Table
105 2).

106

107 Before testing, the soil was prepared by ploughing at a 40 cm depth. For all of the
108 “cutting planters”, cuttings of a diameter of 9 to 25 mm and length of 200 to 220 mm
109 were used. The “universal planters”, in addition to working with to those used for the
110 “cuttings planters”, also worked with the black locust rooting plants that were 0.60 m in
111 height. The “rod planters” worked with rods that had a diameter of 20 to 40 mm and a
112 length of 3.00 metres.

113

114 *2.1. Field capacity*

115

116 To attribute fuel and energy consumption and CO₂ emission to the work surface unit,
117 the field capacities of all of the planters were calculated. Field capacity was determined
118 considering the expended time, which was recorded following the CIOSTA (Comité
119 International d’Organisation Scientifique du Travail en Agriculture) methodology [25].
120 Each time element was quantified using a centesimal digital stopwatch (Hanhart®

121 PROFIL 5). Specifically, the field capacity was calculated by dividing the worked
122 surface area by the unit time and was expressed in ha h^{-1} .

123

124 2.2. *Fuel consumption*

125

126 The fuel consumption for the entire planting operations was determined by the
127 “topping-off system.” This method involves measuring the fuel consumption by
128 refilling the tractor tank after each test. The tank was refilled using a 2000 cm^3 glass
129 pipe with 20 cm^3 graduations, corresponding to the accuracy of the measurements. In
130 this work, the fuel consumption was determined considering the manoeuvres that were
131 carried out in the headland up to the point of a change in the forward direction and the
132 runs that were necessary to load the planters.

133 To determine the specific fuel consumption for the planting operations, the actual power
134 required to move the planters was calculated in relation to the traction force and the
135 forward speed used in the working conditions. Specifically, the traction force was
136 measured using a tractor of 140 kW of nominal power (tractor A) and a dynamometer
137 Allemano TCA with an accuracy of 0.03%. The net force required to move only the
138 planters was calculated as the difference between the force required to pull the tractor
139 coupled with each planter (tractor B + planter) and that necessary to pull only tractor B
140 (Fig. 1).

141

142 The lubricant consumption was estimated as a function of diesel consumption according
143 to the ASABE methods [19].

144

145 *2.3. Energy consumption*

146

147 In this experiment, the total energy required for vSRC planting was determined by
148 considering the direct energy consumption – the energy input to perform the planting
149 operation (fuel and lubricant consumption) – and the indirect energy consumption – the
150 energy used for the manufacturing the tractors and implements. In particular, an energy
151 content of 92.0 MJ kg⁻¹ for the tractors and an average value of 69.0 MJ for each
152 kilogram of machine mass was considered for all of the planters [20]. The direct energy
153 input was calculated considering an energy content of 37.0 MJ L⁻¹ for the diesel [21]
154 and 83.7 MJ kg⁻¹ for the lubricant [20]. Additionally, 1.2 MJ kg⁻¹ was added to these
155 values, as additional fossil energy source was used in their transportation and
156 distribution [22].

157 In this study, a lifetime of 10,000 and 5,000 hours was considered for the tractors and
158 the planters, respectively [23]. The energy spent for maintenance and repair was
159 considered to be 55% of the energy required for manufacturing the machines [24]. The
160 energy requirement for the production of the cuttings, rooting plants, and rods was not
161 considered in this evaluation.

162 The energy output was attributed to the unit surface worked and biomass harvested,
163 considering a dry matter energy content of poplar wood of 18.8 MJ kg⁻¹. This
164 calculation was performed considering an average biomass production of 15 Mg ha⁻¹ per
165 year and a 6 year rotation with harvesting carried out every 2 years [25].

166

167 *3.3. Environmental assessment*

168

169 The environmental impact of the planting operations was calculated based on the CO₂
170 emission due to the fuel combustion during the work and machinery manufacturing.
171 Specifically, a value of 3.76 kg per litre of diesel [26-27] and a value of 2.94 kg for each
172 kg of lubricant [28] released into the atmosphere were assumed. In addition, a value of
173 159 g per each MJ of energy content in the machines was considered in the calculation
174 of the frequency of maintenance and repair on the environmental impact [12].

175

176 The data were processed using Microsoft Excel and SPSS 21 (2015) statistical software,
177 using an ANOVA procedure with a GLM approach and adopting a significance level of
178 $\alpha = 0.05$. Eventual differences between treatments were checked with the Scheffe's test
179 because it has a higher statistical power given this data distribution [29]. Scheffé's
180 method is a single-step multiple comparison procedure which applies to the set of
181 estimates of all possible contrasts among the factor level means [30].

182

183 **3. Results**

184

185 *3.1. Field capacity*

186

187 The highest field capacity (1.20 ha h⁻¹) was obtained using the Salix Maskiner Step (rod
188 planter) independent of the tree species considered (poplar or willow) (Table 3). In
189 contrast, the lowest field capacity was observed for the universal planters (Allasia R1
190 and Berto), with values that ranged between 0.27 ha h⁻¹ and 0.29 ha h⁻¹. In this case, no
191 difference was noted between the tree species tested. Intermediate values in productivity
192 (0.56-0.57 ha h⁻¹) were obtained from the cutting planters.

193

194 Results showed significantly different performances only between the planter
195 categories; there were no significant differences between specific makes and models
196 that were included in each category (Table 3).

197

198 *3.2. Fuel consumption*

199

200 The diesel consumption varied between 6.19 and 8.89 litres per hour (Table 4). The
201 universal planters showed the lowest value, while the Salix Maskiner Step (Rod planter)
202 showed the highest value. In the trials, the hourly fuel consumption increased according
203 to the power of the tractor, with a linear trend that was independent of the planter's type
204 and the tree species planted (Fig. 2) (Table 4)..

205

206 Referring to the fuel consumption ~~of~~ for the unit of worked surface, the best
207 performances were obtained by the Salix Maskiner Step (7.82 L ha⁻¹), while the worst
208 performances were observed in the Allasia R1 planter (22.24 L ha⁻¹) (Table 5). That
209 difference should not be underestimated because by using a correct planter, it is possible
210 to save a substantial amount of diesel (3 times).

211

212 Results showed significant differences in the values between the planter categories,
213 which could be due to the different working width and forward speed of the planters. In
214 fact, the universal planters that worked only with one row showed the highest fuel
215 consumption per unit surface, while the lowest value was obtained by the Salix

216 Maskiner planter, which worked with two rows and with a high forward speed (up to 4
217 km h⁻¹) (Table 5).

218

219 No difference was noted between tree species (poplar, willow and black locust) in the
220 fuel consumption (Table 5).

221

222 Results indicate the average specific fuel consumption in the planting operation of 63.5
223 g kWh⁻¹. In addition, for this parameter, no differences between the planter types and
224 tree species were observed in the statistical analysis (Table 6).

225

226 *3.3. Energy consumption*

227

228 The energy consumption of the tested planters ranged between 356 and 1,028 MJ ha⁻¹ as
229 a function of the differences in their mass, fuel consumption and field capacity. In
230 particular, the rod planter showed the lowest value, while the universal planters showed
231 the highest value. Regarding these values for the material planted, only 54 kJ per plant
232 (cutting) was observed with the Salix Maskiner, while approximately 154 kJ per plant
233 was calculated for the universal planters. In general, the cutting planters presented
234 values that were approximately 60% less than those of the universal planters (Table 6).

235

236 Results did not indicate any difference between the tree species (poplar, willow and
237 black locust) that were planted (Table 6).

238

239 *3.4. Environmental assessment*

240

241 The CO₂ emission calculated in this study ranged between 31.19 kg ha⁻¹ (5 g per plant)
242 and 95.79 kg ha⁻¹ (14 g per plant). Different values were obtained for each planter
243 category during the CO₂ emission calculation. An average value of 92 kg ha⁻¹ (14 g per
244 plant) was observed for the universal planters. These values were approximately 40%
245 higher than those calculated for the cutting planters and 65% higher than those
246 calculated for the rod planter. Additionally, for this parameter, no differences between
247 tree species were noted during the statistical analysis carried out at a significance level
248 of $\alpha = 0.05$ (Table 7).

249

250 **4. Discussion**

251

252 For field capacity, better results (1.20 ha h⁻¹) were obtained using the rod planter
253 because with this machine, it is possible to operate at a higher forward speed (4.0 km h⁻¹).
254 By contrast, universal planters showed lower field capacities (0.28 ha h⁻¹) compared
255 to cutting planters (0.56 ha h⁻¹) only as a function of the number of rows worked (one
256 row instead of two rows). In fact, assuming an equal working width for both machine
257 categories, there are no differences regarding the working rate. These results are in line
258 with those obtained in other studies [13, 15-16].

259

260 Hourly fuel consumption is proportional to the tractor's engine power [31]. High values
261 were obtained for planters coupled to tractors with a high nominal power. Regarding
262 fuel consumption per unit surface, the situation changes because the fuel consumption is

263 linked to the working rate. In fact, the best results were obtained by the Salix Maskiner
264 because with this planter, it is possible to operate on two rows simultaneously with a
265 high forward speed (up to 4.0 km h⁻¹) [16].

266

267 Furthermore, the data analysis indicated that for vSRC planting, it is possible to
268 consider an average specific fuel consumption of a tractor of 63.5 g kWh⁻¹. This value is
269 approximately 50% lower than the values obtained in biomass-harvesting operations
270 (115-120 g kWh⁻¹) [24, 32-33].

271

272 The energy consumption analysis indicated that for vSRC planting, up to 1,04 MJ ha⁻¹ is
273 necessary when using universal planters, while this value decreased by approximately a
274 factor of five when the rod planters are used. This low value can be attributed to a
275 different working width and forward speed [15]. Therefore, improvements can be
276 obtained by building planters with a double planting device. As to raising forward
277 speed, the solution is more complex. The low forward speed is linked to human work
278 because the planters are manually fed [16]. Therefore, to increase forward speed, it is
279 necessary to develop a specific device that is able to feed the planter automatically. In
280 fact, the setup of automatic planting devices could allow to obtain good results, not only
281 in terms of the work productivity [33-34], but also in terms of the energy efficiency.

282

283 The energy consumption observed in the planting operations was only 1.7% of the total
284 energy input to the vSRC plantation [10]. Furthermore, considering a biomass
285 production of 15 Mg per year and a cycle of 2 years [25, 35], the energy required by the
286 planting operations has a low impact on the total biomass production (minor, at 0.5%).

287 This value is lower (approximately 60%) than the energy input to the harvesting
288 operations that was obtained by Fiala and Becenetti [12] (1.1% of the energy content in
289 biomass produced).

290

291 In this study, the energy consumption of the universal planters – planters that work with
292 all forestry species – is constant for all of the tested forestry species. This situation
293 could be positive because it permits the selection of tree species as a function of only
294 site conditions and their cultivation limits and potentialities [36]. In contrast, the type of
295 planting material (rods, cuttings or rooting plants) could directly influence the choice of
296 planter models and, consequently, the energy consumption.

297

298 Furthermore, the data analysis shows a different value for the CO₂ emission during
299 biomass planting as a function of planter type. Lower results were observed for the rod
300 planters (31 kg ha⁻¹) in comparison to 92 kg ha⁻¹ emitted when universal planters were
301 used. This difference can be attributed to the differing productivity of the planters. In
302 fact, in this study, the rod planter presented the highest values, while the universal
303 planters presented the lowest values. Nevertheless, a high forward speed could have
304 negative impacts on crop performance or survival. In general, these results are in line
305 with those obtained during an environmental impact assessment of biomass production
306 by dedicated poplar plantations [37-38].

307

308 **5. Conclusions**

309

310 The energy input of vSRC planting is linked to different planter types and,
311 consequently, to different types of propagation material (rods, cuttings and rooting
312 plants). The rods planter has the lowest energy consumption and CO₂ emission. In
313 contrast, no difference was found when comparing the different tree species (poplar,
314 willow and black locust). This study have also demonstrated that the energy
315 consumption of planting operations is very small compared to the energy content in
316 biomass produced (approximately 0.5%). Furthermore, this work showed that the
317 specific fuel consumption that is required by vSRC planting is lower than 5% compared
318 to that required for biomass harvesting.

319 Finally, in the future, it would be interesting to conduct a specific evaluation on
320 productivity, energy consumption and CO₂ emission during the production of the
321 different planting materials to obtain a complete profile of the total energy input and
322 CO₂ emission required in the planting operations.

323

324

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