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

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Abstract

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

This work showed that the energy input and CO_2 emission of vSRC planting is linked to different planter types and, consequently, to the type of planting material used (rods, cuttings and rooting plants). Among the combinations tested, rods planters showed the lowest value for energy consumption (356 MJ ha^{-1}) and CO_2 emission (31 kg ha^{-1}) compared to universal planters type (1,028 MJ ha^{-1} and 92 kg ha^{-1}). No difference between tree species was observed in this experiment. Results highlighted that the energy input required by the planting operation is only 1.7% of the total energy input of the vSRC.

Keywords

Short Rotation Coppice, planters, productivity, fuel consumption, energy input, CO_2 emission

1. Introduction

In Europe, there are two different methods of SRC cultivation: very Short Rotation Coppice (vSRC) with a very high density, from 5,500 to 14,000 plants per hectare, and a harvesting cycle of 1-4 years, and Short Rotation Coppice (SRC) with a high density, from 1,000 to 2,000 plants per hectare, and a harvesting cycle of 5-7 years [1].
In general, because the trees do not have a small diameter (>150 mm), the SRC with the highest rotation time (5-7 years) offers woodchips of high quality, with a high fibre content (85–90%) and a favourable particle-size distribution. On the contrary, vSRC presents a high bark content (>20%) [2-3] and occasionally a mediocre particle-size distribution that is often too rich in ash (>10%) [2, 4]. Nevertheless, farmers prefer the vSRC cultivation model because it has a lower rotation period and allows for a more rapid change of the tree culture in the case of poor economic benefits [5]. Furthermore, its cultivation and harvest machines and methods are more familiar to farmers.

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

Over the years, many aspects of vSRC have been studied - economic sustainability [8], environmental impact [9-10], and harvesting systems [11-12] - but SRC planting has not been well studied [13]. In fact, the machines and implements used in planting operations are adapted from other agricultural sectors (mainly the horticultural sector) or are only prototypes [14-15]. Generally, the choice of planters is made on the basis of the tree species used in vSRC because different tree species present a different planting material (rods, cuttings, and rooting plants) and consequently require different types of planters. In fact, in poplar and willow vSRC, it is possible to use cuttings and rods, while in black locust and eucalyptus vSRC, only rooting plants can be used [13, 16].

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

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

2. Materials and methods

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

Because these planters have a large mass (approximately 600-700 kg) and size, they require a tractor of adequate mass to guarantee longitudinal stability during manoeuvres. In the test, each planter was coupled with a tractor with the minimum mass required to guarantee longitudinal stability during the manoeuvres (Table 1). All of the tractors chosen showed a nominal power of at least 44 kW.

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

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

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

All of the tests were performed under the same weather conditions (air temperature 9-11 C°, and relative humidity 69-73%) and lasted for 3 days. The planters were allotted by random methods. Because the planters showed a different working width (3 and 6 metres as a function of the number of rows worked), each test consisted of five full runs (1000 metres) carried out continuously (with four turns). For this reason, during data analysis, a different surface worked by the planters was considered, which consisted of 3000 m^2 for planters equipped with only a planting device (one row) and 6000 m^2 for planters that worked with two planting devices (two rows). The author considered a distance of 1000 m to be sufficient to determine the fuel consumption and productivity [15]. Each combination of planter and tree species was replicated three times, for a total of 42 replications (black locust was planted only with the "universal planters") (Table 2).

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

2.1. Field capacity

To attribute fuel and energy consumption and CO_2 emission to the work surface unit, the field capacities of all of the planters were calculated. Field capacity was determined considering the expended time, which was recorded following the CIOSTA (Comité International d'Organisation Scientificue du Travail en Agricolture) methodology [25]. Each time element was quantified using a centesimal digital stopwatch (Hanhart®

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

2.2. Fuel consumption

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

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

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

2.3. Energy consumption

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

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

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

3.3. Environmental assessment

The environmental impact of the planting operations was calculated based on the CO_2 emission due to the fuel combustion during the work and machinery manufacturing. Specifically, a value of 3.76 kg per litre of diesel [26-27] and a value of 2.94 kg for each kg of lubricant [28] released into the atmosphere were assumed. In addition, a value of 159 g per each MJ of energy content in the machines was considered in the calculation of the frequency of maintenance and repair on the environmental impact [12].

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

3. Results

3.1. Field capacity

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

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

3.2. Fuel consumption

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

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

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

Maskiner planter, which worked with two rows and with a high forward speed (up to 4 km h^{-1}) (Table 5).

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

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

3.3. Energy consumption

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

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

3.4. Environmental assessment

The CO_2 emission calculated in this study ranged between 31.19 kg ha^{-1} (5 g per plant) and 95.79 kg ha^{-1} (14 g per plant). Different values were obtained for each planter category during the CO2 emission calculation. An average value of 92 kg ha^{-1} (14 g per plant) was observed for the universal planters. These values were approximately 40% higher than those calculated for the cutting planters and 65% higher than those calculated for the rod planter. Additionally, for this parameter, no differences between tree species were noted during the statistical analysis carried out at a significance level of $\alpha = 0.05$ (Table 7).

4. Discussion

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

Hourly fuel consumption is proportional to the tractor's engine power [31]. High values were obtained for planters coupled to tractors with a high nominal power. Regarding fuel consumption per unit surface, the situation changes because ~~the~~ fuel consumption is linked to ~~the~~ working rate. In fact, the best results were obtained by the Salix Maskiner because with this planter, it is possible to operate on two rows simultaneously with a high forward speed (up to 4.0 km h^{-1}) [16].

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

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

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

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

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

Furthermore, the data analysis shows a different value for the CO_2 emission during biomass planting as a function of planter type. Lower results were observed for the rod planters (31 kg ha^{-1}) in comparison to 92 kg ha^{-1} emitted when universal planters were used. This difference can be attributed to the differing productivity of the planters. In fact, in this study, the rod planter presented the highest values, while the universal planters presented the lowest values. Nevertheless, a high forward speed could have negative impacts on crop performance or survival. In general, these results are in line with those obtained during an environmental impact assessment of biomass production by dedicated poplar plantations [37-38].

5. Conclusions

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

Finally, in the future, it would be interesting to conduct a specific evaluation on productivity, energy consumption and CO_2 emission during the production of the different planting materials to obtain a complete profile of the total energy input and CO_2 emission required in the planting operations.

References

[1] Di Muzio Pasta V, Negri M, Facciotto G, Bergante S, Maggiore TM. Growth dynamic and biomass production of 12 poplar and two willow clones in a short rotation coppice in northern Italy. In: 15th European biomass conference and exhibition, from research to market deployment. Proceedings of the international conference held in Berlin, Germany; 2007. pp. 749-754.

[2] Benomar L, Des Rocher A, Larocque Gr. The effect of spacing on growth, morphology and biomass production and allocation in two hybrid poplar clones growing in the boreal region of Canada. Trees: Struct Funct 2012; 26 (3): 939-49

[3] Phelps JE, Isebrands JG, Jowett D. Raw material quality of short rotation intensively cultured Populus clones. I. A comparison of stem and branch properties at three spacing. IAWA Bulletin n.s; 1982. P.193-200.

[4] Spinelli R, Nati C, Sozzi L, Magagnotti N, Picchi G. Physical characterization of commercial woodchips on the Italian energy market. Fuel 2011;90(6):2198-2202.

[5] Armstrong A, Johns C, Tubby I. Effect of spacing and cutting cycle on the yield of poplar grown as an energy crop. Biomass Bioenerg 1999,17(4):305-14.

[6] Guidi W, Piccioni E, Bonari E. Evapotranspiration and crop coefficient of poplar and willow short-rotation coppice used as vegetation filter. Bioresource technolog 2008;99:4832-40.

[7] Gonzalez-Garcìa S, Moreira MT, Feijoo G, Murphy RJ. Comparative life cycle assessment of ethanol production from fast-growing wood crops (black locust, eucalyptus and poplar). Biomass Bioenerg 2012;39:378-88.

[8] Hauk S, Knoke T, Wittkopf S. Economic evaluation of short rotation coppice systems for energy from biomass: a review. Renewable and Sustainable Energy Review 2011;29:435-48.

[9] Manzone M, Airoldi G, Balsari P. Energetic and economic evaluation of a poplar cultivation for the biomass production in Italy. Biomass Bioenerg 2009;33:1258-64.

[10] Manzone M, Bergante S, Facciotto G. Energetic and economic evaluation of a poplar plantation for woodchips production in Italy. Biomass Bioenerg 2014;60:164-70.

[11] Spinelli R, Magagnotti N, Picchi G, Lombardini C, Nati C. Upsized harvesting technology for coping with the new trends in short-rotation. Appl Eng Agric 2011;27:551-557.

[12] Fiala M, Becenetti J. Economic, energetic and environmental impact in short rotation coppice harvesting operations. Biomass Bioenerg 2012;42:107-13.

[13] Bush C, Volk AV, Eisenbies MH. Planting rates and delays during the establishment of willow biomass crops. Biomass and Bioenergy 2015;83:290-6

[14] Lowthe-Tomas SC, Slater FM, Randerson PF. Reducing the establishment costs of short rotation willow coppice (SRC): A trial of a novel layflat planting system at an upland site in mid-Wales. Biomass Bioenerg 2010;34:677-86.

[15] Balsari P, Airoldi G, Facciotto G. Messa a dimora di un impianto di pioppo da biomassa. Sherwood 2002;81:49-54.

[16] Manzone M, Balsari P. Planters performances during a very Short Rotation Coppice. Biomass Bioenerg 2014;67:188-92.

[17] Djomo SN, Kasmioui OE, Ceulemans R. Energy and greenhouse gas balance of bioenergy production from polar and willow: a review. GCB Bioenergy 2011;3:181-97.

[18] Bolli P, Scotton M. Lineamenti di tecnica della meccanizzazione agricola. Bologna, Italy; Edagricole 1987.

[19] ASAE American Society of Agricultural Engineers. ASAE Standards: Agricultural Machinery Management 1999. EP466.2.

[20] Jarach M. On equivalence values for analysis and balance energy in agriculture (in Italian). Riv Ing Agr 1985,2:102-14.

[21] Bailey A, Basford W, Penlington N, Park J, Keatinge J, Rehman T, et al. A comparison of energy use in conventional and integrated arable farming in the UK, Agriculture Ecosystems Environment 2003;97:241-53.

[22] Pellizzi G. Use of energy and labour in Italian agriculture. Journal of Agricultural Engineering Research 1992;52:111-9.

[23] Fluck RC. Energy sequestered in repairs and maintenance of agricultural machinery. Trans ASAE 1985;28(3).

[24] Nati C, Spinelli R, Fabbri P. Wood chips size distribution in relation to blade wear and screen use. Biomass Bioenerg 2010;34:583-7.

[25] Facciotto G, Bergante S, Lioia C, Mughini G, Rosso L, Nervo G. Come scegliere e coltivare le colture da biomassa. Suppl Forlener L'informatore Agrario 2005;34:27-30.

[26] Soane BD, Ball BC, Arvidson J, Basch G, Moreno F, Roger-estrade J. No-till in northern, western and south-western Europe: a review of problems and opportunities for crop production and the environment. Soil Till Res 2012;118:66-87.

[27] Sarauskis E, Buragiene S, Masilionyté L, Romaneckas K, Avizienyté D, Sakalauskas A. Energy balance, costs and CO2 analysis of tillage technologies in maize cultivation. Energy 2014;69:227-35.

[28] Lal R. Carbon emissions from farm operations. Environ Int 2004;30:981-90.

[29] Keppel G, Wickens TD. Design and analysis: A researchers handbook (4rd Edition), 2004. Upper Saddle River, NJ: Pearson.

[30] Sheffe H. A method for judging all contrasts in the analysis of variance. Biometrika 1953;40(1-2):87-110.

[31] Manzone M, Spinelli, R. Efficiency of small-scale firewood processing operations in Southern Europe. Fuel Processing Technology 2014;122:58-63.

[32] Spinelli R, Magagnotti N, Paletto G, Preti C. Determining the impact of some wood characteristics on the performance of a mobile chipper. Silva Fennica 2001;45:85-95.

[33] Manzone M, Spinelli R. Wood chipping performance of a modified forager. Biomass Bioenerg 2013;55.101-106.

[34] Rantala J, Laine T. Productivity of the M-planter tree-planting device in practice. Silva Fennica 2010;44(5):859-69.

[35] Pullen DWM, Cowell PA. The effect of implement geometry on the hoe path of a steered rear-mounted inter-row weeder. Biosyst Eng 2006;94(3):373–86.

[36] Rosso L, Facciotto G, Bergante S, Vietto L, Nervo G. Selection and testing of populus alba and Salix spp. as bioenergy feedstock: preliminary results. Appl Energy 2013;102:87-92.

[37] San Miguel G, Corona B, Ruiz D, Landholm D, Laina R, Tolosana E, et al. Environmental, energy and economic analysis of a biomass supply chain based on a poplar short rotation coppice in Spain. Journal of Cleaner production 2015; (in press).

[38] Roedl A. Production and energetic utilization of wood from short rotation coppice - a life cycle assessment. The International Journal of Life Cycle Assessment 2010;15(6):567-78.