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Abstract

The rising price of fossil fuel and the increasing environmental concern encourage the use of biomasses as energy sources. Aim of this study was to compare two poplar SRC and vSRC (6 and 3 years rotation cycle) with an annual crop (maize), used for biomass production in North Italy.

The average of the biomass production was 13.9 Mg DM ha^{-1} per year for the SRC and vSRC poplar and 19.2 Mg DM ha^{-1} for the maize.

The energy consumption for the poplar cultivations was about 15 GJ ha^{-1} per year, which represented only the 6% of the energy biomass product (about 257 GJ ha^{-1} per year).

The input value of the maize was higher (26.8 GJ ha^{-1} per year). In this case, the input value was about the 7% of the energy content in the biomass product (about 370 GJ ha^{-1} per year).

During the vSRC cultivation an amount of 8090 kg CO_2 eq ha^{-1} was emitted, 6420 kg CO_2 eq ha^{-1} for the SRC and 26370 kg CO_2 eq ha^{-1} for the maize.

Compared to the maize, the poplar SRC (or vSRC) crops are interesting from an energetic point of view, while maize requires less manpower, but it has major problems related to the landscape biodiversity.

Keywords

Energy; poplar SRC; maize; biomass production

1. Introduction

The rising price of fossil fuel and the environmental concern encourage the use of biomasses as energy sources [1]. From an environmental point of view, the interest in the use of biomass is chiefly related to the emitted greenhouse gases (GHG) during the burning, the same absorbed during the growth phase [2].

The most common biomasses are multi-year crops (Short Rotation Coppice, SRC) and annual crops. The former are mainly cultivated for wood biomass production to be used in gasification and in boiler plants [3,4], whereas the latter are used for biogas production [5].

In north Italy, crops for biomass production have been included in the cultivation plans of several farms: they may increase the farmers' revenue thanks also to low input requirements and to the combined possibility to exploit set-aside areas [6].

Actually, there are two different methods of SRC cultivation: the very Short Rotation Coppice (vSRC) with high tree density (from 5500 to 7000 plants per hectare and an harvesting rotation period of 1-4 years) and the Short Rotation Coppice (SRC) with a density from 1,000 to 2,000 plants per hectare and an harvesting rotation of 5-7 years [7]. In north Europe farmers usually choose the vSRC cultivation model [8] for the climatic conditions. In Italy, instead, the farmers prefer the SRC method, because the recently developed poplar hybrids have enhanced the productivity and improved the biomass quality (with an higher calorific value), with an higher wood/bark ratio [9]. The SRC method is also preferred because in the main regions of north Italy the local government finances this cultivation by the mean of rural development plans.

The main species cultivated in SRC are: poplar (*Populus x euroamericana*) [10], willow (*Salix spp*) [11] and black locust (*Robinia pseudoacacia* H.) [12].

Farmers may also produce biomass using annual crops [13], which require higher input [14] than multiyear crops but have a shorter cycle, giving to the farmer the possibility to change the crops every year in function of the market demand [15].
The most common annual crops are: wheat (*Triticum aestivum* H.), triticale (*Triticosecale hybrid*), and maize (*Zea mays* H.) [16]. In the last years, also forages [17] and many sorghum (*Sorghum bicolor* L.) hybrids [18-19] have been tested for biogas production. In Italy [20] and in Europe [21] the maize is the most widely used crop as feedstock for anaerobic digestion.

Poplar and maize cultivations are preferred by north Italian farmers because they are well known since many years and give the best results in term of biomass production [11,16].

In order to evaluate the energetic, social and environmental convenience of biomass production, in this study two multi-year crops (poplar vSRC and SRC) and an annual crop (maize) cultivated in an Italian farm were compared. Manpower, energy consumption, and CO_2 emission for their cultivation was analyzed for each crop.

2. Materials and method

The Authors considered two poplar short rotation coppices and a maize crop, comparing their energetic, environmental and social suitability for biomass production, being aware that maize energy crops are in competition with food production.

2.1. Field crop characteristics

Data were collected in the fields of the experimental farm “MEZZI”, close to Casale Monferrato (AL), during the 2007-2013 period. Five hectares of SRC, 5 ha of vSRC and 4 ha of maize were surveyed.

A starting density of 6700 plants per hectare (3.00 x 0.50 m spacing) was present in the vSRC plantation and the harvest was carried out every 2 years [22]. For the SRC plantation, instead, the starting poplar density was 1,100 plants per hectare (3.00 × 3.00 m spacing) with one harvest at the end of the cultivation cycle, 6 years long [23].

The sowing density of the maize was 74,000 seeds per hectare and the biomass harvest was done at the end of each year cycle [24].

Since each crop has a different duration cycle, a 6 years period was considered (1 SRC, 3 vSRC and 6 maize cycles).

2.2. Agricultural operations and machines

For each crop the soil was prepared with a ploughing 0.40 m deep, a seed bed fertilization (500 kg ha^{-1} of 8.24.24 - N, P, K) and a secondary tillage performed with two harrowing interventions (Tables 1, 2 and 3).

Poplar cutting (0.25 m in length and 10 – 25 mm in diameter) was performed in vSRC plantation, while poplar rods (1.50 m in length and 25 – 45 mm in diameter) was made in SRC plantation. Planting operations were provided with two different planters: Allasia T2 for cuttings planting [25] and Allasia V1 for rods planting [26].

In the maize cultivation a pneumatic seed drill with 6 seeding elements was used.

Fertilization, weed control, insect control and irrigation, necessary for a good biomass production [27], were carried out in each crop.

An heavy cultivator and a disc harrow were used respectively for the stumps removal in poplar plantations and for the maize stalks chopping.

A chipper prototype Gandini Bio-harvester in SRC [28] and a self-propelled harvester CLASS 850 (with a specific cutting head for little trees) in vSRC [29] were used for the biomass harvesting. The Class 850 harvester was also used for the maize harvesting. Two tractors with trailers were used for the biomass transport in the farm (about 400 meters far).

The biomass harvested was measured weighing all the used trailers, scaled on a certified weighbridge. In the meantime the exact bulk volume was also determined after leveling the load. The biomass produced was calculated at an annual basis, as the average of the total harvested biomass (differently for each crop, depending on the duration cycle) in the examined period (6 years).

2.3. Time consumption and manpower

For each machine, working times and manpower requirements were recorded in field, according to the CIOSTA (Comité International d'Organisation Scientifique du Travail en Agriculture) methodology, for at least a 5,000 m^2 area and for periods not shorter than 2 hours [30]. For the planter the tests were carried out considering a period of three hours. Two couples of photocells (ZOOM® Z2E, 50 meters far from headland boundary) were used to measure the forward speed, while distances were measured by a flexible ruler (LUX®, 2 mm accuracy). Travel and working times were recorded using a centesimal digital stopwatch (Hanhart® PROFIL 5).

The manpower requirement was determined considering the number of the operators and the real working time registered to carry out each agricultural operation.

2.4. Energy and fuel consumption

The energy consumption was determined considering all the energy inputs, both direct (fuel and lubricant) and indirect (machine, equipment and mineral fertilizer energy contents). Machine fuel consumption was determined refilling the machine tank at the end of each working phase. The tank was refilled using a 2-liters glass pipe with 0.02 liter graduations, to ensure the measurements accuracy. The lubricant consumption was determined in function of the fuel consumption using the 2% value of the fuel consumption, as specified by Piccarolo [31]. The amount of fuel consumed during each agricultural operation (l) was multiplied by the low heating value of diesel fuel (35.28 MJ l^{-1} [32]), to calculate the direct energy cost.

Indirect energy costs of materials were estimated multiplying the input rate of each material with its energy intensity (Table 5) [33]. Indirect energy costs for agricultural machinery production were calculated multiplying the embodied energy coefficient by the machines weight and life span (Tables 4-5) [34]. Concerning the repair and maintenance energy content, the 55% of the necessary energy for the machine manufacturing was considered [35].

The total energy output was estimated multiplying the total biomass harvested with the energy content in biomass (18.5 MJ kg^{-1} DM for the poplar [14], 19.3 MJ kg^{-1} DM for the maize [36]).

The human work was expressed in manpower per hour required for each agricultural operation, but it was not considered as energy content.

2.5. Environmental assessment

The environmental impact of the chipping operations was calculated using the CO_2 emitted by fuel combustion during both the field work and the machine manufacturing. About 3.76 kg of CO_2 per litre of diesel fuel [37-38] and an average of 2.94 kg of CO_2 chilogram of lubricant [39] were considered. Concerning the manufacturing, an emission factor of 0.159 kg of CO_2 per each MJ of energy content into the machine was used [33].

3. Results

3.1. Time consumption and manpower

The cultivation of the SRC and vSRC required respectively 27 and 20 hours WU ha^{-1} per year. These values are quite high, if compared with the maize cultivation (7 h WU ha^{-1} per year).

In detail, for the vSRC the highest manpower requirements were in the cutting planting (24.5%) and in the biomass harvesting (about 18.3%) (Table 6). In the SRC the operation the highest manpower demand were in the biomass harvesting (45.1%) and in the rod plantation (17.1%).

The operation with the highest manpower consumption was the biomass harvesting also for the maize cultivation, but the seeding operation (homologous to the planting for the SRC and vSRC) had a lower value (13.7%) (Table 6).

Analysing the working rates (Table 7), it comes out that the machines used in vSRC and SRC have a lower work capacity, especially in planting and harvesting operations, also if minor values were obtained in stump removal.

The average of the biomass production was 13.9 Mg DM ha^{-1} per year for the SRC and vSRC poplar and 19.2 Mg DM ha^{-1} for the maize.

3.2 Fuel and energy consumption

The diesel fuel consumption was different in function of the considered crop. The higher value (98.8 l ha^{-1} per year) was observed in the maize cultivation, the lower in the SRC (59.0 l ha^{-1} per year), while in vSRC an intermediate value (70.5 l ha^{-1} per year) was registered. Concerning the produced biomass, similar values were obtained in vSRC and maize crops (5.07 and 5.15 l $MgDM^{-1}$), with a lower value in SRC (4.24 l $MgDM^{-1}$).The cultural operation with higher incidence on diesel fuel consumption were the ploughing for maize (40.5%) and the harvesting for vSRC and SRC (41.1% and 45.2% respectively). The mineral fertilizaztion, on the contrary, registered the lowest incidence in all the analyzed crops (Table 8).

The energy consumption for the poplar vSRC cultivation was 14.8 GJ ha^{-1} per year and it was slightly inferior to SRC (15.2 GJ ha^{-1} per year).

These values represent only the 6% of the total energy biomass production (about 257 GJ ha^{-1} per year, obtained from 13.9 Mg DM ha^{-1} of biomass production).

The input energetic value for the maize was higher (26.8 GJ ha^{-1} per year), about the 7% of the energy content of the biomass product (about 370 GJ ha^{-1} per year).

The output/input ratio is between 16.9 (vSRC) and 17.4 (SRC) for the short rotation coppice and 13.8 for the maize cultivation.

The highest energy requirements were observed in the soil fertilization, in the harvest and in the transport operations, in all the crops (Table 9).

3.3. Environmental assessment

Data processing highlighted that during the vSRC cultivation an amount of 8090 kg CO_2 eq ha^{-1} was emitted, 6420 kg CO_2 eq ha^{-1} for the SRC and 26370 kg CO_2 eq ha^{-1} for the maize. These values correspond to 96.28 kg CO_2 eq $MgDM^{-1}$ for vSRC, 76.94 kg CO_2 eq $MgDM^{-1}$ for vSRC and 228.33 kg CO_2 eq $MgDM^{-1}$ for maize. Comparing the CO_2 emissions among the operations in the different crops, it can be observed that higher values were always obtained from fertilization and harvesting operations, regardless of the crop type. Lower values were obtained in the ploughing, harrowing and planting/seeding operations (Table 10).

Discussion

The highest manpower requirement obtained in SRC cultivation, regardless of the plant density, can be attributed to the low mechanization level of the crop management operations. Many machines and specific equipment used for this crop are actually only prototypes with a low working rate due to a low automation level. In fact, the operations with an high manpower requirement are the crop planting and the biomass harvesting, performed only with prototypes [26, 40].

The low manpower requirement for the maize cultivation is also due to a longer tradition in this crop cultivation (more than 100 years) [41]: accordingly, the used machines and equipment have been improved during the time. For this reason, in the last 50 years the manpower demand for the maize cultivation has been reduced by 8 times (this value has been calculated comparing current machines and implements with the same used in sixties).

The maize highlights better results in the sowing operation because the seed drills have an higher working rate compared to the cutting and rod planters [26, 42-43].
If the technology will be improved in vSRC and SRC cultivation, we can hope that in few years the necessary manpower to grow them will settle below the current values. At the same time, it is important to remember that the prototype’s set up is very difficult and onerous in terms of time for the SRC cycle, being it longer than annual crops (3 or 6 years).

Considering the energy balance, the poplar plantation, with a 3 or 6 years rotation and a biomass production of about 14 Mg DM ha^{-1} per year, independently from the plant density, is very interesting because the output/input energetic ratio is higher than 16.9. This value is 3.1 points higher than the maize. The better results obtained in the vSRC and SRC cultivation can be attributed to a minor energy input for the crop fertilization necessary to guarantee an high biomass production.

The energy consumption obtained in this work is comparable with the results obtained by other authors [44-45]. Moreover, a positive energy balance for all crops is in accordance with other experimentations [38,46]. Nevertheless, if in the next few years the biomass production of vSRC and SRC will have the same increment observed in the last 50 years for the maize (+ 250%) [46], the ratio output/input will be even higher compared to the present value, as also analyzed in the model developed by Busato *et al.* [48]. For all the biomass types considered in this study, the fertilization is the most expensive regarding energy, because higher are the inputs in this operation, as verified also by Andrea *et al.* [49].

Annual crops as maize, differently from vSRC and SRC plantations, can offer the possibility to change the crop each year, according to the market trends, but the multi-year plantations allow to reduce the incidence of economic costs and energy consumption associated to the planting operation on the total values [15]. Another parameter to be considered is the available time in planting/sowing operation: cuttings and rods planting are compressed between March and April [22], while maize for biomass production can be sowed from March to July [50].

An advantage in the wood biomass plantations may also be found both in the environmental and biodiversity aspects [51]. Agricultural operations for wood biomass plantations require lower CO_2 emission than maize (about 2.5 time). This aspect is important because CO_2 emission causes environmental pollution [52], especially when the maize is used to produce biomass for energy production to replace fossil oil [53-54]. Furthermore, SRC cultivation requires also a lower fuel consumption. This aspect has also an healthy consequence on the operator, who is less exposed to diesel exhaust [55].
In SRC cultivations there is an higher presence of animals compared to annual crops [56], enhancing the biodiversity. In fact, a consistently higher bird diversity can be recorded in SRC than in a traditional farmland habitat [57] both in summer and winter [58]. SRC is moreover strongly influenced by the landscape into which the crop is introduced [59-60]. For highly mobile animals such as birds, the landscape composition plays a central role in terms of plantations tenure [61].

Maize cultivation will always have the problems linked to the landscape biodiversity and the ethics related to the fact that a food crop is used to produce biomass for energy use. The use of the land for food or for bioenergy use is a debated question [62] and at this purpose perennial lignocellulose energy crops as SRC and vSRC may be a good compromise to balance the bioenergy and the food production.

Conclusions

This study has been carried out in north Italy where, in the last years, many farmers introduced crops to produce biomass for energy use in their agricultural planes. Thanks to the governmental incentives, to enhance the use of renewable energy, the farmers decided to cultivate more maize (instead of planting poplars), especially for electrical energy production.

In contrast, the results obtained in this experimentation highlight that the poplar plantations, independently from the cycle length (3 or 6 years), show an higher energetic ratio (about 3 points higher) and a lower CO_2 emissions (about 2.5 time) compared to maize cultivation. The better energetic and environmental results in vSRC and SRC cultivation are especially due to a minor energy input for the crop management.

Moreover, the poplar plantations presence enhance the landscape biodiversity.

On the contrary, maize cultivation requires lower manpower.

The SRC mechanization improvement will play a fundamental role to reduce the required manpower: at this point, SRC could really become competitive.

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Tables

Table 1 - Agricultural operations and production factors in the vSRC crop

	Operation (n°)	**Operation type**	**Material used**
Start of the cycle	1	Seed bed fertilization	8.24.24-N.P.K. (500 kg ha^{-1})
	1	Soil preparation	-
Cultural operations at the first year and at the first year after the biomass harvest	1	Top-dressing	Urea (87 kg ha^{-1})
	1	Pre-emergence chemical weed control	Metolaclor (1700 g ha^{-1}) Linuron (500 g ha^{-1}) Pendametilin (800 g ha^{-1})
	1	Pesticide application	Chloropyrifos-metyl (120 g ha^{-1}) Cypermethrin (12 g ha^{-1}) Fenitrothion (285 g ha^{-1})
	3	Mechanical weed control	-
	1	Irrigation	-
Cultural operations at the second year and at the second year after the biomass harvest	1	Top-dressing	Urea (87 kg ha^{-1})
	1	Pesticide application	Chloropyrifos-metyl (120 g ha^{-1}) Cypermethrin (12 g ha^{-1}) Fenitrothion (285 g ha^{-1})
	2	Mechanical weed control	-
	1	Irrigation	-
	3	Biomass harvesting	-
End of the cycle	1	Stump removal	-

Table 2 - Agricultural operations and production factors in the SRC crop

	Operation (n°)	Operation type	Material used
Start of the cycle	1	Seed bed fertilization	8.24.24-N.P.K. (500 kg ha^{-1})
	1	Soil preparation	-
Cultural operations at the first year	1	Top-dressing	Urea (87 kg ha^{-1})
	1	Pre-emergence chemical weed control	Metolaclor (1700 g ha^{-1}) Linuron (500 g ha^{-1}) Pendametilin (800 g ha^{-1})
	1	Pesticide application	Chloropyrifos-metyl (120 g ha^{-1}) Cypermethrin (12 g ha^{-1}) Fenitrothion (285 g ha^{-1})
	2	Mechanical weed control	-
	1	Irrigation	-
Cultural operations after the first year	1	Top-dressing	Urea (87 kg ha^{-1})
	1	Pesticide application	Chloropyrifos-metyl (120 g ha^{-1}) Cypermethrin (12 g ha^{-1}) Fenitrothion (285 g ha^{-1})
	2	Mechanical weed control	-
	1	Irrigation	-
End of the cycle	1	Biomass harvesting	-
	1	Stump removal	-

Table 3 - Agricultural operations and production factors in the maize crop

	Operation (n°)	Operation type	Material used
Start of the cycle	1	Seed bed fertilization	8.24.24-N.P.K. (500 kg ha^{-1})
	1	Soil preparation	-
Agricultural operations	1	Top-dressing	Urea (87 kg ha^{-1})
	1	Pre-emergence chemical weed control	Metolaclor (1700 g ha^{-1}) Linuron (500 g ha^{-1}) Pendametilin (800 g ha^{-1})
	1	Pre-emergence chemical weed control	Nicosulfuron (40 g ha^{-1}) Dicamba (200 g ha^{-1})
	1	Mechanical weed control	-
	3	Irrigation	-
End of the cycle	1	Biomass harvesting	-
	1	Chopping stalks	-

Table 4 – Machines technical characteristics

Machines	N°	Power (kW)	Mass (kg)	Lifetime (h)	Working width (m)	Load capacity (m^3)
Plow	1	-	1160	2000	1.6	-
Harrow (tillage)	1	-	1500	2000	4.0	-
Harrow (SRC and vSRC weed control)	1	-	750	2000	2.1	-
Weeder (maize weed control)	1	-	450	2000	3.5	-
Planter (vSRC)	1	-	850	1500	3.0	-
Planter (SRC)	1	-	450	1500	3.0	-
Seed drills (maize)	1	-	1450	1500	4.5	-
Fertilizer spreader	1	-	300	2000	8.0	0.6
Air -assisted sprayer (poplar pesticide application)	1	-	550	1500	3.0	1.0
Boom sprayer (pre-emerg. weed control)	1	-	280	1500	12	0.8
Self-propelled boom sprayer (maize pesticide application)	1	103	4100	1500	18	2.0
Harvester (vSRC - maize)	1	303	12600	7000	3.0 - 4.5	-
Harvester (SRC)	1	190	11000	7000	3.0	-
Disks harrow (chopping stalks)	1	-	1350	2000	4.0	-
Stump redder	1	-	450	2000	1.5	-
Trailer for biomass transportation	2	-	3700	3000	-	35.0
Tractor	2	125	5900	7000	-	-
Tractor	1	48	4500	4000	-	-

Table 5 – Primary energy content

Material	Primary energy content (MJ kg^{-1})	Bulk density to 15°C (kg dm^{-3})
Diesel fuel	41.5	0.88
Motor oil	83.7	0.93
Tractors and self-propelled machines	92.0	-
Implements	69.0	-
N	73.3	-
P	13.4	-
K	9.2	-
Herbicide	81.5	-
Biomass (poplar)	18.5*	-
Biomass (maize)	19.3*	

Note: *referred to the dry matter (DM)

Table 6 - Manpower requirement

Operation	Crop type		
	vSRC (%)	SRC (%)	Maize (%)
Mineral fertilization	1.1	0.6	7.6
Ploughing	6.5	3.9	22.5
Harrowing	3.0	1.8	11.3
Planting/Seeding	24.5	17.1	13.7
Weed control	9.3	5.6	9.8
Top dressing	8.8	4.8	
Pesticides application	8.5	9.2	-
Irrigation	15.1	9.0	4.9
Biomass harvesting and transport	18.3	45.1	25.9
Stump removal/chopping maize stalks	4.9	2.9	4.3

Table 7 – Working rates

Operation	Crop type		
	vSRC (ha h^{-1})	**SRC (ha h^{-1})**	**Maize (ha h^{-1})**
Mineral fertilization	5.6	5.5	5.6
Ploughing	0.7	0.7	0.8
Harrowing	1.7	1.8	1.7
Planting/Seeding	0.5	0.6	2.3
Weed control	1.3	1.3	2.6
Top dressing	1.6	1.6	2.6
Pesticides application	3.2	3.2	5.8
Irrigation	0.3	0.3	0.5
Biomass harvesting and transport	0.1	1.1	2.5
Stump removal/chopping maizestalks	0.6	0.4	3.4

Table 8 – Influence of the fuel consumption in the different operations

Operation	Crop type		
	vSRC (%)	SRC (%)	Maize (%)
Mineral fertilization	0.5	0.5	1.9
Ploughing	9.0	10.5	40.5
Harrowing	1.9	2.1	7.6
Planting/Seeding	2.7	3.8	8.4
Weed control	25.8	15.1	3.1
Top dressing	8.5	10.2	3.2
Pesticides application	5.0	5.9	1.6
Irrigation	-	-	-
Biomass harvesting and transport	41.1	45.2	28.3
Stump removal/chopping maizestalks	5.6	6.7	5.3

Table 9 – Energy consumption

Operation	Crop type		
	vSRC (%)	SRC (%)	Maize (%)
Mineral fertilization	19.1	21.4	23.8
Ploughing	4.0	4.5	5.8
Harrowing	1.5	1.7	2.9
Planting/Seeding	4.9	2.9	2.0
Weed control	4.7	5.7	3.9
Top dressing	34.9	41.3	49.8
Pesticides application	2.2	1.1	-
Irrigation	2.0	1.7	2.5
Biomass harvesting and transport	24.5	17.2	7.7
Stump removal/chopping cornstalks	2.2	2.5	1.6

Table 10 – CO_2 eq emissions

Operation	Crop type		
	vSRC (%)	**SRC (%)**	**Maize (%)**
Mineral fertilization	18.9	23.9	31.1
Ploughing	0.6	0.8	1.2
Harrowing	0.2	0.3	0.5
Planting/Seeding	0.5	0.6	0.4
Weed control	4.5	4.6	0.4
Top dressing	30.0	37.8	31.2
Pesticides application	6.9	8.7	3.7
Biomass harvesting and transport	36.7	21.4	31.2
Stump removal/chopping cornstalks	1.6	2.1	0.3