Life cycle assessment: an application to poplar for energy cultivated in Italy

Jacopo Bacenetti,[1] Sara González-García,[2] Aira Mena,[1] Marco Fiala[1]

[1]Department of Agricultural Engineering, University of Milano, Italy; [2]Department of Chemical Engineering, School of Engineering, University of Santiago de Compostela, Spain

Abstract

The development of the bioenergy sector has led to an increasing interest in energy crops. Short rotation coppices (SRC) are forestry management systems in which fast-growing tree species are produced under intensive cultivation practices to obtain high wood chips yields. In Italy, most SRC plantations consist of poplar biomass-clones. SRC plantations can be carried out with different management systems with diverse cutting times; consequently, the cultivation system can be crucial for attaining high yields depending on: i) short and ii) medium cutting frequency. Nowadays, the larger part of Italian SRC is based on 2-year cutting short rotation forestry (SRF) but the best quality of wood chips is linked to 5-year plantation medium rotation forestry (MRF). This work compares an SRF and an MRF poplar plantation located in the Po Valley in northern Italy. In particular, a life cycle assessment (LCA) was carried out to evaluate their energy demand and greenhouse gas emissions. The LCA software SimaPro 7.10 was used to create the LCA model and to assure an accurate impact assessment calculation. The analysis shows several differences between MRF and SRF in terms of fertiliser requirements and intensive agricultural activities. Results highlight that MRF produces a more sustainable wood chip production than SRF according to energy and environmental concerns. Furthermore, *hot spots* were identified in both SRF and MRF due to the high energy consumption and the related emissions. These *hot spots* were: i) mineral fertilisation; ii) mechanical weed-control; iii) harvesting and biomass transport.

Correspondence: Jacopo Bacenetti, Department of Agricultural Engineering, University of Milano, Italy. Tel. +39.0250316869 - Fax: +39.0250316845.
E-mail: jacopo.bacenetti@unimi.it

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Introduction

European farmers are becoming increasingly interested in the production of energy crops following the most recent changes in the common agricultural policy and the rapid development of the bioenergy sector (Spinelli *et al.*, 2008). Among cropping systems, the short rotation coppices (SRC) seem to reflect the farmers' economical expectations. In fact, SRC allows (Spinelli *et al.*, 2008) shorter return times than traditional wood plantations (at least 30 years). The SRC are wood crops usually defined as silvicultural management practices in which fast-growing tree species are cultivated under intensive management (weed and pest control, use of fertilisers and irrigation) in order to obtain high biomass yields (Bergante *et al.*, 2010). However, in Italy, the study of SRCs is still new (Manzone *et al.*, 2009), although over the last 15 years, encouraged by very favourable grant programmes, SRC have been established on about 6500 ha in the Po Valley area (Gasol *et al.*, 2010; Bergante *et al.*, 2010), mainly (>60%) in the Lombardy Region (Fiala *et al.*, 2010). Furthermore, in this area, there is a growing interest in the production of biofuels since several thermoelectric power plants fed by biomass have been recently built (Bergante *et al.*, 2010).

In Italy, species that can be used are poplar, willow, black locust and eucalyptus, but most plantations consist of poplar biomass-clones (Fiala *et al.*, 2010; Bergante *et al.*, 2010). This species has proved to be extremely well suited to biomass production due to its fast initial growth, high photosynthetic capacity, and large wood biomass production.

In Italy, poplar energy crop cultivation is carried out under intensive conditions and the rotation (or cutting frequency) is usually shorter (2 years) than in other European countries (3-4 years in Sweden and the UK). The cutting frequency of poplar coppice plantations depends on the plant density and on the growth rate. The development of new poplar clones, as well as the improvement in cultivation techniques, has led to a considerable increase in biomass yield (>17 $t_{DM}\cdot ha^{-1}\cdot yr^{-1}$; dry matter) (Bergante *et al.*, 2010).

SRC poplar plantations consist of coppice periodically cut clear to stimulate sucker growth. Different management systems can be used and these are based on either short or medium cutting frequency. These systems are respectively called short rotation forestry (SRF) and medium rotation forestry (MRF), and the main differences between them concern: i) type of propagation materials (SRF: cuttings; MRF: stumps); ii) plant density (SRF: 5500-6500 cuttings$\cdot ha^{-1}$; MRF: 1100-1300 stumps$\cdot ha^{-1}$); iii) cutting interval (SRF: 1-2 years; MRF: >5 years).

Nowadays, most Italian short rotation crops are based on 2-year cutting but the best quality of biofuel originates from 5-year plantations, mainly because of the lower ash content that results from the higher wood/bark ratio (Guidi *et al.*, 2008). Consequently, in the near future, MRF will be more widespread.

This work aims to assess both the energy demand and the greenhouse gas (GHG) emissions related to the poplar cultivation in the Po Valley in northern Italy, considering two different cultivation systems (SRF and MRF) applied to real plantations.

The general aims of this study are to: i) gather the inventory data both for SRF and MRF, quantifying their effects on the environment and energy resources; ii) identify the cultivation systems *hot spots*; iii) suggest some possible improvements. To study the impact of Italian poplar plantations, a life cycle assessment (LCA) has been carried out. Two productive scenarios have been analysed based on experimental data collected from commercial SRF and MRF plantations. The purpose of the LCA has been to determine the best current production practice from an environmental point of view.

Materials and methods

The life cycle assessment (LCA) approach is a methodology for the comprehensive valuation of the impact that a *product* brings on the environment throughout its whole life cycle. LCA is an objective process to evaluate the environmental burdens associated with a product by measuring the consumption of natural resources and the emissions to environmental compartments, and to identify and implement opportunities to achieve environmental improvements.

The LCA software SimaPro 7.10, developed by PRé Consultants (PRé Consultants bv, Amersfoort, The Netherlands, http://www.pre-sustainability.com/), has been used to create the LCA model and to assure the impact assessment calculation.

Following ISO 14040 standard guidelines (ISO, 2006), all the production factors have been considered. LCA defines the environmental profile for the assessed production by quantifying the environmental effects.

In this paper, for both poplar SRF and MRF cultivation systems, the global warming potential (GWP) and the cumulative energy demand (CED) have been calculated.

The GWP is a relative measure of how much heat a GHG traps in the atmosphere; it compares the amount of heat contained in a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon dioxide. The CED represents the whole energy demand, (valued as primary energy) related to the production, use and disposal of an economic good.

The cumulative energy output (CEO) has been calculated considering the total wood chip harvested dry mass and its lower heating value (LHV) (Fiala *et al.*, 2010). The net energy ratio (NER) is the ratio between the CEO and the CED.

Since the system boundary set in this study does not take into consideration the conversion of the wood chips into energy (heat and/or electricity), according to other short rotation crops, LCA studies focused on wood chip production (Heller *et al.*, 2004; González-García *et al.*, 2012); the *cultivated surface* (*i.e.,* one hectare of poplar plantation under the two analysed cultivation systems) has been selected as functional unit (FU).

Poplar cultivations

Both the SRF and MRF analysed plantations are located on two different farms of the Lombardy Region, at Ostiano, in the province of Cremona (45°12'N, 10°15'E). This area has a sub-continental climate with rainfall mainly concentrated in spring and autumn (yearly average: 745 mm year^{-1}) and daily temperatures of 9.3°C (average minimum) and 20.1°C (average maximum). Both the energy crop cultivations can be divided into the following phases: i) soil preparation and planting; ii) management and harvesting; iii) soil restoration.

The general schemes of SRF (2-year cutting frequency) and MRF (5-year cutting frequency) cultivation systems are shown in Figure 1.

Table 1 presents all the field operations carried out during the whole SRF and MRF cultivation period as well as the years in which they are carried out. The main characteristics of the two poplar plantations are reported in Table 2.

Soil preparation and planting

During the 1st year, according to both cultivation systems, soil was: i) fertilised with cattle manure (rate 50 t ha^{-1}); ii) ploughed; and iii) harrowed. The manure applied presents a moisture content of 80-82% wet basis (wb), an average content of 4.5 kg of N t^{-1}, 2.0 kg of P_2O_5 t^{-1} and 3.5 kg of K_2O t^{-1}.

After soil preparation, different planting programmes were adopted for the SRF and the MRF systems. Unrooted 22 cm cuttings of *AF2* poplar clone were planted in the SRF plantation with a density of 5560 cuttings ha^{-1} (distance of 0.5 m on each row, 2.8-3.0 m between rows). For MRF, 2 m plant-rods of *AF2* poplar clone were planted with a density of 1150 plants rod ha^{-1} (distance of 2.8-3.0 m on each row, 2.8-3.0 m between rows). In both plantations, lanes allow the use of conventional wheeled tractors to perform all the mechanical operations.

After planting, the chemical weed-control was carried out; spraying glyphosate (concentration 31%; 4 kg ha^{-1}) was sprayed once for the SRF and twice for the MRF. The two sprayings of the MRF was neces-

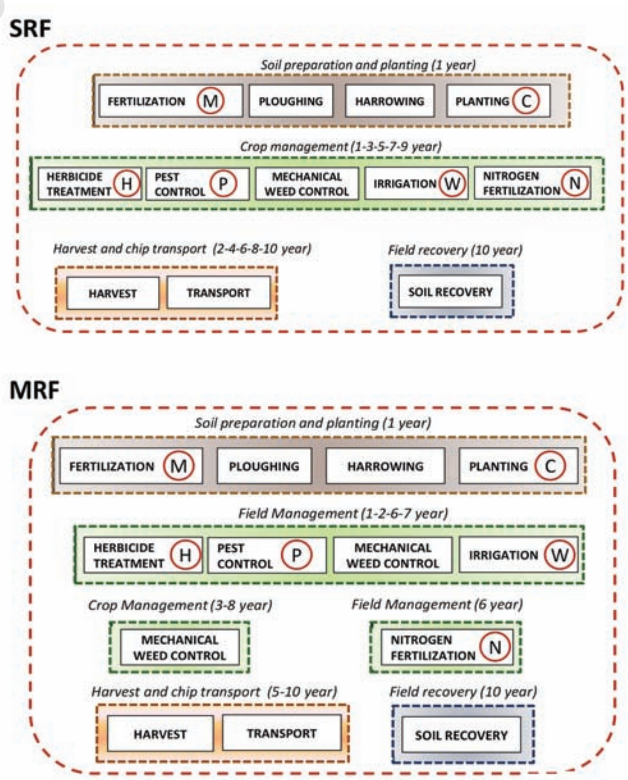

Figure 1. Scheme of the system boundaries for short rotation forestry (SRF) and medium rotation forestry (MRF) poplar cultivations. M, manure; C, cuttings; H, herbicide; P, pesticide; N, nitrogen fertilization; W, water.

Table 1. Poplar short rotation forestry and medium rotation forestry: field operations timeline and inventory data.

Operation	Year of passing	Tractor (A) Mass and power	Implement (B) Type of machine	Implement (B) Mass (kg)	Implement (B) Operating time* (h ha^{-1})	A+B Fuel consumption* (kg ha^{-1})	Rate*
Soil preparation and planting (1st year)							
Organic fertilization	SRF and MRF: 1	6730 kg 120 kW	Manure spreader	2500	0.45	4.0	SRF and MRF 50 t·ha^{-1} manure°
Ploughing	SRF and MRF: 1	6730 kg 120 kW	Plough	1500	1.70	20.5	-
Harrowing	SRF and MRF: 1	5050 kg 90 kW	Rotary harrow	1000	2.00	23.5	-
Planting	SRF and MRF: 1	6730 kg 120 kW	Planter	630	1.42	20.3	SRF: 5560 cuttings·ha^{-1} MRF: 1150 plant rods·ha^{-1}
Chemical weed control#	SRF: 1	4580 kg 80 kW	Sprayer	550	0.33	3.3	SRF and MRF 4 kg·ha^{-1} MRF: 1^{-1}
Irrigation§	SRF and MRF: 1	-	-	-	-	-	SRF and MRF 400 m^3·ha^{-1}
Pest control^	SRF and MRF: 1	4580 kg 80 kW	Sprayer	550	0.33	3.3	SRF and MRF 2 kg·ha^{-1}
Chemical weed control*	SRF: 1 MRF: 1-1	4580 kg 80 kW	Sprayer	550	0.33	3.3	SRF and MRF 4 kg·ha^{-1}
Mechanical weed control	SRF and MRF: 1	5050 kg 90 kW	Rotary harrow	1000	2.20	25.3	-
Wood chips harvesting/transport and crop managing							
Harvesting	SRF: 2-4-6-8-10	13560 kg 343 kW	Combine harvester	-	1.20	72.0	-
	MRF: 5-10	17500 kg 200 kW	Harvester		3.08	126.6	
		5050 kg 90 kW	Forestry trailer		5.00	61.9	
		16000 kg 150 kW	Chipper		3.00	100.7	
Biomass transport	SRF: 2-4-6-8-10 MRF: 5-10	4580 kg 80 kW	3 tipping trailers	5500	2.50	16.0 17.5	
Nitrogen fertilization$	SRF: 3-5-7-9 MRF: 6	5050 kg 90 kW	Fertilizer spreader	350	0.28	3.4	SRF:80 kg N·ha^{-1} MRF:200 kg N·ha^{-1}
Chemical weed control**	SRF: 3-5-7-9 MRF: 2-6-6-7	4580 kg 80 kW	Sprayer	550	0.33	3.3	SRF:4 kg·ha^{-1} MRF:2 kg·ha^{-1}
Pest control^	SRF: 3-5-7-9 MRF: 2-6-7	4580 kg 80 kW	Sprayer	550	0.33	3.3	SRF and MRF 2 kg·ha^{-1}
Mechanical weed control	SRF: 3-5-7-9	5050 kg 90 kW	Rotary harrow	1000	2.20	25.3	MRF: 2-2-3-6-6-7-7-8
Irrigation	SRF: 3-5-7-9 MRF: 2-5-6	-	-	-	-	-	SRF and MRF: 400 m^3·ha^{-1}
Soil restoring							
Soil restoration	SRF and MRF: 10	6730 kg 120 kW	Hoeing machine	1000	5.00	60.0	-

SRF, short rotation forestry; MRF, medium rotation forestry. *Values related to a single passing; °Manure composition: 80-82% moisture content, 4.5 kg N · t^{-1}, 2.0 kg P_2O_5 · t^{-1}, 3.5 kg K_2O · t−1; #Glyphosate (31%); §Water from the near river without pumping system; ^Deltamethrin; $Urea (46%); **Gluphosinate-ammonium (11.3%).

sary to control a climbing weed (*Convolvulus* spp.). Pest control requires only one treatment according to both the cultivation systems, using gluphosinate-ammonium (concentration 11.3%; 2 kg ha^{-1}).

A mechanical weed-control operation (soil light-harrowing) was also carried out and, finally, due to the high water needs of poplar, plantations were irrigated using 400 $m^3 \cdot ha^{-1}$ of water collected from the near Oglio river and distributed through canals by gravity; it is not, therefore, necessary to pump water.

Wood chip harvesting/transport and crop management

Short rotation forestry

According to this system, harvesting took place in years 2, 4, 6, 8 and 10 using a self-propelled forage combine harvester equipped with a special biomass-header (Fiala and Bacenetti, 2012a and 2012b). The harvester directly loads the fresh chipped biomass on the trailers (no. 3 tipping trailers pulled by wheel tractors), which transport the material to the farm storage (distance: 2.5 km). A cumulative wood chip production of 168.5 $t_{DM} \cdot ha^{-1}$ has been measured in this plantation (Fiala and Bacenetti, 2012a and 2012b).

After each harvesting operation, excluding the last one, the following operations have been carried out: i) nitrogen fertilisation (urea 46% N, 80 kg $N \cdot ha^{-1}$); ii) weed control (gluphosinate-ammonium: concentration 11.3%, 4 $kg \cdot ha^{-1}$); iii) pest control (deltamethrin, 2 $kg \cdot ha^{-1}$); iv) mechanical weed control; and v) irrigation (400 $m^3 \cdot ha^{-1}$).

Medium rotation forestry

In this system, although the total duration is ten years, cutting take place only twice (every 5 years), using: i) a self-propelled harvester (felling operation); ii) a tractor coupled with a trailer equipped with pincers (whole tree transport from field to chipping place); and iii) a fixed wood chipper. The chipping machine directly loads the fresh biomass on trailers (no. 3 tipping trailers pulled by wheel tractors) which transport the material to the farm storage (distance: 2.0 km). The cumulative wood chip production of the MRF plantation has been estimated to be 173 $t_{DM} \cdot ha^{-1}$ (35 t_{WB} ha^{-1}; moisture 55% wb).

Crop management includes: i) nitrogen fertilization (urea 46% N, 200 $kg \cdot ha^{-1}$ of N) after the harvesting operation excluding the last one; ii) weed control (gluphosinate-ammonium: concentration 11.3%, 4 $kg \cdot ha^{-1}$) in years 2, 6 (two times) and 7; iii) pest control (deltamethrin, 2 $kg \cdot ha^{-1}$,) in years 2, 6 and 7; iv) mechanical weed-control in years 2 (two times), 3, 6 (two times), 7 (two times) and 8; v) irrigation (400 $m^3 \cdot ha^{-1}$) in years 2, 5 and 6.

Soil restoring

In both the cultivation systems, after the last biomass harvesting (10th year), the soil will be restored by a hoeing machine.

Inventory analysis

A central step of LCA consists in making a model of the product life cycle with all the environmental input and output; this data collection stage is usually named Life Cycle Inventory (LCI).

Primary and site-specific information has been collected mainly by local tests as well as interviewing the two farmers involved. The two SRC plantations have not yet been removed; SRF is in its 5th year while MRF is in its 4th.

In detail, for both the poplar cultivation systems, the data on technical characteristics of machines, the operating time and the fuel consumption originate from field trials, specifically carried out on organic and mineral fertilization, ploughing, chemical and mechanical weed control, and pest control. For the SRF system, experimental data from years 2 and 4 were collected on biomass harvesting and transport operations while for the MRF system, since the plantation has not been yet harvested, the technical data refer to previous studies carried out in similar conditions (Fiala *et al.*, 2010; Bergante, 2010; González-García *et al.*, 2012; Bacenetti and Fiala, 2011).

Equally, since for both the SRF and MRF systems the final soil restoration has not been carried out (poplar cycle still in progress), the data utilised in the analysis are gathered from other research (Gasol *et al.*, 2009; Bacenetti and Fiala, 2011; Fiala and Bacenetti, 2012a and 2012b).

Secondary data for the input factors (urea, deltamethrin, glyphosate and gluphosinate-ammonium, oil and lubricants) have been assumed from the Ecoinvent 2.2 Database (Althaus *et al.*, 2007). The production cost of the cattle manure has not been included in the analysis (by-product resulting from another process); only its distribution and the derived diffuse emissions have been analysed.

Carbon stored inside the biomass has been estimated on the basis of the carbon percentage of dried biomass (Fiala *et al.*, 2010); both above and below ground biomass (roots and stools) have been considered since the latter represents a potential pool for carbon storage. A below/above ground biomass ratio of 0.20 (Matthews, 2001) has been assumed. For both the SRF and MRF cultivation systems, no change in the overall soil carbon content has been assumed because the fields were previously dedicated to poplar for industrial purposes (paper and furniture). A wood chip LHV of 18.5 $GJ \cdot t_{DM}^{-1}$ has been considered (Fiala *et al.*, 2010).

Methodology

Among the steps defined within the life cycle impact assessment stage of the standardized LCA methodology, only classification and characterisation stages (ISO, 2006) (Guinée, 2011) were considered here.

Normalisation and weighting were not conducted because these optional aspects did not provide additional significant information pertinent to the study objectives.

The assessment has been focused on the GWP. The characterisation model developed by the Intergovernmental Panel on Climate Change (IPCC) was selected for development of the characterisation factors, expressed as the global warming potential for a time horizon of 100 years (GWP100).

Furthermore, an energy analysis was carried out based on the cumulative non-renewable fossil and nuclear CED (VDI - Richtlinie, 1997), computed according to Althaus *et al.* (2009).

SimaPro 7.3.2 software was used for the computational implementation of the inventories (PRé Consultants bv).

Allocation procedure

Since only the production of useful biomass (wood chips) has been considered, the allocation is not required and all the environmental effects have been assigned to the harvested wood chips. During poplar

Table 2. General information about the short rotation forestry and medium rotation forestry poplar plantations.

	Unit of measure	SRF	MRF
Age	Year	5	4
Field size	ha	2.398	2.187
Field shape	-	Polygonal	Polygonal
Average distance from farm storage	km	2.5	2.0
Average basal tree diameter at cut	cm	9.90	21*
Duration	Year	10	10
Wood chips yield	$tDM \cdot ha^{-1} \cdot year^{-1}$	16.85	17.30°

SRF, short rotation forestry; MRF, medium rotation forestry. *Estimated values because the MRF plantation has not already harvested; °Average value on the basis of 2nd and 4th years wood chips yield.

growth, further biomass is produced but not harvested (leaves and stools); just like parts of the natural process in the coppice management system, it was assumed that these bio-materials do not cause emissions.

Results

Table 3 reports the energetic (CEO, CED, NER) and the environmental (fixed CO_2, GHG, GWP) performances, related to the selected FU for both the SRF and the MRF cultivation systems. Similarly, Figure 2 shows the comparison between the MRF and the SRF performances, assuming the SRF system as baseline.

From the environmental point of view, the production of wood chips from the MRC system results in lower GHG emissions (-6.2%) than the SRF system; also considering the CED, the best responses are achieved from the MRF (-11.0%). These results agree with other recent studies on poplar SRF (Bergante *et al.*, 2010) and on black locust SRF (González-García *et al.*, 2012).

Global warming potential

The production of renewable biomass (above and below ground) presents a carbon sink due to CO_2 taken up by the biomass during its growth. This biomass CO_2 absorption *offsets* the GHG emissions related to the SRC cultivation, like the CO_2 caused from: i) fuel combustion in tractor (or self-propelled machine) engines; ii) the fabrication of agro-chemicals; and iii) the on-field emissions (N_2O from fertilisers, which contribute to the net GWP score and are included in the analysis). Table 4 shows the contribution of each operation involved in both poplar management systems in GWP: 5660 and 5307 t of fossil CO_2/ha^{-1} originate from all activities associated, respectively, to the SRF and the MRF cultivation systems. But, at the same time, -370.8 and -380.6 t CO_2 are fixed during the biomass growth for the SRF and the MRF systems, respectively.

In terms of GHG emissions, the *hot spots* (Table 4) are: i) the mechanical weed control; ii) the fabrication of urea; iii) the harvesting and biomass transport. N_2O and fossil-CO_2 dominate the GHG emissions with shares of 18.1% and 81.8% in the SRF and 22.7% and 75.6% in the MRF system, respectively.

Energy performances

The consumption of different non-renewable (fossil and nuclear) and renewable sources has been analyzed in terms of energy equivalent. Concerning the CED, 59.7 GJ ha^{-1} and 84.6 GJ ha^{-1} are required throughout the 10-year plantation under MRF and SRF cultivations, respectively; this means that the SRF cultivation system requires approximately 12% more energy than the MRF system. This is mainly due to the higher rate of fertilisers and the more rigorous cycle management (in terms of harvesting, fertilizing and pest control events). N fertilization, mechanical weed-control and wood chip harvesting represent the energy input *hot spots*, with corresponding contributions of 28%, 26% and 12% in the SRF system, and 24%, 15% and 31% in the MRF system.

Also, in consideration of CEO, the MRF system gives the best results, reaching 3200.5 GJ·ha^{-1} *versus* the 3117.8 GJ·ha^{-1} for the SRF system.

Consequently, the NER (energy output compared to the energy consumption) for the biomass production is much more favorable for the MRF system (NER=42.1) than for the SRF (NER=36.4).

Table 3. Environmental and energy results related to the functional unit (FU=1 ha of short rotation forestry and medium rotation forestry).

Results	Unit of measure	SRF	MRF
CEO	GJ eq·ha^{-1}	3117.8 (100%)	3200.5 (102.7%)
CED	GJ eq·ha^{-1}	83.3 (100%)	74.2 (89.0%)
NER=CEO/CED	-	36.4 (100%)	42.1 (115.7%)
Fixed CO_2 (in the total biomass)	t CO_2 eq·ha^{-1}	370.8 (100%)	380.6 (102.7%)
GHG emissions	kg CO_2 eq·ha^{-1}	5660.5 (100%)	5307.4 (93.8%)
GWP	t CO_2 eq·ha^{-1}	-365.1 (100%)	-375.3 (102.8%)

SRF, short rotation forestry; MRF, medium rotation forestry; CEO, cumulative energy output; CED, cumulative energy demand; NER, net energy ratio; GHG, green house gases; GWP, global warming potential.

Table 4. Short rotation forestry and medium rotation forestry cultivations system: greenhouse gases emissions for each operation.

Operation	SRF		MRF	
	kg CO_2 eq·ha^{-1}	%	kg CO_2 eq·ha^{-1}	
Organic fertilization	154.5	2.7%	137.1	2.6%
Ploughing	98.9	1.7%	87.8	1.7%
Planting*	245.4	4.3%	108.2	2.0%
Harrowing	116.4	2.1%	103.3	1.9%
Chemical weed control	94.4	1.7%	91.8	1.7%
Pest control*	72.9	1.3%	51.2	1.0%
Mechanical weed control	755.2	13.3%	1005.3	18.9%
Nitrogen fertilization*	1094.7	19.3%	588.0	11.1%
Harvesting	1402.0	24.7%	905.6	17.1%
Biomass transport	558.1	9.8%	1276.1	24.0%
Soil restoration	125.9	2.2%	111.7	2.1%
On-field emissions°	948.1	16.7%	841.3	15.9%
Total	5660.5	100%	5307.4	100%

SRF, short rotation forestry; MRF, medium rotation forestry. *Including the mechanical operation and the employed material (cuttings/rod, chemical, fertilizer); °Emissions from the soil due to mineral and organic nitrogen application.

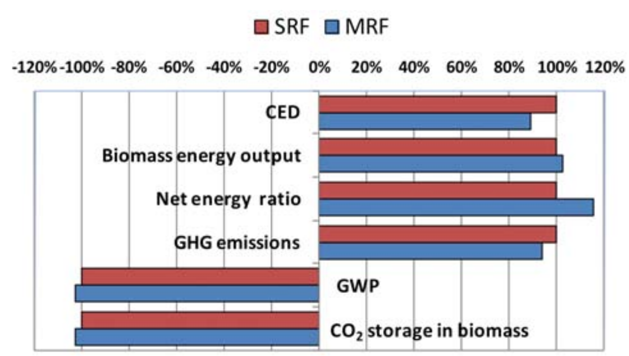

Figure 2. Poplar short rotation forestry (SRF) and medium rotation forestry (MRF) energetic and environmental compared performances. The SRF cultivation system is assumed as baseline (index=100%). CED, cumulative enregy demand; GHG, greenhouse gases; GWP, global warming potential.

Discussion

In Italy, the most important specie planted for energy use (wood chip production) is the poplar (Bergante *et al*., 2010; Bacenetti and Fiala, 2011). The biomass yield and its quality (*i.e.,* cellulose, lignin and ash contents) depend heavily on several factors which must be taken into account. In this paper, the cultivation techniques (field operations, fertilizers, chemicals and water etc.) as well as the cultivation system (cutting frequency) have been carefully considered.

Poplar plantations managed under the MRF cultivation system provide better environmental performances than those under the SRF system. This result can be extended to other short rotation coppice species also cultivated in Italy. González-García *et al.* (2012) checked the cultivation of black locust under the same two management systems and also their results confirm that the MRF system gives a higher biomass yield with a less intensive production process in terms of CED (lower number of operations). Higher biomass yields for MRF poplar plantations have also been identified by Fang *et al.* (1999) and by Guidi *et al*. (2009).

Taking into account the results obtained in this paper, special attention should be paid to some aspects in order to further reduce the environmental impact related to the SRF and the MRF cultivation systems. In particular, these aspects concern the use of N-fertilisers and the intensity of certain agricultural operations (mechanical weed control, biomass harvesting and transport) which represent the *hot spots* both for GHG emissions and for energy consumption.

NER is considerably higher for the MRF (+15.7%) than for the SRF system. However, under both systems, NER is higher than values obtained in previous research (14-19 in Turhollow and Perlack, 1991; 29 in Matthews, 2001; 8.8 in Walle *et al.*, 2007; 8.0 in Manzone *et al.*, 2009). In any case, it must be considered that, in the present study, the wood chip yield is quite a lot higher.

Nitrogen mineral fertilisation has been identified as a very intensive operation and the most energy-demanding step of the entire biomass production cycle (Gasol *et al.*, 2009; Di Candilo *et al.*, 2010; Fiala and Bacenetti, 2012a and 2012b). The use of manure (or digestate from anaerobic digestion plants) instead of mineral fertilisers could help to reduce the energetic and the environmental loads.

Overall, under the studied conditions, a comparison of the SRF and the MRF systems shows that the poplar plantation with a longer rotation achieves the best result in terms of both energy resources and the environment. This difference is certainly due to the higher MRF system yield but also to: i) the lower nitrogen fertilisation; ii) the different planting material; and iii) the low intensity of applied mechanisation.

The above results do not refer to small and experimental plots but concern two real farm poplar plantations with a total surface of 4.5 ha. For most of the field operations, the data inventory was drawn up on the results of specific field tests carried out during the first growing years.

Further research will take collect experimental data also regarding future operations and, in addition, will compare several poplar plantations characterised by the same management system.

Conclusions

Two SRC poplar plantations (managed under two different cultivation systems), located in the Lombardy region of northern Italy, devoted to biomass production for energy purposes (wood chips), were monitored in detail. The best cultivation system to obtain environmentally more sustainable wood chips was clearly identified. Several differences were observed in terms of fertiliser requirements and intensive agricultural activities. According to the environmental results, the MRF, based on a 5-year cutting frequency, is the best cultivation system to obtain a more environmentally sustainable biofuel source, characterised by higher biomass yield, lower energy requirements and lower levels of CO_2 emissions.

Under both the SRF and the MRF cultivation systems, the environmental and energy *hot spots* were identified as: i) mineral fertilisation; ii) mechanical weed-control; iii) harvesting and biomass transport

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