Environmental performances of Giant Reed (*Arundo donax* L.) cultivated in the Mediterranean.

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Abstract

Several authors highlighted the high yields and low environmental impacts associated with the cultivation of perennial rhizomatous grasses (PRGs). Moreover, the cultivation in marginal or poor cultivated land is suggested to not compromise food security and to overcome land use controversies. However, the consequences in terms of environmental impacts of using different type of soils are still not clear. Thus, the main objective of this study was to assess the environmental performance of two giant reed (GR) systems cultivated in a fertile loam soil (FL) and in a poor sandy loam soil (PSL) thought a cradle to plant gate LCA. The following indicators were analyzed: energy balance, GHG emissions (including LUC), and the main impacts on air, water and soil quality. The annualized soil carbon sequestration was in both systems more than twofold the total GHG emitted, equal to -6464 kg CO_2eq ha^{-1} in FL and -5757 kg CO_2eq ha^{-1} in PSL. Overall, the results of our study highlighted that soil characteristics affected not only GR yield level but also its environmental impact that seems to be higher in PSL system both on hectare and tonne basis. As a consequence, the production of GR biomass on this type of soil could led to higher environmental impacts and a more extended land requirement.

Highlights:

Keywords: perennial rhizomatous grasses (PRGs), soil organic carbon (SOC), carbon sequestration, Life Cycle Assessment (LCA), greenhouse gas emission (GHG), energy efficiency

1 Introduction

The demand for sustainable renewable biological resources as feedstock for bioenergy and biofuel production is currently expanding, due to concern of climate change and energy security (Ragauskas et al., 2006; EIA, 2013). Among renewable energy sources, biofuels are expected to be the main form of energy for transport for decades, and could contribute to ease the transition away from finite energy sources towards renewable ones, while mitigating global climate change (Harvey & Pilgrim, 2011; Sims *et al*., 2006; El Bassam, 2010; Chum et al., 2011; Gabrielle et al., 2014).

Perennial rhizomatous grasses (PRGs) are an attractive source of feedstock for biofuel production, owing to the high yield potential, low environmental impact and good attitude to energy conversion these crops generally show (Lewandowski et al., 2003; Rettenmaier et al., 2010). Bioenergy crop production is expected to be restricted to marginal or poor cultivated land in order not to compromise food security and to overcome land use controversies (Shortall, 2013). However, this is constrained when the high establishment costs of PRGs is associated with relatively lower yields. In fact, the comparison of switchgrass (*Panicum virgatum* L.) and miscanthus (*Miscanthus* x *giganteus* Greef. et Deu.) performances under rainfed conditions in Mediterranean environment highlighted a yield reduction of about 40% from a silty loam to a sandy soil in both species (Roncucci et al., 2014; Nassi o Di Nasso et al., 2015).

Among PRGs, giant reed is one of the most promising for Mediterranean environments. The crop displays good yield potentials and low input requirements in both fertile and marginal soils (Lewandowski et al., 2003; Angelini et al., 2005; Nassi o Di Nasso et al., 2013). To date, most of the information on giant reed have dealt with its productivity and nutrient dynamics, while few attempts have been made to explore the environmental performances of giant reed cultivation (Mantineo et al., 2009; Fazio and Monti, 2011; Forte et al., 2015).

The life cycle assessment (LCA) has proven to be a suitable methodology to evaluate the environmental performance of energy crop and bioenergy supply chains, while also being the methodology adopted by the European Commission to evaluate the sustainability of biofuels (EC, 2009). A considerable number of studies addressed environmental impacts of biomass and biofuels production, nonetheless the main factors that could affect the bioenergy crop performances appear still unclear and many site-specific variables could strongly influence the LCA analysis. Two of the most utilized indicators in LCA studies are the energy efficiency and greenhouse gas (GHG) emissions. A positive energy balance is the first issue to be addressed when considering energy as the end-product (Cherubini et al., 2011). During crop production phase, the maximization of the energy balance may be seek through a reduction of input and/or an increase of output. Since crop productivity plays a predominant role on driving the level of the outputs, it is fundamental to maximize crop yields, even when resources (e.g. crop inputs, water, soil quality, solar radiation) are limited (Karp & Shield, 2008). When investigating the energy balance of perennial crops under different crop managements in the Mediterranean, some authors have highlighted an higher energy efficiency of giant reed respect to other species (e.g. miscanthus) (Angelini et al., 2009; Mantineo et al., 2009; Monti et al., 2009; Fazio and Barbanti, 2014).

Using the LCA approach, Fazio and Monti (2011) have confirmed a lower GHG emissions of giant reed respect to annual crops and other PRGs, thus confirming the potential contribution of these crops to GHGs reduction targets. Nevertheless, the production of biofuels may not be necessarily carbon neutral, as emissions of CO_2, CH_4 and N_2O during crop cultivation phase and feedstock conversion may reduce or completely counterbalance GHG savings of the substituted fossil fuels (Crutzen et al., 2007; Fargione et al., 2008; Johnson, 2009; Searchinger et al., 2011; Don et al., 2012). Indeed, the carbon footprint of bioenergy crops may considerably vary taking into account different soil conditions and management practices. For instance, the inclusion of changes in soil organic carbon (SOC) due to land use change (LUC) within LCA of bioenergy crops has been shown to significantly influence estimates of total and net GHG emissions (Adler et al., 2007; Brandao et al., 2011; Felten et al., 2013; Sanscartier et al., 2014). This ensues from the fact that cultivating perennial species may increase SOC stock while sequester carbon from the atmosphere (Hansen et al., 2004; Anderson-Texeira et al., 2013; Agostini et al, 2015; Ferchaud et al., 2015).

The potential of these species to sequester carbon is however site-specific, as it depends on the former land use history, on climate and soil characteristics (Lemus and Lal, 2005; Powlson et al., 2011; Agostini et al, 2015). It has been proposed that C sequestration under perennial energy crops should be at least 0.25 t C ha^{-1} $year^{-1}$ in order to make the crop C-neutral when converted to biofuel. To date, estimates of C sequestered under these crops range between 0.6 and 3.0 t C ha^{-1} $year^{-1}$ (Agostini et al., 2015).

In this work we used data originating from two long term experiments involving giant reed cultivated under Mediterranean conditions (Central Italy) to analyze the environmental performance of giant reed cropping systems in two contrasting soils thought a cradle to plant gate LCA. Two main objectives were identified: (i) to evaluate the effect of soil characteristics on the overall environmental impact of giant reed; (ii) to assess the importance of soil organic carbon changes in the overall GHG balance of this crop.

2 Materials and methods

2.1 Functional unit and system boundaries

The life cycle assessment (LCA) methodology was applied thought a cradle to plant gate LCA in rainfed giant reed systems grown in two experimental trials in Central Italy with different soil characteristics.

Depending on the objective, the sustainability of a bioenergy chain can be assessed through different Functional Units (FUs). Here, two FUs were chosen to explore the results: 1 ha of giant reed and 1 tonne of dry GR biomass.

The system boundaries included: (i) the agricultural production subsystem, i.e. rhizome nursery, giant reed planting, cultivation and destruction; (ii) the harvested biomass transport subsystem, from the field to the plant gate (Figure 1).

The cultivation of giant reed was modelled including the overall lifespan of the cropping systems and it was organized in three sub-phases: crop establishment, crop cultivation, plant destruction, as suggested by many authors for the modellisation of perennial crops (Bessou et al., 2013). The considered giant reed lifespan was 12 years for both systems, thereby all the energy and resources consumption for the cultural practices and related emissions to the environment were annualized. The biomass conversion phase was not included in the present study.

Fig. 1 -> System boundary

2.2 Giant reed system inventory

2.2.1 Giant reed rhizome nursery

Data for the production of giant reed rhizomes were retrieved from an existing nursery (BioChemtex Agro, Tortona, Italy). Soil preparation was performed by ploughing and chemical weed control (glyphosate 4 kg ha^{-1}). The nursery was established using giant reed micropropagated plants (10,000 plants per hectare). Plants were fertilized with 160 kg N ha^{-1}, 122 kg P_2O_5 ha^{-1}, 122 kg K_2O ha^{-1}. Subsequently, after two years of growth, rhizomes were harvested. Each hectare of nursery allowed about 8 hectares of giant reed plantation to be established with a plant density of 20,000 plant per hectare. Giant reed rhizomes were assumed to be transported for 50 km by tractor and trailer with an estimated consumption of about 470 kg diesel per hectare of nursery to be established.

2.2.2 Giant reed cultivation

Giant reed experimental fields were carried out in soils previously cultivated with annual crops at the Centre for Agro-Environmental Researches of the University of Pisa, in San Piero a Grado

(Pisa), Italy. The climate is typically Mediterranean with mean annual precipitation of 907 mm and mean annual temperature of 15°C (long term average 1986-2013).

Two giant reed experiments were used as source of primary data for the cultivation on a fertile loam soil, characterized by good organic matter and nutrient availability (FL) (Angelini et al., 2009) and on a poor sandy loam soil, showing low organic matter and nutrient availability (PSL) (Nassi o Di Nasso et al. 2013). The characterization of the soils is given in Table 1.

Tab. 1 Soil characteristics.

Data for the FL system were collected from 1992 to 2003. Mouldboard ploughing (30-40 cm) was performed in the autumn before transplanting. Seedbed preparation was conducted in the spring, immediately before planting, with a double-disk harrowing and a field cultivator. Pre-plant fertiliser was distributed at a rate of 100 kg N ha^{-1} (urea), 100 kg P_2O_5 ha^{-1} (triple superphosphate) and 100 kg K_2O ha^{-1} (potassium sulphate), taking into account the nutrient availability of this soil.

Crop was established with 20,000 rhizomes per hectare. Mechanical weeding was performed during the establishment year, while irrigation treatment and pest control were never necessary over the crop lifespan (Angelini et al. 2009). The same fertilization rate was applied annually in spring time in the following years.

Data for the PSL system were collected from 2009 to 2013. Chisel ploughing was performed in the autumn of 2008, followed by rotary harrowing immediately before transplanting. Crop was fertilized at crop establishment and yearly with 120 kg N ha^{-1} (urea), of 120 kg P_2O_5 ha^{-1} (triple super phosphate), 120 kg K_2O ha^{-1} (potassium sulphate), in relation to the lower nutrient level of this soil. The planting density at the establishment was of 20,000 plants ha^{-1}. Weeding, irrigation and pest control were never necessary (Nassi o Di Nasso et al. 2013).

In both FL and PSL systems, giant reed was harvested in autumn through a cutter-shredder-loader. Giant reed dry yields equalled to 36.9 t d.m. yr^{-1} in FL, as average of 12 years, and 18.2 t d.m. yr^{-1} in PSL, as average over 5 years of growth.

The destruction of giant reed plantation at the end of the 12^{th} year of growth was supposed to be performed through a combination of mechanical (i.e. cultivator) and chemical treatments (two applications of 7.5 kg of glyphosate each).

2.2.3 Giant reed biomass transport to the plant

The transport of giant reed biomass was assessed from the field to the plant gate. Biomass was assumed to be loaded on a walking floor truck with 94 m^3 payload capacity (28 t) and transported to the plant for 70 km. The average diesel consumption was supposed to be about 5 kg of diesel per t of biomass (BioChemtex Agro, personal communication).

The life cycle inventory from the field to the plant gate of the FL and PSL systems is reported in Table 2. Giant reed biomass is the only output from cultivation phase, so no allocation of inputs and environmental impacts was necessary.

Table 2: LCI of cultivation and transport.

2.3 Impact assessment

2.3.1 LCIA impact categories

In this study, a set of indicators was used to characterize the environmental sustainability of giant reed cultivation, namely the energy balance, the gross and net greenhouse gas (GHG) emissions and the main impacts on air, water and soil quality, namely eutrophication potential, acidification potential, ozone layer depletion potential and photochemical ozone creation potential.

The modellisation and the impact assessment of the giant reed systems were performed using the GaBi6 software package developed by PE International (GaBi6, 2013), the bundled professional database (GaBi6, 2013) and the ecoinvent database (ecoinvent Centre 2007, version 2.2).

2.3.2 Energy analysis

In order to assess the amount of energy spent in exchange for energy gained, the primary energy required for the cultivation and the transport of 1 hectare and 1 dry tonne of giant reed biomass was evaluated through the Cumulative Energy Demand (CED). Thereafter, Gross Energy (GE), representing the amount of energy produced, was calculated by multiplying the dry biomass yield by the lower heating value (LHV). The LHV of giant reed biomass was 17.6 MJ kg^{-1}, as reported by Angelini et al. (2009). Based on GE and CED, two different indicators were used in energy assessments: Net Energy (NE), as the difference between GE and CED, and Energy Efficiency (EE), as the ratio between GE and CED.

2.3.3 GHG emissions

To assess the greenhouse gas emissions was used the Global Warming Potential excluding biogenic carbon (GWP) impact category, CML version April 2013 (Guinée et al. 2002). Direct and indirect N_2O soil emissions from nitrogen fertilisers were calculated using the IPCC methodology and emissions factors (IPCC, 2006). Biogenic carbon, such as carbon stored in giant reed biomass, was not considered in the LCA according to the ILCD Handbook and IPCC Guidelines (EC, 2010; IPCC 2006). Total GHG emissions were defined as the sum of the cultivation and transport phases.

Annual soil carbon sequestration due to land use change (LUC) from arable to perennial crop was included in the analysis of both giant reed systems. Data on soil carbon evolution in L system were collected after 12 years of giant reed cultivation (unpublished data). Similarly, soil carbon sequestration rate in SL system was derived using data reported by Roncucci et al. (2015). The annual increment of soil organic carbon (0-0.3 m) in L and SL systems is presented in Table 3.

Tab. 3: Annual soil C sequestration.

Soil carbon storage, expressed on an annual basis as t C ha^{-1} yr^{-1}, was converted into t CO_2 ha^{-1} yr^{-1} using a CO_2/C molar mass ratio of 3.66 (44 g $mole^{-1}$ CO_2/12 g $mole^{-1}$ C). Then, net GHG emissions were calculated subtracting the CO_2 sequestered in soil from the total GHG emissions.

Indirect Land Use Change (iLUC) effects occurs at global scale and it cannot be exactly allocated to the cultivation of specific crop since it is linked to the cultivation of energy crop via economic market mechanisms. Besides, to date there is no common accepted methodology to assess iLUC and values found in literature are characterized by large uncertainty (Finkbeiner, 2014). Thereby, indirect LUC effect were not included in the present study.

2.3.3 Eutrophication potential

The eutrophication potential was assessed taking into account nitrogen (N) and phosphorous (P) compounds release to environment in giant reed systems grown in loam or in sandy loam soils. N balance was defined and quantified considering site-specific conditions for the main input and output flows. Inputs included: (i) N supplied by precipitations, calculated as product of the annual rainfall (m^3 ha^{-1}) and its mean value of nitrogen concentration (2 mg N L^{-1}); (ii) N supplied by fertilisers, equal to 100 and 120 kg of N ha^{-1} $year^{-1}$ in loam or in sandy loam soils, respectively and (iii) available N from organic matter mineralization. In both soils, available nitrogen per year was calculated as product of the initial N soil content (Table 1) (kg N ha^{-1}), and the mineralisation coefficient (k_2). As in Boiffin et al. (1986) and Bockstaller and Girardin (2003), k_2 was calculated for each soil as follows:

$$k_2 = 1200\, f_\theta / [(c + 200)\,(l + 200)]$$

where f_θ is a temperature factor given by $f_\theta = 0.2\,(T-5)$, T is mean annual air temperature (°C), c is clay content (g kg^{-1}) and l is limestone content (g kg^{-1}). Since aboveground giant reed residues are modest (Nassi o di Nasso et al; 2010), their contribute to nitrogen availability in the soil was considered negligible. Moreover, biomass turnover of rhizomes and roots was not taken into account as nitrogen source, due to the uncertainty of its contribution.

Outputs included: (i) nitrogen uptakes related to the harvested biomass, as product of biomass nitrogen concentration (Nassi o di Nasso et al., 2011 and 2013) and biomass dry yield reported in Angelini et al. (2009) and Nassi o Di Nasso et al. (2013); (ii) nitrogen emissions to air for ammonia volatilisation and direct and indirect nitrous oxide emissions (IPCC, 2006) (iii) nitrogen emissions to soil and water for nitrates leaching. N losses for leaching were calculated at monthly time steps adopting a modified version of the simplified method of Shaffer et al. (2010) as:

$$NL = NAL \cdot (1.0 - e^{-k \cdot WAL/[(1-(BD/PD)) \cdot D_{leach}]})$$

with NL the annual N leaching (kg N ha^{-1} yr^{-1}); NAL the N potentially available for leaching (kg N ha^{-1} yr^{-1}), calculated as 50% of all the N in input; k is an empirical constant (1.2); WAL is water available for leaching (cm); BD the soil bulk density (mg m^{-3}); PD the soil particle density (mg m^{-3}); we used a general value of 2.65 and D_{leach} the leaching depth (cm): the depth beyond which N may be considered leached. D_{leach} was set equal to the approximate maximum rooting depth of the crops assessed. For giant reed we assumed 100 cm (Monti and Zatta, 2009). WAL was estimated as difference between the annual precipitation (cm) and the annual crop evapotranspiration (cm) (Triana et al., 2014).

Ammonia volatilized was estimated using the EMEP/CORINAIR emission factors (EMEP/CORINAR, 2002). The overall N balance was reported in Table 4.

Tab. 4: N balance.

Emissions of phosphorous were estimated considering three different emissions to water, leaching and run-off of soluble phosphate, erosion of soil particle containing phosphorus, following the approach of PCR for arable crop (PCR 2013:05 v 1.0).

2.3.4 Sensitivity and uncertainty analysis

A sensitivity analysis was performed to identify key parameters in the model. A variation of ±25 % from baseline values was applied across all of the main parameters. The overall model uncertainty was quantified for each indicator using Monte Carlo simulation as suggested by Huijbregts (1998), with 1,000 iterations.

3 Results

3.1 Net energy and energy efficiency of giant reed cultivation

The CED necessary for the cultivation of giant reed was similar in the two systems, equal to 25.7 GJ ha^{-1} and 26.0 GJ ha^{-1}, in FL and PSL respectively (Table 5). The use of fertilizers was the highest contributor in both systems, representing the 65% in FL and the 77% in PSL of the total energy requirement. Diesel consumption for the cultivation phase represented 26% and 13% of the total energy demand, in FL and PSL respectively. Among crop operations, harvest showed the highest diesel consumption (data not shown).

In terms of energy output, GE was proportional to the crop yield, ranging from 649 GJ ha^{-1} in FL to 321 GJ ha^{-1} in PSL. On an hectare basis, the net energy was about twofold in FL soil compared to PSL soil. Conversely, the NE showed similar values when calculated on a tonne basis, around 16 GJ t^{-1}. Regarding the EE, a ratio between energy output and energy input of about 25 GJ GJ^{-1} was observed in FL, while in PSL the value was halved to 12 GJ GJ^{-1}, both on hectare and tonne basis.

Tab. 5 -> CED, GE, NE, EE fase agricola + trasporto

3.2 Net GHG emissions of giant reed cultivation

The GHG emissions of giant reed cultivation amount to 2521 kg CO_2eq ha^{-1} for the FL and to 2667 kg CO_2eq ha^{-1} for the PSL. Emissions directly (N_2O emissions from soil) and indirectly (fertilizer production) related to fertilisation are the main contributors, exceeding the half of the total emissions for FL (32% and 42%, respectively) and more noticeably for PSL (36% and 47%, respectively) (Table 6). Nursery phase and the establishment accounted in both cases only for the 1.5% and about 5% of the total emissions. Similarly, system destruction accounted for about 1% of the total emissions, mainly due to the use of a herbicide for land clearing.

The annualized soil carbon sequestration was in both cases more than twofold the total GHG emitted, equal to -6464 kg CO_2eq ha^{-1} in FL and -5757 kg CO_2eq ha^{-1} in PSL. So, the net GHG balance for both GR systems is negative, that is in the cultivation phase they sequestered more CO_2 than the GHG emitted in the giant reed life cycle.

Tab. 6 -> GHG cultivation phase

3.3 Other indicators at cultivation phase

The evaluation of other indicators (AP, EP, ODP, POCP) showed an overall worse performance of PSL compared to the FL, with on average slight differences on hectare basis and marked differences on tonne basis (Fig. 2). On the whole, main sources of emissions to environment were at cultivation phase mainly related to fertilizers production, direct emissions from soil and diesel consumption.

In details, for AP highest values was observed in the PSL, showing 12% higher value on hectare basis (FL 44 and PSL 50 kg SO_2eq ha^{-1}) and 56% on tonne basis (FL 1.2 and PSL 2.7 kg SO_2eq t d.m.$^{-1}$). The main contributors were related to fertilizer production (32%) and its emissions from the soil (58%) for both systems.

EP showed a similar trend, with +30% higher impact in PSL on hectare basis (FL 20 and PSL 28 kg PO_4eq ha^{-1}) and +65% on tonne basis (FL 0.5 and PSL 1.5 kg PO_4eq t $d.m.^{-1}$). Here the direct and indirect emissions related to fertilization amounted to 89% and 93%.

The impact as ODP was related mainly to fertilizer production, covering on average 89% of emissions in both systems on hectare basis (FL 8.5 E-05 and PSL 1.0 E-04 kg R_{11}eq ha^{-1}) and on tonne basis (FL 2.3 E-06 and PSL 5.6 E-06 kg R_{11}eq t $d.m.^{-1}$).

The net POCP impact was mainly related in both systems to fertilizer production and secondarily to diesel consumption, while emissions from soil showed a negative values due to nitrogen monoxide emissions. On hectare basis L showed slightly higher values than SL (+14%) (L 1.0 and SL 0.9 kg $ethene_{eq}$ ha^{-1}), while on tonne basis L showed marked lower values (-73%) (L 0.028 and SL 0.048 kg $ethene_{eq}$ t $d.m.^{-1}$).

Fig 2 -> Other indicators....

3.4 Results of giant reed cultivation and transport

The biomass transport from the farm to the plant gate considerably increase the impact of the two systems (Table 7). Indeed, on hectare basis, biomass transport represents the 35% and the 21% of the total energy input in FL and PSL, respectively. The net energy (NE), inclusive of both agricultural and transport phases, is higher for the FL, 610.1 GJ ha^{-1}, than for the PSL, 288.2 GJ ha^{-1}. In term of energy efficiency (EE) the FL system performs better than the PSL showing a EE value of 16.5 respect to 9.8. Similarly, GHG emissions related to the transport of GR biomass are higher in the FL respect to the PSL, representing the 25% and the 14% of the total emissions for FL and PSL, respectively.

The impact on AP and EP slightly increased adding the transport to the plant by 9% and 4%, for FL and PSL respectively. On the contrary the impact for ODP and POCP was markedly affected by biomass transport, indeed ODP increase by 24% and 12% for FL and PSL, while values of POCP rose by 39% and 27%.

Table 7 -> tutti gli indicatori

3.5 Sensitivity and Montecarlo analysis

The sensitivity analysis revealed that the most influential parameters were soil carbon sequestration (GWP), nitrogen fertilization rate (AP, GWP, EP) and GR yield, due in particular to harvest and transport consumption (EE, POCP) (Table 8).

The outcomes of the Monte Carlo analysis revealed that uncertainty of the main parameters of the model had a significant influence on the LCA results. AP, EP, ODP, POCP showed an overall uncertainty from -38 to + 60% in both GR systems, while EE shower a lower value from 8 to -13% on average. GWP was largely affected by soil C sequestration, in both soils the inclusion of soil C caused a huge uncertainty of about -115% to 70% compared to the average value (Table 8).

Table 8 -> sensibilità/Montecarlo

4 Discussions

To date, only a few studies have investigated the environmental profile of a giant reed cropping system. To the best of our knowledge this is the first attempt to analyze the effect of soil characteristics on the LCA of giant reed, comparing crop performances in a fertile loam soil or in a poor sandy loam soil under Mediterranean conditions. In addiction, the present study analysed the whole giant reed lifetime (nursery, establishment, cultivation, destruction phases) and the biomass transport to the plant.

Overall, the comparison of the two GR systems highlighted slightly differences on hectare basis that were amplified on tonne basis due to marked differences in crop yield. Afterwards, GR yield represents the key parameter influencing the environmental performances of the two systems.

The values of yield under rainfed conditions chosen as representative for FL and PSL are in line with the mean values observed by several authors in the Mediterranean with an average crop yield 20 t d.m. ha^{-1} yr^{-1} in poor soils (Fagnano et al. 2015; Cosentino et al., 2014; Lewandowski et al, 2003; Hidalgo and Fernandez, 2001) and about 35 t d.m. ha^{-1} yr^{-1} in fertile soils (Corno et al., 2014; Ceotto et al, 2015). In our study, giant reed yields doubled from a poor to a fertile soil. The analysis of literature highlighted that GR yields are strongly affected not only by environmental and soil characteristics (Corno et al., 2014), but also by management practices such as fertilization and irrigation (Cosentino et al., 2008; Ceotto et al., 2015).

In general, PRGs are characterized by a low input requirements compared to annual crops and consequently the overall environmental impact lies in the management of fertilization, in particular for fertilizer production, and in direct field emissions such as N_2O, NO, NH_3 (Forte et al. 2015; Monti et al. 2009; Fazio and Monti, 2011). It is widely recognized that perennial herbaceous crops present higher energy efficiency than annual crops (Nassi o Di Nasso et al., 2013; Monti, 2009; Bohemel et al., 2008). Among perennial crops, giant reed is considered one of the most promising for Mediterranean environments owing to its great yield potential while demanding for low input requirements (Nassi o Di Nasso et al., 2013).

Comparing our results with those reported by other authors (Table 9), being the calorific value of giant reed biomass rather similar among studies, it resulted that crop yield was the most relevant factor in determining the energy indicators. Values of CED in this paper are similar to Mantineo et al. (2009) and higher than Fazio and Barbanti (2014) (+53%). Nonetheless, Mantineo et al. (2009) included energy costs for irrigation while Fazio and Barbanti (2014) showed halved diesel consumption mainly due to the adoption of different harvesting yards. On the contrary, these differences were not related to the inclusion of nursery and destruction phases, accounting for less than 5% of CED. In fact, nursery, crop establishment and destruction phases are usually excluded from the system boundaries of perennial species. However, their weight is strictly related to the lifespan of the perennial cropping system.

Concerning GE, it was almost twice in FL than in PSL, and comparing this value with literature data, it was exclusively related to biomass yield. The energy efficiency of PSL performed worst compared to FL, showing halved values. In addition, our EE results confirmed available data ranging from 16 to 21. Respect to other perennial herbaceous and woody crops (Table 9), giant reed seems to be characterized by: i) higher input requirements (24 GJ ha^{-1} as mean value of data reported in Table 9 for GR) than miscanthus and switchgrass (13 GJ ha^{-1}) and woody crops (5 GJ ha^{-1}); higher GE due to the yield level; but lower EE (19, 34, 45 in giant reed, other PRGs and woody crops, respectively). However, some authors comparing giant reed and miscanthus in the Mediterranean (Fazio and Barbanti, 2014; Mantineo et al., 2009; Angelini et al, 2009) highlighted a better energy performance of giant reed respect to miscanthus. Subsequently, above mentioned differences may be related to the site-specific conditions, that affect crop management and the choice of mechanical means, but also to the energy coefficients adopted, especially for fertilizers.

Many study in literature highlighted the key role and the benefits of perennial crops in the mitigation of GHG emissions, especially when compared to conventional annual crops (Drewer et al., 2012; Don et al., 2012; Fazio et al, 2014).

GHG gross emissions in both systems accounted for more than 2500 kg CO_2eq ha^{-1} yr^{-1}, showing value in line with Forte et al (2015) and more than twice than data reported by Fazio and Monti (2011), following the same trend previously described for energy balance. CO_2 emissions resulted to be the main contributor to the GHG gross emissions in both systems (average 67% of total emissions), related mainly to fertilizers production and diesel consumption at cultivation. Secondary, N_2O emissions accounted for on average 28% of gross emissions, almost completely due to direct and indirect nitrous oxide emissions from soil. Other studies highlighted higher importance of N_2O emissions in biomass production, reporting values equal 40% of total GHG emissions in switchgrass and about 50% in sugar cane and miscanthus (Cherubini and Jungmeier, 2010; Renouf et al, 2010; Godard et al., 2013).

However, up to now no data exist on direct soil GHG emissions on GR systems and the majority of the available studies estimated N_2O emissions using IPCC emission factor, that is characterized by a large uncertainty without considering site-specific factors related to soil and environmental conditions (Skiba and Smith, 2000). Indeed, the use of the same emission factor in both GR systems could have overestimated nitrous oxide emissions in PSL system, since poor and/or sandy soils are characterized by well aerated conditions and lower mineralization rates (Rochette, 2008; Hellebrand et al., 2010). Moreover, the inclusion of direct soil GHG emissions from GR cultivation in LCA studies can be improved with measured data by using chamber or eddy covariance methods.

Besides, lower nitrous oxide and nitrate losses could be attributed to PRGs compared to conventional cropping systems owing to their higher nitrogen use efficiency (Lewandowski and Schmidt, 2006; Lemus et al., 2008; Nassi o di Nasso et al., 2011, 2013; Don et al., 2012; Roncucci et al., 2014).

In our study, the inclusion of the annual soil sequestration, based on soil measurement after several years of GR cultivation in the Mediterranean environment, confirmed giant reed as a net GHG sink, both in a fertile loam soil or in a poor sandy loam soil, due to a marked soil C sequestration rate equal to 1.8 and 1.6 t C ha^{-1} yr^{-1}, respectively. However, data on the two soil types were recorded after a different number of GR cultivation yield (5 and 12 in PSL and FL respectively), thus in poor soils an higher annual sequestration rate could be achievable after more than 10 years of GR cultivation (Agostini et al., 2015). The annual C sequestration rate reported in this paper largely exceeds the minimum mitigation requirement (0.25 t C ha^{-1} yr^{-1}) under herbaceous and woody perennial reported by Agostini et al. (2015), in order to make the crop C-neutral when converted to biofuel.

These values are in line with those reported by Ceotto et al (2011) in silty loam soil after 7 years of GR cultivation and slightly higher than data recorded after 9 years by Cattaneo et al. (2014) and by

Fagnano et al. (2015) in clay loam soils. Comparing the annual soil C sequestration of giant reed with other PRGs, similar values were observed with average values of 1.2 - 1.6 t C ha^{-1} yr^{-1} for miscanthus and switchgrass respectively (Agostini et al., 2015). It is worthy to mention that while several data were recorded on the amount of different C inputs to soil, such as litter, roots and rhizomes, for miscanthus and switchgrass, no information is available on the influence of different C input for giant reed. However, it is possible to presume a lower amount of C input from litter due to the limited leaf loss of giant reed in the senescence phase, and subsequently a key role of belowground organs (Dragoni et al., 2015; Nassi o di Nasso et al., 2013).

However, the potential of perennial crops to offset CO_2 emissions through soil C sequestration depends on the rate of soil C additions, the long-term capacity of soil C storage and the stability of C sequestered (McLaughlin et al., 2002). In fact, C stock in the soil is temporary and it could be lost after the end of the plantation period (Anderson-Teixeira et al., 2013). Furthermore, re-cultivation after the abandonment of perennial energy crops can cause large SOC losses when root and rhizomes are removed that can be limited by the direct ploughing of below ground biomass. However, the amount of SOC loss, from PRGs to subsequent cultivation, depends on the stability of SOC and on further cropland management (Don et al., 2012).

Thus, the effect of soil organic carbon inclusion in the overall GHG balance of perennial crops is that GR cultivation is not a net sources of GHG emissions, but is a quantitatively important sink of carbon.

Overall, the comparison of the two GR systems highlighted that even if all the analyzed indicators showed slightly higher values on hectare basis, these differences were amplified on tonne basis (Fig. 3). As a consequence, the production of GR biomass on poor lands could led to an high environmental impacts and an higher land requirement.

Fig 3 -> Overall results

4 Conclusions

The results of our study highlighted how the soil characteristics affect not only the yield level of GR but also its environmental impact that seems to be higher in poor land. Then, in both case studies, the sustainability assessment of GR feedstock supply chain can be optimized focusing on N fertilization, especially type of fertilizers, nitrogen rate and time of application, and on harvest yards that are the main technical aspects influencing all the indicators analysed. However, to guarantee the sustainability of the bioenergy chains it is necessary to enrich these evaluations also with economic analysis and to extend the study to the whole chain including the biomass conversion phase (Bryngelsson and Lindgren, 2013). Although the mitigation of GHG emissions seems to be the most important benefit of GR cultivation, perennial energy production can provide several ecosystem services respect to annual crops that have to take into account, such as the restoration of contaminated soils and of waste waters, the reduction of soil erosion phenomena, the reduction of nutrient losses and the enhanced of biodiversity. Thus, in order to improve knowledge on GR and to favour its cultivation for different end uses (energy, biomaterials, fine chemicals etc.) the provision of these ecosystem services should be taken into account in the evaluation of the sustainably of these cropping systems at different scales.

In fact, to identify the most suitable areas for a sustainable cultivation of GR, the opportunity to combine its cultivation in poor and fertile soils have to be deepened by landscape studies in different environments. Actually, in planning biomass availability for energy plant feeding it could be useful to combine the use of biomass from heterogeneous areas as strategy to control the main bottlenecks affecting the sustainability of bioenergy systems realized exclusively on fertile (competition for land use with food crops) or poor (low income, high land requirement) lands.

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Figures caption

Fig 1: Giant Reed Systems Boundaries; in the continuous line the system investigated in this paper.

Fig. 2: Giant Reed systems results of other indicators on hectare and tonne basis.

Fig. 3: Normalized results for the six indicators on hectare and tonne basis.