Medium-term effect of perennial energy crops on soil organic carbon storage

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Abstract

The scope of this study was to evaluate the effect of perennial energy crops on soil organic carbon (SOC) storage. A field experiment was undertaken in 2002 at Anzola dell'Emilia (Bologna), in the lower Po Valley, Northern Italy. Five perennial energy crops were established on a land area which had been previously cultivated with arable crops for at least 20 years. The compared crops are: the herbaceous perennials giant reed and miscanthus, and the woody species poplar, willow and black locust, managed as short rotation coppice (SRC). SOC was measured in 2009, seven years after the start of the experiment, on an upper soil layer of 0.0-0.2 m and a lower soil layer of 0.2-0.4 m. The study aimed to compare the SOC storage of energy crops with alternative land use. Therefore, two adjacent areas were sampled in the same soil layers: i) arable land in steady state, cultivated with rainfed annual crops; ii) natural meadow established at the start of the experiment. The conversion of arable land into perennial energy crops resulted in SOC storage in the upper soil layer (0.0-0.2 m) ranging from 1150 to 1950 kg C ha^{-1} year^{-1} during the 7-year period. No significant differences were detected in SOC among crop species. We found no relationship between the harvested dry matter and the SOC storage. The conversion of arable land into perennial energy crops provides a substantial SOC sequestration benefit even when the hidden C cost of N industrial fertilizers is taken into account. While the SOC increased, the total N content in the soil remained fairly constant. This is probably due to the low rate of nitrogen applied to the perennial crops. However, our data are preliminary and the number of years in which the SOC continues to increase needs to be quantified, especially for the herbaceous species giant reed and miscanthus, with a supposedly long duration of the useful cropping cycle of 20 years or longer.

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Introduction

Many nations have formulated policies promoting the production and use of biomass to generate heat, power and liquid transport fuels (FAO, 2008). These policies were boosted by the perspective of the depletion of oil reserves and the concerns about energy security and global climate change (Koh and Ghazoul, 2008). Nonetheless, there is an intense debate in the scientific literature over the advantages and disadvantages of using cropland for producing biomass for energy. Some scientists, but certainly not all, believe that energy crops have a positive effect on the mitigation of CO_2 emissions (Payne, 2010). Other authors have advised against the undesired effects of a widespread diffusion of energy crops on the global carbon cycle (Crutzen *et al*., 2008; Fargione *et al*., 2008; Searchinger *et al*., 2008). Two major aspects need to be considered when assessing the contribution of energy crops on meeting future energy demand with limited environmental impact: i) the amount of fossil energy that is required to produce each unit of renewable energy; ii) the greenhouse gas (GHG) emissions that are released in the process (Liebig *et al*., 2008). Therefore, the amount of soil organic carbon (SOC) released by or sequestrated into the soil is a crucial component of the life cycle analysis (LCA) of energy crops (Anderson-Texeira *et al*., 2009). LCA is a system analysis tool that provides information on the full environmental effects of a product, service or system from its cradle (extraction of raw materials) to its grave (management of waste). Until now, only a few LCA studies on energy crops have considered the change in SOC (Brandão *et al*., 2011). Indeed, producing biomass for energy and SOC storage are often regarded as conflicting land-use options for the mitigation of climate change (Rootzen *et al*., 2010; Righelato and Spracklen, 2007). On the one hand, annual grain crops, notably maize (*Zea mays* L.) and soybean (*Glicine Max* (L.) Merr.), when devoted to produce biofuels, are poorly suited to improve carbon cycling because they require annual tillage and high agronomic input for nitrogen fertilization and pest control, which implies high greenhouse gas emissions from fossil energy sources (Farrel *et al*., 2006). On the other hand, perennial lignocellulosic crops have the potential to provide a range of benefits for both ecosystem services and SOC storage compared with arable land (Rowe *et al*., 2009). Perennial plants, grown on soils poorly suited for grain production, were suggested to maximize the reduction of GHG emission of energy crops (Crutzen *et al*., 2008; Tilman *et al*., 2009). In literature there is a general consensus that the conversion of arable land to perennial energy crops will result in SOC storage, while the conversion of permanent grassland into perennial energy crops might not be as beneficial (King *et al*., 2004; Rowe *et al*., 2009). Several studies addressed SOC sequestration with short rotation systems (Grigal and Berguson, 1998; King *et al*., 2004), while others considered the effect of herbaceous perennials (Bransby *et al*., 1998; Liebig *et al*., 2008). Nevertheless, to our knowledge, no studies have yet compared the effect of woody and herbaceous perennial crops on SOC storage at the same location. There is, then, an increasing need to quantify the amount of SOC that might be stored in soil profiles with diverse energy land-use options.

Long-running field experiments, with permanent plots extended over years, are extremely useful to provide an insight into soil processes subject to change over decades, like SOC dynamics and soil fertility itself. (Richter *et al*., 2007).

The scope of this study was to assess the SOC storage of woody and herbaceous perennial energy crops.

Materials and Methods

Site characterization and agronomic details

A field experiment was undertaken in 2002, and is still ongoing, at the CRA-CIN station at Anzola dell'Emilia (Bologna), in the lower Po Valley, Northern Italy (44° 32' N, 11° 80' E, 38 m a.s.l.). The soil of the site is loam-silty, classified as Udifluventic Haplustepts fine silty, mixed mesic (Soil Survey Staff, 2003). The main physical and chemical characteristic of the soil are reported in Table 1. The location is characterized by an annual average precipitation of about 600 mm. The climate is temperate sub-continental, due to the long distance (approximately 200 km) from the sea.

The following lignocellulosic crops are compared: two herbaceous perennials, giant reed (*Arundo donax* L.) and miscanthus (*Miscanthus x giganteus* hybrid); and three woody perennials, managed as short rotation coppice, poplar (*Populus x canadensis* hybrid), willow (*Salix alba* L.) and black locust (*Robinia pseudoacacia* L.). The herbaceous perennials were harvested every year, while the SRC were harvested every two years. The herbaceous perennial giant reed and miscanthus were fertilized annually with 120 kg N ha^{-1}, applied in the form of urea, + 120 kg P_2O_5 ha^{-1}, applied in form of superphosphate; the SRC of poplar and salix were fertilized every two years, after each harvest, with 120 kg N ha^{-1} in the form of urea + 120 kg P_2O_5 ha^{-1}; and the SRC of black locust, a legume species, receives zero nitrogen + 120 kg P_2O_5 ha^{-1} every two years, after each harvest.

The perennial crops were only irrigated during the summer of the first year, with three irrigations of 30 mm during the season, with the aim of facilitating crop establishment. In the subsequent years, the experiment was not irrigated. Weeds were controlled mechanically during the first year of crop establishment. Insect populations were controlled chemically in poplar and willow. The experimental design was a randomized block with four replications. The dimension of each individual plot was 40 m^2. Owing to budget limitations, only the first three replications were sampled to measure SOC.

Before starting the experiment, the land area had been cultivated with annual arable crops for at least 20 years. In fact, the dairy farm activities at the experimental station ceased in 1980. Therefore, no alfalfa meadows have been cultivated and no livestock manure has been applied to the soil since then.

Unfortunately, the SOC was not measured at the start of the experiment, because the initial scope of the field trial was to evaluate biomass productivity and qualitative characteristics of the investigated crops. However, the presence of adjacent areas with alternative land use, namely arable land in steady state, and arable land converted into a natural meadow, allowed the SOC for alternative options of land use to be evaluated. We then measured the SOC of the five crops and adjacent areas in February 2009, seven years after the start of the experiment. At the beginning of the experiment, a permanent meadow was allowed to establish on a contiguous strip within the field. The meadow gradually evolved into a stable association between grass and white ladino clover (*Trifolium repens* L.). The meadow was mowed twice a year, at the end of May and at the end of September. The aboveground biomass was finely cut and left on the soil surface. The meadow was not fertilized. This provided the opportunity to assess the SOC storage as influenced by a permanent meadow in which nitrogen was entering the ecosystem via symbiotic fixation. Moreover, an adjacent area, cultivated with rainfed arable crops, i.e. grain sorghum (*Sorghum bicolor* (L.) Moench), wheat (*Triticum vulgare* L.) and sugarbeet (*Beta vulgaris* L. var. saccharifera), was used as control for SOC content. Crop residues of sorghum and sugarbeet were returned to the soil, while wheat straw was baled and removed from the soil. Three replications of soil samples were also collected on the two adjacent areas cultivated with the permanent meadow and the arable land. We hypothesized that soil cultivated with arable crops was in a steady state for SOC, while the land use change deriving from the conversion of arable land to energy crops, and the conversion to permanent meadow, could result in SOC sequestration. The same approach was used by Hansen *et al*. (2004). Working in Denmark, these authors compared the SOC of a 9- and a 16-year old miscanthus plantation with those of adjacent areas with grassland and arable row crops. Similarly, Kahle *et al*. (2001), working in Germany, compared the SOC of miscanthus with that of adjacent grassland.

Soil sampling and analysis

Soil samples were collected from all plots on 25 February 2009, about seven years after the start of the experiment. For each plot, five independent soil cores were collected at a distance of about 0.5 m, for the soil layers 0.0-0.2 m and 0.2-0.4 m. Soil cores were collected using a 7 cm diameter soil sampler drill, model Eijkelkamp. The five cores of each plot were combined in one sample and sieved. The sieved soil was used to determine the organic C through chromic acid digestion, according to the Walkley-Black method and total N using the Kjeldahl method, according to Page *et al*. (1982). A soil bulk density of 1.663 Mg m^{-3} (± 0.04) was determined by collecting undisturbed soil samples using cylinders of 98 cm^3 pressed horizontally into the soil. This value of bulk density was used to calculate the amount of organic carbon per unit soil. The annual carbon gain was calculated as the difference between the average value of SOC of individual treatments and the average value of SOC for the arable land, divided by the number of years from the start of the experiment.

Table 1. Chemical and physical characteristics of the soil.

	Soil layer (m)	
	0-0.2	0.2-0.4
Sand, (g/100g)	24	25
Silt, (g/100g)	55	55
Clay, (g/100g)	21	20
Field capacity, (% vol.)	32	31
Wilting point, (% vol.)	22	21
Porosity, (% vol.)	37	37
Bulk density, (Mg m-3)	1.663	1.663
pH (in H_2O)	8.18	8.28
$CaCO_3$ total, (g/100g)	20	21
$CaCO_3$ active, (g/100g)	3.25	3.87
N total (Kjeldahl), (g/1000 g)	1.12	1.50
Organic matter (Walkey & Black), (g/100 g)	1.05	1.28
P available (Olsen), (mg/kg)	15.8	10.2
K exchangeable, (mg/kg)	180	193
CSC, (mq/100 g)	10.7	11.1

Statistical analysis

The analysis of variance (ANOVA) of SOC data was performed using the GLM procedure of the SAS systems (SAS, 1989). Since we compared the SOC of the five treated crops in permanent meadow and arable soil, not initially included in the experimental design, in ANOVA analysis we treated data as from a completely randomized experimental design. Selected contrasts were calculated to assess the significance of differences in SOC storage between specific combinations of land use. The relationship between SOC and soil nitrogen content, and between harvested dry matter yield and SOC, were evaluated using the PROC REG of the SAS systems (SAS, 1989).

Results and Discussion

Soil organic carbon content

The average values of SOC content, and the annual C gain, for the soil layers 0.0-0.2 m and 0.2-0.4 m, are reported in Table 2. The conversion of arable land into perennial energy crops resulted in SOC storage; in the upper soil layer 0.0-0.2 m, ranging from 1150 to 1950 kg C ha^{-1} y^{-1} during a 7-year period. No significant differences were detected among crop species. Our findings are consistent with Bransby *et al.* (1998) who reported that perennial grasses in the US Midwest added to the soil upper meter about 1100 kg C ha^{-1} year^{-1} for a 5-year period.

Compared to the arable land, the SOC of the 0.0-0.2 m layer was +48% for willow, +42% for both giant reed and poplar, +28% for black locust and miscanthus, and +19% for permanent meadow. However, only the SOC of willow, giant reed and poplar are statistically different from the SOC of arable land (P<0.05), while miscanthus and black locust are significantly different from arable land (P<0.1). The annual

Table 2. Soil organic carbon and annual C gain in the soil layers 0.0-0.2 m and 0.2-0.4 m. The apparent average gain was estimated as a difference between soil organic carbon of individual treatments and the value of arable land. Means sharing common letters are not statistically different for P≤0.05 (LSD). In the ANOVA table the value of probability is shown when P<0.10.

Soil layer	0.0-0.2 m		0.2-0.4 m	
	SOC (Mg C ha^{-1})	Annual C gain (kg C ha^{-1} y^{-1})	SOC (Mg C ha^{-1})	Annual C gain (kg C ha^{-1} y^{-1})
Species				
Willow	39.40^{a}	1945	31.03^{a}	585
Giant reed	37.68^{a}	1700	27.33^{ab}	63
Poplar	37.63^{a}	1692	27.80^{ab}	126
Miscanthus	34.03^{ab}	1178	26.03^{b}	-126
Black locust	33.87^{ab}	1154	27.67^{ab}	111
Meadow	31.65^{ab}	838	28.20^{ab}	190
Arable land	25.78^{b}	0	26.90^{ab}	0
ANOVA	P>F		P>F	
Crops	0.08		ns	
Selected contrast				
Arable land *vs* crops	0.006		ns	
Meadow *vs* crops	ns		ns	
Willow *vs* arable land	0.006		0.095	
Giant reed *vs* arable land	0.013		ns	
Poplar vs arable land	0.014		ns	
Miscanthus *vs* arable land	0.067		ns	
Black locust *vs* arable land	0.072		ns	
Willow *vs* meadow	0.083		ns	

SOC, soil organic carbon; [a,b]means sharing common letters are not statistically different for P≤0.05 (LSD). In the ANOVA table the value of probability is shown when P<0.10; ns, not significant.

C gain that we estimated for poplar in the present experiment, around 1690 kg C ha^{-1} year^{-1}, are in good agreement with Grigal and Berguson, (1998). On the basis of a study on a poplar plantation conducted in the USA, the authors suggest that after an initial period of loss, carbon sequestration can be expected at the rate of 1000-1600 kg C ha^{-1} year^{-1}, over a 10-15 year period. Moreover, the annual C gain that we estimated for miscanthus, about 1180 kg C ha^{-1} year-1, are consistent with Hansen *et al.* (2004) who indicated an annual soil C gain with miscanthus in Denmark of between 780 and 1130 kg C ha^{-1} year^{-1}.

Although the SOC storage of perennial crops tends to be higher compared to permanent meadow, in most of the cases these differences are not statistically significant. Only the comparison between willow and permanent meadow was significant (P<0.1). The SOC of the 0.2-0.4 m layer remained quite constant regardless of the land use. Interestingly, only willow significantly raised SOC storage, compared to arable soil, in the 0.2-0.4 m soil layer (P<0.1).

The SOC accumulated after seven years of willow cultivation, 39.4 Mg C ha^{-1} in the soil profile 0.0-0.2 m, is close to that reported for a bamboo stand (Bambusa spp.) in India; 42.1 Mg C ha^{-1} (Nath *et al.*, 2009) for the same soil layer. However, the cumulative carbon stock for willow in the soil profile up to 0.4 m, i.e. 70.4 Mg C ha^{-1}, is distinctly lower than the value of 82.4 Mg C ha^{-1} observed in Lodi, Lombardy, Northern Italy, after ten years of annual application of 66 Mg farmyard manure ha^{-1} (Ceotto *et al.*, 2006). However, it is important to note that in the case of farmyard manure, the crop residues used in composting farmyard manure were produced by external land areas. Consequently, farmyard manure application is likely to increase SOC at the expense of a larger land area providing crop residues (Tomasoni *et al.*, 2011).

In literature, there is a general consensus that SOC is the result of the interaction between climate, vegetation and soil management. Therefore, several factors could have played a contributory role in the observed SOC storage:

- the prolonged canopy cover of the perennial crops and the presence of surface mulch could have determined favorable microclimatic conditions. In fact, SOC tends to increase with a decrease in mean temperature and with an increase in precipitation (Grigal and Berguson, 1998);
- SOC oxidation via microbial activity tends to decrease in the conversion to zero tillage due to lower soil O_2 (King *et al.*, 2004);
- the amount of biomass not harvested and returned to the soil, its above- to below-ground allocation, and the nature of organic compound that are produced (Grigal and Berguson, 1998).

Overall, the amount of SOC sequestration determined by the conversion from arable land to perennial crops with zero tillage is at first sight impressive. Nevertheless, it is quite obvious that the SOC storage cannot be maintained at the initial rate indefinitely (King *et al.*, 2004). In literature, there is no consensus about the number of years necessary to reach a new equilibrium. Estimates vary from only six years (Paustian *et al.*, 1997), to 10-15 years (Grigal and Berguson, 1998), up to 15-20 years (West and Post, 2002).

The hidden carbon costs of nitrogen fertilization

While the benefits of increasing SOC on soil fertility, water retention and crop production are undisputed, some authors have expressed caution about the real benefit of SOC storage on global C cycle (Schelsinger, 1999; Schelsinger, 2000; Olness *et al.*, 2002). In particular, Schelsinger (2000) argued that the SOC stored is often higher in fertilized fields, but this carries a hidden C cost that should be considered in evaluating the overall benefit in terms of global C balance.

Schlesinger (1999) indicated a factor of 1.436 moles of CO_2-C released per mole of nitrogen when accounting for the full carbon cost of industrial nitrogen fertilizer, including manufacture, transport and application. Taking into account the ratio C to CO_2, i.e. 12/44=0.27, such an amount results in 1.436/0.27=5.32 kg CO_2 per kg N. Moreover, according to Crutzen *et al*. (2008) when 1 kg of nitrogen is supplied to a field crop, about 3-5% is released, sooner or later along the N cycle, in the atmosphere in the form of N_2O, a potent greenhouse gas with a global warming potential (GWP)= 296, in CO_2 equivalents. We here assumed the average value of 4% emissions, then 40 g N-N_2O emitted per kg of nitrogen applied; N/N_2O=0.636, hence 40/0.636= 62.9 g N_2O x 296 (CO_2)=18616 g, i.e. 18.6 kg CO_2 per kg N. Such an amount should be added to the 5.32 kg CO_2 per kg N mentioned before to obtain an overall amount of 23.92 kg CO_2 per kg N applied to the crops. On the basis of the above assumptions, and taking into account the rate of N supplied annually to the crops we estimated the gross and net soil C gain in CO_2 equivalent (Table 3). Obviously, the hidden C cost is equal to zero for black locust, a legume specie that was not fertilized with N. The N related CO_2 emission ranged from 20% of gross SOC gain for willow, to 66% for miscanthus. Thus, the net SOC gain was positive for all the compared crops.

However, the number of years in which the SOC will continue to increase still has to be evaluated. As soon as the SOC reaches a new equilibrium, the hidden C cost of nitrogen fertilization will no longer be compensated by soil C sink. However, it is important to consider that at least 10 Mg dry matter ha^{-1} $year^{-1}$ will be still available for displacing fossil fuels. King *et al*. (2004) indicated that willow and miscanthus provide 25 and 36 times, respectively, as much energy as they consume in production. As Bransby *et al*. (1998) pointed out, SOC sequestration is a one-off benefit, while the benefit from replacing fossil fuels is continuous and cumulative.

Moreover, Olness *et al*. (2002) pointed out that N represents a critical aspect of soil C sequestration. The authors underlined that since N is about 9% of soil organic matter (SOM), a source of N is needed to allow the storage of SOC. Therefore, an increase of 0.1 % in SOC for a layer of 0.15 m, assuming bulk density of 1.2 and a nitrogen efficiency of 50 %, requires 328 kg N ha^{-1}. Consequently, when the N embodied in soil organic matter is provided by industrial fertilizers, an environmental cost in terms of fossil energy used (and CO_2 released) should be taken into account. Our findings provide evidence which contrasts with the assumptions of these authors. In fact, we found a very poor relationship between SOC and soil total nitrogen content (Figure 1).

Under our experimental conditions, the increase in SOC was not accompanied by a concomitant increase in soil N. In other words, with the perennial crops and the natural meadow, the SOC rose while the N content remained fairly constant; therefore, the C to N ratio increased rather than remained constant. It is worth noting that our energy crops have received little N supply, ranging from 60 to 120 kg N ha^{-1} y^{-1}, and this is likely the reason for the fact that there was no increase in soil N. However, we observed no increase in soil N content even for black locust; a nitrogen fixing crop not fertilized with N. In fact, the C to N ratio of black locust in the 0.0-0.2 m soil layer, i.e. 8.74 ±0.77, was in the observed range of the other species: 7.73-10.75 (*data not shown*).

Finally, our data of soil C and N content for woody species are in good agreement with Rau *et al*. (2009) who investigated soil C and N as affected by natural vegetation in the Great Basin of the US. These authors reported that the soil under tree microsites had higher C to N ratio than interspace microsites.

Relationship between soil organic carbon and biomass yield

The average annual dry matter yield of the compared species for the period 2002-2007 is shown in Figure 2. Under our experimental conditions, giant reed was a superior crop in terms of productivity, while the SRC of poplar and willow provided a modest biomass yield (Di Candilo *et al*., 2008). The relationship between the average dry matter yield and the SOC in the 0.0-0.2 m upper layer is shown in Figure 3. There is no significant relation between the harvested aboveground biomass of the crops and their SOC. Therefore, the productivity of the perennial energy crops is a poor predictor of SOC storage.

Normally, C is added to the soil by deposition and decay of plant dry

Table 3. Gross and net annual soil organic carbon gains for the 0.0-0.2 m soil layer, and nitrogen related CO_2 emissions estimated on the basis of annual rates of nitrogen fertilization.

Crop	Gross SOC gain (kg CO_2 ha^{-1} y^{-1})	Rates of N supply (kg N y^{-1})	N related GHG emission (kg CO_2 ha^{-1} y^{-1})	Net SOC gain (kg CO_2 ha^{-1} y^{-1})
Willow	7132	60	1435	5697
Giant reed	6234	120	2870	3364
Poplar	6205	60	1435	4769
Miscanthus	4320	120	2870	1449
Black locust	4232	0	0	4232
Meadow	3073	0	0	3073

N, nitrogen; SOC, soil organic carbon; GHG, greenhouse gas.

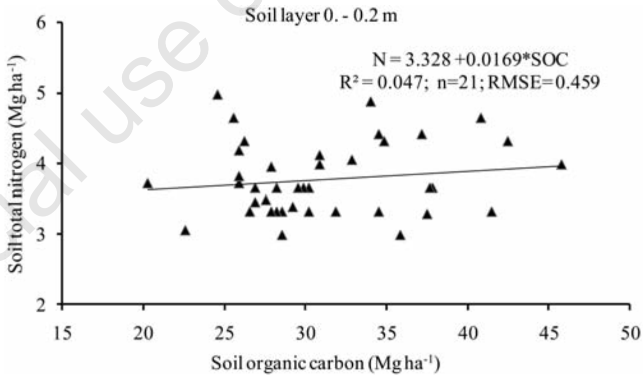

Figure 1. Relationship between soil organic carbon and soil total nitrogen in the 0.0-0.2 m soil layer.

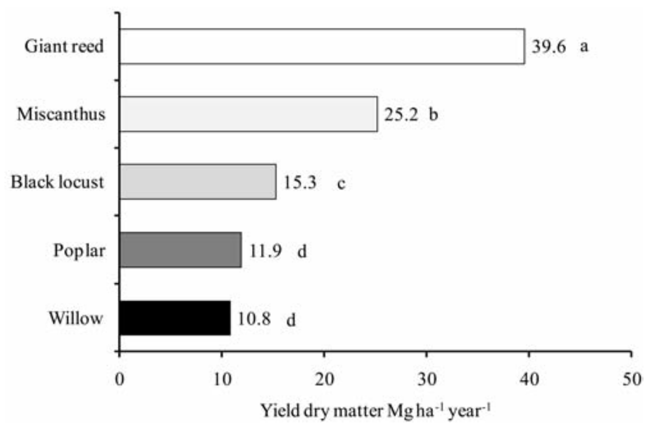

Figure 2. Average annual dry matter yield of the compared species for the period 2002-2007. Yields of biennially harvested species were halved to place them on an annual basis. Means sharing common letters are not statistically different for P≤0.05 (Tukey test). ANOVA: species P<0.0001; selected contrasts: giant reed *vs* other species P<0.0001; herbaceous crops *vs* woody crops P<0.0001; poplar and black locust *vs* willow P<0.0045. Modified from Di Candilo *et al.*, 2008.

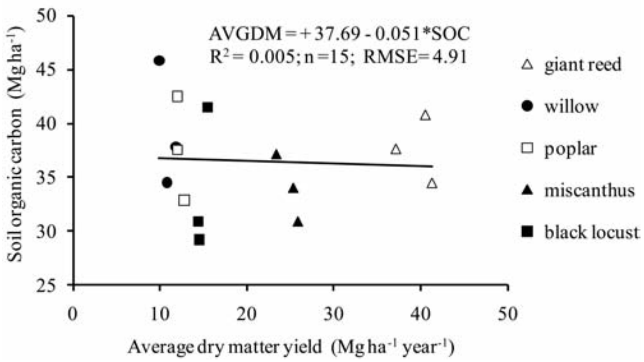

Figure 3. Relationship between average annual dry matter yield (2002-2007) and soil organic carbon in the upper 0.0-0.2 m soil layer. Data of individual crop species are shown.

matter on the soil surface and also by root senescence within the soil. It is important to point out that we have not measured the amount of C input to the soil with falling leaves and the fine root turnover. Therefore, we cannot infer that harvestable biomass is related to C input to the soil. Woody species normally lose all their leaves during the autumn, before the harvest of biomass which is performed every two years during the winter. Therefore, they provide abundant litter on the soil surface. On the contrary, giant reed and miscanthus tend to maintain most of their senesced leaves attached to the stems, which are consequently harvested every year, during the winter period. In addition, different plant species might have a different fine root turnover and composition. Thus, differences in harvestable biomass production could be compensated by the intrinsic attitude of the plant species to provide C input to the soil.

Our findings are partially in contrast with Liebig *et al*. (2008). These authors found a positive, but still weak, relationship between the harvested aboveground biomass of switchgrass (*Panicum virgatum* L.) and the annual change in SOC in several locations along the central and northern Great Plains of the USA.

Conclusions

The conversion of arable land into perennial energy crops provided a substantial SOC sequestration benefit for a 7-year period. However, the soil acts as a C sink only in the 0.0-0.20 m upper layer. When the hidden C cost of industrial N fertilizers is taken into account, the SOC gain is still substantial. Differences in biomass productivity are not associated with the rise in SOC. While the SOC increased, the total N content in the soil remained fairly constant among the different options for land use, including the nitrogen fixing crop black locust.

Our data are preliminary, however, and the number of years in which the SOC will continue to increase needs to be quantified, in particular for the herbaceous species giant reed and miscanthus, with a supposedly long duration of useful cropping cycle of 20 years or longer. But then a key question arises: at the end of the cropping cycle will the C stay there? If the soil is converted back to arable land, the benefit of C sequestration will probably be lost in a few years. On the contrary, if perennial energy crops could be rotated, avoiding deep soil tillage, the SOC storage will be assured. As Marland *et al*. (2001) pointed out, the permanence of sequestered C is a matter of liability, because it implies the commitment to long-term vigilance in the management of the captured C.

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