GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2012) **4**, 420–434, doi: 10.1111/j.1757-1707.2011.01142.x

REVIEW

The contribution of switchgrass in reducing GHG emissions

ANDREA MONTI, LORENZO BARBANTI, ALESSANDRO ZATTA and WALTER ZEGADA-LIZARAZU

Department of Agroenvironmental Science and Technology, University of Bologna, Viale Fanin 44, 40127, Bologna, Italy

Abstract

The contribution of switchgrass (***Panicum virgatum*** L.), a perennial C_4 grass, in reducing greenhouse gas (GHG) emissions was reviewed under three main areas; the impact on carbon dioxide (CO_2), nitrous oxide (N_2O), and methane emissions (CH_4), whilst also taking into account the effects of land conversion to switchgrass. Switchgrass is able to enhance biomass accumulation in a wide range of environmental conditions, which is the premise for considerable carbon assimilation and storage in the belowground organs. The progress in some areas of crop husbandry (e.g., tillage and fertilization) has fostered benefits for carbon storage, while restraining GHG emissions. As root biomass is the main indicator of soil carbon sequestration, switchgrass's dense and deep rooting is a relevant advantage, although uncertainty still exists about the crop's belowground biomass accumulation. In agreement with this, most LCA studies addressing CO_2 emissions report significant benefits from switchgrass cultivation and processing. Beside CO_2, switchgrass performed better than most other biomass crops also in terms of N_2O emission. In the case of CH_4 emission, it may be argued that switchgrass should act as a moderate sink, i.e., contributing to mitigate CH_4 atmospheric concentration, but a substantial lack of information indicates the need for specific research on the topic. Land conversion to switchgrass is the latest issue which needs to be addressed in LCA studies: not surprisingly, the net CO_2 abatement appears remarkable if switchgrass is grown in former arable lands, although it is slightly negative to positive if switchgrass replaces permanent grassland. In conclusion, switchgrass could significantly contribute to mitigate GHG emissions, although areas of uncertainty still exist in the assessment of soil carbon storage, N_2O and CH_4 emissions, and the effects of converting lands to switchgrass. Further improvements must, therefore, be achieved to strengthen the crop's remarkable sustainability.

Keywords: bioenergy, biofuel, carbon, climate change, global warming, land use change

Received 30 September 2011; revised version received 30 September 2011 and accepted 20 October 2011

Introduction

Global warming and increasing concentration of atmospheric greenhouse gases (GHG) have prompted considerable interest in the potential role of soil and plant biomass (Watson *et al.*, 2000), together containing about 2.7 times more carbon (C) than the atmosphere (Watson *et al.*, 1996; Schlesinger, 1997), in mitigating climate change. Since the industrial revolution, the atmospheric CO_2 concentration has increased by around 37% and, consequently, global temperatures have risen by approx. 0.8 °C (Metz *et al.*, 2007). Recent studies show that a global warming of more than 1 °C, relative to 2000, exceeds the adaptive capacity of many systems, thus resulting in unpredictable risks for living species and irreversible effects on the earth's climate (Mastrandrea & Schneider, 2004; Hansen *et al.*, 2006). On the other hand, global temperatures are projected to increase further by 1.1–6.4 °C over the next century, thus actions need to be taken urgently to mitigate greenhouse gas (GHG) emissions in the atmosphere (Metz *et al.*, 2007).

Agriculture occupies about 40–50% of the Earth's land surface and accounts for 10–12% of anthropogenic GHG-emissions (5.1–6.1 Gt $CO_{2\text{-eq}}$ yr^{-1}). Despite considerable annual CO_2 exchanges between agricultural lands and the atmosphere, the net flux is minimal (0.04 Gt CO_2 yr^{-1}, less than 1% of global anthropogenic emissions). Therefore, nearly all GHG emissions from agriculture are methane (CH_4) and nitrous oxide (N_2O) that account for about 60% and 50% of global anthropogenic N_2O and CH_4 emissions, respectively (Metz *et al.*, 2007). In general, N_2O emissions are generated by N fertilization, whereas

Correspondence: Andrea Monti, tel. + + 39 051 209 6653, fax + 39 501 209 6241, e-mail: a.monti@unibo.it

the main source of CH_4 emissions are livestock production and manure management. In addition, N_2O and CH_4 emissions from agricultural activities increased by 17% from 1990 to 2005 (US-EPA, 2006), and are projected to further increase by 35–60% up to 2030 (Mosier & Kroeze, 2000; FAO, 2003), unless improved agricultural practices and agronomic strategies are adopted (Follett *et al*., 2001).

A significant global GHG mitigation contribution can therefore be expected from agriculture, especially through improved crop and land management devised to enhance soil carbon sequestration, and by replacing fossil fuels with agricultural feedstocks used for energy. Estimates by Eggelston *et al*. (2006) show that the agricultural GHG mitigation potential is 350–700 MtC per year, to which 300–1300 MtC from the displacement of fossil fuels should be added by dedicating 10–15% of agricultural land to energy crops. Methane and nitrous oxide emissions from agriculture could be reduced by 15–56% and by 9–26%, respectively, by growing energy crops. Other estimates show the global potential for GHG mitigation in agriculture by 2030 is from 200 to 1800 $MtCO_{2\text{-eq}}$ yr^{-1} (Fawcett & Sands, 2006; Fujino *et al*., 2006; Kemfert *et al*., 2006; Smith & Wigley, 2006); nonetheless, it should be stressed that these estimates are very uncertain due to a knowledge gap regarding CH_4, N_2O, and soil C-emissions, and the unpredictable price of carbon (Smith *et al*., 2007).

Like all renewable energy sources, energy crops displace the production of an equivalent amount of energy from fossil fuels and thus have the potential to reduce GHG emissions. However, converting the potential bioenergy production into GHG mitigation potential is not straightforward, as carbon offsets of energy crops relative to fossil fuels depend on several factors that make the emissions balance positive, neutral or negative, to an extent depending, among others, on crop productivity, quality of gas emissions, amount of carbon stored in the soil, the sectors where bioenergy is used (electricity, transport etc.), and the efficiency with which energy crops are produced.

Due to the high biomass productions, deep root systems (Ma *et al*., 2000a; Sommer *et al*., 2000) and conservative agricultural practices that limit oxidative processes and thus soil organic carbon (SOC) losses, perennial grasses offer a concrete possibility to partially restore the SOM pool (Potter *et al*., 1999; Reicosky, 2003; Pacala & Socolow, 2004; Lemus & Lal, 2005). It should also be recognized that, compared with other grasses, bioenergy crops provide a dual contribution to GHG savings: not only do they store considerable amounts of carbon in the soil, but they also replace an equivalent amount of fossil energy. For example, Turhollow & Perlack (1991) estimated that carbon dioxide emissions from the combustion of aboveground biomass of switchgrass is 1.9 kg GJ^{-1}, compared with 13.8, 22.3, and 24.6 kg GJ^{-1} of gas, petroleum, and coal, respectively. Switchgrass (*Panicum virgatum* L.), a gramineous rhizomatous C_4 perennial grass native to North America, was first proposed as an energy crop to the US Department of Energy in 1994 (D.J. Parrish, personal communication), and since then it has been attracting growing interest worldwide, as testified by the increasing number of publications per year: 42–144 per year, the average of the last two 4-year periods, respectively (from Scopus and Web of Science).

In this framework, the objective of the present review was to scan the potential contribution of switchgrass to limit GHG emissions. Three sections are addressed separately, reflecting specific aspects that relate specifically to different GHG emissions.

The first examines the effects of switchgrass cultivation and processing (LCA) on carbon emissions. The contrasting role of intensive agricultural practices on CO_2 emissions is discussed, such as the amount of nitrogen fertilizers that is proportional to the release of CO_2 and N_2O emissions on one hand, and its increase of fossil fuel displacement per unit land area (thus reducing CO_2 emissions) by enhancing the aboveground biomass accumulation, on the other. The effects of soil conservation practices achieved with switchgrass compared with conventional tillage in preserving soil carbon storage were also reviewed. There is evidence of an alarming decline in soil organic matter (SOM) due to inappropriate soiltillage; however, if agricultural practices are reduced to the minimum, such as with switchgrass, C-source soils can rapidly shift to C-sink soils, sequestering up to 60–70% of the depleted C pool (Kucharik *et al*., 2001; Monti *et al*., 2001; Lal, 2002, 2003; West & Post, 2002; Gregorich *et al*., 2005; Ussiri & Lal, 2009).

In the second section, we reviewed nitrous oxide (N_2O) emissions by growing switchgrass. Nitrous oxide is an intermediate in the reaction sequence of denitrification and a minor by-product of nitrification (Eggelston *et al*., 2006) with considerably higher global warming power (296 times) than CO_2 (Robertson & Grace, 2004). A total of 27 studies were reviewed that generally revealed considerable benefits from switchgrass in terms of N_2O savings with respect to fossil counterparts, both by cultivation practices and over the life cycle.

In the last section, we reviewed the methane (CH_4) emissions, a greenhouse gas that has 21 times more global warming power than CO_2 (Chan & Parkin, 2001).As switchgrass production is not related to wetland agriculture (e.g., rice fields, etc.), its CH_4 emissions are minimal. Ten g of CH_4 kg N^{-1} is usually considered as the customary value for CH_4 emission from agricultural activities, thus its contribution to the total GHG emission is relatively small (Cherubini & Jungmeier, 2010). However, we found significant uncertainties in the few data available, and the potential benefits deriving from switchgrass cultivation and processing are therefore only indicative.

Finally, as the land use change is generally omitted or included as an omitted-variable bias in the LCA calculations, the importance of taking into account direct or indirect land use changes (LUC and iLUC) in assessing the GHG of switchgrass was discussed.

Carbon savings

The influence of crop management on C savings

Carbon sequestration by switchgrass depends on root development (Parrish *et al.*, 2003) and several other factors such as crop residues (Tufekcioglu *et al.*, 2003; Anderson-Texeira *et al.*, 2009), climate and soil conditions (Lemus & Lal, 2005), autotrophic respiration (Williams *et al.*, 2004), initial SOM inventory (Bransby *et al.*, 1998; Garten & Wullschleger, 1999), type of converted land (Fargione *et al.*, 2008), soil bulk density and redox potential (Oades, 1988; Grigal & Berguson, 1998; Baer *et al.*, 2002; Sanderson, 2008), crop combination (Tilman *et al.*, 2006), nitrogen fertilization and conservative tillage practices (Mehdi *et al.*, 1999; Ma *et al.*, 2000a; Conant *et al.*, 2001; Lee *et al.*, 2007).

Among agricultural practices, soil tillage, nitrogen fertilization, and the harvest pattern likely play the most important role in carbon emissions. Fargione *et al.* (2008) showed how tillage of natural ecosystems can cause significant organic matter losses that will offset C sequestration by the established crop for several years. Switchgrass sowing can be carried out in rows or by seed broadcasting and even under no-tillage. In many cases, no-tillage may be the only profitable alternative to cultivate this crop and to reduce soil erosion problems. No-tillage and other forms of conservation tillage are known to reduce soil respiration and the consequent CO_2 emissions with respect to conventional tillage (Lal, 1997; Ussiri & Lal, 2009). However, no-tillage should only be adopted when favorable soil conditions (well balanced bulk density and porosity; rapid drainage) occur, as firm, wet soils are prone to higher N_2O and CH_4 losses. This could potentially reverse the benefits achieved in terms of reduced CO_2 emissions. Furthermore, the use of no-tillage reduces the energy inputs in terms of fuels for machinery and can therefore reduce CO_2 emissions.

Nitrogen fertilization plays an indirect role in carbon emissions as a strong enhancer of plant growth, in turn reflecting on potential carbon storage. For example, Lee *et al.* (2007) showed that soil C increased from 1.9 to 2.8 Mg C ha^{-1} yr^{-1} with an application of 0 and 224 kg ha^{-1} yr^{-1} of mineral N, respectively, and up to a rate of 4.0 Mg C ha^{-1} yr^{-1} with manure (224 kg N-eq ha^{-1} yr^{-1}). In general, switchgrass can recover and incorporate between 10% and 40% of the applied nitrogen into its organic matter (Bransby *et al.*, 1998). However, depending on the fertilization rate, the allocation of carbohydrates between roots and shoots may change. For example, Heggenstaller *et al.* (2009) indicated that a rate of 140 kg N ha^{-1} favored the allocation of carbohydrates to the roots and their growth. On the other hand, at higher rates (220 kg N ha^{-1}) shoots were the preferential sink of carbohydrates. In addition, nitrogen fertilization was shown to increase root N concentration, not root C concentration (Ma *et al.*, 2000a). The consequent decrease in root C/N ratio (from about 57 g g^{-1} with no N to 30 g g^{-1} with 200 kg N ha^{-1}) will probably lead to better humification, and therefore to a higher sequestration of root carbon (Ammann *et al.*, 2009). In addition to marginal improvements in biomass productivity, elevated nitrogen fertilization can create severe lodging problems, increase the ash content in the biomass, nitrogen leaching, water pollution, and increased CO_2 emissions associated with the energy consumed during the fertilizer production phase. Therefore, efficient and specific fertilization management programs are needed that allow optimum biomass growth and partitioning of carbohydrates which in turn will sequester more carbon in the above- and belowground parts of the plant and at the same time reduce operational emissions.

Using organic wastes (manure, slurries, etc.) as N sources for switchgrass fosters a recycling of these biomasses in a nonfood crop, which is often more desirable than in food crops. Organic fertilizers also allow a significant saving in the amount of energy used for the production of mineral fertilizers (3.26 kg CO_2-e kg^{-1} N; Ecoinvent Centre, 2004), although allowances should be made for the higher consumption of energy in the handling, transport, and distribution of organic fertilizers.

Harvesting is another important factor to preserve soil carbon content. When switchgrass is harvested after senescence, biomass losses occur (leaves and heads) which in one way reduces productivity, but in another can add carbon to the soil organic matter. As mentioned earlier, switchgrass is normally harvested once a year, but there is no general consensus about the effects of the single vs. double cut strategy on carbon savings. A double cut system apparently enhances aboveground biomass, in turn reducing CO_2 emissions through a higher fossil fuel displacement (Table 1); however, the long-term double cut system generally weakens the crop with a consequent strong decrease of biomass yield, probably due to an insufficient accumulation of reserves in the storage organs (Sanderson *et al.*, 1999; Reynolds *et al.*, 2000; Thomason *et al.*, 2004; Fike *et al.*, 2006; Monti *et al.*, 2008). At the same time, the mid-season cut may shift assimilates from root to shoot regrowth, curbing the amount of belowground carbon available for storage (Ma *et al.*, 2000a). It appears that one cut per year is more beneficial in view of a restraint in CO_2 emissions, as it enhances carbon translocation to the belowground organs, in turn favoring carbon rhizodeposition and/or assimilation in the following season. Moreover, one cut per year reduces the use of harvest machinery, thus decreasing CO_2 emissions. To our knowledge, only one study (Al-Kaisi & Grote, 2007) addressed the effects of long-term harvesting intervals. The authors indicated that annually harvested switchgrass caused higher soil CO_2 emissions than a 5-year interval harvesting, probably due to a different root biomass of switchgrass under the two harvesting systems.

Table 1 Biomass yield with single vs. double cut harvest in a series of experimental cases in switchgrass

Location	Years	Cuts yr^{-1}	Biomass yield (Mg ha^{-1})	Source
Dallas, TX, USA	5	1	7.1	Sanderson *et al.* (1999)
		2	6.6	
Stephenville, TX, USA	5	1	14.8	Sanderson *et al.* (1999)
		2	8.7	
Knoxville, TX, USA	5	1	17.4	Reynolds *et al.* (2000)
		2	18.7	
Ames, IA, USA	2	1	13.5	Vogel *et al.*(2002)
		2	13.0	
Mead, NE, USA	2	1	11.0	Vogel *et al.* (2002)
		2	11.3	
Chickasha, OK, USA	3	1	16.0	Thomason *et al.* (2004)
		2	20.0	
Perkins, OK, USA	3	1	9.8	Thomason *et al.* (2004)
		2	10.4	
Princeton, KY, USA	3	1	12.7	Fike *et al.* (2006)
		2	14.5	
Raleigh, NC, USA	3	1	11.9	Fike *et al.* (2006)
		2	17.0	
Jackson, TN, USA	3	1	11.3	Fike *et al.* (2006)
		2	13.8	
Knoxville, TN, USA	3	1	18.7	Fike *et al.* (2006)
		2	21.3	
Blacksburg 'A', VA, USA	3	1	11.0	Fike *et al.* (2006)
		2	13.6	
Blacksburg 'B', VA, USA	3	1	10.7	Fike *et al.* (2006)
		2	16.2	
Orange, VA, USA	3	1	11.6	Fike *et al.* (2006)
		2	13.5	
Morgantown, WV, USA	3	1	14.5	Fike *et al.* (2006)
		2	13.4	
Ozzano, Bologna, Italy	4	1	14.9	Monti *et al.* (2008)
		2	14.1	
St. Lambert, Québec, Canada	1	1	11.5	Massé *et al.* (2010)
		2	11.9	
Stillwater, OK, USA	3	1	15.9	Aravindhakshan *et al.* (2010)
		2	15.4	
Frederick and Burneyville, OK, USA	2	1	13.6	Guretzky *et al.* (2011)
		2	18.0	

In some cases, data are approximated from graphical presentations.

Soil carbon sequestration

Root biomass is by far the most important indicator for estimating potential soil C sequestration (Sommer *et al.*, 2000; Lemus & Lal, 2005); understanding switchgrass root development and dynamics could be therefore useful for predicting the potential contribution of this crop to carbon sequestration. Perennial grasses are known to develop deep roots and store considerable belowground biomass with a below- to aboveground biomass ratio of about 2 : 1 in the long-term (Wilts *et al.*, 2004). Although some authors reported that the belowground biomass of switchgrass did not exceed 52–57% of the total biomass (Bowden *et al.*, 2010), it generally exhibited an outstanding ability to extend to considerable depth in the soil, with a belowground biomass often exceeding the aboveground biomass (McLaughlin & Walsh, 1998; Ma *et al.*, 2000b), meaning values up to four or five times higher than those of maize (Zan *et al.*, 1997) and sorghum (Monti & Zatta, 2009). Unfortunately, there is still great uncertainty about long-term belowground biomass accumulation patterns and rooting depth of switchgrass (Bransby *et al.*, 1998; Don *et al.*, 2011), which may be ascribed to different environmental conditions and sampling methodologies. Belowground biomass varied considerably (2.8–16.8 Mg ha^{-1} yr^{-1}) across the experiments, which could be partially explained by the very different soil profiles (10–350 cm) sampled for root biomass determination (Table 2). Even though the correlation between root biomass and soil profile was relatively high (r = 0.61), we were unable to find a clear relationship between the two variables ($P = 0.11$).

Along with rooting depth, root size was found to play a key role in the soil C-turnover (Trumbore & Gaudinski, 2003; Strand *et al.*, 2008), given the important role of fine roots in soil carbon deposition (Richter *et al.*, 1999). To our knowledge, only one study quantified the fine (0–2 mm diameter), small (2–5 mm) and coarse (> 5 mm) switchgrass roots (Tufekcioglu *et al.*, 2003), which revealed that the fine roots were considerably higher in switchgrass than in poplar (+57%), cool-season grasses

Table 2 Measured and estimated switchgrass root biomass and soil C accumulation rates

Location	Soil type	Plant age (yr)	Profile (cm)	Root biomass (Mg ha^{-1} yr^{-1})	C accum. rate	Source
Texas	Silty-clay-loam	3	0–30	–	1.2	Ocumpaugh *et al.*, 2003
Alabama	Sandy-loam	4	0–75	5.9–9.8	–	Bransby *et al.*, 1998
SW-Quebec	Chicot sandy-loam	4	0–60	6.0–8.1	−11–(−8)	Mehdi *et al.*, 1999
Pennsylvania; New York; New Jersey	Fine-loamy; Coarse-loamy; coarse-silty	9–18	0–120	–	ns–30%*	Corre *et al.*, 1999
Alabama	Several types	3	0–300	–	−0.2–4.6	Ma *et al.*, 2000a
Alabama	Sandy-clay	10	0–350	–	+28–45%†	Ma *et al.*, 2000a
Montreal	Rocky shallower; high fertility	4	0–60	2.8–4.0	1.1	Zan *et al.*, 2001
USA	Several	Several	0–100	–	0.53–0.78‡; 1.40§	McLaughlin *et al.*, 2002¶
USA (13 locations)	Several	Several	0–90	–	1.7	Sanderson *et al.* **
Alabama	Decatur silt-loam	6	0–15	–	+65%	Tolbert *et al.*, 2002
Virginia and Tennessee	–	5	0–90	6.6–10.9	~ 1	Parrish *et al.*, 2003
Virginia and Tennessee	–	10	0–90	8.6–13.6	+42%††	Parrish *et al.*, 2003
Iowa	Riparian buffer	7	0–125	16.8	0.8	Tufekcioglu *et al.*, 2003
North Dakota	Loamy; fine-silty; coarse-loamy	3	0–90	5.9–6.5	10.1	Frank *et al.*, 2004
Tennesee, Kentuky, Virginia	Several (4 sites)		0–50		+22–43%	Garten & Wullschleger, 1999
Minnesota; North Dakota; South Dakota	Several (42 sites)	2–19	0–120	6.7	15.3‡‡	Liebig *et al.*, 2005
Minnesota	Degraded to poor fertile	–	0–60	–	0.48–2.70§§	Tilman *et al.*, 2006
South Dakota	Silty-clay-loam	4	0–90	–	2.40–4.01	Lee *et al.*, 2007
Pennsylvania	Silty-loam	7	0–30	7.4–14.0	−14–33%	Sanderson, 2008
North Dakota; South Dakota; Nebraska	Several (10 sites)	Several	0–120	–	0.60–4.30	Liebig *et al.*, 2008
USA	Several types	Several	0–30	–	0.40–0.68	Anderson-Texeira *et al.*, 2009¶
North Italy	Fine-silty	8	0–120	8.5 ± 0.7 (SE)	–	Monti & Zatta, 2009

In some cases, data are approximated from graphical presentations.
*ns (insignificant increase) till the 16th year then an increase by 30% until the18th compared with C_3– cropland;
†percentage of increase with respect to fallow land;
‡compared with cropland;
§compared with degraded lands;
¶simulation study;
**personal communication in McLaughlin *et al.* (2002);
††soil organic matter (SOM);
‡‡more SOC than cropland;
§§in switchgrass monoculture or combined crops.

(+44%), maize (+641%) and soybean (+748%). These results may partially explain the outstanding capacity to sequester C in the soil shown by switchgrass (Frank *et al.*, 2004). Considering that the maximum annual rate of soil C sequestration for perennial vegetation is usually less than 1 Mg C ha^{-1} yr^{-1} (Post & Kwon, 2000), Zan *et al.* (2001) measured a SOC rate of 1.1 Mg C ha^{-1} yr^{-1} in southwestern Quebec over a 4-year period, whereas rates of up to 2.4–4.0 Mg C ha^{-1} yr^{-1} were reported by Lee *et al.* (2007) in a switchgrass crop grown in the Conservation Reserve Program (CRP) in South Dakota (Table 2). It is worth mentioning that in old CRP sites not including switchgrass, Gebhart *et al.* (1994) measured 1.1 Mg C ha^{-1} yr^{-1} over a 5-year period (0–100 cm), meaning less than half the rates achieved by switchgrass. Sanderson (2008)measured a 33–140% increase in soil C content in the upper 5 cm layer after 7 years, about 20% of which derived from switchgrass. Corre *et al.* (1999) showed that in the upper 5 cm, soil C derived from switchgrass increased from 25% to 72% from the 9th to the 18th year. However, in a higher layer (0–30 cm) the soil C increase was considerably lower or insignificant. In a similar study, Garten & Wullschleger (1999) showed that about 22–43% of soil C in the surface 10 cm originated from switchgrass after 5 years. The same authors, in another study (Garten & Wullschleger, 2000), predicted the potential recovery of SOC in switchgrass grown on degraded lands and reported a 12% increase in SOC inventory over a period of 10 years following establishment. About 75–90% of the SOC was mineral-associated organic matter (MOM) with a turnover from 26 to 40 years, whereas the rest was particulate organic matter (POM) with a turnover time of 2–4 years. Overall, coarse root C in switchgrass plots was 23.8–58.7 mg cm^{-2}, hence significantly higher than in maize (0–2.2 mg cm^{-2}) and fescue (2.5–18.5 mg cm^{-2}) (Garten & Wullschleger, 2000). The significant increase of soil carbon levels under switchgrass was confirmed by several other studies. Ocumpaugh *et al.* (2003) reported that in Texas the average soil carbon levels (0–30 cm) increased by 20% in a 3-year switchgrass plant. Sanderson (2008) and McLaughlin (1993) showed a 30% increase in SOC in Virginia after 4 years of switchgrass cultivation. However, in some cases less than 1 Mg ha^{-1} yr^{-1} of SOC rate was estimated. For example, in a simulation study over the first 10 years of switchgrass cultivation, McLaughlin *et al.* (2002) calculated 0.78 Mg C ha^{-1} yr^{-1}. Likewise, in a review study including 146 site-treatment combinations, Anderson-Texeira *et al.* (2009) reported that the cultivation of switchgrass caused an increase of SOC in the top 30 cm by 0.40–0.68 Mg ha^{-1} yr^{-1}, a relatively high amount, however, as the authors showed that in the same period maize reduced the soil C reserves by 3–8 Mg ha^{-1} yr^{-1} with crop residue removal.

Perennial grasses generally have 70–90% of root biomass in the upper 0.3–0.4 m of soil, thus most of the SOC changes can be expected to occur in this layer (Garten & Wullschleger, 1999; Ma *et al.*, 2000b; Tufekcioglu *et al.*, 2003; Liebig *et al.*, 2008). Nonetheless, a pronounced ability by switchgrass to colonize the deep soil layers was also found (Ma *et al.*, 2000b; Liebig *et al.*, 2005; Monti & Zatta, 2009). Deep root allocation will probably provide more stable C pools, in turn strongly influencing SOC turnover, as carbon is less susceptible to mineralization at deeper layers (Grigal & Berguson, 1998; Ma *et al.*, 2000b). In reviewing 87 cases, Anderson-Texeira *et al.* (2009) found that the SOC accumulation determined by switchgrass tended to increase with sampling depth, but the relationship was not significant; conversely, in the present review (Table 2) we found the correlation between sampling depth and SOC increase to be highly significant($r = 0.79$, $P \leq 0.01$). Plant density (20–120 cm row spaced) was found to not influence the rooting depth of switchgrass (Ma *et al.*, 2000a).

Life cycle carbon emissions by switchgrass

Life cycle C-emissions can vary considerably with feedstock type, production process (Farrell *et al.*, 2006), and land use (Table 3). Only in very few cases did switchgrass lead to negative environmental effects; for example Pimentel & Patzek (2005) reported that ethanol-switchgrass production requires about 50% more fossil energy than fossil-ethanol production. However, the literature is generally consistent in reporting significant benefits from switchgrass. In a recent study by Adler *et al.* (2007), poplar and switchgrass showed the greatest potential among several annual and perennial crops in mitigating CO_2 emissions. The largest benefits, approx. −210 g CO_2-e m^{-2} yr^{-1}, occurred when switchgrass was used to produce electricity by gasification (−24 g CO_2 MJ^{-1}). Skinner & Adler (2010) measured an annual net ecosystem exchange (NEE) ranging from −112 to −910 g CO_2-e m^{-2} yr^{-1} for a spring-harvested switchgrass over 5 years. The authors also estimated that the net biome productivity (NBP), i.e., the real amount of C sequestration per year given by all carbon in- and out-fluxes of the field including harvested biomass, ranged from −112 to −344 g CO_2-e m^{-2} yr^{-1}. Adler *et al.* (2007) also calculated that switchgrass could reduce the emissions (CO_2 equivalents) by up to 93% compared with fossil counterparts, and by about one-fifth and one-third of those of maize and hybrid poplar grown under conventional tillage. Wu *et al.* (2006) calculated a fuel life cycle assessment which revealed that a mixture of 85% switchgrass-ethanol and 15% gasoline (E85, v/v) can lead to approx. 60% and 85% savings in C-emission compared with fossil transport fuel and petroleum, respectively. Similar results were found by Bai *et al.* (2010) comparing switchgrass-E85 with gasoline (Table 3). Monti *et al.* (2009) analyzed the cradle-to-farm gate impacts in four perennial energy grasses and compared it with a wheat-maize rotation. They found about 50% less emissions by perennial lignocellulosic grasses with respect to a conventional rotation. Moreover, switchgrass showed the highest land-based environmental benefits in six impact categories of nine, and 27–32% lower impacts than other perennials on marine-water ecotoxicity, i.e., the category most affected by energy crops. In general, among the annual and perennial energy crops considered, switchgrass generally resulted in the most favorable CO_2

Table 3 Cradle-to grave GHG emission savings by switchgrass compared with other crops

Source	End-product	Process	Counterpart	GHG savings	GHG units	Methodology
Wu *et al.*, 2006	Bio-ethanol[*]	Hydrol./Ferment.	Gasoline	60–62	%	GREET[§]
	CHP (Bio-DME)[†]	Gasification	Petroleum	82–84	%	GREET
	CHP (Bio-FTD)[‡]	Gasification	Petroleum	85–87	%	GREET
Adler *et al.*, 2007	Bio-electricity	Gasification	Coal	93	%	DAYCENT
				69	g C-e MJ^{-1}	DAYCENT
				210	g C m^{-2} yr^{-1}	DAYCENT
Bai *et al.*, 2010	Bio-ethanol[*]	Hydrol./Ferment.	Gasoline	65	%	LCA
Cherubini & Jungmeier, 2010	Multiple fuels	Biorefinery	Oil & nat. gas	79	%	LCA
				201	g C m^{-2} yr^{-1}	LCA
Monti & Fazio, unpublished[*]	Bio-FTD	Gasification	Diesel	86	%	LCA
		Gasification	Diesel	192	g C m^{-2} yr^{-1}	
	CHP	Combustion	Natural gas	87	%	LCA
		Combustion	Natural gas	291	g C m^{-2} yr^{-1}	
	Bio-ethanol	Hydrol./Ferment.	Gasoline	82	%	LCA
		Hydrol./Ferment.	Gasoline	206	g C m^{-2} yr^{-1}	
Campbell *et al.*, 2009	Bio-electricity	Multiple processes	Gasoline	200–700	g C m^{-2} yr^{-1}	EBAMM[**]
	Bio-ethanol	Hydrol./Ferment.	Gasoline	220	g C m^{-2} yr^{-1}	Several models
Patzek, 2010;	Bio-ethanol	Hydrol./Ferment.	Gasoline	−35	%	LCA
				7	g C-e MJ^{-1}	LCA
Fritsche *et al.*, 2009;	Bio-heat	Gas-heating	Coal	86	%	GEMIS[††]
			Natural gas	89	%	GEMIS
Schmer *et al.*, 2008;	Bio-ethanol	Hydrol./Ferment.	Gasoline	63–118[‡‡]	%	EBAMM
Farrell *et al.*, 2006;	Bio-ethanol	Hydrol./Ferment.	Gasoline	~21	g C-e MJ^{-1}	EBAMM
Samson & Stamler, 2009	Bio-electricity	Combustion	Coal	351	g C m^{-2} yr^{-1}	GREET, GHGenius[§§]
	Bio-electricity	Combustion	Oil	337	g C m^{-2} yr^{-1}	GREET, GHGenius
	Bio-electricity	Combustion	Natural gas	270	g C m^{-2} yr^{-1}	GREET, GHGenius
	Bio-ethanol	Hydrol./Ferment.	Gasoline	135	g C m^{-2} yr^{-1}	GREET, GHGenius
Gaunt & Lehmann, 2008[¶¶]	Bioelectricity	Slow pyrolysis	Natural gas	114	g C m^{-2} yr^{-1}	IPCC default
	Bioelectricity	Slow pyrolysis	Coal	173	g C m^{-2} yr^{-1}	factors
Qin *et al.*, 2006		Co-firing (coal)	Coal	92	%	Environ. biocomplex. analysis
Ney & Schnoor, 2002	CHP	Combustion	Coal	102 ± 68[***]	g C-e MJ^{-1}	Incremental LCA

*E85 (mixture 85%ethanol and 15% gasoline);
†Dimethyl ether (DME);
‡Fischer-Tropsch diesel (FTD);
§Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation;
¶unpublished;
**Energy and Resources Group Biofuel Analysis Meta-Model;
††Global Emissions Model for integrated Systems by Oeko-Institut;
‡‡94% average of 10 switchgrass fields over a 5-year period;
§§GHGenius 3.14 program (Natural Resources Canada);
¶¶the authors calculated that in a biochar production system (50% energy) GHG saving can increase to 339 and 380 by displacing natural gas and coal with switchgrass, respectively;
***68 indicates the uncertainty in LCA calculated by the in- and outer-core analysis over thirty activities identified by the authors. In some cases, data were approximated from graphical presentations or converted in g C m^{-2} yr^{-1} from g CO_2 ha^{-1} yr^{-1}.

emission-based scenario (Monti *et al.*, 2009). In addition, significant net emission savings, up to 82% compared with coal, were also found in a more recent study (Monti & Fazio, unpublished), in which switchgrass for bioelectricity showed the lowest environmental loads. McLaughlin & Walsh (1998) estimated that by converting switchgrass to ethanol and including belowground C stocks, C-emission savings would be approx. 30 times higher per unit land area compared with maize (2.98 vs. 0.09 Mg C ha^{-1} yr^{-1}). The environmental benefits of switchgrass-ethanol compared with maize-ethanol were emphasized by Farrell *et al.* (2006) who pointed out that only cellulose (switchgrass)-ethanol offers large reductions in C-emissions. Likewise, Luo *et al.* (2010) showed that global warming potential (GWP) of switchgrass-ethanol was consistently lower than that of maize stover, sugarcane (and bagasse), flax shives, and hemp hurds.

In an optimized system for bioenergy and biochar production from switchgrass, Gaunt & Lehmann (2008) estimated up to 380 g C m^{-2} yr^{-1} avoided by displacing fossil fuels with switchgrass (Table 3). The authors pointed out that a strategy that combines pyrolysis for bioenergy production with application of biochar to soil is more effective in mitigating climate change than producing solely bioenergy. Fritsche *et al.* (2009) estimated life cycle impacts of several bioenergy systems in different European environmental zones, and found the emissions by switchgrass (5.7 kg CO_2 eq. GJ^{-1}) much lower than those of biogas and maize-ethanol (36.5 and 61.3 kg CO_2-e GJ^{-1}, respectively). The authors also estimated that an oil heating system emits 0.3–0.4 kg CO_2-e per kWh_{th}, i.e., about tenfold more than switchgrass. The positive results on carbon emission containment from switchgrass-solid fuels are also proved in terms of bioethanol production (Tilman *et al.*, 2006). Based on actual production data from 10-year switchgrass fields and considering an annual C sequestration of 0.14 Mg CO_2 Mg^{-1} aboveground biomass (switchgrass) per year (Andress, 2002), Schmer *et al.* (2008) estimated that switchgrass-ethanol averaged 94% lower emissions than gasoline. However, solid biofuel seems to outperform liquid biofuels in terms of land use efficiency as well as of GHG mitigation. In the case of switchgrass, Campbell *et al.* (2009) reported that the gross transportation output per hectare is 85% greater for bioelectricity than for cellulosic ethanol, and net GHG offsets were 108% greater for bioelectricity than for bioethanol. Samson & Stamler (2009) estimated about 5 Mg CO_2 per hectare of total GHG offsets by displacing gasoline with second generation switchgrass-ethanol. Nonetheless, it should be recognized that other issues such as water use, human toxicity, economic benefits, etc., would need to be assessed before establishing that bioelectricity is preferred over bioethanol.

Nitrous oxide

In general, annual crops produce about three times more emissions than unmanaged successional lands and perennial crops (Robertson *et al.*, 2000). Along with N fertilizers, other sources such as crop type, soil organic matter content, soil pH and texture may play important roles in controlling the activity of nitrifiers and denitrifiers and thus N_2O emissions (Stehfest & Bouwman, 2006).

To the best of our knowledge, very few studies have examined the impact of switchgrass on nitrous oxide emissions. This is probably mainly due to the high spatial and temporal variability in N_2Ofluxes (Robertson & Grace, 2004), that makes spot measurements with small chambers poorly representative in a global perspective. Most of the emission values reported in the literature are estimates based on emission factors and calculation guidelines developed by Eggelston *et al.* (2006) and LCA studies such as Qin *et al.* (2006), Adler *et al.* (2007), Crutzen *et al.* (2008) among others. In addition, the discrepancies between the reported emissions depend on how they are calculated and expressed. Generally speaking, the surplus nitrogen is particularly susceptible to N_2O emission (McSwiney & Robertson, 2005). Consequently, improving N use efficiency through a precise estimation of crop needs and timely fertilizer application will reduce N_2O emissions (Schlesinger, 1997).

The influence of crop management on N_2O emissions

Almost all agricultural practices can be a significant source of direct (from agricultural lands) and indirect (from volatilization/deposition and leaching/runoff) N_2O emissions of anthropogenic origin.

Even though the N_2O emissions from switchgrass were lower than those from other perennial grasses and annual crops, N_2O remained the primary source of GHG emissions and this was associated with the crop production phase (KimS & Dale, 2004; Adler *et al.*, 2007; Kavdir *et al.*, 2008). One of the best options to reduce the considerable impact of fertilization in GHG emissions is, therefore, to minimize the use of N fertilizers or to develop and use more efficient N-use strategies, such as the adoption of fertilizer best management practices that could reduce N_2O emissions by 30–40% (CAST-Council for Agricultural Science & Technology, 2004). These practices in general include the appropriate amount, timing, and placement of fertilizers (Bransby *et al.*, 1998; CAST-Council for Agricultural Science & Technology, 2004; Burton *et al.*,2008; Cherubini & Jungmeier, 2010), and in particular the response of switchgrass to fertilizers depends on precipitation, cultivar, harvest management, and the symbiotic relationship with arbuscular mycorrhizal fungi (Vogel, 2004).

Using organic fertilizers in lieu of mineral ones leads to contrasting effects on N_2O emissions: depending on whether the comparison is based on the amount of total (Kjeldhal) or available (mineral) nitrogen supplied, the application of mineral fertilizers led to a short-term increase of N_2O emissions with respect to organic N sources (Dittert *et al.*, 2005), or the opposite (Jones *et al.*, 2007). The latter case implies that a certain amount of organic N is rapidly mineralized to nitrates, fueling the pool most responsible for N_2O losses when soil moisture and temperature are not limiting factors (Jones *et al.*, 2007). Over an annual basis, N_2O emissions from mineral vs. organic N sources were either statistically equivalent (Meng *et al.*, 2005; Lampe *et al.*, 2006; Dambreville *et al.*, 2008; Sawamoto *et al.*, 2010), or the latter type released more N_2O (Jones *et al.*, 2007; Chirinda *et al.*, 2010), or even the opposite (Shimizu *et al.*, 2010). However, the comparisons between N_2O emissions from alternative fertilizers and especially between their emission factors appear to be biased by the fact that no common basis, i.e., total N vs. mineral N vs. NH_4-N, is assumed in the literature.

Intercropping with legumes could also be an option, although the decomposition of their residues may contribute to postharvest N_2O emissions. In any case, the limited results available suggest that, when compared with other crops, switchgrass is particularly good at mitigating the soil N_2O emissions associated with N fertilizer applications.

Even if Vogel (2004) indicated 10–12 kg N ha^{-1} for each Mg ha^{-1} of biomass produced for switchgrass, the optimal nitrogen fertilization dose for this crop varies widely (Table 4). Therefore, balancing the nitrogen supply to achieve full yield potential while avoiding nutrient excess is a task to be pursued with particular care in reducing N_2O emissions (Schimel, 1986; Heaton *et al.*, 2004). Bransby *et al.* (1998) indicated that the ability of switchgrass to recover the applied nitrogen is 16% higher than that of wheat and maize, thus confirming other positive findings about the potential impact of

Table 4 Biomass yield with and without nitrogen, nutrient balance, and apparent recovery in a series of experimental cases in switchgrass

Location	Years	Cuts yr^{-1}	Applied N* (kg ha^{-1})	Biomass yield (Mg ha^{-1})	N balance† (kg ha^{-1})	Source
Beeville, TX, USA	3	1	0	3.8	-	Muir *et al.* (2001)
	3	1	168	14.3	-	
Stephenville, TX, USA	7	1	0	6.0	-	Muir *et al.* (2001)
	7	1	168	8.3	-	
Shorter, AL, USA	1	1	0	3.7	-	Ma *et al.* (2001)
	1	1	224	12.0	-	
Ames, IA, USA	2	2	0	8.0	−55	Vogel *et al.* (2002)
	2	2	120	12.0	0	
Mead, NE, USA	2	2	0	9.0	−90	Vogel *et al.* (2002)
	2	2	120	10.0	−10	
Chickasha, OK, USA	4	1	0	16.6	−149	Thomason *et al.* (2004)
	4	1	448	17.7	276	
Chickasha, OK, USA	4	3	0	20.9	−276	Thomason *et al.* (2004)
	4	3	448	22.5	129	
Perkins, OK, USA	4	1	0	9.2	−90	Thomason *et al.* (2004)
	4	1	448	10.3	322	
Perkins, OK, USA	4	3	0	11.5	−136	Thomason *et al.* (2004)
	4	3	448	11.9	264	
Blacksburg and Orange, VA, USA	3	2	0	11.0	−76	Lemus *et al.* (2008a)
	3	2	30	12.1	−71	
	3	2	90	13.3	−37	
Lucas and Wayne, IA, USA	5	1	0	3.9	−187	Lemus *et al.* (2008b)
	5	1	112	4.9	−113	
	5	1	224	5.2	−41	
Frederick and Burneyville,OK, USA	2	1	0	10.4	−41	Guretzky *et al.* (2011)
	2	1	135	15.0	32	
	2	1	180	15.5	67	
Frederick and Burneyville, OK, USA	2	2	0	12.2	−95	Guretzky *et al.* (2011)
	2	2	135	18.0	−48	
	2	2	180	22.8	−55	

*Unfertilized vs. near-optimum rates of N;
†applied – removed N.

switchgrass on N_2O emission savings (KimS & Dale, 2004; Adler *et al.*, 2007; Kavdir *et al.*, 2008).

The high nitrogen use efficiency of switchgrass could be one of the reasons for the 75% lower N_2O emission from switchgrass than miscanthus reported by Zeri *et al.* (2009) in one of the few side-by-side comparisons of N_2O fluxes associated with the growth of these grasses. Importantly, some studies showed that the highest N_2O fluxes occur just after N fertilizer application and/or after large rainfall events (Davidson, 1992; Burton *et al.*, 2008), so the intrinsic ability of the crop to take up nitrogen immediately after its application can be decisive in mitigating N_2O fluxes. It has been shown that volatilization of N as NH_3 occurs at a rate of 2–10% of total mineral N application (Eggelston *et al.*, 2006), compared with about 1% of synthetic N emitted as N_2O, whereas 0.75% of NO_3-N leached to groundwater (about 30% of total N applied) is converted to N_2O. This means that about 1.32% of N in synthetic fertilizer is estimated to be emitted as N_2O (Eggelston *et al.*, 2006).

Although Bransby *et al.* (1998) had found evidence that the apparent recovery of nitrogen by switchgrass does not change with varieties and harvest time, further studies revealed that the balance between applied and removed nitrogen tends to be negative in the double harvest system and positive in the single harvest system (Table 4), potentially leading to higher N_2O emissions. Moreover, it is assumed that N_2O emission could be decreased by increasing switchgrass productivity, but due to the direct and positive relationship between increased yields and fertilization dose, the effective potential for reducing GHG emission is counteracted by N_2O emissions. Comparing a biorefinery fed with switchgrass biomass with the traditional fossil fuel refinery, Cherubini & Jungmeier (2010) indicated that the use of switchgrass has a net reduction in GHG emissions, but that N_2O emissions were about ten times higher than in the fossil fuel refinery mainly because of the fertilization level used for growing the crop (112 kg N ha^{-1}). The high emissions of N_2O could, perhaps, be partially ascribed to the decomposition of the soil organic matter and dead roots, but it seems that this point was not taken into account by the authors. According to their computations, the production phase of switchgrass was responsible for 80% of the GHG emissions, approx. 40% of which were N_2O emissions, mostly due to fertilizers and chemicals, transport and harvest, in that order of importance. In addition, the computation by Qin *et al.* (2006) showed that of the total N_2O emissions 68.9% were due to the production and use of fertilizers and atrazine, 30.5% to switchgrass combustion in boilers, and the remaining traces to other agricultural and processing activities. These data suggest that with appropriate management of fertilizers and with the development of efficient conversion technologies, significant N_2O emission can be avoided.

Methane

The atmospheric concentration of CH_4 has drastically increased in the last few centuries, most likely due to intensive agricultural activities and the use of fossil fuels (Metz *et al.*, 2007). Soils can be either a source or a sink of methane, depending on land use and climatic conditions (Chan & Parkin, 2001; Robertson & Grace, 2004; Dutaur & Verchot, 2007). Factors affecting the capacity of soil to oxidize atmospheric CH_4, therefore to act as a sink, are soil temperature, moisture, pH, and soil N status (Tlustos *et al.*, 1998). It is well documented that forest soils and grasslands are net consumers of CH_4, whereas cultivated soils have a lower sink potential and in both cases, this potential is further reduced by agronomic and fertilization practices (Tlustos *et al.*, 1998; Chan & Parkin, 2001; Dutaur & Verchot, 2007; Kara & Özdýlek, 2010; Kim *et al.*, 2010). Mosier *et al.* (1991), for example, indicated that annual fertilization increases the N_2O fluxes and at the same time decreases the CH_4 uptake in the soil by 41%, meaning an increased concentration of both gases in the atmosphere. The same authors also reported that high N turnover, whether native or due to fertilization, results in the suppression of CH_4 uptake. On the other hand, in mid and late unmanaged successional forests, N_2O emissions were almost completely offset by CH_4 oxidation (Robertson *et al.*, 2000). Moreover, in unfertilized and undisturbed grasslands, methane uptake was 1.4 and 2 times higher than in fallow lands and wheat cultivated lands (Mosier *et al.*, 1991). Thus, considering that switchgrass is a perennial grass with similar characteristics to native grasslands, and also has low fertilization requirements and high N uptake efficiency, and that tillage is practiced only at the establishment year, methane flux contributions from this crop to net GHG emissions may be close to zero. In an LCA assessment of net GHG of several energy crops including switchgrass, Adler *et al.* (2007) indicated that CH_4 oxidation was the smallest GHG sink, and that the estimated CH_4 uptake of switchgrass was -1.41 g CO_2-e m^{-2} yr^{-1}, whereas another study from the Chariton Valley Biomass Project estimated that during the agronomic practices to establish switchgrass, the total CH_4 emissions were 23 g CO_2-e m^{-2}, and that during harvesting the emissions were 17.4 g CO_2-e m^{-2} (Ney & Schnoor, 2002). Currently, however, the information available on CH_4 flux contributions to net GHG emission from switchgrass is very limited, probably because of its aforementioned small GHG sink force, so most LCAs and other studies did not take it into account, nor explicitly mention it. This is not to say that actual CH_4 flux measurements in switchgrass are inexistent as far as we know. In one of the few complete sets of data available from an LCA assessment of a power generation chain (Qin *et al.*, 2006), it was shown that in contrast to N_2O emissions, the largest CH_4 emissions are produced during the processing/combustion phase of switchgrass and not during the crop production phase. The degradation of the lost switchgrass biomass accounted for 90% of the total CH_4 emissions, although 5% was due to the combustion in boilers (Qin *et al.*, 2006). In any case, actual values based on field measurements are urgently needed to more precisely estimate CH_4 emissions from the production/transformation phases of switchgrass to different end-uses. Even though it is believed that CH_4 emissions have a negligible effect on the overall GHG budget, these kinds of measurements would probably help to reduce the large number of uncertainties in its estimation.

Land conversion to switchgrass

Direct land use change (LUC) accounts for the in/out-fluxes deriving from land conversion to a new use (e.g., tropical forest to oil palm). Land use conversion to energy crops can have very different environmental effects in terms of GHG emissions depending on the type of converted land, e.g., forest, grassland, native ecosystems, intensively cultivated croplands or degraded lands, as well as on the type of energy crop (Penman *et al.*, 2003; Righelato & Spracklen, 2007; Fargione *et al.*, 2008). For example, the net CO_2 abatement from growing switchgrass can vary from very significant to insignificant, if arable lands or permanent grasses are converted, respectively (Bransby *et al.*, 1998; Bullard & Metcalfe, 2001; McLaughlin *et al.*, 2002). It was estimated that almost 170 years would be needed to restore C losses caused by conversion of forest land to corn-based ethanol (Searchinger *et al.*, 2008); although this seems to be an overestimation, it is an indication of the considerable effects of changing land use patterns. On the other hand, converting croplands to perennial grasses such as switchgrass was found to increase soil C stock at a rate of 1.1 Mg C ha^{-1} yr^{-1} (Gebhart *et al.*, 1994), meaning that 17 Mha of land enrolled in the Conservation Reserve Program (CRP) may have the potential to sequester about 45% of C-emissions from U.S. agriculture. Similar conclusions were reached by Watson *et al.*, (2000) and Penman *et al.*, (2003) which estimated up to 1.2 Mg C ha^{-1} yr^{-1} of SOC storage by the conversion of arable lands to perennial energy grasses, due to the ability of perennial crops to accumulate large amounts of net primary products in their root system. Switchgrass, in particular, resulted in a considerable ability to accumulate belowground biomass (McLaughlin & Walsh, 1998; Ma *et al.*, 2000b). Likewise, Garten & Wullschleger (2001) predicted long-term (up to 30 years) regional gains in SOC, especially with land conversion from cropland to switchgrass. The authors found negative to positive effects (approx. −1 to 1 Mg C ha^{-1} yr^{-1}) by converting pasture to switchgrass, and always positive effects by converting cropland to switchgrass (up to approx. 2.8 Mg C ha^{-1} yr^{-1}).

Although LUC is not a new issue in soil carbon studies – more than 20 years ago Hall & Scurlock (1991) pointed out that LUC would probably be the main factor impacting on soil carbon contents in the future – it is only recently that GHG emissions as a result of converting arable lands, natural ecosystems, permanent grassland, the savannah, etc., were characterized (Eggelston *et al.*, 2006) and that LUC emissions were recognized in LCA studies. Nonetheless, LUC data are missing in most LCA-bioenergy studies, thus exposing them to the risk of critically biased LCA outcomes (Penman *et al.*, 2003; Farrell *et al.*, 2006; Croezen *et al.*, 2010; Searchinger, 2010). Fritsche *et al.* (2010) showed that CO_2-e emissions can increase four times by including LUC in the LCA calculations for oil palm-biodiesel, with the crop replacing a tropical rainforest, or even higher for soybean cultivated in humid savannah lands for the production of fatty acid methyl ester (FAME). Likewise, Gnansounou *et al.* (2009) analyzed GHG emissions in nine types of lands converted to energy crops and found CO_2 emissions strongly affected by LUC, i.e., from –80% in severely degraded grassland to +5% in forested land. The authors also considered an annual energy crop (wheat) converted to bioethanol, which can be expected to provide much less C storage than perennial grasses such as switchgrass, especially in long-term C-depleted soils (Liebig *et al.*, 2005; Fargione *et al.*, 2008). For example, Tolbert *et al.* (2002) showed an almost 70% SOC increase in the upper 15 cm soil layer in 3-year switchgrass grown on traditional croplands. Finally, Cherubini & Jungmeier (2010) tested the importance of LUC through a sensitivity analysis; they found that GHG annual emissions of the biorefinery system decreased from more than 100 000 Mg CO_2-e to almost zero, with 0.2 and 1.1 Mg C ha^{-1} of soil C sequestration, respectively. Therefore, it can be concluded that much more attention should be paid to LUC emissions to provide reliable LCA outcomes.

Not only direct land use change, but also indirect LUC (iLUC), i.e., the overall displacement of cropland in response to the increased production of biofuels, should be taken into account in quantitative GHG emission estimations (Fritsche *et al.*, 2010; Searchinger, 2010). However, although some progress has been made in predicting the amount of cropland that could be replaced by biofuels and how much emission the change in land use will produce, iLUC effects cannot be quantified directly and need to be modeled on a global scale by coupling complex economic and biophysical models. Overall, significant uncertainty still persists regarding iLUC emissions; it therefore appears unwise to assign emission coefficients to iLUC in GHG balances based on current knowledge (Searchinger *et al.*, 2008). Nonetheless, Fritsche *et al.* (2010) showed that adding iLUC plus LUC emissions to LCAs could result in almost double GHG emissions per unit of energy. Moreover, a recent iLUC simulation study by Croezen *et al.* (2010) revealed that GHG emissions of biofuels on a European and global scale were 20–60 g CO_2-e MJ^{-1}, i. e., 25–75% of C-emissions per MJ of the amount of petrol and diesel fuel being substituted. Further studies are therefore needed to define specific criteria for quantifying consistent iLUC values to appropriately include them in GHG emission balances.

Conclusions

Our review reveals that switchgrass could contribute to reducing GHG emissions throughout its life cycle when used as a bioenergy feedstock. Nonetheless, significant sources of uncertainty relating to the GHG balance must be urgently addressed, especially on soil carbon sequestration (Ney & Schnoor, 2002), direct- and indirect land use change (Fritsche *et al.*, 2010), and the emissions of highly impacting greenhouse gases such as N_2O and CH_4 (Robertson & Grace, 2004). The generation of such information will help to reduce uncertainties and to delineate robust development policies and innovative technologies for producing and transforming switchgrass. In the case of N_2O, switchgrass seems to reduce the emissions compared with most perennial and annual crops because of its lower fertilization requirements and high N use efficiency. In any case, among the GHGs associated with switchgrass cultivation and other similar grasses, N_2O fluxes from fertilization practices constitute the primary source of GHG emissions, whereas, on the other hand, CH_4 emissions are always considered as minimal. However, more experimental data in long-term trials across wide precipitation and temperature gradients are needed to reduce the uncertainties in the coefficient factors used to estimate their impacts at a global level. Most LCA studies on bioenergy systems do not include the source of the data or use modeled data based on conjecturable assumptions, so there is an urgent need to support research activities on these topics to provide measured data and validate models.

Cultivation and management practices that impact both yield and GHG emissions include crop establishment, fertilization timing and rates, control of weeds and pests, harvest time and method. The decision on when and how much nitrogen fertilizer should be applied, for example, will determine the amount of nutrient leaching/runoff and emissions of N_2O produced. Therefore, an in-depth evaluation of such factors, as well as their interactions, is necessary to refine agricultural practices to both maximize yields and mitigate GHG emissions from switchgrass. Moreover, substantial environmental benefits such as the reduction of soil erosion and nutrient leaching could be achieved by the use of improved products and agronomic practices. However, it has to be taken into account that a practice that is highly effective in reducing emissions at one site may be less effective or even counterproductive elsewhere. Such practices should therefore be flexible and easily adaptable to the prevailing local conditions.

In addition to the extensive root systems of switchgrass, adopting no-tillage practices may further help to improve soil physical properties and to maintain, if not increase, the soil C levels, and at the same time, reduce fossil energy requirements. Again, this could significantly contribute to CO_2 savings. Even though the ability of switchgrass to develop deep roots is widely recognized and documented in the literature, and the below- and aboveground biomasses of switchgrass were quantified in a significant number of studies, we found the correlation between root and aboveground biomass insignificant. Restricting soil samples to the upper layers while at the same time increasing the repetitions thus appears to be a reasonable compromise, although root allocation to depth, especially of fine roots which were found to be abundant in switchgrass, can play a very important role in determining the C-turnover. Importantly, considerable variability emerged from reviewing several articles on switchgrass capacity to sequester carbon. The reason for such uncertainty is not well understood; however, it is likely related to plant ages, sampling periods, soil types, and the difficulties in quantifying the actual amount of carbon added to the soil system by plant roots due to the continuous and simultaneous fluxes of carbon compounds between the soil-plant-atmosphere continuum. Moreover, in the case of switchgrass establishment on a former cropland, there is limited information on when a new equilibrium in SOC can be reached and therefore on the time span during which carbon sequestration cannot contribute to reducing CO_2 emissions. Some authors estimate that up to 50 years may be needed to reach the equilibrium (Lemus & Lal, 2005).

Although some evidence suggests greater savings when switchgrass is converted to electricity than cellulose-bioethanol, other issues need to be assessed before establishing that bioelectricity is the ideal and preferred method of conversion. Regardless of the conversion method, there is general consensus in the literature that GHG emissions from switchgrass are generally lower than those from other energy crops currently used for bioenergy purposes.

Some studies report trivial GHG savings from converting permanent grasslands to switchgrass, while significant positive effects on carbon sequestration were achieved by displacing croplands.Therefore, switchgrass cultivation should be limited to degraded or abandoned areas, or croplands, taking into account the food priority production. Indirect land use changes (iLUC) cannot be quantified at present as such studies are still in their infancy. Nonetheless, there is evidence that ignoring or underestimating the iLUC effects can greatly bias the GHG balance of switchgrass. A considerable number of studies are therefore imperative to identify specific criteria for estimating LUC and iLUC and to understand and quantify consistent values, which can be appropriately included in GHG emission balances.

References

Adler PR, Del Grosso S, Parton W (2007) Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. *Ecological Applications*, **17**, 675–691.

Al-Kaisi MM, Grote JB (2007) Cropping systems effects on improving soil carbon stocks of exposed subsoil. *Soil Science Society American Journal*, **71**, 1381–1388.

Ammann C, Spirig C, Leifeld J, Neftel A (2009) Assessment of the nitrogen and carbon budget of two managed temperate grassland fields. *Agriculture, Ecosystems and Environment*, **133**, 150–162.

Anderson-Texeira KJ, Davis SC, Masters MD, Delucia EH (2009) Changes in soil organic carbon under biofuel crops. *Global Change Biology Bioenergy*, **1**, 75–96.

Andress D (2002) *Soil Carbon Changes for Bioenergy Crops*. Argonne National Laboratory, US Dept of Energy, Argonne, IL, 26 p.

Aravindhakshan SCEpplin FMTaliaferro CM (2010) Economics of switchgrass and miscanthus relative to coal as feedstock for generatingelectricity. *Biomass and Bioenergy*, **34**, 1375–1383.

Baer SG, Kitchen DJ, Blair JM, Rice CW (2002) Changes in ecosystems structure and function along a chronosequence of restored grasslands. *Ecological Applications*, **12**, 1688–1701.

Bai Y, Luo L, van der Voet E (2010) Life cycle assessment of switchgrass-derived ethanol as transport fuel. *International Journal of Life Cycle Assessment*, **15**, 468–477.

Bowden R, Wayman S, Ernst CL, Mitchell R (2010) Aboveground and belowground biomass and nitrogen retranslocation in switchgrass (*Panicum virgatum*). Proc. ASA, CSSA, and SSSA 2010 Int. Annual Meeting, Oct. 31 – Nov. 4, Long Beach, CA. ASA, CSSA, and SSSA, Madison, WI.

Bransby DI, McLaughlin SB, Parrish DJ (1998) A review of carbon and N balances in switchgrass grown for energy. *Biomass Bioenergy*, **14**, 379–384.

Bullard M, Metcalfe P (2001) Estimating the energy requirements and CO_2 emissions from production of the perennial grasses Miscanthus, switchgrass and reed canary grass. ADAS Report for the Department of Trade and Industry. ETSU B/U1/00645/REP. The House of Commons, London.

Burton DL, Zebarth BJ, Gillam KM, MacLeod JM (2008) Effect of split application of fertilizer nitrogen on N_2O emissions from potatoes. *Canadian Journal of Soil Science*, **88**, 229–239.

Campbell JE, Lobell DB, Field CB (2009) Greater transportation energy and GHG offsets from bioelectricity than ethanol. *Science*, **324**, 1055–1057.

CAST-Council for Agricultural Science and Technology (2004) *Climate Change and Greenhouse Gas Mitigation: Challenges and Opportunities for Agriculture*. CAST, Ames, IA, 120 p.

Chan ASK, Parkin TB (2001) Effect of land use on methane flux from soil. *Journal of Environmental Quality*, **30**, 786–797.

Cherubini F, Jungmeier G (2010) LCA of a biorefinery concept producing bioethanol, bioenergy, and chemicals from switchgrass. *International Journal of Life Cycle Assessment*, **15**, 53–66.

Chirinda N, Carter MS, Albert KR, Ambus P, Olesen JE, Porter JR, Petersen So (2010) Emissions of nitrous oxide from arable organic and conventional cropping systems on two soil types. *Agriculture, Ecosystems and Environment*, **136**, 199–208.

Conant RT, Paustian K, Elliot E (2001) Grassland management and conversion into grassland: effects on soil carbon. *Ecological Applications*, **11**, 343–355.

Corre MD, Schnabel RR, Shaffer JA (1999) Evaluation of soil organic carbon under forests, cool-season and warm-season grasses in the northeastern US. *Soil Biology and Biochemistry*, **31**, 1531–1539.

Croezen HJ, Bergsma GC, Otten MBJ, van Valkengoed MPJ (2010) *Biofuels: Indirect Land Use Change and Climate Impact*. CE Delft, Delft, June 2010, 62 p.

Crutzen PJ, Mosier AR, Smith KA, Winiwarter W (2008) N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmospheric Chemistry and Physics*, **8**, 389–395.

Dambreville C, Morvan T, Germon JC (2008) N_2O emission in maize-crops fertilized with pig slurry, matured pig manure or ammonium nitrate in Brittany. *Agriculture, Ecosystems and Environment*, **123**, 201–210.

Davidson EA (1992) Sources of nitric-oxide and nitrous oxide following wetting of dry soil. *Soil Science Society of America*, **56**, 95–102.

Dittert K, Lampe C, Gasche R *et al*. (2005) Short-term effects of single or combined application of mineral N fertilizer and cattle slurry on the fluxes of radiatively active trace gases from grassland soil. *Soil Biology and Biochemistry*, **37**, 1665–1674.

Don A, Osborne B, Carter MS, Drewer J, Flessa H, Freibauer A (2011) Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil C. *Global Change Biology Bioenergy*, doi: 10.1111/j.1757-1707.2011.01116.x.

Dutaur L, Verchot LV (2007) A glozrbal inventory of the soil CH_4 sink. *Global Biogeochemestry Cycles*, **21**, GB4013, doi: 10.1029/2006GB002734.

Ecoinvent Centre (2004) Ecoinvent Data v1.1. Available at: http://www.ecoinvent.org (accessed 25 July 2011).

Eggelston S, Buendia L, Miwa K, Ngara T, Tanabe K (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Agriculture, Forestry and Other Land Use*. Institute for Global Environmental Strategies (IGES) for the IPCC, Hayama, Kanagawa, Japan, 654 p.

FAO (2003) *World Agriculture: Towards 2015/2030*. An FAO Perspective. FAO, Rome, 97 p.

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land Clearing and the Biofuel Carbon Debt. *Science*, **319**, 1235–1237.

Farrell AE, Plevin RJ, Turner BT, Jones AD, O'Hare M, Kammen DM (2006) Ethanol can contribute to energy and environmental goals. *Science*, **311**, 506–508.

Fawcett AA, Sands RD (2006) Non-CO2 greenhouse gases in the second generation model. Multi-greenhouse gas mitigation and climate policy. *Energy Journal*, **3**, 305–322.

Fike JH, Parrish DJ, Wolf DD, Balasko JA, Green JT Jr, Rasnake M, Reynolds JH (2006) Switchgrass production for the upper southeastern USA: influence of cultivar andcutting frequency on biomass yields. *Biomass and Bioenergy*, **30**, 207–213.

Follett RF, Kimble JM, Lal R (2001) The potential of U.S. grazing lands to sequester soil carbon. In: *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect* (eds Follett RF, Kimble JM, Lal R), pp. 401–430. Lewis Publishers, Boca Raton, Florida.

Frank AB, Berdahl JD, Hanson JD, Liebig MA, Johnson HA (2004) Biomass and carbon partitioning in switchgrass. *Crop Science*, **44**, 1391–1396.

Fritsche UR, Rausch L, Schmidt K (2009) *Life cycle analysis of GHG and air pollutant emissions from renewable and conventional electricity, heating, and transport fuel options in the EU until 2030*. Updated Report for the European Environment Agency (EEA). Oeko-Institut, Freiburg, Germany, 66 p.

Fritsche UR, Sims REH, Monti A (2010) Direct and indirect land-use competition issues for energy crops and their sustainable production – an overview. *Biofuels Byproducts & Biorefining*, **4**, 692–704.

Fujino J, Nair R, Kainuma M, Masui T, Matsuoka Y (2006) Multigas mitigation analysis on stabilization scenarios using AIM global model. Multi-greenhouse gas mitigation and climate policy. *Energy Journal*, **3**, 343–354.

Garten CT, Wullschleger SD (1999) Soil carbon inventories under a bioenergy crop (Switchgrass): measurement limitations. *Journal of Environmental Quality*, **28**, 1359–1365.

Garten CT, Wullschleger SD (2000) Soil carbon dynamics beneath switchgrass as indicated by stable isotope analysis. *Journal of Environmental Quality*, **29**, 645–653.

Garten CT, Wullschleger SD (2001) Soil carbon and nitrogen dynamics under switchgrass: integration of field data and modeling to ensure sustainability. Bioenergy feedstock development programs: subcontractors and collaborators meeting, Memphis, TN, November 7–9, 2001, Oak Ridge National Laboratory, Oak Ridge, TN.

Gaunt JL, Lehmann J (2008) Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. *Environmental Science & Technology*, **42**, 4152–4158.

Gebhart DL, Johnson HB, Mayeux HS, Polley HWJ (1994) The CRP increases soil organic carbon. *Journal of Soil and Water Conservation*, **49**, 488–492.

Gnansounou E, Dauriat A, Villegas J, Panichelli L (2009) Life cycle assessment of biofuels: energy and greenhouse gas balances. *Bioresource Technology*, **100**, 4919–4930.

Gregorich EG, Rochette P, van denBygaart AJ, Angers DA (2005) Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. *Soil and Tillage Research*, **83**, 53–72.

Grigal DF, Berguson WE (1998) Soil carbon changes associated with short rotation systems. *Biomass and Bioenergy*, **14**, 371–374.

Guretzky JA, Biermacher JT, Cook BJ, Kering MK, Mosali J (2011) Switchgrass for forage and bioenergy: harvest and nitrogen rate effects on biomass yields and nutrient composition. *Plant and Soil*, **339**, 69–81.

Hall DO, Scurlock JMO (1991) Tropical grasslands and their role in the global carbon cycle. In: *Modern Ecology: Basic and Applied Aspects*. (eds Esser G, Overdieck D), pp. 659–678. Elsevier, Amsterdam.

Hansen J, Sato M, Ruedy R, Lo K, Lea DW, Medina-Elizade M (2006) Global temperature change. *PNAS*, **103**, 14288–14293.

Heaton E, Voigt T, Long SP (2004) A quantitative review comparing the yields of two candidate C_4 perennial biomass crops in relation to nitrogen, temperature and water. *Biomass and Bioenergy*, **27**, 21–30.

Heggenstaller AH, Moore KJ, Liebman M, Anex RP (2009) Nitrogen influences biomass and nutrient partitioning by perennial, warm-season grasses. *Agronomy Journal*, **101**, 1363–1371.

Jones SK, Rees RM, Skiba UM, Ball BC (2007) Influence of organic and mineral N fertiliser on N_2O fluxes from a temperate grassland. *Agriculture, Ecosystems and Environment*, **121**, 74–83.

Kara EE, Özdýlek HG (2010) The effect of nitrogenous fertilizers on methane oxidation in soil. *Ekoloji*, **74**, 1–9.

Kavdir Y, Hellebrand HJ, Kern J (2008) Seasonal variations of nitrous oxide emission in relation to nitrogen fertilization and energy crop types in sandy soil. *Soil and Tillage Research*, **98**, 175–186.

Kemfert C, Truong TP, Bruckner T (2006) Economic impact assessment of climate change-A multi-gas investigation with WIAGEMGTAPEL-ICM. Multi-greenhouse gas mitigation and climate policy. *Energy Journal*, **3**, 375–389.

Kim DG, Isenhart TM, Parkin TB, Schultz RC, Loynachan TE (2010) Methane flux in cropland and adjacent riparian buffers with different vegetation covers. *Journal of Environmental Quality*, **39**, 786–797.

KimS , Dale BR (2004) Cumulative energy and global warming impact from the production of biomass for biobased products. *Journal of Industrial Ecology*, **7**, 147–162.

Kucharik CJ, Brye KR, Norman JM, Foley JA, Gower ST, Bundy LG (2001) Measurements and modeling of carbon and nitrogen cycling in agroecosystems of southern Wisconsin: potential for SOC sequestration during the next 50 years. *Ecosystems*, **4**, 237–258.

Lal R (1997) Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO_2- enrichment. *Soil and Tillage Research*, **43**, 81–107.

Lal R (2002) Soil carbon dynamics in crop and rangeland. *Environmental Pollution*, **116**, 353–362.

Lal R (2003) Global potential of soil carbon sequestration to mitigate the greenhouse effect. *Critical Review on Plant Science*, **22**, 151–184.

Lampe C, Dittert K, Sattelmacher B, Wachendorf M, Loges R, Taube F (2006) Sources and rates of nitrous oxide emissions from grazed grassland after application of ^{15}N-labelled mineral fertilizer and slurry. *Soil Biology and Biochemistry*, **38**, 2602–2613.

Lee DK, Owens VN, Doolittle JJ (2007) Switchgrass and soil carbon sequestration response to ammonium nitrate, manure and harvest frequency on conservation reserve program land. *Agronomy Journal*, **99**, 462–468.

Lemus R, Lal R (2005) Bioenergy crops and carbon sequestration. *Critical Reviews in Plant Sciences*, **24**, 1–21.

Lemus R, Parrish DJ, Abaye O (2008a) Nitrogen-use dynamics in switchgrass grown for biomass. *BioEnergy Research*, **1**, 153–162.

Lemus R, Brummer EC, Burras CL, Moore KJ, Barker MF, Molstad NE (2008b) Effects of nitrogen fertilization on biomass yield and quality in largefields of established switchgrass in southern Iowa, USA. *Biomass and Bioenergy*, **32**, 1187–1194.

Liebig MA, Johnson HA, Hanson JD, Frank AB (2005) Soil carbon under switchgrass stands and cultivated cropland. *Biomass and Bioenergy*, **28**, 347–354.

Liebig MA, Schmer MR, Vogel KP, Mitchell RB (2008) Soil carbon storage by switchgrass grown for bioenergy. *Bioenergy Research*, **1**, 215–222.

Luo L, va der Voet E, Huppes G (2010) Energy and environmental performance of bioethazrnol from different lignocelluloses. *International Journal of Chemical Engineering*, **2010**, 1–12, article ID 740962.

Ma Z, Wood CW, Bransby DI (2000a) Impacts of soil management on root characteristics of switchgrass. *Biomass and Bioenergy*, **18**, 105–112.

Ma Z, Wood CW, Bransby DI (2000b) Soil management impacts on soil carbon sequestration by switchgrass. *Biomass and Bioenergy*, **18**, 469–477.

Ma Z, Wood CW, Bransby DI (2001) Impact of row spacing, nitrogen rate, and time on carbon partitioning of switchgrass. *Biomass and Bioenergy*, **20**, 413–419.

Massé D, Gilbert Y, Savoie P, Belanger G, Parent G, Babineau D (2010) Methane yield from switchgrass harvested at different stages of development in Eastern Canada. *Bioresource Technology*, **101**, 9536–9541.

Mastrandrea MD, Schneider SH (2004) Probabilistic integrated assessment of 'dangerous' climate change. *Science*, **304**, 571–575.

McLaughlin SB (1993) New switchgrass biofuels research program for the southeast. In: Proc. Annual Automotive Technol. Dev. Conhactor's Coordinating Meeting, 2–5 November 1992, Dearborn, MI, pp. 111–115. Society of Automotive Engineers, Warrendale Marshall, PA, USA.

McLaughlin SB, Walsh ME (1998) Evaluating environmental consequences of producing herbaceous crops for bioenergy. *Biomass and Bioenergy*, **14**, 317–324.

McLaughlin SB, Ugarte DGDL, Garten CT, Lynd LR, Sanderson M, Tolbert VR, Wolf DD (2002) High-value renewable energy from prairie grasses. *Environmental Science and Technology*, **36**, 2122–2129.

McSwiney CP, Robertson GP (2005) Nonlinear response of N_2O flux to incremental fertilizer addition in a continuous maize (*Zea mays* L.) cropping system. *Global Change Biology*, **11**, 1712–1719.

Mehdi B, Zan C, Girouard P, Samson R (1999) Soil organic carbon sequestration under two dedicated perennial bioenergy crops. In: *Biomass: A Growth Opportunity in Green Energy Andvalue-Added Products*. Proc. 4th Biomass Conference of the Americas, Vol 1. Oakland, California. 29 August-2 September, 1999, pp. 17–23. Pergamon, Oxford, UK.

Meng L, Ding W, Cai Z (2005) Long-term application of organic manure and nitrogen fertilizer on N_2O emissions, soil quality and crop production in a sandy loam soil. *Soil Biology and Biochemistry*, **37**, 2037–2045.

Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (2007) *Climate Change 2007: Mitigation of Climate Change*. Cambridge University Press, Cambridge, UK, 852 p.

Monti A, Zatta A (2009) Root distribution and soil moisture retrieval in perennial and annual energy crops in northern Italy. *Agriculture, Ecosystems and Environment*, **132**, 252–259.

Monti A, Venturi P, Elbersen HW (2001) Evaluation of the establishment of lowland and upland switchgrass (Panicum virgatum L.) varieties under different tillage and seedbed conditions in northern Italy. *Soil and Tillage Research*, **63**, 75–83.

Monti A, Bezzi G, Pritoni G, Venturi G (2008) Long-term productivity of lowland and upland switchgrass cytotypes as affected by cutting frequency. *Bioresource Technology*, **99**, 7425–7432.

Monti A, Fazio S, Venturi G (2009) Cradle-to-farm gate life cycle assessment in perennial energy crops. *European Journal of Agronomy*, **31**, 77–84.

Mosier A, Kroeze C (2000) Potential impact on the global atmospheric N_2O budget of the increased nitrogen input required to meet future global food demands. *Chemosphere-Global Change Science*, **2**, 465–473.

Mosier A, Schimel D, Valentine D, Bronson K, Parton W (1991) Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands. *Nature*, **350**, 330–332.

Muir JP, Sanderson MA, Ocumpaugh WR, Jones RM, Reed RL (2001) Biomass production of 'Alamo' switchgrass in response to nitrogen, phosphorus, and row spacing. *Agronomy Journal*, **93**, 896–901.

Ney RA, Schnoor JL (2002) *Greenhouse Gas Emission Impacts of Substituting Switchgrass for Coal in Electric Generation: The Chariton Valley Biomass Project*. Center for Global and Regional Environmental Research, Universityof Iowa, Iowa City.

Oades JM (1988) The retention of organic matter in soils. *Biogeochemistry*, **5**, 35–70.

Ocumpaugh WR, Sanderson MA, Hussey MA, Read JC, Tischler CR, Reed RL (2003) *Evaluation of Switchgrass Cultivars and Cultural Methods for Biomass Production in the South-Central US*. Final Report. Oak Ridge National Laboratory, Oak Ridge, TN.

Pacala S, Socolow R (2004) Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science*, **305**, 968–972.

Parrish DJ, Wolf DD, Fike JH, Daniels WL (2003) *Switchgrass as a Biofuel Crop for the Upper Southeast: Variety Trials and Cultural Improvements*. Final Report for 1997 to 2001. Oak Ridge National Laboratory, Oak Ridge, TN.

Patzek TW (2010) Ethanol production using switchgrass required 50% more fossil energythan the ethanol fuel produced. *Sustainability*, **2**, 3158–3194.

Penman J, Gytarsky M, Hiraishi T *et al*. (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry – IPCC 2003*. Institute for Global Environmental Strategies (IGES) for the IPCC, Hayama, Kanagawa, 632 p.

Pimentel D, Patzek T (2005) Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. *Natural Resources Research*, **14**, 65–76.

Post WM, Kwon KC (2000) Soil carbon sequestration and land-use change: processes and potential. *Global Change Biology*, **6**, 317–327.

Potter KN, Tobert HA, Johnson HB, Tischler CR (1999) Carbon storage after long-term grass establishment on degraded soils. *Soil Science*, **164**, 718–725.

Qin X, Mohan T, El-Halwagi M, Cornforth G, McCarl BA (2006) Switchgrass as an alternate feedstock for power generation: an integrated environmental, energy and economic life-cycle assessment. *Clean Technologies and Environmental Policy*, **8**, 233–249.

Reicosky DC (2003) Tillage-induced CO_2 emissions and carbon sequestration: effect of secondary tillage and compaction. In: *Conservation Agriculture*. (eds Garcia-Torres L, Benites J, Martinez-Vilela A, Holgado-Cabrera A), pp. 291–300. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Reynolds JH, Walker CL, Kirchner MJ (2000) Nitrogen removal in switchgrass biomass under two harvest systems. *Biomass and Bioenergy*, **19**, 281–286.

Richter DD, Markewitz D, Trumbore SE, Wells CG (1999) Rapid accumulation and turnover of soil carbon in a re-establishing forest. *Nature*, **400**, 56–58.

Righelato R, Spracklen DV (2007) Carbon mitigation by biofuels or by saving and restoring forests? *Science*, **317**, 902.

Robertson GH, Grace PR (2004) Greenhouse gas fluxes in tropical and temperate agriculture: the need for a full-cost accounting of global warming potentials. *Environment, Development and Sustainability*, **6**, 51–63.

Robertson GH, Paul EA, Harwood RR (2000) Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. *Science*, **289**, 1922–1925.

Samson RA, Stamler BS (2009) Going Green for Less: Cost-Effective Alternative Energy Sources. C.D. Howe Institute Commentary. No 282 ISSN 0824-8001, Toronto, Ontario, 28 p.

Sanderson MA (2008) Upland switchgrass yield, nutritive value, and soil carbon changes under grazing and clipping. *Agronomy Journal*, **100**, 510–516.

Sanderson MA, Reed ML, McLaughlin SB *et al*. (1996) Switchgrass as a sustainable bioenergy crop. *Bioresource Technology*, **56**, 83–93.

Sanderson MA, Read JC, Reed RL (1999) Harvest management of switchgrass for biomass feedstock and forage production. *Agronomy Journal*, **91**, 5–10.

Sawamoto T, Yoshida R, Abe K, Matsunaka T (2010) No significant difference in N_2O emission, fertilizer-induced N_2O emission factor and CH_4 absorption between anaerobically digested cattle slurry and chemical fertilizer applied timothy (*Phleum pratense* L.) sward in central Hokkaido, Japan. *Soil Science and Plant Nutrition*, **56**, 492–502.

Schimel DS (1986) Carbon and nitrogen turnover in adjacent grassland and cropland ecosystems. *Biochemistry*, **2**, 345–357.

Schlesinger WH (1997) *Biogeochemistry: An Analysis of Global Change*. Academic Press, San Diego, CA.

Schmer MR, Vogel KP, Mitchell RB, Perrin RK (2008) Net energy of cellulosic ethanol from switchgrass. *PNAS*, **105**, 464–469.

Searchinger TD (2010) Biofuels and the need for additional carbon. *Environmental Research Letters* **5**, 024007, doi: 10.1088/1748-9326/5/2/024007.

Searchinger TD, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J *et al*. (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319**, 1238–1240.

Shimizu M, Marutani S, Desyatkin AR, Jin T, Nakano K, Hata H, Hatano R (2010) Nitrous oxide emissions and nitrogen cycling in managed grassland in Southern Hokkaido, Japan. *Soil Science and Plant Nutrition*, **56**, 676–688.

Skinner RH, Adler PR (2010) Carbon dioxide and water fluxes from switchgrass managed for bioenergy production. *Agriculture, Ecosystems and Environment*, **138**, 257–264.

Smith KA, Conen F (2004) Impacts of land management on fluxes of trace greenhouse gases. *Soil Use and Management*, **20**, 255–263.

Smith SJ, Wigley TML (2006) Multi-gas forcing stabilization with the miniCAM. Multi-greenhouse gas mitigation and climate policy. *Energy Journal*, **3**, 373–391.

Smith P, Martino D, Cai Z, Gwary D, Janzen HH, Kumar P *et al*. (2007) Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society*, **B**, 363.

Sommer R, Denich M, Vlek PGL (2000) Carbon storage and root penetration in deep soils under small-farmer land-use systems in the eastern Amazon region. *Plant and Soil*, **219**, 231–241.

Stehfest E, Bouwman L (2006) N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data andmodelling of global annual emissions. *Nutrient Cycling in Agroecosystems*, **74**, 207–228.

Strand AE, Pritchard SG, McCormack ML, Davis MA, Oren R (2008) Irreconcilable differences: fine-root life spans and soil carbon persistence. *Science*, **319**, 456–458.

Thomason WE, Raun WR, Johnson GV, Taliaferro CM, Freeman KW, Wynn KJ, Mullen RW (2004) Switchgrass response to harvest frequency and time and rate of applied nitrogen. *Journal of Plant Nutrition*, **27**, 1199–1226.

Tilman D, Hill J, Lehman C (2006) Carbon-negative biofuels from low-inputhigh-diversity grassland biomass. *Science*, **314**, 1598–1600.

Tlustos P, Willison TW, Baker JC, Murphy DV, Pavlikova D, Goulding KWT, Powlson DS (1998) Short-term effects of nitrogen on methane oxidation in soils. *Biology and Fertility of Soils*, **28**, 64–70.

Tolbert VR, Todd DE, Mann LK, Jawdy CM, Mays DA, Malik R *et al*. (2002) Changes in soil quality and below-ground carbon storage with conversion of traditional agricultural crop lands to bioenergy crop production. *Environmental Pollution*, **116**, S97–S106.

Trumbore SE, Gaudinski JB (2003) The secret lives of roots. *Science*, **302**, 1344–1345.

Tufekcioglu A, Raich JW, Isenhart TM, Schultz RC (2003) Biomass, carbon, and nitrogen dynamics of multi-species riparian buffers within an agricultural watershed in Iowa, USA. *Agroforestry Systems*, **57**, 187–198.

Turhollow AF, Perlack RD (1991) Emissions of CO_2 from energy crop production. *Biomass and Bioenergy*, **1**, 129–135.

U.S. Department of Energy (DOE) (1999) Carbon Sequestration. Office of Fossil Energy, U.S. Dept. of Energy. Available at: http://www.fe.doe.gov/coal power/sequestration/index.html

US-EPA (2006) Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990–2020. United States Environmental Protection Agency, EPA 430-R-06-003, June 2006. Washington, D.C.. Available at: http://www.epa.gov/climatechange/economics/downloads/GlobalMitigationFullReport.pdf (accessed 26 March 2007).

Ussiri DAN, Lal R (2009) Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. *Soil and Tillage Research*, **104**, 39–47.

Vogel KP (2004) Switchgrass. In warm-Season (C4) grasses. *Agronomy Monogram*, **45**, 561–588.

Vogel KP, Brejda JJ, Walters DT, Buxton DR (2002) Switchgrass biomass production in the Midwest USA: harvest and nitrogen management. *Agronomy Journal*, **94**, 413–420.

Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ (2000) *Land Use, Land-Use Change, and Forestry – IPCC 2010*. Cambridge University Press, Cambridge, UK, 375 p.

Watson RT, Zinyowera MC, Moss RH (1996) *Climate change 1995 – impacts adaptation and mitigation of climate change: scientific and technical analysis*. Contribution of Working Group II to the Second Assessment Report of Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 878 p.

West TO, Post WM (2002) Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Science Society of American Journal*, **66**, 1930–1946.

Williams MA, Rice CW, Owensby CE (2004) Carbon andnitrogen pools in a tallgrass prairie soil under elevated carbon dioxide. *Soil Science Society American Journal*, **68**, 148–153.

Wilts AR, Reicosky DC, Allmaras RR, Clapp CE (2004) Long-term corn residue effects: harvest alternatives, soil carbon turnover, and root-derived carbon. *Soil Science Society of American Journal*, **68**, 1342–1351.

Wu M, Wu Y, Wang M (2006) Energy and emission benefits of alternative transportation liquid fuels derived from switchgrass: a fuel life cycle assessment. *Biotechnology Progress*, **22**, 1012–1024.

Zan C, Fyles J, Girouard P, Samson R, Doan M (1997) Carbon storage in switchgrass and short-rotation willow plantations. In: *Making a Business from Biomass in Energy, Environment, Chemicals, Fibers, and Materials*, Vol 1 (eds Overend RP, Chornet E), pp. 355–361. Elsevier Science, Oxford, UK.

Zan CS, Fyles JW, Girouard P, Samson RA (2001) Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in southern Quebec. *Agriculture Ecosystem and Environment*, **86**, 135–144.

Zeri M, Hickman GC, Bernacchi C (2009) Fluxes of nitrous oxide and carbon dioxide over four potential biofuel crops in Central Illinois. American Geophysical Union, Fall Meeting 2009, abstract #A34A-02. American Geophysical Union, San Francisco, CA, USA.