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REVIEW

Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon

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Abstract

Bioenergy from crops is expected to make a considerable contribution to climate change mitigation. However, bioenergy is not necessarily carbon neutral because emissions of CO_2, N_2O and CH_4 during crop production may reduce or completely counterbalance CO_2 savings of the substituted fossil fuels. These greenhouse gases (GHGs) need to be included into the carbon footprint calculation of different bioenergy crops under a range of soil conditions and management practices. This review compiles existing knowledge on agronomic and environmental constraints and GHG balances of the major European bioenergy crops, although it focuses on dedicated perennial crops such as *Miscanthus* and short rotation coppice species. Such second-generation crops account for only 3% of the current European bioenergy production, but field data suggest they emit 40% to >99% less N_2O than conventional annual crops. This is a result of lower fertilizer requirements as well as a higher N-use efficiency, due to effective N-recycling. Perennial energy crops have the potential to sequester additional carbon in soil biomass if established on former cropland (0.44 Mg soil C ha^{-1} yr^{-1} for poplar and willow and 0.66 Mg soil C ha^{-1} yr^{-1} for *Miscanthus*). However, there was no positive or even negative effects on the C balance if energy crops are established on former grassland. Increased bioenergy production may also result in direct and indirect land-use changes with potential high C losses when native vegetation is converted to annual crops. Although dedicated perennial energy crops have a high potential to improve the GHG balance of bioenergy production, several agronomic and economic constraints still have to be overcome.

Keywords: biofuel, carbon debt, carbon footprint, land management, methane, *Miscanthus*, nitrous oxide, short rotation coppice, soil organic carbon

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Greenhouse gas saving with bioenergy – a European perspective

The European Union has committed to increase the proportion of renewable energy from 9% in 2010 to 20% of total energy consumption by 2020 (EU, 2009). Biomass currently accounts for almost two-thirds of the total renewable energy in Europe, including 18% of renewable electricity (IEA, 2010). Bioenergy feedstock consists of forest products (e.g., wood, pellets), industrial and agricultural residues (e.g., straw, sawdust), conventional crops (e.g., maize (*Zea mays*) and dedicated energy crops (e.g., hybrid poplar (*Populus* ssp.) or *Miscanthus* spp.), that is, crops primarily grown to provide raw materials for energy generation. Biomass produced on agricultural land is referred to as 'modern bioenergy' and is expected to play an important role in meeting Europe's greenhouse gas (GHG) reduction targets. Simulation models predict that 17–21 million hectare (Mha) of additional land will have to be converted to energy crop production to meet the targets of bioenergy share set by EU policies for 2020 (EU, 2007; Hastings *et al.*, 2009a; Ozdemir *et al.*, 2009). Current energy crop production systems in Europe are diverse. They have emerged from region-specific histories of bioenergy use, political factors, investment incentives, market opportunities, business and technology-led developments and climatic and soil considerations (Venendaal *et al.*, 1997). The largest production of dedicated perennial energy crops, based on the fraction of total cropland, occurs in Finland (reed canary grass), the United Kingdom and Ireland (*Miscanthus*), Sweden (willow), Italy (*Miscanthus* and poplar) and Denmark (willow) (Fig. 1).

In June 2010, the European Commission adopted new measures to increase the sustainability of liquid biofuel. Biofuels comprise around 70% of European bioenergy use (AEBIOM, 2010; EurObserv'ER, 2010; European Bio-

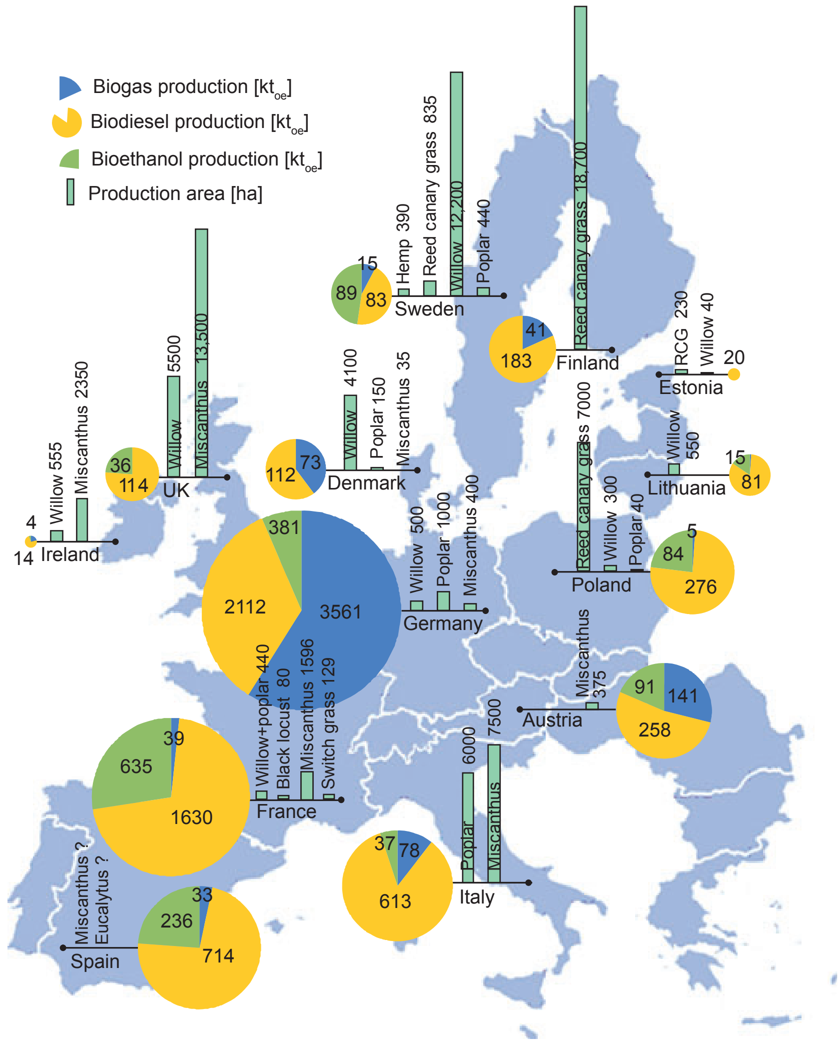

Fig. 1 Energy crops in Europe: production area (ha) of dedicated energy crops and energy production (kt$_{oe}$) of conventional energy crops (E. Miller, personal communication; M. McDonagh, personal communication; A. Grelle, personal communication; AEBIOM, 2010; EurObserv'ER, 2010; European Biodiesel Board, 2010; FNR, 2010; Larsen, 2010). Data compilation for 2009/2010.

diesel Board, 2010). Independent audits should ensure that biofuels from energy crops deliver GHG savings of at least 35% when compared with fossil fuels, rising to 50% in 2017 and to 60% in 2018. Bioenergy production and use is supported by governments as a source of domestic energy supply (energy security) and as a source of income and employment in rural regions. While GHG mitigation also played a role in this rationale, conventional energy crops are not optimized for low GHG footprints. Although carbon (C) emitted during combustion is balanced by C fixed by photosynthesis, bioenergy is not necessarily C neutral because of GHG emissions released during crop growth, field management, feedstock processing and transport. Additional to C emitted as carbon dioxide (CO_2) to the atmosphere, other GHGs, particularly methane (CH_4) and nitrous oxide (N_2O) have to be taken into account. To compare the contribution of the latter two gases to the GHG balance, the much larger global warming potential of CH_4 and N_2O relative to CO_2 has to be considered. Over a 100 year time horizon, the global warming potential of N_2O and CH_4 are 298 and 25 times larger than that of CO_2, respectively (Forster *et al.*, 2007). In addition, C emissions may arise due to land-use changes associated with bioenergy production and this has to be paid back over a certain time period as a so-called carbon debt, which is part of the GHG balance of bioenergy feedstock (Fargione *et al.*, 2008). The GHG balance of energy crops depends not only on the crop type but also on climate, soil and management, especially fertilization and tillage practices, as well as previous land-use. In the worst case, the apparently positive effect of substituting fossil fuels by bioenergy could be completely counterbalanced, or even negative, due to N_2O emissions during crop production (Crutzen *et al.*, 2008). Soil N_2O emissions account, on average, for around 27% (range: 5–80%) of the GHG balance of biofuels produced from food crops (Armstrong *et al.*, 2002; Lettens *et al.*, 2003; JEC, 2008; Smeets *et al.*, 2009; Hoefnagels *et al.*, 2010). There are numerous reviews and reports of life cycle analyses (LCA) that performed cradle to grave analysis of bioenergy products including GHG emissions during biomass production. However, many LCA are inconclusive and inconsistent because of different system boundaries that determine which energy and GHG fluxes are attributed to bioenergy as a product, and because calculations of GHG emissions during crop production are crude (Schlamadinger *et al.*, 1997). A large uncertainty in LCAs is associated with N_2O emissions from feedstock production (St Clair *et al.*, 2008). There have been few field measurements of the GHG fluxes during energy crop production. Consequently, bioenergy LCAs often totally ignore field-associated N_2O and CH_4 fluxes, or rely on simple emission factor approaches, such as the Intergovernmental Panel on Climate Change (IPCC) methodology (IPCC, 2006). This approach assumes a constant proportion (1%) of N fertilizer applied is emitted as N_2O. The fact that soil microbial production and emission of N_2O is controlled in a complex way by a range of abiotic and biotic factors, such as fertilization, oxygen availability and the mineralization of organic matter is ignored (Skiba & Smith, 2000; Robertson & Groffman, 2007). Thus, IPCC default values only provide a very general estimate of N_2O emissions and cannot assess regionalized or site-specific effects of crop species on GHG fluxes. Moreover, fertilizer-induced N_2O emission may also be underestimated if indirect emissions from rivers, coastal zones, animal husbandry and atmospheric N depositions are not taken into account (Crutzen *et al.*, 2008). For CH_4 field emissions may only be significant in organic soils with high ground water tables. Most mineral soils are CH_4 sinks; their sink strength depending mainly on soil porosity (Hutsch, 2001; Conrad, 2009).

In contrast to CH_4 and N_2O, emissions or uptake of CO_2 is largely a transitional phenomenon due to changes in ecosystem C stocks. Carbon stocks accumulate or decrease after changes in land-use, crop and management type or climatic conditions only until they have reached a new equilibrium. The CO_2 balance of energy crops can be estimated by C stock changes in above and below ground biomass and in soils. This strongly depends on the previous land-use and former C stock levels, especially for the largest terrestrial C pool, the soil organic carbon (SOC) pool. Land-use types with high SOC stocks, such as grasslands on organic soils, are more susceptible to land-use change to conventional energy crops than low C systems, such as croplands on well-drained soils (Poeplau *et al.*, 2011). On the other hand, perennial energy crops may help to recapture SOC that was previously lost by cultivation (Dondini *et al.*, 2009).

There is clearly an urgent need to better quantify the specific effects of land-use change associated with the production of conventional and dedicated energy crops on the GHG balance. Increased bioenergy production in industrialized countries may trigger land-use changes in other countries (Fargione *et al.*, 2008; Searchinger *et al.*, 2008, 2009; Fritsche *et al.*, 2010). For the bioenergy consuming countries, direct land-use changes are referred to as 'internal direct land-use change'. If bioenergy feedstock is imported and the direct land-use change to energy crops takes place somewhere outside the bioenergy consuming country, it is referred to as 'external direct land-use change'. It is a direct land-use change, as it refers to a direct conversion to energy crops on land that had been used differently before. In addition, there is a land-use change that compensates for increased bioenergy production to sustain food and animal feedstock demand and that indirectly causes similar emissions. This 'indirect land-use change' takes place either in the same (internal indirect land-use change) or another country (external indirect land-use change). Deforestation of tropical primary forests can be a direct or indirect land-use change and causes very large C stock changes with a major impact on the GHG balance of bioenergy production (Palm *et al*., 1999; Don *et al*., 2011).

Currently, the limited but increasing number of field studies on the GHG balance of energy crops is the only basis on which future trajectories of lower GHG footprints can be evaluated. The GHG footprint related to the production of modern bioenergy feedstock can be improved by applying existing knowledge and ecological principles, even though fully quantitative recommendations for site-specific optimal choices at farm level are not yet possible. Using published literature and preliminary results from ongoing research, this review aims to:

1. estimate the land areas under modern bioenergy systems in Europe, the energy crop types and the type of energy use (solids, biogas, liquid fuels);
2. assess the agronomic and climate-related characteristics of all major European energy crops;
3. examine the field-specific GHG emissions associated with different energy crop types and management practices to provide possible abatement strategies;
4. highlight the most critical gaps in our understanding of GHG emissions related to energy crops.

Bioenergy systems: definitions and current production status

Bioenergy is defined as all energy that is produced from biological mass that is available on a renewable basis (used directly or as byproducts or waste). It includes liquid fuels (first- and second-generation biofuels for transportation), gaseous fuels (biogas) and solid fuels or biomass fuels (for co-firing, heating, electricity generation and bio-refining). In 2008, bioenergy accounted for 10% [50 exajoule (EJ), which is 10^{-18} J] of the global primary energy consumption, but energy crops only contribute to 0.3% of the total energy, which is 6% of the total bioenergy produced (IEA, 2010). The remaining 94% of the bioenergy consumption is still non-commercial fire wood utilized mainly in developing countries (IEA, 2010). The global technical potential of bioenergy is controversial but could be 200–500 EJ yr^{-1} at competitive costs by 2050 (Fischer & Schrattenholzer, 2001; Dornburg *et al*., 2010). Expansion of bioenergy production is limited by the land area available in order not to compromise food security or other ecosystem services (FAO, 2008; Smith *et al*., 2010; Wirsenius *et al*., 2010). Even if 10% of global agricultural and forest residues were available only 5% of the total transport fuel demand could be met in 2030 (IEA, 2010). However, other estimates are less optimistic and calculate bioenergy potentials between 30 and 120 EJ yr^{-1} (WBGU, 2008).

European bioenergy production almost doubled during the last 15 years and currently supplies 7% of the total primary energy (IEA, 2010). Around 3% (3.1 Mha) of EU cropland is used for bioenergy (EU, 2007). Around 70% of the European crop-derived bioenergy production is used for biofuels for transport, mainly as biodiesel and ethanol (AEBIOM, 2010). Currently biofuel production is almost completely dependent on annual food crops, such as oilseed rape (*Brassica napus*), sugar beet (*Beta vulgaris*), maize or cereals. These will be referred to subsequently as 'conventional energy crops'. More than 70% of the European biofuel production is from oilseed rape (AEBIOM, 2010). The rapidly increasing share of bioenergy, in proportion to total energy consumption, has been realized by increasing the production area of all conventional crops or so-called first generation bioenergy crops. Conventional energy crops can be used for either food or bioenergy, with potential consequences for food prices and food security. Surprisingly, there are almost no data available on the proportion of conventional crops used for energy, food or fodder for European countries, only the production of different bioenergy types (Fig. 1). Conventional energy crops rely on multiple inputs to achieve high yields and there is little difference between the cultivars and management used for food production or bioenergy. Breeding programmes and genetic manipulation may eventually produce conventional energy crops with lower input requirements. Quality-related parameters such as protein content and composition are of minor importance for the bioenergy market while oil, cellulose or starch and water content during harvest are of major interest (Zegada-Lizarazu *et al*., 2010). Additional to biofuel feedstock, conventional energy crops are already used in biogas production. Biogas plants are popular in Germany, Austria and Denmark (Fig. 1); about 700 000 ha of land is used to produce mainly maize silage for biogas. This is 11% of the total maize production area but less than 1% of the European cropland area.

A small but growing proportion (3%) of bioenergy production is derived from dedicated crop species such as willow (*Salix* spp.), *Miscanthus,* reed canary grass (*Phalaris arundinacea*), hybrid poplar, switch-grass (*Panicum virgatum*), giant reed (*Arundo donax*) and hemp (*Cannabis sativa*) (AEBIOM, 2010). In total, these cover around 100 000 ha of land in Europe but with large regional differences (Fig. 1). The dedicated energy crops are mostly perennials that produce biomass for electricity and heating but may, in future, become feedstock for second-generation biofuels, such as ethanol derived from lingo-cellulose or biorefined biodiesel produced through gasification and the Fischer-Tropsch process (Woods *et al*., 2008; Sims *et al*., 2010).

One form of the dedicated energy crops is short rotation coppicing (SRC), which is a system of semi-intensive cultivation of fast-growing, woody species in plantations. The rotations between harvests are short (3–4 years) in comparison with longer rotations in typical forests and dependent on rapid regeneration from remaining roots and stumps. In Europe, around 50 000 ha of SRC have been established for bioenergy production. Willow, poplar, red alder (*Alnus rubra*) and black locust (*Robinia pseudoacacia*) are the most significant species cultivated because of their high yields and, particularly in southern Europe, also *Eucalyptus* spp. Productivity of SRC are similar or even higher than that of conventional energy crops and 20–50% less N fertilizer is needed due to efficient remobilization of reserves (Scholz & Ellerbrock, 2002; Karp & Shield, 2008; Table 1). SRC are intensive land-use systems with often double the yields when compared with conventional forest systems (Table 1). Coppicing was a traditional forest practice throughout Europe for production of fire wood until the late 19th century. In some parts of South Eastern Europe and Italy, coppicing is still applied in forest stands or was abandoned only recently. It is increasing again, due to opportunities in the bioenergy market, for example, in Sweden around 10 000 ha of SRC willow was established with governmental support during the 1990s. Wood chips from SRC are mostly produced on agricultural land and defined as agricultural crops.

Fast-growing tree species (e.g., eucalyptus, poplar and alder) managed as short rotation forests (SRF) are another form of intensification with rotation lengths of 8–20 years. Globally, there are 125 Mha of commercial forest plantations, which is around 3.5% of the total forest area (Grace, 2005). SRF are managed to produce not only bioenergy but also timber or pulp. The impact of SRF on C sequestration is uncertain, as non-harvested wood directly contributes to C sequestration in ecosystems (Obersteiner *et al*., 2010). For the growing lifetime of new forests, little difference in C sequestration has been found if the biomass is left as a C store in the forest or used as an energy substitute for coal (Cannell, 2003). In this review, we restrict our assessment to SRC plantations on former agricultural land that are used for bioenergy production.

Reed canary grass is a potential energy crop in the boreal region with almost 20 000 ha established in Scandinavia (Fig. 1; Venendaal *et al*., 1997; Lewandowski *et al*., 2003b). The crop is adapted to short growing seasons and low temperatures and is resistant to drought and flooding. Reed canary grass grows well on most kinds of soils but the highest biomass is reached on wet, humus-rich soils (e.g., cutaway peatlands abandoned after peat extraction).

Miscanthus is one of the most promising dedicated energy crops with around 16 000 ha being established in the United Kingdom and Ireland (Fig. 1), even though the climate optimum of this perennial C_4 grass is situated much further south. *Miscanthus* has been used for local co-firing in heat and power plants.

Many more perennial (switch-grass, giant reed) and annual crops [hemp, Ethiopian mustard (*Brassica carinata*), sorghum] are currently being examined for their suitability for bioenergy. However, none of the above has been grown at a significantly large scale within Europe and their full potential remains largely unknown. Switch-grass is one of the most popular dedicated energy crops in the United States and could have potential for semiarid regions in Europe (Oliver *et al*., 2009). Current selected genotypes, however, have a poor temperature tolerance and generally provide lower energy yields compared with *Miscanthus* (Heaton *et al*., 2004).

One of the most critical questions for any dedicated energy crop is the economic benefit. Production costs per GJ of bioenergy from dedicated energy crops may be roughly one-third of that from conventional energy crops (de Wit & Faaij, 2010). However, large scale establishment of dedicated energy crops is hampered by high establishment costs and investment in new machinery, as well as the absence of a yearly income with SRC and the lack of expertise or experience. The economic long-term commitment of farmers to create a market for the lifetime of the crop cycle, which can be up to 25 years, needs to be matched by equal commitment of biomass users and governments. Some of the obstacles may be overcome by new EU bioenergy targets, which should increase demand and price. Moreover, the wider utilization of ligno-cellulose as a feedstock for second-generation biofuels will foster the use of biomass from perennial energy crops (Oliver *et al*., 2009).

Agronomic and climate-related characteristics of bioenergy production

Conventional and dedicated crops for bioenergy use

A wide range of conventional and non-conventional crop species could be used as energy crops, but not all of them meet the requirements of a high yielding environmentally sustainable feedstock for bioenergy use. The most important cultivation and management practices that impact on both the yield and GHG balance are

Table 1 Biomass yields of conventional and dedicated energy crops for European countries

	Maize grain*	Wheat grain*	Barley grain*	Potatoes*	Sugar beet*	Maize silage*	Round wood overbark*	Miscanthus dry matter†	SRC Willow dry matter‡
	Mg $ha^{-1}yr^{-1}$								
Austria	9.5	5.0	4.5	30.1	64.8	45.7	3.4	17.0	11.0
Belgium	11.1	8.2	7.3	43.4	67.1	45.9	3.4	16.0	10.0
Bulgaria	3.5	3.0	2.7	13.1	17.9	10.1	1.4		
Croatia	5.3	3.9	3.1	10.2	37.4	24.2		18.0	11.0
Czech Republic	6.7	4.7	3.9	22.6	48.3	32.5	3.4	19.0	13.0
Denmark		7.1	5.2	39.6	56.7	35.5	3.1	22.0	8.0
Estonia		2.3	2.0	13.3		21.3	1.6		5.0
Finland		3.4	3.2	23.2	34.2		1.5		5.0
France	8.6	6.9	6.2	40.6	75.4	40.3	2.7	15.0	9.0
Germany	8.7	7.3	5.9	39.8	58.2	43.6	3.7	19.0	9.0
Greece	8.9	2.2	2.3	23.1	61.5	49.5	0.5	20.0	10.0
Hungary	5.7	3.9	3.3	22.4	44.4	23.9	2.4	16.0	8.0
Ireland		8.7	6.6	34.0	49.0	1.0	2.5	11.0	6.0
Italy	9.2	3.3	3.6	24.4	48.1	51.8	1.3	15.0	3.0
Latvia		2.9	2.0	13.6	35.8	21.9	1.9		5.0
Lithuania	3.1	3.3	2.4	12.9	36.2	25.2	2.1		9.0
Luxembourg	7.9	6.0	5.2	30.7		27.0	3.3	18.0	8.0
The Netherlands	11.1	8.2	5.9	43.3	60.5	44.4	2.9	15.0	10.0
Poland	5.7	3.6	3.0	18.1	40.9	41.5	2.0	15.0	8.0
Portugal	5.5	1.4	1.4	14.7	65.6		2.9	20.0	1.0
Romania	3.1	2.5	2.3	13.8	23.4	15.8		13.0	8.0
Slovakia	5.0	3.9	3.2	15.2	42.1	21.9	3.0	16.0	7.0
Slovenia	6.9	4.4	3.7	21.5	44.6	40.8	2.5	16.0	10.0
Spain	9.6	2.7	2.7	29.4	66.6	45.5	1.1	14.0	8.0
Sweden		5.9	4.1	29.8	47.8		1.7	5.0	4.0
Switzerland	8.9	5.9	6.2	37.2	71.9		3.2	14.0	8.0
United Kingdom		7.7	5.7	41.0	55.0	3.1	2.9	15.0	9.0

*Eurostat mean yields for the period 1990–2006.
†Modelled using MiscanFor (Hastings *et al.*, 2009a) for the period 1990–2002.
‡Modelled using the SalixFor model (A. Hastings, unpublished results) for the period 1990–2002: SalixFor follows the energy use efficiency approach of Monteith (Monteith, 1977; Hastings *et al.*, 2009b), which is a common method in crop growth modelling (Williams *et al.*, 1989; Ewert, 2004). The model is parameterized for *Salix*, grown as a short rotation coppice crop, with a 3 year cycle, using data from Lindroth & Bath (1999), Bullard *et al.* (2002), Matthews *et al.* (2002), Ericsson *et al.* (2006) and Evans *et al.* (2007). Yield mass is calculated according to meteorological and soil data (Hastings *et al.*, 2009b). Meteorological inputs to the model are mean temperature, temperature range, precipitation and cloud cover; soil inputs are field capacity and wilt point. Radiation is calculated from the latitude and time of year by the method described in the SWAT Theoretical Documentation (Neitsch *et al.*, 2002), including a cloud correction factor (Hastings *et al.*, 2009b). Potential evapotranspiration is calculated using the Thornthwaite equation with a Penman adjustment factor (Hastings *et al.*, 2009b). Downregulation terms for evapotranspiration, radiation use efficiency and leaf area index are calculated according to available soil water using an Aslyng discontinuous linear process description (Aslyng, 1965; Hastings *et al.*, 2009b). The modelled crop is also subject to drought and frost kill (Hastings *et al.*, 2009b).

as follows: soil preparation and sowing/planting, irrigation, fertilization timing and rates, weed and pest control, harvest method and timing. An evaluation of such factors, and their interactions, is necessary to refine cultural practices to maximize yields and mitigate GHG emissions. Maize is probably the most common bioenergy feedstock. It is a high yielding crop and management practices are well established (Birch *et al.*, 2003; Tables 1 and 2). On the other hand, sweet sorghum has recently attracted great interest as a potential for bioethanol feedstock production in Southern Europe (Zegada-Lizarazu *et al*., 2010). Due to deep roots and low water demand, it is capable of persisting for longer during dry periods. Sweet sorghum requires almost 40% less nitrogen fertilizer than maize (Smith & Buxton, 1993).

Perennial grasses such as *Miscanthus*, *Phalaris* and switch-grass require different agricultural practices from those used for many conventional crops. The establishment period is the most critical phase for successful development of perennial grasses, requiring a proper weed control and, if necessary, supplemental fertilization and irrigation (Parrish & Fike, 2005. Switchgrass and *Phalaris* produces fertile seeds; its propagation and establishment is relatively cheap and easy compared with sterile rhizomatous crops such as *Miscanthus x giganteus*, which is currently propagated asexually. But there may be problems with colonization beyond the field boundaries, particularly with *Phalaris*. Switchgrass is sown in rows or by surface broadcasting. *Miscanthus* rhizomes are planted in freshly cultivated soils in spring after the risk of frost. When *Miscanthus* and switch-grass are harvested between autumn and spring, most of the nutrients have already been translocated to the rhizomes, which improves the feedstock quality, saves fertilizer, but reduces dry matter yields by about 30–50% (Lewandowski *et al*., 2000, 2003b; Vogel *et al*., 2002; Sanderson & Adler, 2008; Heaton *et al*., 2009). *Miscanthus* species with the largest potential biomass production (Jones & Walsh, 2001) are *M. x giganteus, Miscanthus sacchariflorus* and *Miscanthus sinensis*. *Miscanthus x giganteus* is a naturally occurring sterile hybrid so that all plantings are genetically the same. Its natural geographic range extends from north eastern Siberia, 50°N in the temperate zone to Polynesia 22°S, in the tropical zone, and westwards to central India. In Europe, *M. x giganteus* has been developed as an energy crop with productivity trials going back to the 1970s. Results of these indicate harvestable *Miscanthus* yields that range from 10 to 40 Mg ha^{-1} yr^{-1} (Lewandowski *et al*., 2000; Clifton-Brown *et al*., 2001; Christian *et al*., 2008). Converted into energy, *Miscanthus* gives the highest average energy yields per area among a range of crop types examined (Table 2).

Near-permanent vegetative cover is provided by SRC, with only short periods every 3 years or so, with little or no plant cover, after the crop has been coppiced. Willow and poplar are ideal energy crops, as they produce high yields (Table 1), can be propagated vegetatively, have a broad genetic base and a short breeding cycle. Chemical and/or mechanical weed control is required during the establishment period and after each harvest. Unfortunately, willow, poplar and *Miscanthus* show in some cases a higher water consumption compared with conventional crops if soil water is not limited (Finch *et al*., 2004; Guidi *et al*., 2008; Dimitriou *et al*., 2009; Rowe *et al*., 2009; Table 3). A 5% and 10% higher water consumption was measured for *Miscanthus* and willow, respectively, compared with wheat and permanent grassland under similar soil and climate conditions (Borek *et al*., 2010). However, water use depends on water availability, which is site-specific and weather dependant. Thus, at some sites and seasons the general trend of water consumption was complex and reversed (Berndes, 2002; Dimitriou *et al*., 2009). For SRC, water use increases during the rotation cycle with the highest evapotranspiration measured in the final year before cutting (Finch *et al*., 2004). A higher interception loss has been found for *Miscanthus*, but also a higher water use efficiency associated with C_4 photosynthesis (Finch *et al*., 2004). *Miscanthus* and SRC have deeper roots (>2 m), than agricultural crops that enables them to use and deplete deeper groundwater resources, although this could be a disadvantage by affecting the local hydrological balance (Neukirchen *et al*., 1999; Crow & Houston, 2004). Average biomass yields of willow and poplar under European climatic conditions range 3–12 Mg ha^{-1} (Kauter *et al*., 2003; Keoleian & Volk, 2005; Table 1), with maximum yields under optimal conditions reaching up to 28–30 Mg ha^{-1} yr^{-1}. Eucalyptus yields of up to 26 Mg ha^{-1} yr^{-1} were reported from Greece (Ceulemans *et al*., 1996). A high energy density of woodchips results in energy yields per area, which are mostly higher than yields of other energy crops except *Miscanthus* (Table 2).

A largely ignored bioenergy crop, even though it provides many important ecosystem services, are the perennial grasslands (Murphy & Power, 2009). Tilman *et al*. (2006) reported that even low-input high-biodiversity grasslands could provide biomass yields of 3.7 and 6.0 Mg DW ha^{-1} yr^{-1} on degraded or fertile prairie soils, respectively. The high biodiversity of these grasslands may also reduce the risk of inter-annual fluctuations in production (Tilman *et al*., 2006).

Fertilization

Fertilizer application rates are directly linked to GHG emissions for both conventional and energy cropping systems *via* concomitant N_2O emissions from soils and additional GHG emissions associated with fertilizer production and transport. Fertilizer application practice depends on soil conditions and agro-economic constraints, which are highly variable throughout Europe. However, the N-fertilizer demand of perennial crops such as *Miscanthus* and poplar was always much lower when compared with annual crops. Perennial energy crops have a higher nitrogen use efficiency and thus, less N loss as N_2O or nitrate (Fig. 2; Lewandowski &

Table 2 Energy density and yields of conventional and dedicated energy crops for European countries

	Maize grain*	Wheat grain*	Barley grain*	Potatoes*	Sugar beet*	Maize silage*	Round wood overbark*	Miscanthus dry matter†	SRC Willow dry matter‡
Energy density ($GJ\ Mg^{-1}$)	11	11	11	2.9	2.9	3.9	18	18	18
	$GJ\ ha^{-1}\ yr^{-1}$								
Austria	104	56	49	88	190	176	62	306	198
Belgium	123	90	81	127	196	176	60	288	180
Bulgaria	39	33	30	38	52	39	25		
Croatia	59	43	34	30	109	93		324	198
Czech Republic	74	51	43	66	141	125	60		234
Denmark		79	57	116	166	136	55	396	144
Estonia		26	23	39		82	28		90
Finland		37	35	68	100		26		90
France	95	77	69	119	221	155	48	270	162
Germany§	96	81	65	117	170	167	67	342	162
Greece	98	24	26	68	180	190	8	360	180
Hungary	63	43	37	66	130	92	44	288	144
Ireland		96	72	100	143	4	45	198	108
Italy	102	36	40	72	141	199	23	270	54
Latvia		32	22	40	105	84	35		90
Lithuania	34	36	27	38	106	97	38		162
Luxembourg	87	66	58	90		104	59	324	144
The Netherlands	123	90	66	127	177	171	53	270	180
Poland	63	40	34	53	120	159	36		144
Portugal	60	16	16	43	192		51	360	18
Romania	34	28	25	41	68	61			144
Slovakia	56	43	36	45	123	84	54	288	127
Slovenia	77	48	41	63	131	157	45	288	180
Spain	106	30	30	86	195	175	20	252	144
Sweden		66	45	87	140		30	90	72
Switzerland	98	65	69	109	211		58	252	144
United Kingdom		85	63	120	161	12	52	270	162

Data sources for energy density (Peterson & Hustrulid, 1998; Matthews, 2001; Lewandowski *et al*., 2003a; Baitz *et al*., 2004; Patzek, 2004; Pimental & Patzek, 2005; Gerin *et al*., 2008; Koga, 2008).

*Eurostat mean yields for period 1990–2006.

†Modelled using MiscanFor (Hastings *et al*., 2009a).

‡Modelled using SalixFor (unpublished results). For model details see Table 1.

§including ex-GDR from 1991.

Schmidt, 2006; Boehmel *et al.*, 2008; Karp & Shield, 2008). Moreover, N demand is reduced due to effective N recycling and repartitioning to the rhizome after the first frost in *Miscanthus* and after leaf fall for poplar and willow. This is also a major economic advantage of using perennial energy crops. For *Miscanthus* only minimal N fertilization is required. If *Miscanthus* is harvested in spring then the C/N ratio is very high, up to 482 (Heaton *et al.*, 2009). Average European atmospheric N deposition rates of 9–12 kg N ha^{-1} yr^{-1} are sufficient to replace most of the N lost with the harvested biomass (Holland *et al.*, 2005).

For SRC, fertilization with waste water has been successfully applied in Sweden, reducing the need for chemical fertilizers (Perttu, 1999). Willow, however, seems to be more N demanding than poplar (Venendaal *et al.*, 1997; Jug *et al.*, 1999). For eucalyptus, fertility management is a major issue when it is grown on poor soils typical of the Mediterranean regions. The use of longer rotations, intercropping with N fixing crops or trees and returning nutrient rich organic material after harvest can minimize fertilization requirements (Heilman & Norby, 1998; Zegada-Lizarazu & Monti, 2011).

Lifetime and site preparation for perennial energy crops

Most SRC plantations have been established on arable land due to the relatively small risk of establishment failure and the lower investment costs for site preparation and weed control when compared with establish-

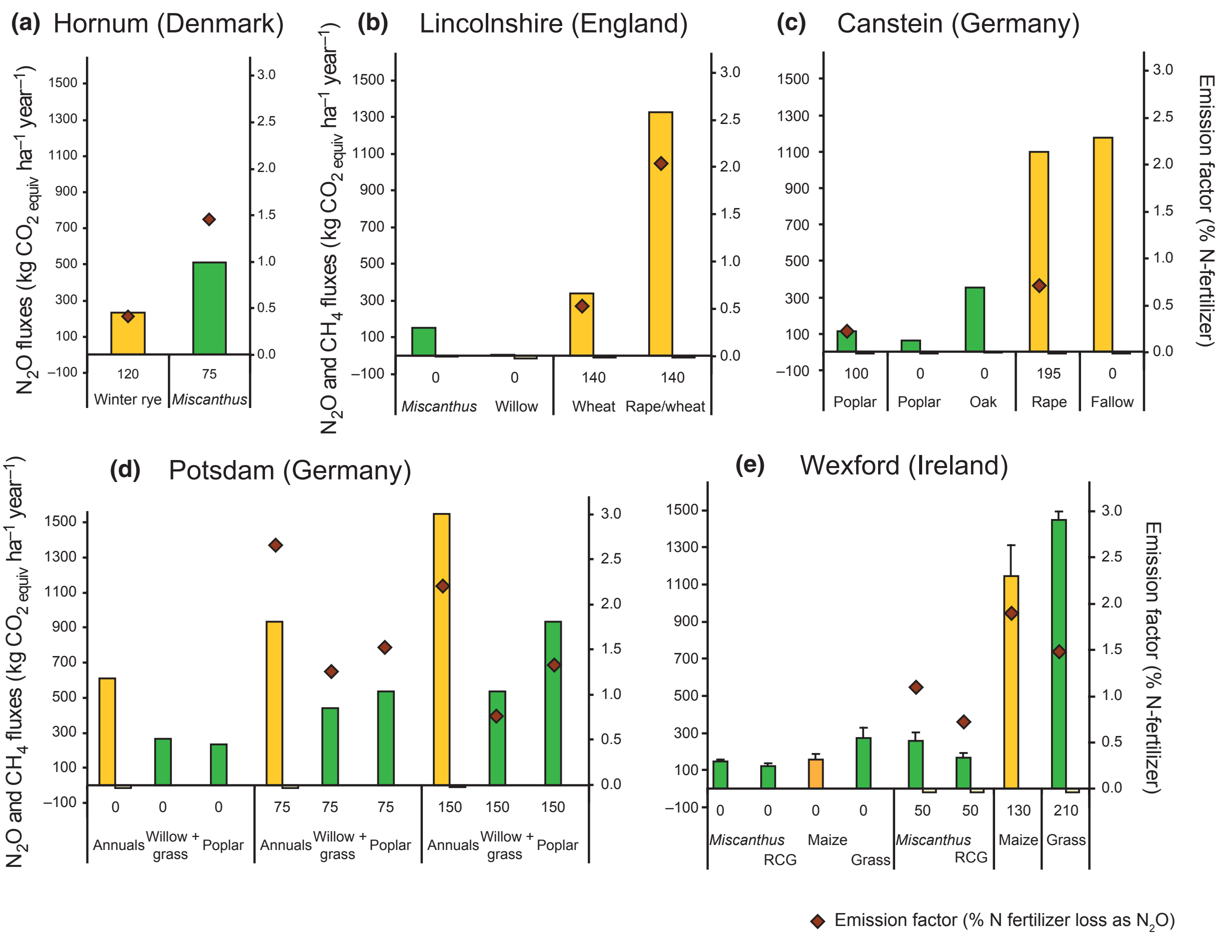

Fig. 2 Field measurements of N_2O (coloured bars) and CH_4 (clear bars below the zero line) fluxes (kg $CO_{2\ equiv}$ ha^{-1} yr^{-1}) and N_2O emission factors (% N fertilizer loss as N_2O, diamond symbol) of dedicated energy crops (green) when compared with conventional crops (yellow) at five European locations. Emission factors are not corrected for N_2O fluxes of unfertilized plots. Measurement periods and references: (a) April to October 1995 (Jørgensen *et al.*, 1997), (b) June 2008 to November 2010 (J. Drewer *et al.*, unpublished results), (c) April 1996 to March 1997 (Flessa *et al.*, 1998) and (d) 1999–2007 (complete years) (Hellebrand *et al.*, 2010). 'Annuals' refers to a crop rotation of triticale, rye, rape and cannabis. (e) 2008–2010 (complete years) (G. Lanigan *et al.*, unpublished results). Errors display standard deviation of three annual budgets. 'Grass' refers to a *Lolium pratense* silage pasture, 'RCG' refers to reed canary grass.

ment on grasslands. If SRC is established on sites under permanent vegetation, i.e., grasslands or woodland, partial or complete ploughing is required. Such management practices would have a negative effect on SOC stocks (see Carbon balance). Ploughing can improve the establishment success of SRC, for example, subsoil ploughing (to 35–40 cm depth) may be required to remove a sub-surface pan or an impermeable barrier that would otherwise limit growth.

The economic lifetime of perennial energy crops such as SRC and *Miscanthus* is probably limited to a few decades. For example, after full establishment, poplar and willow plantations can be harvested in rotation cycles of 3–5 years for 25–30 years (Kauter *et al*., 2003; Keoleian & Volk, 2005). Thereafter, the stems of coppiced trees become so large that they present difficulties for harvesting with currently existing and common machinery. Commercial biomass plantations of eucalyptus are usually harvested 6 or 7 years after establishment, with two additional rotations (Bernardo *et al*., 1998). As the stand ages, decreasing yields at harvest are expected, although reports to date are scarce. The removal of mature SRC plantations often involves mechanical operations to a depth of 90 cm to remove or plough in stools and rhizomes. Similarly, long-term yield series for *Miscanthus* and other perennial grass plantations indicate that old stands (>15 years) may need to be replanted. For example in Ireland, the observed biomass yields of *Miscanthus* were up to 20% lower than expected from modelling when the stand age exceeded 10 years (Clifton-Brown *et al*., 2007). At present there is no clear explanation for these observed reductions in expected yield, but it is possibly due to the increasing physical space occupied by old non-vigorous rhizomes that reduce the productivity per unit area.

Use of marginal land vs. fertile land for energy crop production

A main uncertainty in predicting future potential bioenergy production is the available land that could be converted to energy crops (Berndes *et al*., 2003). Globally, the estimated available area suitable for bioenergy production varies between 240 and 500 Mha (WBGU, 2008). Bioenergy feedstock production is expected to be restricted to so-called marginal or abandoned land in order not to compromise food security. However, most land classified as marginal or temporarily abandoned is still used, e.g., for transitional farming or subsistence farming. Furthermore, such land may harbour a high biodiversity or contain significant C stocks that will be lost upon cultivation (Eggers *et al*., 2009). In the EU, the set-aside programme was suspended in 2008 in a response to increasing food prices. This programme supported the production of energy crops, as non-food production was allowed on set-aside land. Approximately, 6 Mha (around 8% of total cropland) had been set aside in the EU-15 of which 800 000–900 000 ha were cultivated with non-food crops, mainly for bioenergy. Of all EU set-aside land, 20% was taken into cultivation as an immediate response to the suspension of the set-aside scheme and further re-cultivation is expected to take place in the future. Contrary to the political aim to open up marginal land for bioenergy crops current production takes place mainly on fertile cropland in direct competition with food production. Expansion of bioenergy production to marginal land is further constrained by the high establishment costs of perennial energy crops and the often relatively low yields.

Greenhouse gas balance and soil C balance of bioenergy feedstock

The GHG budget of bioenergy feedstock production depends on the net balance of CO_2, CH_4 and N_2O emissions during crop production and associated land-use changes and fossil fuel use during fertilizer and pesticide manufacture, transport and fuel for field machinery. In this review, only the GHG emissions of the bioenergy feedstock during growth will be considered to focus on the field-specific effects of direct land-use change to bioenergy, which is the most complex part of any LCA analysis. Typically, soil emissions or uptake of N_2O and CH_4 are measured in the field at the plot scale using small chambers (Hutchinson & Mosier, 1981). Recent technology has now facilitated the use of field scale measurements using laser eddy covariance techniques (Neftel *et al*., 2010). The CO_2 balance is derived either from eddy covariance flux measurements or from total ecosystem C stock inventories.

Nitrous oxide

Emissions of N_2O from soils and adjacent water bodies are able to turn the life cycle GHG balance of energy crops from a net sink into a net source (Crutzen *et al*., 2008; Searchinger *et al*., 2008). The production of N_2O is a result of the microbial processes of nitrification and denitrification. These processes are controlled by soil management, such as fertilization and tillage, and abiotic factors such as climate, frost and thaw frequency, soil porosity, moisture content, pH and organic C availability (e.g., Skiba & Smith, 2000; Ruser *et al*., 2001; Jungkunst *et al*., 2006; Stehfest & Bouwman, 2006). Mineral fertilizers for agricultural production are the largest single global N_2O source. The emission of N_2O and also the emission factor (N_2O emission per applied N fertilizer) are crop-specific with up to a 700% difference between different crop types for the same site, fertilization rate and measurement period (Kaiser & Ruser, 2000).

Whether an increased share of energy crops would decrease agricultural and total GHG emissions, requires an evaluation relative to a reference scenario, i.e., a conventional crop grown on the same soil under the same climatic conditions or compared with the use of conventional fossil fuels. The choice of the reference scenario is crucial and strongly determines the outcome of such a comparison (Smeets *et al.*, 2009). The only five European data sets known to us that compare fluxes from conventional crops and dedicated energy crops under same environmental conditions are displayed in Fig. 2 – two of them are new unpublished data sets. They derive from five different sites covering a climate gradient from North-Western Europe to Central Europe. All flux data were obtained by weekly to biweekly measurements using closed chamber techniques. For all sites, N_2O fluxes were high in comparison to CH_4 uptake (see Methane). Perennial dedicated energy crops showed significantly lower N_2O emissions than conventional energy crops except for Hornum, the Danish site, which is characterized by a short measurement period that was restricted to one vegetation period (Jørgensen *et al.*, 1997). On SRC plantations, N_2O emissions were reduced, on average, by 64% (95% confident interval: 24 to >99%, n = 11) compared with conventional annual crops (Fig. 2, Table 3). This was not only an effect of reduced fertilization on SRC but also the loss of N fertilizer as N_2O (emission factor) was reduced by 64% (95% confident interval: 25 to >99%, n = 7). This can be attributed to the higher nitrogen use efficiency of perennial crops. In a nine year study in Michigan, United States, five to six times smaller N_2O emissions were measured for a poplar plantation compared with conventional cropland systems (Robertson *et al.*, 2000). Similar reductions in N_2O emissions (up to 95%) and emission factors (between 43% and 64%, when compared with wheat/maize) have been observed for *Miscanthus* and reed canary grass at two sites with full annual flux measure-

Table 3 Greenhouse gas balance and water use efficiency of the main conventional and dedicated energy crops

Crop type	Energy-specific water use efficiency * (m³ GJ^{-1})	N_2O emissions † (kg $CO_{2\ equiv}$ ha^{-1} yr^{-1})	N_2O emission factor ‡ (% N_2O per N fertil.)	Additional soil organic C § (kg $CO_{2\ equiv}$ ha^{-1} yr^{-1})	Additional below ground biomass C ¶ (kg $CO_{2\ equiv}$ ha^{-1} yr^{-1})
Miscanthus	Medium–high (9–20)	Low	Low	Gain (about 2500)	High (1300–1700)
Switch-grass	High	Low	Low	Gain	Medium (560–940)
Reed canary grass	Medium (14)	Low–medium	nd	Gain (on mineral soils)	nd
Other perennial grasses	nd	Variable 1.3 (0.2–5.8, n = 71)	Variable 1.3 (0.2–5.8, n = 71)	Gain (600–900)	nd
Willow	Medium (12)	Low (0.2–1.5, n = 6)	Low (0.2–1.5, n = 6)	Gain (mean: 1600)	Medium (200–890)
Poplar	Medium (22)				
Maize	Variable (9–73)	High	High	Loss (−2959 to −2050)	Zero
Oil rape seed	Low (67–100)	High 2.0 (0.1–3.4, n = 48)	High 1.8 (0.4–4.5, n = 48)	Loss (−1500 to −1250)	Zero
Wheat	Variable (14–40)	High 2.0 (0.2–8.8, n = 150)	High 1.4 (0.0–6.0, n = 150)		Zero
Potato/beet	Variable (13–71)	Very high 4.7 (0.3–16.0, n = 83)	Very high 2.7 (0.2–15.4, n = 83)	High loss (−4200 to −2800)	Zero

*Water use efficiency (water consumption per bioenergy unit) (Berndes, 2002; Gerbens-Leenes *et al.*, 2009; Borek *et al.*, 2010).
†Mean and min and max (in brackets) and number of compiled studies of annual N_2O fluxes. Sources (Eulenstein *et al.*, 2011), for grassland (R. Dechow, personal communication; compiled European data set) and for short rotation forests (SRF) see Fig. 2.
‡Mean and min and max (in brackets) and number of compiled studies of the emission factor that displays the fraction of N fertilizer that is lost as N_2O (R. Dechow, personal communication; compiled European data set) and for SRF see Fig. 2).
§Ranges of additional soil organic C changes due to crop production and after establishment of energy crops on former cropland (mineral soils) for 20 year lifetime (Körschens *et al.*, 1998). Note: Negative balance of annual crops can be balanced by intermediate crops.
¶Ranges of additional below ground biomass C divided by the 20 year lifetime of perennial crop plantations when compared with a cropland (maize) (Rytter, 2001; Zan *et al.*, 2001; Dowell *et al.*, 2009; Heinsoo *et al.*, 2009).

ments (Fig. 2b and e). Thus, land-use change from annual to perennial energy crops significantly reduces area-specific N_2O emissions. Moreover, equally high or even higher energy yields of *Miscanthus* and SRC when compared with conventional energy crops (Table 2) result in high N_2O savings also per produced energy unit. Per unit of bioenergy N_2O emissions decrease with increasing yield per ha. Thus, an increased N-use efficiency, which is the amount of N fertilizer needed per yield of biomass, is the key to reduce N_2O emissions.

Differences between various conventional energy crops seem not to be consistent with the exception of almost twice as high N_2O emissions from potato and beet compared with cereals and oilseed rape (Table 3). There may also be lag effects of crop residues ploughed under in the previous autumn, with residues from oilseed rape causing especially high N_2O emissions, due to their high N content (Hadas *et al.*, 2004). However, these lag effects are poorly understood.

Given proper site selection, dedicated energy crops can be cultivated even on organic soils with low N_2O emissions (Hyvönen *et al.*, 2009). In Finland, mean N_2O emissions of reed canary grass cultivated on drained organic soils was only around 300 kg $CO_{2\ equiv}$ ha^{-1} yr^{-1} (Hyvönen *et al.*, 2009). These N_2O emissions were only a tenth of those from conventional Finish agricultural crops, due partly to the lower fertilizer requirements for reed canary grass. Similarly, the average emissions factor for reed canary grass on Irish mineral soils was only 0.2% (±0.14) of applied N compared to 1.38% (±0.14) for *Lolium* pastures (see Fig. 2e).

Perennial bioenergy crops do not require annual tillage so that tillage-induced N mineralization and the possibility of increased N_2O production as a loss of mineral N is minimized. Reduced tillage may, however, increase N_2O emissions due to decreased soil aeration and higher soil moisture contents (Aulakh *et al.*, 1984; Linn & Doran, 1984; Smith & Conen, 2004; Rochette, 2008). Soil moisture is one of the main variables that control seasonal and inter-annual N_2O production by regulating the oxygen availability (Davidson, 1991; Ball *et al.*, 1999; Skiba & Smith, 2000). The larger emissions from *Miscanthus* compared with the adjacent winter rye at the Hornum, Denmark site (Fig. 2a) may be related to reduced aeration and a higher soil water content, which is thought to be mainly due to accumulation of *Miscanthus* litter (Jørgensen *et al.*, 1997). In contrast, N_2O emissions from *Miscanthus* at the Wexford site, Ireland were lower than those for maize, due to drier soils that resulted from increased water use (Fig. 2e).

Soil compaction caused by agricultural machinery can produce hot spots of N_2O emissions (Hansen *et al.*, 1993; Vermeulen & Mosquera, 2009). Wheel traffic lanes on a potato field led to a 11 times higher annual N_2O emission (up to 937 kg $CO_{2\ equiv}$ ha^{-1} day) compared with emissions outside the compacted lanes (Flessa *et al.*, 1998). Machinery required to harvest perennial crops is similar to those currently used for arable crops, but with less frequent traffic. However, many perennial energy crops are harvested in winter (often in wetter conditions), which could, on the one hand, foster soil compaction and the production of N_2O. On the other hand, the timing of the winter harvest can be flexible and the winter harvest can be performed on frozen soil without compaction in northern-most areas where low temperatures are common. Winter harvesting also allows to keep the water table close to the surface in summer, which helps to conserve soil C in organic soils, e.g., under reed canary grass production.

Zero tillage and the presence of plants may contribute to a reduction in the buildup of soil mineral N concentrations and thereby N_2O production during the autumn/winter period. On arable soils, winter N_2O fluxes account for up to 90% of the total annual emissions (Flessa *et al.*, 1998). Perennial plants have the potential to take up mineral nitrogen all year around, depending on the climatic conditions, leading to reduced N_2O emissions. Winter season N_2O emissions were reduced by 69% on a poplar plantation in comparison to an oilseed rape field at the Canstein site (Germany, see Fig. 2c). Similarly, the N_2O emission factor was reduced by 39% during the winter when compared with a 65% reduction during the vegetation period (Flessa *et al.*, 1998). At the Hornum, Denmark site winter fluxes were not measured thus it is likely that the emission factors (Fig. 2a) are an underestimate.

Emissions of N_2O from dry, well-aerated soils, regardless of the management practice applied, are negligible compared with N_2O emissions from poorly drained and fine-textured soils in high rainfall areas (Rochette, 2008; Hellebrand *et al.*, 2010). On the other hand, on sandy soils direct N_2O emissions may be shifted to indirect emissions from NO_3^- leached into adjacent water bodies (Crutzen *et al.*, 2008; Well & Butterbach-Bahl, 2010). Indirect emissions comprise an important fraction of crop production-related N_2O emissions but at present cannot be assigned to specific sources and crop types. Marginal land is often poorly drained, but could support perennial energy crop production due to a sufficient water supply. The high future demand for energy crops in Europe will likely result in the increased utilization of poorly drained set aside soils for energy crop production. This underlines the importance of choosing crops with a high N-use efficiency, such as *Miscanthus* and SRC, as they reduce the N fertilization demand and subsequently the direct and indirect N_2O emissions, regardless of the soil type they are cultivated on.

Carbon balance

The long-term C balance of bioenergy crops is controlled by changes in soil and biomass C. In particular soils have a large capacity to store and build up C stocks. Changes in SOC are a key issue for future bioenergy production, as extension of production may cause the cultivation of areas that were previously not cropland. In general, annual cropland conversion to perennial crops results in increased SOC stocks but SOC decreased if perennial crops or grasslands are converted to annual crops (Anderson-Teixeira *et al.*, 2009; Poeplau *et al.*, 2011). Even though there is a wide range of grassland management types, on average most grasslands store higher SOC stocks than croplands under similar site conditions (Poeplau *et al.*, 2011). Moreover, the reconversion of abandoned land to cropland causes SOC losses, as most abandoned land accumulated SOC through natural succession to grassland or woodland that would in turn be reduced upon re-cultivation. In an LCA for US croplands, it was estimated that the extension of bioenergy production into abandoned cropland caused a carbon debt of up to 69 Mg CO_2 ha^{-1}. About 48 years of bioenergy production with substitution of fossil fuels would be needed to repay this debt (Fargione *et al.*, 2008). Malca and Freire (2009) reported an SOC loss of 0.24 ± 30% Mg ha^{-1} yr^{-1} (880 kg $CO_{2\ \mathrm{equiv}}$ ha^{-1} yr^{-1}) when oilseed rape was cultivated on set aside land.

The expansion of bioenergy production also provides the possibility to increase current SOC stocks, if the land-use change involves the conversion of annual crops into perennial energy crops. In this case, SOC that had been lost during former cultivation can be re-captured. From the existing studies, we calculated an average (±SE) SOC accumulation of 1622 ± 1586 kg $CO_{2\ \mathrm{equiv}}$ ha^{-1} yr^{-1} for SRC (0.44 Mg C ha^{-1} yr^{-1}) and 2427 ± 3421 kg $CO_{2\ \mathrm{equiv}}$ ha^{-1} yr^{-1} (0.66 Mg C ha^{-1} yr^{-1}) for *Miscanthus* cultivated on former croplands (Fig. 3). These are larger estimates than derived from the IPCC default values (Fritsche & Wiegmann, 2008). However, there was no or even a negative SOC stock change, −4621 ± 2774 (−1.3 Mg C ha^{-1} yr^{-1}) and −316 ± 692 kg $CO_{2\ \mathrm{equiv}}$ ha^{-1} yr^{-1} (−0.09 Mg C ha^{-1} yr^{-1}), if grassland was converted to SRC and *Miscanthus* respectively. Thus, any changes in SOC stocks depend critically on the former land-use history and may dominate the total bioenergy feedstock GHG balance (Table 3). In this data set, no C saturation effect was detected in soils but SOC sequestration remained constant throughout the life cycle of *Miscanthus* and the SRC plantation lifetime (Fig. 3). Dondini *et al.* (2009) projected a steady state SOC of around 100–110 Mg ha^{-1} for an Irish *Miscanthus* site, which is close to levels observed in semi-natural *Miscanthus* grasslands in SE Asia (Shoji *et al.*, 1990). Accumulation of SOC is higher in SRC than that associated with afforestation of croplands using common tree species (Post & Kwon, 2000). The frequent harvest of above ground biomass in SRC plantations leads to the die off of a major fraction of roots that contribute to SOC accumulation as well as accelerating fine root turnover. Fine root production is enhanced in SRC with 1–5 Mg ha^{-1} yr^{-1}, which is 50–100% of the standing fine root stock (Block *et al.*, 2006). In addition, biomass C accumulation in roots and rhizomes, standing above ground biomass and litter may be considerable for perennials (Monti & Zatta, 2009). Under *Miscanthus* 7.5–10 Mg C ha^{-1} as roots and rhizomes were measured in the top 30 cm adding up to 1300–1700 kg $CO_{2\ \mathrm{equiv}}$ ha^{-1} yr^{-1} for a 20 year lifetime (Clifton-Brown *et al.*, 2007; Amougou *et al.*, 2011; Table 3). In established willow SRC plantations 2–9 Mg C ha^{-1} has been measured as below ground biomass, which is 1100–2100 kg $CO_{2\ \mathrm{equiv}}$ ha^{-1} yr^{-1} (Matthews, 2001). Additional C is sequestrated in stumps with more than 6 Mg C ha^{-1} in old plantations, which is 40% of the total biomass C (Matthews, 2001). However, this biomass C stock is temporary and will be lost after the end of the plantation period if roots and rhizomes are removed. Re-cultivation after the abandonment of perennial energy crops will cause a large disturbance to the soil with losses of above ground and below ground biomass and may also results in net SOC losses. These losses may be partly balanced if stools are ploughed in instead of their complete removal. Conversion of forest and grassland to croplands in the temperate zone results in a mean SOC loss of 31% ± 20% and 36% ± 5%, respectively, within 20 years (Poeplau *et al.*, 2011). Whether all of the SOC that accumulated under perennial energy crops will be lost under subsequent cultivation depends on the stabilization of SOC and the type of subsequent cropland management. Scholz (2010) found only minor SOC losses 6 years after re-cultivation of a poplar plantation with rye. Rotation of SRC plantations between fields with a certain fraction of farmland remaining as SRC is a possible strategy. In this case, the mean C stock change of the total farmland can be accounted for as C sink in bioenergy LCAs integrated over at least one plantation lifetime.

For assessing the C balance of bioenergy feedstock, the question of the reference system is crucial. Based on several European SOC inventories, conventional croplands are currently loosing SOC with a mean rate of 0.17 Mg ha^{-1} yr^{-1}, which is 623 kg $CO_{2\ \mathrm{equiv}}$ ha^{-1} yr^{-1} (Ciais *et al.*, 2010). Thus, if conventional cropland is converted to perennial energy crops, this SOC loss would be reduced or eliminated and should be positively accounted for in the GHG balance. There is, however,

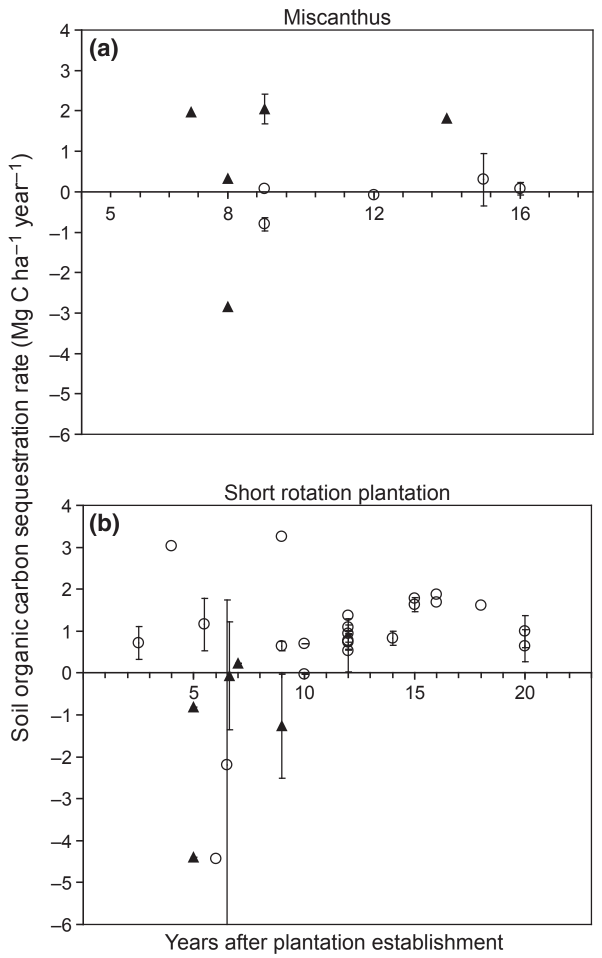

Fig. 3 Soil organic carbon sequestration rates (Mg ha^{-1} yr^{-1}) of *Miscanthus* plantations (a) and short rotation plantations of poplar and willow (b) in the temperate zone as related to the age of the plantation. Data sources *Miscanthus* (a): (Kahle *et al.*, 2001; Hansen *et al.*, 2004; Clifton-Brown *et al.*, 2007; Schneckenberger & Kuzyakov, 2007; Dondini *et al.*, 2009). Data sources short rotation coppicing (b): (Hansen, 1993; Makeschin, 1994; Boman & Turnbull, 1997; Grigal & Berguson, 1998; Jug *et al.*, 1999; Coleman *et al.*, 2004; Gielen *et al.*, 2005; Kahle *et al.*, 2005, 2007; Sartori *et al.*, 2007; Dowell *et al.*, 2009; Mao *et al.*, 2010; Scholz, 2010).

little experimental evidence on SOC stock changes related to an increased fraction of annual energy crops in traditional crop rotations. Most annual cropping systems are associated with a decline in SOC that need to be compensated for by crop residues, organic fertilizers or cover crops. Long-term experiments have shown that beet, potato and maize are the crops with the highest SOC losses (Körschens *et al.*, 1998; Table 3). SOC losses were twice as large for maize and almost three times as large for beet and potato when compared with cereals, indicating the possible negative consequences of increased conventional bioenergy production for SOC stocks. Oilseed rape had similar effects on SOC as cereals, while other studies actually found an SOC accumulation of 0.08–0.16% ± 30% Mg ha^{-1} yr^{-1} under oilseed rape when compared with cereals (Malca and Freire, 2009). Positive SOC balances were found for clover, other legumes and cover crops that may compensate for 43–68% of SOC losses from maize and 32–42% of SOC losses during beet and potato cultivation within 1 year (Körschens *et al.*, 1998). This indicates that actual SOC losses/gains will also depend on the crop rotation and management. Thus, any residual organic material that is extracted from croplands compromises the SOC balance (Lal, 2005). Residues, i.e., straw, if used in bioenergy power plants would need to be replaced by other organic soil amendments to maintain a positive SOC balance. Not only is SOC important directly for the GHG balance but also for soil fertility, erosion protection and water and nutrient retention in soils, all of which indirectly influence the GHG balance.

Methane

In wetland ecosystems, or those with a consistently high water table, such as peatlands and hydromorphic soils, CH_4 emissions may comprise an important part of the GHG footprint of energy cropping systems. Paludiculture, the cultivation of biomass on wet and rewetted peatlands, is an alternative to conventional drainage-based peatland agriculture (Wichtmann & Schäfer, 2007). Ideally, the peatlands should be so wet that peat is conserved and peat accumulation is maintained. Paludiculture uses that part of the net primary production (NPP) that is not necessary for peat formation (which may amount to 80–90% of NPP). In such systems, CH_4 emissions may play a role and should be accounted for in relation to other land-uses on these soils. In contrast, reed canary grass production relies mainly on drained soils or former areas of peat extraction with a lowered ground water table and, thus, low CH_4 emissions (100 kg $CO_{2\ equiv}$ ha^{-1} yr^{-1} at a Finish study site; Hyvönen *et al.*, 2009). In most European cropland systems, the ground water table is more than 10 cm below the surface, which prevents most CH_4 emissions. The majority of cultivated mineral soils acts as a CH_4 sink, with methanotrophic bacteria consuming CH_4 through oxidation (Hutsch, 2001; Fig. 2). Of the bioenergy sites where CH_4 was measured, CH_4 uptake rates were small with between 2 and 17 kg $CO_{2\ equiv}$ ha^{-1} yr^{-1}. Thus, the CH_4 uptake compensates around 3% (up to 5.2% in annual crops and 12.7% in SRC) of the N_2O emissions calculated as CO_2 equivalents. The uptake of CH_4 depends mainly on gas diffusivity, so soils with a high water content or a high bulk density have a small CH_4 sink capacity (Flessa *et al.*, 1995; Dobbie & Smith, 1996;

Hutsch, 2001). Soils may turn into a CH_4 source if they are poorly aerated and compacted by wheel traffic (Hansen *et al.*, 1993; Vermeulen & Mosquera, 2009). There is no direct link between N_2O production and CH_4 consumption but soil conditions that foster CH_4 uptake similarly decrease N_2O production. Forest soils were found to oxidize more CH_4 than cultivated or set aside soils due to ammonia inhibiting CH_4 oxidation (King & Schnell, 1994; Dobbie & Smith, 1996). Thus, taking native vegetation as reference, CH_4 uptake may be decreased under energy crops. However, there was no measured effect of fertilizer rates on CH_4 uptake at the Potsdam and Canstein site (Fig. 2c and d). For the field-specific GHG balance of bioenergy feedstock, CH_4 fluxes are of minor importance and were omitted in the obligations for national GHG reporting under UNFCCC, as they do not exceed the uncertainty range of the estimated N_2O fluxes. Only for bioenergy cultivation on soils with a high ground water table, is it likely that CH_4 efflux may comprise a significant GHG source.

Land-use changes

With the intended 10% biofuel share for EU transport fuel use by 2020, about 17.5 Mha of additional land will have to be dedicated to the production of energy crops (EU, 2007). The European Environmental Agency estimated that there is 13 Mha of suitable land for bioenergy production that is currently available for bioenergy production in the EU-22. It has been estimated that an additional 6 Mha cropland will become available due to abandoning food production over the next 20 years due to increased global market competition for food production (EEA, 2006). However, the EU bioenergy demand will not be covered by domestic production alone. There is already an increasing share of bioenergy biomass imported to the EU, which induces land-use changes not only in the EU itself but globally as external land-use change. European member states anticipate that 50% of bioethanol and 41% of biodiesel will be imported in 2020 (Bowyer, 2010). Palm oil imported from Malaysia and Indonesia has already increased by a factor of seven within 3 years from 2005 (AEBIOM, 2010). Land-use change-induced emissions do not have to be taken into account for bioenergy crops grown on former cropland (C neutral), for perennials grown on former grassland (C neutral) or cropland (C sink, Table 3). Cultivation of grassland leads to C losses of 36% ± 5% in temperate soils, 59% ± 2% globally and almost 100% of above ground and below ground biomass (Guo & Gifford, 2002; Poeplau *et al.*, 2011). This loss is commonly distributed in LCAs over a time period of 20 years and leads to emissions of around 6300 kg $CO_{2\ equiv}$ ha^{-1} yr^{-1} for grassland or forest converted into annual energy crops, assuming an initial SOC stock of 95 Mg ha^{-1} as a default value for moist temperate conditions (IPCC, 2006). Similar carbon debts of 5560 kg $CO_{2\ equiv}$ ha^{-1} yr^{-1} have been estimated for maize production on former native grassland in the United States (Fargione *et al.*, 2008).

In addition to this, there is a need to account for the impact of indirect land-use change that compensates for bioenergy production to sustain food and animal feedstock demand. The additional European demand for biofuels is anticipated to lead to between 4.1 and 6.9 Mha of indirect external land-use change mainly in countries like Brazil and India (Bowyer, 2010). The size of the area and the localization of indirect land-use changes can only be roughly predicted, as they are a result of complex interactions between market fluctuations, international trade, agricultural subsidies, weather variability and established traditions of land management. Their impact can only be roughly estimated using models ranging from complex macroeconomic models with low transparency (e.g., GTAP-E model) to deterministic models, such as the risk-adder approach that estimates average land-use change areas per additional hectare of bioenergy production (Burniaux & Truong, 2002; Fritsche, 2007; Searchinger *et al.*, 2008). A model comparison study revealed that EU ethanol consumption causes indirect land-use changes of 223–743 kha Mt_{oe}^{-1} (1000 hectare per million tons of oil equivalent), and for biodiesel 242–1928 kha Mt_{oe}^{-1} (Edwards *et al.*, 2010). This is in line with the estimates by Bowyer (2010) who calculated 272–457 kha indirect land-use change Mt_{oe}^{-1}. Due to the complexity of global trade and motivations for local land-use change, predictions of indirect land-use change due to increased bioenergy production from different model approaches will remain inconsistent and vague. Weather-induced changes or fluctuations in crop yields will also influence land-use change.

Indirect land-use change needs to be taken into account as a carbon debt if the cultivation reduces the storage of C in biomass and soil, litter or deadwood. Indirect land-use change may account for 66–89% of the total GHG emissions from land-use change for bioenergy production (WBGU, 2008). As long as there is no global climate policy with caps on GHG emissions, the control on these indirect land-use changes and their associated GHG emissions is limited. Some estimates raise concerns about GHG emissions from indirect land-use change that turn biofuels from a GHG sink into a source (Fargione *et al.*, 2008; Searchinger *et al.*, 2008). In particular the cultivation of native vegetation for bioenergy production generally led to the highest soil and total C losses due to their high initial ecosystem C stocks (Palm *et al.*, 1999; Don *et al.*, 2011). The use of additional conventional biofuels up to 2020 on the scale anticipated in the 23 European national renewable energy action plans would lead to between 81% and 167% more GHG emissions than meeting the same need through fossil fuel use (Bowyer, 2010). Specific emissions due to land-use change are especially high for bioenergy systems with low yield per hectare. Technological developments along the supply chain and improved dedicated energy crop types and crop management will reduce the impact of the bioenergy feedstock on the GHG balance. Improving crop yields per hectare, fostered by increased crop prices and improved conversion efficiencies, will decrease the energy-specific carbon debt. Furthermore, less land is needed to meet policy directives. This is only partly considered in future trajectories of direct and indirect land-use change due to anticipated increases in future biofuel production (Quirin *et al*., 2004).

A significant fraction of bioenergy feedstock is derived from waste and crop by-products such as straw, industry residues and manure (30% in Europe) (AEBIOM, 2010). These have a high potential to contribute to future bioenergy production, as they do not induce any land-use change. However, in future the need to mitigate GHG emissions in agriculture by increasing the SOC of croplands may create a competitive market for these 'waste products' as soil amendments to improve SOC and soil fertility and this will increase the value of such waste. Non-harvested by-products such as crop and forest residues left on the ground contribute to SOC sequestration in the ecosystems for a limited transitional period. Whether their harvest and energetic use as a substitute for fossil fuel or their being left on the site results in higher CO_2 savings depends on an array of parameters such as the C saturation level of the ecosystem and the energy investments for collection and transport of residues (Lal, 2005).

Conclusions and critical knowledge gaps

- For the most common conventional energy crops such as maize and oilseed rape, no data on the production area are available for most European countries. Thus, data to evaluate the GHG footprint of bioenergy production and land-use change or effects on food prices and food and animal feedstock import is lacking. Data identifying where and when conventional and dedicated energy crops are, or have been, established (including the former land-use of these production areas) are required.
- Land-use change for bioenergy production should be restricted to land that is or has been cultivated. Any conversion of native vegetation or perennial grasslands would cause C losses from soils and biomass that compromises the CO_2 savings of bioenergy. The GHG balance of bioenergy feedstock is dominated by the SOC balance if land-use change from ecosystems with high SOC stocks is involved, such as conversion from grasslands, forest or peatlands. Perennial energy crops provide the potential for C sequestration for a transitional period if they are established on former croplands.
- There are no enough data to provide GHG balances for different energy crops. However, it is unequivocal that the majority of current annual energy crops have a low GHG efficiency. The CO_2 savings due to bioenergy production are compromised by GHG emissions during feedstock production. These need to be reduced by crop type selection, yield improvement and crop management. Perennial energy crops provide a large abatement potential for N_2O emissions due to low N fertilization demand and higher N-use efficiency and may provide additional CO_2 savings from SOC sequestration.
- More field studies are required to evaluate the impact of perennial energy crops on GHG fluxes in comparison to conventional annual energy crops. The uncertainty of LCAs for bioenergy use can be reduced with better estimates of the field GHG balance. Only through long-term studies can the effects of inter annual climate variability be assessed.
- Biomass yield is the key factor underpinning GHG efficiency and the economic viability of energy crops. Future production of dedicated energy crops depends on the contribution of improvements in yield and productivity due to appropriate selection, breeding and management practices. Dedicated energy crops should be improved for growth on marginal land with low fertility soils that are either water logged or subjected to water deficits. In addition, the N fertilizer use efficiency drives the GHG balance of bioenergy feedstock, as a certain fraction of N fertilizer is lost as N_2O. The challenge for agricultural research is to optimize energy crop yields under the combined constraints of restricted or no fertilizer use and sub optimal soil and water conditions.
- Given the limited area that is available for bioenergy production, the contribution of energy crops to climate change mitigation is likely to remain small (below 10% of global energy supply in 2050) (WBGU, 2008) and can only contribute to a larger assemblage of mitigation measures. However, perennial bioenergy production provides an array of advantages that should be considered additional to the GHG mitiga-

tion effect: increased rural area employment and agricultural income diversification, enhanced biodiversity, improved landscaping, reduced nutrient losses to the ground water and adjacent water bodies. Thus, there are enough reasons to promote the wider use of dedicated energy crops.

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