REVIEW

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

AXEL DON*, BRUCE OSBORNE†, ASTLEY HASTINGS‡, UTE SKIBA§, METTE S. CARTER¶, JULIA DREWER§, HEINZ FLESSA*, ANNETTE FREIBAUER*, NIINA HYVÖNEN∥, MIKE B. JONES**, GARY J. LANIGAN††, ÜLO MANDER‡‡, ANDREA MONTI§§, SYLVESTRE NJAKOU DJOMO¶¶, JOHN VALENTINE∥∥, KATJA WALTER*, WALTER ZEGADA-LIZARI A§§ and TERENZIO ZENONE***

*Johann Heinrich von Thünen Institute, Institute of Agricultural Climate Research, Bundesallee 50, 38116 Braunschweig, Germany, †UCD School of Biology and Environmental Science, University College Dublin, Belfield, Dublin 4, Ireland, ‡Institute of Biological and Environmental Sciences, University of Aberdeen, 23 St Machars Drive, Aberdeen, AB24 3UU Scotland, §Centre for Ecology and Hydrology, Bush Estate, Penicuik, EH26 0QB UK, ¶Biosystems Division, Risø National Laboratory for Sustainable Energy, Technical University of Denmark, PO Box 49, 4000 Roskilde, Denmark, ∥Department of Environmental Science, University of Eastern Finland, BioTeknia 2, PO Box 1627, FI-70211 Kuopio, Finland, **Department of Botany, School of Natural Sciences, Trinity College Dublin, Dublin 2, Ireland, ††Teagasc, Johnstown Castle Research Centre, Wexford, Ireland, ‡‡Department of Geography, Institute of Ecology and Earth Sciences, University of Tartu, Vanemuise St. 46, 51014 Tartu, Estonia, §§Department of Agroenvironmental Science and Technology, University of Bologna, Viale Fanin 44, 40127 Bologna, Italy, ¶¶Department of Biology, University of Antwerp, Universiteitsplein 1, BE-2610 Wilrijk, Belgium, ∥∥Institute of Biological, Environmental and Rural Sciences, Aberystwyth University, Gogerddan, Aberystwyth, SY23 3EB UK, ***Department of Environmental Sciences, University of Toledo, Toledo, 43606 OH, USA

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 CO₂, N₂O and CH₄ during crop production may reduce or completely counterbalance CO₂ 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 N₂O 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

Received 4 April 2011; revised version received 1 July 2011 and accepted 12 July 2011
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* ssp.), 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.

© 2011 Blackwell Publishing Ltd, *GCB Bioenergy*, 4, 372–391
Atmosphere, other GHGs, particularly methane (CH$_4$) and nitrous oxide (N$_2$O) have to be taken into account. The global warming potential of N$_2$O and CH$_4$ are 298 and 25 times larger than that of CO$_2$, respectively (Forster et al., 2008). There have been few field measurements of associated N$_2$O and CH$_4$ fluxes, or rely on simple emission default values only provide a very general estimate of N$_2$O emissions and cannot assess regionalized or site-specific effects of crop species on GHG fluxes. Moreover, fertilizer-induced N$_2$O emission may also be underestimated if indirect emissions from rivers, coastal zones, animal husbandry and atmospheric N deposits 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$_2$O, 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 (Poepflau 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-commerical 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 ligno-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 firewood 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 C₄ 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
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.

| Country          | Maize grain* | Wheat grain* | Barley grain* | Potatoes* | Sugar beet* | Maize silage* | Round wood overbark* | Miscanthus dry matter† | SRC Willow dry matter‡ |
|------------------|--------------|--------------|---------------|-----------|-------------|---------------|-----------------------|------------------------|------------------------|
| 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         |               |                       |                        |                        |
| Finland          | 3.4          | 3.2          | 23.2          | 34.2      | 1.5         |               |                       |                        |                        |
| 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           |                       |                        |                        |
| 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        | 1.6           |                       | 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          | 2.9           | 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 wilth 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).
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 switchgrass 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 switchgrass 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 geographic range extends from north eastern Siberia, 50°N to Polynesia 22°S, in the temperate zone.

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 N₂O 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 N₂O or nitrate (Fig. 2; Lewandowski 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 C₄ 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; Koeleian & 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).

© 2011 Blackwell Publishing Ltd, GCB Bioenergy, 4, 372–391
Table 2  Energy density and yields of conventional and dedicated energy crops for European countries

| Energy density (GJ Mg⁻¹) | Maize grain* | Wheat grain* | Barley grain* | Potatoes* | Sugar beet* | Maize silage* | Round wood overbark* | Miscanthus dry matter* | SRC Willow dry matter* |
|-------------------------|--------------|--------------|---------------|-----------|-------------|---------------|---------------------|-----------------------|-----------------------|
| GJ ha⁻¹ yr⁻¹            | 11           | 11           | 11            | 2.9       | 2.9         | 3.9           | 18                  | 18                    | 18                    |
| 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            |                     |                       |                       |
| 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\(_2\)O (coloured bars) and CH\(_4\) (clear bars below the zero line) fluxes (kg CO\(_2\)\,equiv ha\(^{-1}\) yr\(^{-1}\)) and N\(_2\)O emission factors (% N fertilizer loss as N\(_2\)O, diamond symbol) of dedicated energy crops (green) when compared with conventional crops (yellow) at five European locations. Emission factors are not corrected for N\(_2\)O 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.
mment 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 CO₂, CH₄ and N₂O 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 N₂O and CH₄ 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 (Neffel et al., 2010). The CO₂ balance is derived either from eddy covariance flux measurements or from total ecosystem C stock inventories.

**Nitrous oxide**

Emissions of N₂O 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 N₂O 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 N₂O source. The emission of N₂O and also the emission factor (N₂O emission per applied N fertil-
izer) 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, N₂O fluxes were high in comparison to CH₄ uptake (see Methane). Perennial dedicated energy crops showed significantly lower N₂O 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, N₂O 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 N₂O (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 N₂O emissions were measured for a poplar plantation compared with conventional cropland systems (Robertson et al., 2000). Similar reductions in N₂O 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 * | N₂O emissions † | N₂O emission factor † | Additional soil organic C ‡ | Additional below ground biomass C ‡ |
|-----------------------|----------------------------------------|-----------------|-----------------------|-----------------------------|-----------------------------------|
|                       | m² GJ⁻¹                                | kg CO₂ equiv ha⁻¹ yr⁻¹ | % N₂O per N fertil. | kg CO₂ equiv ha⁻¹ yr⁻¹ | kg CO₂ 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                   | Gain (mean: 1600)           | Medium (200–890)                  |
| Poplar                | Medium (22)                            | Variable (9–73)  | High                  | Loss (−2959 to −2050)       | Zero                              |
| Maize                 | Low (67–100)                           | High 2.0 (0.1–3.4, n = 48) | High                 | Loss (−1500 to −1250)       | Zero                              |
| Oil rape seed         | Variable (14–40)                       | High 2.0 (0.2–8.8, n = 150) | High 1.4 (0.0–6.0, n = 150) | Loss (−4200 to −2800)       | 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) | Loss (−2959 to −2050)       | Zero                              |

*Water use efficiency (water consumption per bioenergy unit) (Bernes, 2002; Gerbens-Leenes et al., 2009; Borek et al., 2010).
†Mean and min and max (in brackets) and number of compiled studies of annual N₂O 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 N₂O (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 N₂O emissions. Moreover, equally high or even higher energy yields of Miscanthus and SRC when compared with conventional energy crops (Table 2) result in high N₂O savings also per produced energy unit. Per unit of bioenergy N₂O 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 N₂O emissions.

Differences between various conventional energy crops seem not to be consistent with the exception of almost twice as high N₂O 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 N₂O 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 N₂O emissions (Hyvönen et al., 2009). In Finland, mean N₂O emissions of reed canary grass cultivated on drained organic soils was only around 300 kg CO₂ equiv ha⁻¹ yr⁻¹ (Hyvönen et al., 2009). These N₂O 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 N₂O production as a loss of mineral N is minimized. Reduced tillage may, however, increase N₂O 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 N₂O 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 (Jorgensen et al., 1997). In contrast, N₂O 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 N₂O emissions (Hansen et al., 1993; Vermeulen & Mosquera, 2009). Wheel traffic lanes on a potato field led to a 11 times higher annual N₂O emission (up to 937 kg CO₂ equiv ha⁻¹ day⁻¹) 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 N₂O. 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 N₂O production during the autumn/winter period. On arable soils, winter N₂O 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 N₂O emissions. Winter season N₂O 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 N₂O 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 N₂O from dry, well-aerated soils, regardless of the management practice applied, are negligible compared with N₂O 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 N₂O emissions may be shifted to indirect emissions from NO₃⁻ leached into adjacent water bodies (Crutzen et al., 2008; Well & Butterbach-Bahl, 2010). Indirect emissions comprise an important fraction of crop production-related N₂O 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 N₂O 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 re-conversion 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 CO₂ ha⁻¹⁻¹. 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 CO₂ 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 CO₂ equiv ha⁻¹ yr⁻¹ for SRC (0.44 Mg C ha⁻¹ yr⁻¹) and 2427 ± 3421 kg CO₂ 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 CO₂ 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⁻¹⁻¹ as roots and rhizomes were measured in the top 30 cm adding up to 1300–1700 kg CO₂ 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⁻¹⁻¹ has been measured as below ground biomass, which is 1100–2100 kg CO₂ equiv ha⁻¹ yr⁻¹ (Matthews, 2001). Additional C is sequestered in stumps with more than 6 Mg C ha⁻¹⁻¹ 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 result in net SOC losses. These losses may be partly balanced if stumps 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 CO₂ 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,
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, CH₄ 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, CH₄ 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 CH₄ emissions (100 kg CO₂ 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 CH₄ emissions. The majority of cultivated mineral soils acts as a CH₄ sink, with methanotrophic bacteria consuming CH₄ through oxidation (Hutsch, 2001; Fig. 2). Of the bioenergy sites where CH₄ was measured, CH₄ uptake rates were small with between 2 and 17 kg CO₂ equiv ha⁻¹ yr⁻¹. Thus, the CH₄ uptake compensates around 3% (up to 5.2% in annual crops and 12.7% in SRC) of the N₂O emissions calculated as CO₂ equivalents. The uptake of CH₄ depends mainly on gas diffusivity, so soils with a high water content or a high bulk density have a small CH₄ sink capacity (Flessa et al., 1995; Dobbie & Smith, 1996;
Soils may turn into a CH₄ source if they are poorly aerated and compacted by wheel traffic (Hansen et al., 1993; Vermeulen & Mosquera, 2009). There is no direct link between N₂O production and CH₄ consumption but soil conditions that foster CH₄ uptake similarly decrease N₂O production. Forest soils were found to oxidize more CH₄ than cultivated or set aside soils due to ammonia inhibiting CH₄ oxidation (King & Schnell, 1994; Dobbie & Smith, 1996). Thus, taking native vegetation as reference, CH₄ uptake may be decreased under energy crops. However, there was no measured effect of fertilizer rates on CH₄ uptake at the Potsdam and Canstein site (Fig. 2c and d). For the field-specific GHG balance of bioenergy feedstock, CH₄ 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 N₂O fluxes. Only for bioenergy cultivation on soils with a high ground water table, is it likely that CH₄ 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; Poepplau 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 CO₂eqv 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 CO₂eqv 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 Mtcoe⁻¹ (1000 hectare per million tons of oil equivalent), and for biodiesel 242–1928 kha Mtcoe⁻¹ (Edwards et al., 2010). This is in line with the estimates by Bowyer (2010) who calculated 272–457 kha indirect land-use change Mtcoe⁻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).
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 CO₂ 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 CO₂ 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 CO₂ 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 N₂O emissions due to low N fertilization demand and higher N-use efficiency and may provide additional CO₂ 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 N₂O. The challenge for agrcultural research is to optimize energy crop yields under the combined constraints of restricted or no fertilizer use and suboptimal 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.

Acknowledgements

This study was funded by the FP7 project GHG-Europe (Grant No. 244122). For help with data and the literature collection, we thank Mohamend Abdalla, René Dechow, Benoît Gabrielle, Achim Grellie and Mike Wilson. S. Njakou Djomo was supported by the European Research Council under the European Community’s Seventh Framework Programme (FP7/2007-2013), ERC grant agreement no. 253366 (POPFULL).

References

AEBIOM (2010) European Biomass Statistics, p. 75. European Biomass Association, Brussels.
Amougou N, Bertrand I, Machet J-M, Recous S (2011) Quality and decomposition in soil of rhizome, root and senescent leaf from Miscanthus x giganteus, as affected by harvest date and N fertilization. Plant and Soil, 338, 83–97.
Anderson-Teixeira KJ, Davis SC, Masters MD, Delucia EH (2009) Changes in soil organic carbon under biofuel crops. GCB Bioenergy, 1, 75–96.
Armstrong AP, Baro J, Darty J, Groves AP, Nikkonen J, Rickeard DJ (2002) CONCAWE Ad Hoc Group on Alternative Fuels. Vol. 2/2002. CONCAWE. Available at: http://www.concawe.be (accessed 8 August 2011).
Batiz M, Binder M, Degen W, Deimling S, Krinke S, Rudloff M (2004) Water implications of selected energy crops cultivation. Env. Impacts Biomass Supply Chains, 59, 197–206.
Barbier ET, Machet J-M, Recous S (2011) Quality and decomposition in soil of rhizome, root and senescent leaf from Miscanthus x giganteus, as affected by harvest date and N fertilization. Plant and Soil, 338, 83–97.
Bai J, Darty J, Groves AP, Nikkonen J, Rickeard DJ (2002) CONCAWE Ad Hoc Group on Alternative Fuels, Vol. 2/2002. CONCAWE. Available at: http://www.concawe.be (accessed 8 August 2011).
Bai J, Darty J, Groves AP, Nikkonen J, Rickeard DJ (2002) CONCAWE Ad Hoc Group on Alternative Fuels, Vol. 2/2002. CONCAWE. Available at: http://www.concawe.be (accessed 8 August 2011).
Bai J, Darty J, Groves AP, Nikkonen J, Rickeard DJ (2002) CONCAWE Ad Hoc Group on Alternative Fuels, Vol. 2/2002. CONCAWE. Available at: http://www.concawe.be (accessed 8 August 2011).
Ball BC, Scott A, Parker JP (1999) Field N2O, CO2 and CH4 fluxes in relation to till- age, compaction and soil quality in Scotland. Soil & Tillage Research, 53, 29–39.
Bernardo AL, Reis MGF, Reis GG, Harrison RB, Firmo DJ (1998) Effect of spacing on growth and biomass distribution in Eucalyptus camaldulensis, E.pellita and E.urophylla plantations in southeastern Brazil. Forest Ecology and Management, 104, 1–13.
Berrones G (2002) Bioenergy and water - the implications of large-scale bioenergy production for water use and supply. Global Environmental Change-Human and Policy Dimensions, 12, 253–271.
Beres G, Hoogwijk M, van den Broek R (2003) The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass & Bioenergy, 25, 1–28.
Birch CJ, Vos J, van der Putten PEL (2003) Plant development and leaf area produc tion in contrasting cultivars of maize grown in a cool temperate environment in the field. European Journal of Agronomy, 19, 173–188.
Block RMA, Rees KCJ, Knight JD (2006) A review of fine root dynamics in Populus plantations. Forest Ecology and Management, 67, 73–84.
Boehmelt C, Lewandowski I, Claupein W (2008) Comparing annual and perennial energy cropping systems with different management intensities. Agricultural Systems, 96, 224–236.
Biomass UR, Turnbull BH (1997) Integrated biomass energy systems and emissions of carbon dioxide. Biomass & Bioenergy, 13, 333–343.
Borek R, Faber A, Kozyra J (2010) Water implications of selected energy crops cultivated on a field scale. Journal of Food Agriculture & Environment, 8, 1345–1351.
Bower C (2010) Anticipated Indirect Land Use Change Associated with Expanded Use of Biofuels and Bioliquids in the EU – An Analysis of the National Renewable Energy Action Plans, p. 24. Institute for European Environmental Policy IEEP, London.
Bullard MJ, Mustilli SJ, McMillan SD, Nixon PM, Carver P, Britt CP (2002) Yield improvements through modification of planting density and harvest frequency in short rotation coppice Salix spp - 1. Yield response in two morphologically diverse varieties. Biomass & Bioenergy, 22, 15–25.
Burniaus J-M, Toung TP (2002) GTAP-E: an energy-environmental version of the GTAP model. In: GTAP Technical Paper Vol. 16, West Lafayette, USA.
Cannell MGR (1996) The influence of soil and coppice cycle on the rooting habit of short rotation poplar and willow coppice. Biomass & Bioenergy, 26, 497–505.
Cauten PJ, Mosier AR, Smith KA, Winwarter W (2008) N2O release from agro- biofuel production negates global warming reduction by replacing fossil fuels. Atmospheric Chemistry and Physics, 8, 389–395.
Davidson EA (1991) Fluxes of nitrogen oxide and nitric oxide from terrestrial ecosy stems. In: Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrogen Oxides and Halomethanes (eds Rogers JE, Whitman WB), pp. 219–235. American Society for Microbiology, Washington, DC.
Dimitriou I, Busch G, Jacobs S, Schmidt-Walter P, Lamersdorf N (2009) A review of the impacts of Short Rotation Coppice cultivation on water issues. Landdeutscher, Dordrecht.
Dobbe KE, Smith KA (1996) Comparison of CH4 oxidation rates in woodland, arable and set aside soils. Soil Biology & Biochemistry, 28, 1357–1365.
Don A, Schumacher J, Freibauer A (2011) Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis. Global Change Biology, 17, 1658–1670.
Donnini D, Hantsings A, Suz G, Jones MB, Smith P (2009) The potential of Miscan thus to sequester carbon in soils comparing field measurements in Carlow, Irel and to model predictions. Global Change Biology Bioenergy, 1, 413–425.
Dornburg V, van Vuuren D, van den G et al. (2010) Bioenergy revisited: key factors in global potentials of bioenergy. Energy & Environmental Science, 3, 258– 267.
Dowell RC, Gibbins D, Rhaoads J, Pallardy SG (2009) Biomass production physiology and soil carbon dynamics in short-rotation-grown Populus deltoides and P. deltoides x P. nigra hybrids. Forest Ecology and Management, 257, 134–142.
Edwards R, Mulligan D, Marelli L (2010) Indirect Land Use Change from Increased Biofuels Demand - Comparison of Models and Results for Marginal Biofuels Production from Different Feedstocks. European Commission Joint Research Centre, Ispra.
EEA (2006) How Much Bioenergy Can Europe Produce Without Harming the Environment? p. 67. European Environmental Agency, Copenhagen.
Egener J, Trolteck K, Falucazi A et al. (2009) Is biodiesel policy harming biodiversity in Europe? Global Change Biology Bioenergy, 1, 18–34.
Ericsson K, Rosengvist H, Ganko E, Pisarek M, Nilsson I (2006) An agro-economic analysis of willow cultivation in Poland. Biomass & Bioenergy, 30, 16–27.
EU (2007) The Impact of a Minimum 10% Obligation for Biofuel Use in the EU-27 in 2020 on Agricultural Markets, Vol. AGRl G-2/WM D, p. 10. European Commission, Brussels.
EU (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/80/EC. O. J. o. t. E. Union (ed Union OjopE), EU, Brussels.
Eulenboln F, Merbach W, von Buttlar C, Augustin J, Werner A (2011) Potenziale Kli mazwirkung des Anbaus von Pflanzen zur Erzeugung von Biomasse, Biokraftstoffen"
GREENHOUSE GAS BALANCE OF BIOENERGY 389

Aufgrund Klimawechsel-Grenzenisionen und Weitere Umweltwirkungen, p. 135. Leibnitz Centre for Agricultural Landscape Research (ZALF), Müncheberg.

EurObservER (2010) Bogen Brunner. In System Solaires le journal des energies renouvelables, Vol. 200, pp. 104-119. Available at: http://www.eurobserv-er.org/pdf/barn200b.pdf (accessed 8 August 2011).

European Biodiesel Board (2010) Production of Biodiesel in the EU. Brussels. Available at: http://www.platferme-biocarburants.ch/en/index.eu-biodiesel.php (accessed 8 August 2011).

Evans S, Baldwin M, Henshall P et al. (2007) Final report: yield models for energy: coppice of poplar and willow. In: Report to DTT, Vol. B/2/00624/00/00 URN. (eds Tubbly I, Poole J), p. 91.

Ewert F (2004) Modelling plant responses to elevated CO2: How important is leaf area index? Annals of Botany, 93, 619-627.

FAO (2008) The State of Food and Agriculture - Biofuels Prospects, Risk and Opportunity. FAO, Rome.

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Production of Biodiesel in the EU. Brussels. Available at: http://www.eurobserv-er.org/pdf/barn200b.pdf (accessed 8 August 2011).

Forster P, Ramaswamy V, Artaxo P et al. (2007) Changes in atmospheric constituents and in radiative forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds Solomon S, Qin D, Manning M et al.), p. 106. Cambridge University Press, Cambridge.

Fritsche U (2007) GHG accounting for biofuels: considering CO2 from leakage. In Work- ing paper prepared for BMU.Oeko-Institut, Darmstadt.

Fritsche U, Wiegmann K (2008) Wissenschaftlicher Beirat der Bundesregierung.

FNU (2010) Annual Report 2009/2010, p. 104. FNR (Agency for Renewable Resources), Gützwon.

Forster P, Ramassamy V, Artaxo P et al. (2007) Changes in atmospheric constituents and in radiative forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds Solomon S, Qin D, Manning M et al.), p. 106. Cambridge University Press, Cambridge.

Frischknecht R, Steffen W, Lotze-Campen H, Cline-Hanseth S, dieckmann M, Arts E, Galvin K, Hope H, Meinke V et al. (2008) Sustainable Development Indicators 2007. In System Solaires le journal des energies renouvelables, Vol. 200, pp. 104-119. Available at: http://www.eurobserv-er.org/pdf/barn200b.pdf (accessed 8 August 2011).

Fritsche U (2007) GHG accounting for biofuels: considering CO2 from leakage. In Working paper prepared for BMU.Oeko-Institut, Darmstadt.

Fritsche U, Wiegmann K (2008) Wissenschaftlicher Beirat der Bundesregierung.

FNR (2010) Annual Report 2009/2010, p. 104. FNR (Agency for Renewable Resources), Gützwon.

Fritsche U, Wiegmann K (2008) Wissenschaftlicher Beirat der Bundesregierung.

Fritsche U (2007) GHG accounting for biofuels: considering CO2 from leakage. In Working paper prepared for BMU.Oeko-Institut, Darmstadt.

Fritsche U, Wiegmann K (2008) Wissenschaftlicher Beirat der Bundesregierung.

Hadas A, Kautsky L, Goek M, Kara EE (2004) Rates of decomposition of plant residues and available nitrogen in soil, related to residue composition through simulation of carbon and nitrogen turnover. Soil Biology & Biochemistry, 36, 255-266.

Hansen EA (1993) Soil carbon sequestration beneath hybrid poplar plantations in the north central united-states. Biomass & Bioenergy, 5, 431-436.

Hansen S, Maehlum JE, Bakken LR (1993) N2O and CH4 fluxes in soil influenced by fertilization and tractor traffic. Soil Biology and Biochemistry, 25, 621-630.

Hansen EM, Christensen BT, Jensen LS, Kristensen K (2004) Carbon sequestration in soil beneath long-term Miscanthus plantations as determined by C-13 abundance. Biomass & Bioenergy, 26, 97-105.

Hastings A, Clifton-Brown J, Wattenbach M, Mitchell CP, Stampf P, Smith P (2009a) Future energy potential of Miscanthus in Europe. Global Change Biology Bioenergy, 1, 180–196.

Hastings A, Clifton-Brown J, Wattenbach M, Mitchell P, Smith P (2009b) The development of MISCANFOR, a now Miscanthus crop growth model: towards more robust yield predictions under different climatic and soil conditions. Global Change Biology Bioenergy, 1, 154-170.

Heaton E, Voigt T, Long SP (2004) A quantitative review comparing the yields of two candidate C4 perennial biomass crops in relation to nitrogen, temperature and water. Biomass & Bioenergy, 27, 21–30.

Heinsoo K, Merilo E, Petrovits M, Koppel A (2009) Fine root biomass and production in a Salix viminalis and Salix dasyclados plantation. Estonian Journal of Ecology, 58, 27–37.

Heidebrand HJ, Strählle M, Scholz V, Kern J (2010) Soil carbon, soil nitrate, and soil emissions of nitrous oxide during cultivation of energy crops. Nutrient Cycling in Agroecosystems, 87, 175–186.

Hoefnagels R, Smeets E, Fau J (2010) Greenhouse gas footprints of different biofuel production systems. Renewable & Sustainable Energy Reviews, 14, 1661–1694.

Holland EA, Braswell BH, Sulzman J, Lamanque JP (2005) Nitrogen deposition onto the United States and western Europe: synthesis of observations and models. Ecological Applications, 15, 38-57.

Hutchinson GL, Mosier AR (1981) Improved soil cover method for field measurement of nitrous-oxygen fluxes. Soil Science Society of America Journal, 45, 311–316.

Hutchins BW (2001) Methane oxidation in non-flooded soils as affected by crop production - invited paper. European Journal of Agronomy, 14, 257–260.

Hyvönen NP, Huttunen JT, Sharpari NJ, Tavi NM, Repo ME, Martikainen PJ (2009) Fluxes of nitrous oxide and methane on an abandoned peat extraction site: effect of reed canary grass cultivation. Bioresource Technology, 100, 4723–4730.

IEA (2010) IEA Statistics - Renewables Information 2010, p. 446. IEA, Paris.

IPCC (2006) IPCC Guidelines for National Greenhouse Gas Inventories. (eds Eggeston HS, Buendia L, Mroa K, Ngara T, Tanabe K). National Greenhouse Gas Inventories Programme, Kanagawa, Japan.

JEC (2008) Well-to-Wheels Analysis of Future Automobile Fuels and Powertrains in the European Context – Well-to-Wheels Study in Version 3. European Council for Automotive R&D (EUCAR), European association for environment, health and safety in oil refining and distribution (CONCAWE), the Institute for Environment and Sustainability of the EU Commission’s Joint Research Centre (JRC/IES). Available at: http://ies.jrc.ec.europa.eu/uploads/media/V3.1%20TW%20Report%2007010 2008.pdf (accessed 8 August 2011).

Jones MB, Walich M (2001) Miscanthus for Energy and Fibre. James and James Ltd., London.

Jorgensen RN, Jorgensen BJ, Nielsen NE, Maag M, Lind AM (1997) N2O emission from energy crop fields of Miscanthus “Giganteus” and winter rye. Atmospheric Environment, 31, 2899–2904.

Jürg A, Mäkchelin F, Rehbrueck KE, Hofmann-Schiade C (1999) Short-rotation plantations of balsam poplar, aspen and willows on former arable land in the Federal Republic of Germany. Il. Soil ecological effects. Forest Ecology and Management, 121, 85–99.

Jungkunst HF, Freihauer A, Neufeldt H, Baruth G (2016) Nitrous oxide emissions from agricultural land use in Germany - a synthesis of available annual field data. Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde, 169, 341-351.

Kahle P, Beuch S, Boelcke B, Lainoweb P, Schulten HB (2001) Cropping of Miscanthus in Central Europe: biomass production and influence on nutrients and soil organic matter. European Journal of Agronomy, 15, 171–184.

Kahle P, Baum C, Boelcke B (2005) Effect of afforestation on soil properties and mycorrhizal formation. Pedosphere, 15, 754-760.

Kahle P, Hildebrandt E, Baum C, Boelcke B (2007) Long-term effects of short rotation forestry with willows and poplar on soil properties. Archives of Agronomy and Soil Science, 53, 673-682.

Kaiser EA, Ruser R (2000) Nitrous oxide emissions from arable soils in Germany - An evaluation of six long-term field experiments. Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde, 163, 249-259.

Karp A, Shield I (2008) Bioenergy from plants and the sustainable yield challenge. New Physiologist, 179, 15–32.

© 2011 Blackwell Publishing Ltd, GCB Bioenergy, 4, 372–391.
Kauter D, Lewandowski I, Claupein W (2003) Quantity and quality of harvestable biomass from Populus short rotation coppice for solid fuel use - a review of the physiological basis and management influences. Biomass & Bioenergy, 24, 411–427.

Keelelaen GA, Volk TA (2005) Renewable energy from willow biomass crops: life cycle energy, environmental and economic performance. Critical Reviews in Plant Sciences, 24, 385–406.

King CM, Schnell S (1994) Effect of increasing atmospheric methane concentration on ammonium inhibition of soil methane consumption. Nature, 370, 282–284.

Koga N (2008) An energy balance under a conventional crop rotation system in Japan: perspectives on fuel ethanol production from sugar beet. Agriculture, Ecosystems & Environment, 125, 101–110.

Könschems M, Weigel A, Schulz F (1998) Turnover of soil organic matter (SOM) and long-term balances - Tools for evaluating sustainable productivity of soils. Zeitschrift Fur Pflanzenernahrung Und Bodenkunde, 161, 409–424.

Lal R (2005) World crop residues production and implications of its use as a biofuel. Bioenergy, 14, 91–101.

Lemtens S, Muys B, Ceulemans R, Moons E, Garcia J, Coppin P (2003) Energy budget and greenhouse gas balance evaluation of sustainable coppice systems for electric power production. Biomass & Bioenergy, 24, 179–197.

Lewandowski I, Schmidt U (2006) Nitrogen, energy and land use efficiencies of Miscanthus, reed canary grass and triticale as determined by the boundary line approach. Agriculture Ecosystems & Environment, 112, 335–346.

Lewandowski I, Clifton-Brown J, Scullock JMO, Huissman W (2000) Miscanthus: European experience with a novel energy crop. Biomass & Bioenergy, 20, 209–227.

Lewandowski I, Clifton-Brown JC, Anderson B et al. (2003a) Environment and harvest time affects the combustion qualities of Miscanthus genotypes. Agronomy Journal, 95, 1274–1280.

Lewandowski J, Scullock JMO, Lindvall E, Christou M (2008) The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass & Bioenergy, 25, 335–361.

Lindroth A, Bath A (1999) Assessment of regional willow coppice yield in Sweden on ammonium inhibition of soil methane consumption. Critical Reviews in Plant Sciences, 19, 1274–1289.

Lindroth A, Bath A (1999) Assessment of regional willow coppice yield in Sweden. Biomass & Bioenergy, 17, 2415–2427.

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

Quin M, Gartner S, Fehnt M, Reinhardt GA (2004) CO2 Mitigation Through Biofuels in the Transport Sector – Status and Perspectives. Institute for Energy and Environmental Research, Heidelberg.

Robertson GP, Geofinna PM (2007) Nitrogen transformation. In: Soil Microbiology, Biochemistry, and Ecology (ed Paul EA). Springer, New York.

Robertson GP, Paul EA, Harwood RR (2000) Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science, 290, 1922–1925.

Rochette P (2008) No-till only increases N2O emissions in poorly-aerated soils. Soil & Tillage Research, 101, 97–100.

Rowe KL, Street NR, Taylor G (2009) Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. Renewable & Sustainable Energy Reviews, 13, 260–279.

Ruiner R, Flesa H, Schilling R, Beese F, Munch JC (2011) Effect of crop-specific field management and N fertilization on N2O emissions from a fine-loamy soil. Nutrient Cycling in Agroecosystems, 89, 177–191.

Ryter RM (2001) Biomass production and allocation, including fine-root turnover, and annual N uptake in lysimeter-grown basket willows. Forest Ecology and Management, 140, 177–192.

Sanderson MA, Adler PR (2008) Perennial forages as second generation bioenergy crops. International Journal of Molecular Sciences, 9, 768–788.

Sartori F, Lal R, Ebinger MH, Eaton JA (2007) Changes in soil carbon and nutrient pools along a chronosequence of poplar plantations in the Columbia Plateau, Oregon, USA. Agriculture Ecosystems & Environment, 122, 325–339.

Schlamadinger B, Apps M, Bohlin F et al. (1997) Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems. Biomass & Bioenergy, 13, 359–375.

Schneekenberger K, Kuzaykov Y (2007) Carbon sequestration under Miscanthus in sandy and loamy soils estimated by natural C-13 abundance. Journal of Plant Nutrition and Soil-Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde, 170, 538–542.

Scholz V (2010) Umweltverträglichkeit von Pappen und Weiden im Vergleich mit anderen Energiepflanzen. Agrarholz, 15. Available at: http://www.fnr-server.de/cm35/fileadmin/allgemein/pdf/veranstaltungen/Agrarholz2010/08_2_Beitrag_Scholz.pdf (accessed 8 August 2011).

Scholz V, Elberrock B (2002) The growth productivity, and environmental impact of the cultivation of energy crops on sandy soil in Germany. Biomass & Bioenergy, 23, 81–92.

Searchinger T, Heimlich R, Houghton RA et al. (2008) Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science, 319, 1238–1240.

Searchinger TD, Hamburg SP, Melillo J et al. (2009) Fixing a critical climate accounting error. Science, 326, 527–528.

Shoji S, Kurebayashi T, Yamada I (1990) Growth and chemical-composition of Japanese sugi spruce in relation to nitrous-oxide production in tilled and nontilled soils. Agriculture, Ecosystems & Environment, 24, 1267–1275.
Sims REH, Mabee W, Saddler JN, Taylor M (2010) An overview of second generation biofuel technologies. Bioresource Technology, 101, 1570–1580.

Skiba U, Smith KA (2000) The control of nitrous oxide emissions from agricultural and natural soils. Chemosphere - Global Change Science, 2, 379–386.

Smeets EMW, Bouwman LF, Stehfest E, Van Vuuren DP, Posthuma A (2009) Contribution of N2O to the greenhouse gas balance of first-generation biofuels. Global Change Biology, 15, 1–23.

Smith GA, Buxton DR (1993) Temperate zone sweet sorghum ethanol-production potential. Bioresource Technology, 43, 71–75.

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

Smith P, Gregory PJ, van Vuuren D et al. (2010) Competition for land. Philosophical Transactions of the Royal Society B-Biological Sciences, 365, 2941–2957.

St Clair S, Hillier J, Smith P (2008) Estimating the pre-harvest greenhouse gas costs of energy crop production. Biomass & Bioenergy, 32, 442–452.

Stehfest E, Bouwman L (2006) N2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. Nutrient Cycling in Agroecosystems, 74, 207–228.

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

Venendaal R, Jorgensen U, Foster CA (1997) European energy crops: a synthesis. Biomass & Bioenergy, 13, 147–185.

Vermeulen GD, Mosquera J (2009) Soil, crop and emission responses to seasonal-controlled traffic in organic vegetable farming on loam soil. Soil & Tillage Research, 102, 126–134.

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.

WBGU (2008) Future Bioenergy and Sustainable Land Use. (ed WBGU) GACoGC). Earthscan, London.

Well R, Butterbach-Bahl K (2010) Indirect emissions of nitrous oxide from nitrogen deposition and leaching of agricultural nitrogen. In: Nitrous Oxide and Climate Change (ed Smith K), p. 162. Earthscan Publications Ltd., Sterling, UK.

Wichtmann W, Schäfer A (2007) Alternative management options for degraded fens – utilisation of biomass from rewetted peatlands. In: Wetlands: Monitoring, Modeling and Management (eds Okruszko T, Maliby E, Szatyłowicz J, Światek D, Kotowski W), pp. 273–279. Taylor & Francis/Balkema, Leiden, the Netherlands.

Williams JR, Jones CA, Kiniry JR, Spanel DA (1989) The epic crop growth-model. Transactions of the Asae, 32, 497–511.

Wirsénas S, Azar C, Bernades G (2010) How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agricultural Systems, 103, 621–638.

de Wit M, Faij A (2010) European biomass resource potential and costs. Biomass & Bioenergy, 34, 188–202.

Woods J, Black M, Murphy R (2008) Future feedstocks for biofuel systems. In: Biofuels: Environmental Consequences and Interactions with Changing Land Use (eds Howarth RW, Bringezu S), pp. 207–224. Cornell University, Ithaca, NY, USA.

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

Zegada-Lizarazu W, Monti A (2011) Energy crops in rotation. A review. Biomass & Bioenergy, 35, 12–25.

Zegada-Lizarazu W, Elbersen HW, Cosentino SL, Zatta A, Alexopoulos E, Monti A (2010) Agronomic aspects of future energy crops in Europe. Biofuels, Bioproducts and Biorefining, 4, 674–691.