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Bioenergy from "surplus" land: environmental and socio-economic implications

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Abstract

The increasing demand for biomass for the production of bioenergy is generating land-use conflicts. These conflicts might be solved through spatial segregation of food/feed and energy producing areas by continuing producing food on established and productive agricultural land while growing dedicated energy crops on so called "surplus" land. Ambiguity in the definition and characterization of surplus land as well as uncertainty in assessments of land availability and of future bioenergy potentials is causing confusion about the prospects and the environmental and socio-economic implications of bioenergy development in those areas. The high level of uncertainty is due to environmental, economic and social constraints not yet taken into account and to the potentials offered by those novel crops and their production methods not being fully exploited. This paper provides a scientific background in support of a reassessment of land available for bioenergy production by clarifying the terminology, identifying constraints and options for an efficient bioenergy-use of surplus land and providing policy recommendations for resolving conflicting land-use demands. A serious approach to factoring in the constraints, combined with creativity in utilizing the options provided, in our opinion, would lead to a more sustainable and efficient development of the bioenergy sector. Unless the sustainability challenge is mastered, the interdependent policy objectives of mitigating climate change, obtaining independence from fossil fuels, feeding and fuelling a growing human world population and maintaining biodiversity and ecosystem services will not be met. Despite the advanced developments of bioenergy, we still see regional solutions for designing and establishing sustainable bioenergy production systems with optimized production resulting in social, economic and ecological benefits. Where bioenergy production has been identified as the most suitable option to overcome the given problems of energy security and climate change mitigation, we need to determine which bioenergy cultivation systems are most suitable for the respective types of surplus land, by taking into account issues such as yields, inputs and costs, as well as potential environmental and socio-economic impacts.

Keywords
Marginal land, degraded land, energy crops, biomass, HNV, biodiversity, ecosystem services, land-use change, land-use competition, sustainability, bioenergy

Introduction

The use of land is a key link between human activities and the environment, and it is one of the major drivers of environmental and biodiversity change (EEA 2010). Agriculture, forestry, transport, manufacturing and housing are the primary human activities which alter the state and the functions of land through land-cover conversion and/or land-use intensification (EEA 2010). Due to conflicting demands for rural land for the production of food, animal feed, fibre and biomass for energy and biobased materials (e.g. bioplastics) it is becoming increasingly evident that land is a finite resource. For example, the amount of arable land per capita has decreased from 0.41 to 0.21 hectare since 1960 (FAO 2009), and the pressure on the remaining land will increase as a result of the growing number of animals in agriculture and the growing need for land for bioenergy resources to replace fossil fuels (OECD-FAO 2009; Tirado et al. 2010). These growing demands are likely to require conversion of additional land to agricultural use and/or improvements in the productivity on existing land. Conflicts emerging from the demand for land will require land-use decisions that involve trade-offs among and between those demands and objectives for nature, soil, water, civil protection and human livelihood in rural communities (Lobley and Winter 2009; EEA 2010; Kamimura et al. 2011).

Bioenergy is counted among the most relevant renewable energy carriers, providing about 60 % of renewable energy from biomass and waste in OECD countries and even a higher share of more than 80 % in non-OECD countries (IEA 2010). By aiming to improve energy security, mitigate climate change and provide added value to rural regions, target systems for the transition towards a more sustainable energy supply system are established in many countries. Those policies are driving bioenergy implementation and will stimulate further growth of the bioenergy sector. There is a common agreement that those policies should not harm the sustainable development in general, but the translation into a concrete framing is still incomplete. Examples are the renewable energy directive of the EU (European Union 2009) and GBEP sustainability indicators for bioenergy (FAO 2011).

The increasing demand for biomass for production of heat, power, biofuels and biobased materials is generating land-use conflicts which are discussed in the food versus fuel controversy (Baffes and Haniotis 2010) and the debate about indirect land-use change (iLUC) effects (Wiegmann et al. 2008). These conflicts might be solved through the integration of food and biomass production systems and/or spatial segregation of food/feed and biomass producing areas. For example, it has been argued that integrating biomass farming and food and feed farming can solve both local food shortages and increase the income of the world's poorest people (Fresco 2007). In a parallel approach, we focus here on the idea to continue producing food on established and productive agricultural land whereas dedicated bioenergy crops are grown on so called "surplus" land (RFA 2008). A variety of concepts for bioenergy production based on minimal or no land competition were developed (e.g. Field et al. 2008; Cotula et al. 2008; Campbell et al. 2008; UNEP 2009; Dale et al. 2010; Zhuang et al. 2011). However, clear definitions and an unambiguous terminology and characterisation of those types of supposedly surplus land, which is crucial for the approach of producing food on established farmland and biomass on surplus land, are missing. We apply a critical view on this idea of targeting the cultivation of bioenergy plants on surplus land only, because environmental and socio-economic constraints which might restrict the availability and potentials of surplus land are often not taken into consideration. A discussion of the question whether food or energy production should be prioritized when facing land scarcity and of the ethical implications of the delineation between food producing and energy producing land areas is beyond the scope of this paper. Those issues are already discussed by other authors elsewhere (e.g. Spangenberg and Settele 2009a)

The spectrum of dedicated energy crop feedstock suggested to be grown on such surplus land is wide, including prairie grasses (McLaughlin et al. 2002), perennial grasses such as *Miscanthus,* short-rotation coppice (SRC) of willow or poplar (Christersson and Sennerby-Forsse 1994; Hastings et al. 2009), multipurpose trees such as Mulberry (Tang et al. 2010), *Jatropha* (Sieg 2006) and CAM (Crassulacean acid metabolism) plants (Borland et al. 2009). Given the ambiguity surrounding the question of which type of feedstock to grow on which type of surplus land, it doesn't come as a surprise that both national and global assessments of the availability of surplus land and of its potentials for bioenergy production vary considerably (Graham 2007; Field et al. 2008; Marland and Obersteiner 2008). Extensive reviews on the availability of land for bioenergy production reveal that major uncertainties continue to exist (Berndes et al. 2003; Offermann et al. 2011). Those uncertainties are largely due to inconsistent definitions of the term bioenergy, large differences in the underlying assumptions of the agronomic potential of bioenergy crops on the respective types of land and limited availability of data on land use (Campbell et al. 2008; Dornburg et al. 2010; Offermann et al. 2011). Most assessments overestimate the land area available for bioenergy crops because constraining factors such as water, productivity, social aspects and nature conservation are not taken into account (van Vuuren et al. 2009; Haberl et al. 2010; Beringer et al. 2011). Haberl et al. (2010), in a critical review of modelling and calculation approaches, conclude that there are no scientific studies at present that resolve the scientific challenges related to the assessment of future bioenergy potentials.

Moreover, a lack in scientific rigor in the framework of bioenergy from surplus land is causing uncertainty and confusion about its environmental and socio-economic implications. Claims of ethical, economic and environmental gains and benefits arising from bioenergy production on surplus land require unambiguous definitions for surplus land and a reassessment of the concrete types of land and feedstock in question (RFA 2008). Before land is converted, the suitability of specific locations for bioenergy production should be evaluated by taking into account the land's true existing use (in contrast to coarse land-use classification data), its productivity potential, the net carbon impact of its conversion and its existing environmental value (RFA 2008). As we might hardly find surplus land without people, the social implications of a land's use have to be taken into account as well (Giller et al. 2007), including for instance the livelihoods it supports, the number of families it nurtures and the jobs it provides.

Finally, where bioenergy ought to be cultivated for ethical or environmental reasons might differ from where it may in fact come to be cultivated for economic reasons (Johannson and Azar 2007). A major challenge for science is thus to clarify the realistic production potentials of surplus land with respect to extent, performance and sustainability of bioenergy plantations. In addition, there is a need for guidance in land management, to balance the societal and environmental costs and benefits of any land conversion towards production of dedicated energy crops (Berndes et al. 2003; UNEP 2009).

Therefore, the aim of this paper is to provide a scientific background in support of a reassessment of land available for bioenergy production by

i) clarifying the terminology of surplus land;
ii) identifying factors constraining use of surplus land for bioenergy production with respect to landscape functions, ecosystem services , environmental value and socio-economic considerations;
iii) identifying options for efficient bioenergy use of surplus land with respect to constraining factors;
iv) providing policy recommendations for resolving conflicting land-use demands and for guiding bioenergy cropping systems to support sustainable land management.

The basic assumption of our discussion is that bioenergy developments will have a fundamental impact on the respective surplus lands, as reaching the bioenergy targets set by many countries would require landscape-scale changes of land use. The conditions under which surplus land can be used sustainably will depend on the specific characteristics of the land, on the type and scale of the bioenergy pathways and on their potential environmental and socio-economical impacts.

Understanding surplus land

Surplus land can be seen as the all-embracing umbrella term for areas potentially available for bioenergy cultivation. Although there is no clear definition for this term, we can distinguish two different origins of surplus land: 1) land currently not in use for the production of food, animal feed, fibre or other renewable resources due to poor soil fertility or abiotic stress, and 2) land currently no longer needed for food and feed production because of intensification and rationalization of production, resulting in yield increases and thus a reduced requirement for land (Faaij 2007; Rounsevell et al. 2006). It is, however, questionable whether such an intensification of agricultural production could be achieved in a sustainable and ethically acceptable manner (The Royal Society 2009; Phalan et al. 2011) and whether it would indeed free up land for purposes other than feeding the growing human world population (Ruttan 1999). The implications of producing energy crops on surplus land of this second origin might in particular affect land currently marginal for agricultural production due to low grade soils or adverse climatic conditions. We will thus focus our considerations on such marginal lands rather than on freed up high productive lands for which considerations about implications for the environment, economy and society would not go far beyond the existing discussion on sustainable production of food/feed crops.

Surplus land includes i) land cover of various categories that is currently not used for agricultural or forest production for reasons other than poor availability of natural resources (e.g. socio-economic or political reasons), and ii) land with poor conditions for agricultural or forest production. The understanding of which categories of land can be used to grow dedicated bioenergy crops varies considerably. Some studies suggest that lower grade agricultural lands that have passed a filtering according to criteria of yield and suitability mapping as well as environmental and socio-economic factors should be considered suitable for bioenergy crop production (Lovett et al. 2009; Jingura et al. 2011). Others suggest including types of land with varying agronomic potentials and environmental values such as grassland, saline land, marshland, reed swamp and tidal flats (Yan et al. 2008). Even land risers, land boundaries and land along highways and roads, which were not subject to any prior sustainability considerations, have been suggested (Tang et al. 2010). Sustainable use of such lands for production of dedicated energy crops requires a careful definition and characterization of land sources and of their potentials (Wiegmann et al. 2008). In the following we discuss definitions of land classes often subsumed as surplus land (of origin 1 or 2) with regard to their availability and suitability for energy crop cultivation.

Fallow land

Fallow land should not be viewed as surplus land which is permanently available, but as part of a production cycle (Krasuska et al. 2010). Fallow is a part of a crop rotation and describes the temporary suspension of cultivation for at least one vegetation period to achieve a recovery of soil fertility. In Spain, for example, fallow is a common cultural practice in the rain-fed cereal growing areas of the central plains, where land remains fallow for two consecutive years followed by a crop rotation with winter cereals and oilseeds. Some energy crops might however qualify as recovery crops during fallow periods.

Set aside

Set aside is a politically motivated suspension of cultivation either in the framework of an agri-environment scheme or as a mechanism to reduce food production. Set aside can be either rotational or permanent. In the EU, set-aside land may be used for the production of non-food crops, including energy crops (Alexopoulou et al. 2010). Technically, set aside is not surplus land but still some energy crops such as wildflower strips for biogas could be adopted for agri-environment schemes within set-aside programmes (Vollrath and Kuhn 2010).

Abandoned land

Abandoned land was previously used for agriculture or pasture, but has been abandoned for economical or political reasons and not converted to forest or urban areas (Field et al. 2008). Strijker (2005) emphasises that abandonment can be a consequence of physical, environmental, social and economic forces and can arise on both fertile and less-fertile soils, triggered by higher labour costs, higher land costs, lower product prices, and new techniques. Therefore three categories of abandoned land could be considered i) land abandoned because of increases in agricultural productivity (see description of surplus land of the second origin above), ii) land abandoned because of its inferior agricultural performance, and iii) land abandoned for economic reasons such as higher income levels in industrial jobs, increasing rents or reduced subsidies. Agricultural productivity of lands abandoned due to inferior fertility might be poor but still suitable for energy crop cultivation without the need of a preceding restoration.

Marginal land

Marginal land is often used as an umbrella term for describing idle, under-utilized, barren, inaccessible, degraded or abandoned lands, lands occupied by politically and economically marginalized populations, or land with characteristics that make a particular use unsustainable or inappropriate (Dale et al. 2010). The most suitable definition with respect to issues of land use and land-use change is the economical definition as an area where cost-effective production, under given environmental conditions, cultivation techniques, agriculture policies as well as macro-economic and legal conditions is not possible (Schroers 2006). Land is marginal if the combination of yields and prices barely cover the cost of production (Dale et al. 2010). This economic delineation is however variable as in particular the food price level can fluctuate by a factor two and more from year to year. The economic definition of marginal land so far also does not factor in subsistence agriculture or ecological services the land provides, nor does it include spiritual or cultural values (Wiegmann et al. 2008; Dale et al. 2010). Therefore, categorizing or quantifying marginal lands underlies great uncertainties and results in wide-ranging estimates of availability and suitability for bioenergy crops (Dale et al. 2010).

Degraded land

The term degraded is related to the productivity potential of the land (Wiegmann et al. 2008). Degraded land is a concept widely adapted using data from FAO and UNEP (e.g. GLASOD degradation data, Land Degradation Assessment in Drylands – LADA, FAO TERRASTAT). In the current literature, the term is used for a wide variety of land cover types including abandoned farmland and secondary tropical forests but also postmining areas and badlands (Plieninger and Gaertner 2011). Plieninger and Gaertner (2011) suggest a conceptual separation of degraded and abandoned land. We follow their suggestion that the use of the term degraded land should be restricted to lands considered as the end product of severe and substantial loss of productivity and soil fertility. This process is difficult to reverse and thus degraded lands are of reduced usefulness to agricultural production. The process of land degradation is a long-term loss of ecosystem function and services, either human (overexploitation or other improper use of land) or naturally induced (Wiegmann et al. 2008). The feasibility of using degraded land for energy crop production depends on the severity of degradation and on the time horizon over which the productivity of the land could potentially be restored. The EU included the concept of degraded (or contaminated) land in its renewable energy Directive 2009/28/EC (2009) counting a bonus of 29 gCO_2 equiv. per MJ biofuel or bioliquid (equivalent to 40 % of displaced petroleum emissions) if biomass is obtained from restored degraded (severely degraded or heavily contaminated) land. "Natural" degradation processes may occur in natural habitats with sparse vegetation canopy and naturally low productivity (see also waste land). Both anthropogenically and naturally degraded lands can harbour high levels of biodiversity or very unique and thus valuable components of biodiversity. Even if not cultivated, they could still provide food or medicinal resources for indigenous peoples.

Reclaimed land

This land class enfolds postmining areas and land previously used for industrial purposes or certain commercial uses (brownfields). The land may be contaminated by low concentrations of hazardous waste or pollution, and has the potential to be reused once it is remediated. The reclamation of those areas through human intervention may be effective but the potential and time scale for reclamation depends on the severity of the previous human impact and whether for example the area was stripped of topsoil (Daily 1995). The term reclaimed is also applied in the context of drainage and subsequent agricultural use of land which was too wet for farming.

Waste land

This term is also related to the productivity potential of land but in contrast to degraded land, waste land is characterized by physical and biological conditions that are "naturally" unfavourable for human land use (Wiegmann et al. 2008). It includes land without important vegetation cover or agricultural potential such as active dunes, salt flats, rocky outcrops, deserts, ice caps and arid mountain regions. Due to the boundaries of cultivation as set by climate and soil, these areas cannot be cultivated under conventional conditions and, therefore, are usually not suitable for production of dedicated energy crops (Wiegmann et al. 2008). Crop breeding and biotechnology, including genetic engineering, continue to expand the range of growing conditions for biofuel feedstock and may eventually permit expansion to areas once deemed too poor in quality to support agriculture (Dale et al. 2010). The agricultural boundaries of arid and severely degraded lands might now get realigned, for example by the development of CAM plants such as agave, which are adapted to arid conditions, as an economically viable source of bioethanol (Borland et al. 2009). Without an increase in external inputs, yields on such waste lands will however always be limited by the physiological needs of the plants.

A weakness of this classification scheme might be that the land classes are not on an equal hierarchical level but they may intersect or resemble sub-classes of higher categories (Fig. 1; Wiegmann et al. 2008; Wicke 2011). Figure 1 provides an overview of the interrelationships of the land classes with respect to productivity and the needs for land restoration. Nevertheless, we emphasise the need of being as precise as possible with respect to the lands' characteristics when considering surplus land for energy crop production.

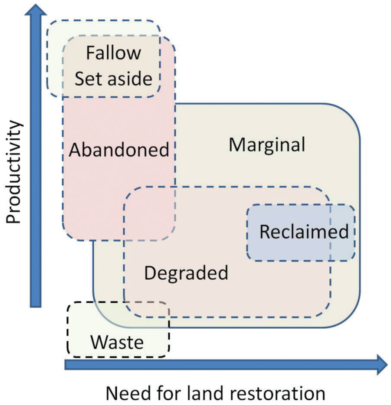
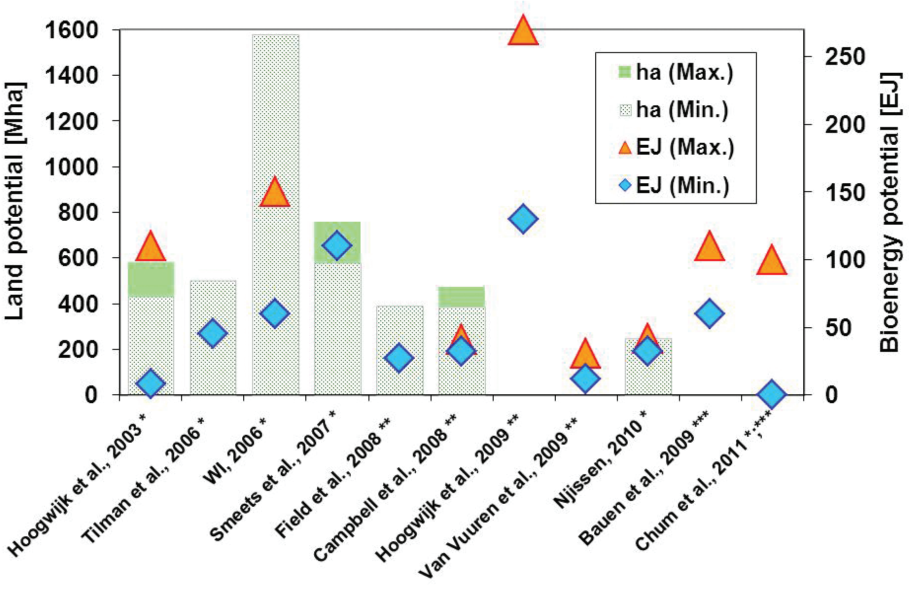


Figure 1. Scheme of the interrelation of different classes of surplus land (see text above) and their relationship to productivity and the needs for land restoration.

Assessment of land availability

For bioenergy production, degraded land, abandoned land and marginal land are probably the most important and are thus the main categories considered in studies of land availability (Fig. 2).

However, the relative proportions of classes of surplus land might differ between regions. Due to the difficulty of definition and different approaches (e.g. theoretical or technical potential) and depending on the objective and/or availability of data and crops considered (annual crops, lignocellulosic crops), the global bioenergy land potentials range from 250 Mha to 1,580 Mha. The associated estimated bioenergy potentials range from 0 EJ to about 250 EJ mainly due to a great variety of yield assumptions (from 1 - 33 t dry matter ha^{-1} yr^{-1}) and restrictions considered. A moderate estimation of bioenergy potential not explicitly considering degraded lands was given by BMVBS (2010), calculating a global technical potential in 2020 of 15 EJ from agricultural land, 36 to 57 EJ from forestry and 30 EJ from residues like straw, excrements or organic waste. In comparison, the Global Total Primary Energy Supply (i.e. the sum of all energy resources worldwide) was estimated to be about 509 EJ yr^{-1} in 2009 (IEA 2011). Chum et al. (2011) estimate a range from 0 -100 EJ for biomass production on deforested or otherwise degraded or marginal land that is judged unsuitable for conventional agriculture but suitable for some bioenergy schemes. Estimates of zero technical bioenergy potential (Fig. 2) suggest that land requirements, extensive grazing management or subsistence agriculture for example, and poor economic performance need to be taken into account when considering the use of marginal lands for bioenergy (Chum et al. 2011).



* degraded land, ** abandoned agricultural land, *** marginal land

Figure 2. Land and bioenergy potential of different surplus land categories

Accordingly, clearer definitions of these concepts and consideration of economic, environmental and social factors are needed to calculate and develop surplus land potentials (depending on the country context and regional conditions) and to avoid allocation of lands on which local user groups depend for their livelihoods (Cotula et al. 2008).

An assessment of land availability would have to acknowledge that bioenergy use can be classified by its scale, source, processing, distribution and consumption. It can scale from farm-size use of surplus biomass not needed for food, fodder, fuel, construction or soil improvement up to landscape size industrial cultivation of energy crops with processing in either decentralised processing plants or in industrial-sized central facilities. The scale of possible development will mostly be set by the respective constraints, the spatial extent of the surplus land, and the given economic situation (prices, subsidies, other incentives, business strategies, etc.). Based on the scale possible, very distinct social, environmental and economic impacts can be expected. Whenever applicable, we will thus try comparing impacts of bioenergy systems of varying scales with respect to the constraints and options identified for the respective types of surplus land.

Constraints for the use of surplus land for bioenergy production

Matching the necessity of economic, social and environmental sustainability is certainly one of the biggest constraints for the development of the bioenergy sector. Factors such as biodiversity, amenity use, water demand, fertiliser application and GHG-emissions may all cause opportunity costs and environmental or social side effects (The Royal Society 2008). Thus, before we start using surplus land for energy crop production, we should determine whether that form of land use brings the greatest benefit across a wide range of environmental and socio-economic receptors. Such an appraisal requires knowledge on how constraints might impede or prohibit the development of bioenergy in certain areas and we will thus elaborate on those constraints in the following. One decisive factor for the implementation dynamic or its absence will be if bioenergy makes a positive contribution to the solution of local problems, and that this contribution is recognised as such. This requires studies of the local situation and the identification of problems, the search for the best solutions, and the assessment of whether bioenergy generation is such a solution, or can contribute to it. This paper intends to provide the information about bioenergy production on surplus land necessary for such an assessment.

Marginal yields from marginal or degraded land

Marginal, degraded and abandoned lands are suggested as having high potentials for growing energy crops (Fig. 2). Yet, the production of crops for bioenergy from those land classes is inadequately documented and only a small amount of data from demonstration or modelling projects is available. While plant breeding and modern biotechnological processes have the capability to improve crop performance on lower grade soils, it remains to be seen whether such efforts can produce crops which are economically viable when grown on such soils. Typically, energy crops suitable for less productive soils are optimized for maximum biomass and not for sugar or oil content. Consequently, such crops can be used primarily for second generation biofuels, as far as refineries are an economically viable option in areas characterised by less productive soil**.** An exception is the oil-bearing *Jatropha*, which is usually planted for biodiesel production. The need to account for demand based constraints (e.g. with respect to fertiliser and water use) in order to stay within the „planetary boundaries" identified by Rockström et al. (2009) is a sustainability criterion for bioenergy crop production on marginal soils and limiting conventional industrial sized developments.

For several reasons, yields from marginal lands are typically lower than yields from higher grade soils. Marginal lands often have poor and heterogeneous soils and are situated at "transition zones" between highly fertile crop land and vulnerable ecosystems like protected natural sites, restricting the possibilities for conventional agricultural management. *Jatropha*, for example, may reach a yield from 0.1 t ha^{-1}-12.5 t ha^{-1}, depending on water availability (GTZ 2008; FACT 2010). Fisher et al. (2010) used a modelling approach to calculate land productivity potentials across Europe for a range of energy crops grown on land classified as very suitable, suitable, moderately suitable and marginally suitable. For most crops, yields on very suitable soils were up to three times greater than yields on marginal soils. In Italy, public grants are persuading farmers to adopt poplar SRC independently of the optimal site conditions for the species, in terms of soil quality, climatic conditions and water availability. Paris et al. (2011) showed that under poor soil conditions, even with the adoption of new clones, no increments on the productivity potentialities of the site could be obtained and thus do not recommend adoption of hybrid poplar SRC on marginal soils. In a Finnish study, it was shown that establishment of willow SRC on poor soils would result in greatly reduced productivity or even a complete failure of the plantation (Tahvanainen and Rytkönen 1999).

On degraded land, two major constraints of biomass production are the large efforts and long time period required for the reclamation of degraded land and the low productivity levels of these soils (Dornburg et al. 2010). Degradation generally results in low yield potentials, low yield levels and low nutrient efficiency with risk of harvest loss (Cofie and Penning de Vries 2002). Estimates of high yields of mixtures of native grassland perennials from agriculturally degraded lands in Northern America are questioned on the basis of potential nutrient losses from the system, high expenditures for weed control and an overestimation of availability of such degraded lands (Russelle et al. 2007).

Economically speaking, a relatively low yield could at least partly be compensated by large scale production systems (economics of scale). However, that may either require more staff and thus (probably prohibitively) higher labour costs, or imply a highly automated system which for cost reasons would tend to be based on monoculture plantations with negative impacts on landscape ecosystem services (aesthetic, regulating) and its biodiversity.

Land abandoned due to poor economics of farming, for example after a political transformation period, might have a high potential for bioenergy supply, once the economical situation has changed or payment schemes for farmers have been established (Faaij and Domac 2006; Krasuska et al. 2010). If, however, abandoned land of below average quality gets reinstated for cultivation of dedicated energy crops, yields might be modest (Krasuska et al. 2010).

Low yields resulting from low agronomic potentials of land can have both environmental and socio-economic impacts (see also *Socio-economic factors*). Marginal yields could entail a high land-take for energy crops to match the existing or targeted demand for the respective feedstock. This again could result in conflicts for example with pastoralism and lands of high nature value as well as in indirect land-use change (iLUC; see *Indirect land-use change*). An example for increased land-take is the case for the production of *Jatropha*, which requires large areas of land in semi-arid environments due to relatively poor production of oil on those marginal lands (Giller et al. 2007). Low yields may further increase the need for input of investment, labour and resources, affecting the energy balance such that the energy return on investment (EROI) could easily become critical.

Growing crops on marginal or degraded land might not only affect the quantity of total yield, but also its quality regarding its use for energy or other industrial purposes. Production of energy crops on contaminated soils of reclaimed areas may cause accumulation of contaminants, such as metals (Fernando and Oliveira 2005), hence compromising biomass quality; accumulation by plants has even been discussed as a means of soil remediation (Britt and Garstang 2002). However, when biomass containing increased contents of harmful substances such as cadmium is burned, these substances will remain in the different ash fractions, from which it could be removed by means of relatively simple technical operations (Dimitriou and Aronsson 2005). Lower yields may also concentrate nutrients, such as nitrogen, compromising its use for combustion purposes, for example, due to higher NO_x emissions.

Nature conservation

Although energy crop production on marginal or degraded lands might enrich certain landscape values such as structural heterogeneity or aesthetics (Fernando 2005) if planted not as landscape-wide monoculture but in smaller plots, it might still generate conflicts with biodiversity conservation (Plieninger and Gaertner 2011). In Europe for example, land most susceptible to agricultural marginalisation is likely to be found in extensive farming regions and those where traditional small-scale farming is prevalent (Baldock et al. 1996). Such low-intensity farming systems are of great importance for agricultural biodiversity preservation (Baldock et al. 1996). The recognition that certain patterns of farmland promote biodiversity, particularly landscapes containing a high proportion of semi-natural habitats and a high diversity of low intensity land use, has led to the development of the High Nature Value Farming concept (HNV) in the EU (Beaufoy 2011). Preventing the abandonment and intensification of HNV farmland is beheld as a key action to halt the decline of biodiversity in Europe (EEA 2009). Because direct land-use change and intensification to bioenergy cultivation could have negative effects on biodiversity (Plieninger and Gaertner 2011), current legislation proposed by Germany and the EU on sustainability requirements for biofuel feedstock prohibit the cultivation of bioenergy crops in protected as well as in HNV areas, unless the biomass cultivation is in conformity with the protection objectives of the area in question (BfN 2010; Fritsche et al. 2010). Despite recent findings that SRC and perennial grass crops can potentially benefit farm-scale biodiversity (Dauber et al. 2010; Rowe et al. 2011; Emmerson et al. 2011), establishment of perennial biomass crops on land other than arable fields is still regarded as a threat rather than a benefit to biodiversity (BfN 2010).

Many marginal lands in Europe are dominated by permanent grassland systems (Veen et al. 2009). Species conservation value and soil carbon storage potentials of permanent grassland are potentially in conflict with the strategy of targeting marginal or degraded land for energy crop cultivation (RFA 2008). Restricting the production of dedicated biomass crops to arable land in order to prevent the conversion of permanent grassland could however aggravate the food/energy-conflict and stimulate increased iLUC. A potential way out of this conflict may be provided by using the natural or semi-natural grassland biomass directly for energy conversion (Rösch et al. 2009; Bühle et al. 2010). High biodiversity levels of semi-natural grasslands can only be maintained through continuous management and thus using the biomass yield from semi-natural grasslands could promote the sustainable management of such sites in areas threatened by farm abandonment (Heinsoo et al. 2010). Nevertheless, the quality of the respective biomass depends on the meadow type, with different qualities required for biogas and combustion (Heinsoo et al. 2010). If only one type of conversion technique prevails in a region, pressure will arise to employ common and intensive management across the region to produce uniform biomass. Indeed, first surveys on grassland harvested for biogas in Germany have shown that in 13% of cases farmers have adapted their management to the new end-use by increasing the number of cuts per year by one or two (Baumann et al. 2010). Long term studies in Minnesota, USA, have shown a positive relationship between diversity of prairie grassland and productivity (Fornara and Tilman 2009). However, contradictory results were documented by Adler et al. (2009) who showed that conservation grasslands in the USA with higher numbers of plant species had lower biomass yields and a lower ethanol yield per unit biomass compared with sites with fewer species. This finding could stimulate the management of those grasslands towards low diversity systems, excluding species with undesirable fermentation characteristics.

The species-energy hypothesis (Wright 1983; Haberl et al. 2009) states that human appropriation of net primary production results in lower trophic energy remaining within ecosystems, and therefore reduced capacity of ecosystems to support biodiversity. If true, this provides some concern that commercial bioenergy production might be incompatible with extensive land uses and high nature value agricultural landscapes. Bindraban et al. (2009) reason it unlikely that marginal lands could provide significant yields of biomass in the near term without compromising the natural character of the ecosystem through increased agricultural inputs. A probable consequence of a conventional industrialized approach to bioenergy farming is an increase of the fertilizer application rate in order to obtain adequate levels of production, resulting for example in eutrophication of ground and surface waters and reduction of the EROI. Low bioenergy production intensities (e.g. collection of dead wood from low density or interspersed forest or utilisation of existing biomass) may not support commercial scale bioenergy production and it remains to be seen whether harvesting of existing vegetation (e.g. biomass from semi-natural grasslands) is commercially viable. There is so far little empirical data to support the species-energy hypothesis but, depending on the feedstock, intensive bioenergy production in such areas could exert similar pressures on ecosystem services as intensive food production – as documented by Haberl et al. (2009) for the Danube delta region of Romania.

Concern is also raised from a landscape-scale perspective on biodiversity and ecosystem services with respect to the spatial segregation of food and energy producing areas. Landscape polarisation in terms of optimising one function such as agricultural production only could lead to functional simplification of landscapes, resulting in a limited capacity to support multiple ecosystem services and increased vulnerability to diseases, climatic extremes or spread of invasive species (Foley et al. 2005; Selman 2009).

Pushing the physical boundaries of agriculture through improved crop breeding and bio- and agritechnology is a further bioenergy development which could have serious impacts on (semi-) natural ecosystems which so far were beyond the reach of cultivation. In South America for example, the semiarid scrub forests of the Caatinga, the Cerrado savanna and the savannas and thorn forests of the Chaco are potentially affected by the development of novel energy crops such as agave for ethanol (Beringer et al. 2011). All of these habitats are rich in biodiversity with a large share of endemic species. Converting them to bioenergy plantations might put their high environmental value at risk (Beringer et al. 2011). Those examples make the environmental sustainability of dedicated energy crop plantations outside areas of abandoned or degraded croplands questionable (Beringer et al. 2011). The environmental effects of such expansions of cropland must be carefully monitored so that negative impacts can be counteracted at an early stage (Dale et al. 2010).

Indirect land-use change

A further constraining factor which is so far not adequately taken into account in assessments of bioenergy potentials is indirect land-use change (iLUC) and its environmental and socio-economic consequences (Edwards et al. 2010; Reinhard and Zah 2011). Indirect land-use change occurs when land is converted to cropland somewhere on the globe to meet the demand for commodities displaced by the production of biofuel feedstock. Furthermore, increased bioenergy production can lead to price increases for all agricultural raw materials competing for scarce production factors, which could result in an expansion of arable land into areas that are marginal for agricultural production under current conditions (Bringezu et al. 2009).

It is argued that the cultivation of energy crops on degraded land or abandoned farmland could safeguard against iLUC effects as no displacement of previous cultivation would occur (OEKO 2006; Searchinger 2008). This however is only correct if there truly was no kind of cultivation or other use of those lands before. So far no sound and internationally accredited methodology for inclusion of iLUC issues in bioenergy governance exist (Gawel and Ludwig 2011) and the quality of the output of models recently developed to assess iLUC was found to be insufficient for informing detailed management decisions (Davis et al. 2011). Overall, more realistic analyses are needed, based on feasible production scenarios that take into account the constraints of production technologies, infrastructure and policy (Giller et al. 2007).

Spatially explicit global land-use consequences may be predicted using macro-economic models (e.g. Bringezu et al. 2009; Hellman and Verburg 2010), or by developing plausible land-use scenarios (e.g. Fischer et al. 2010). Such methods involve various socio-economic assumptions relating to effects on trade, food demand and intensity of food production. A simpler approach is to assume that the main iLUC of bioenergy production is the intensification of food production on existing areas (van Dam et al. 2009), or, more frequently, to assume that surplus land is used for bioenergy production. Those simple approaches are limited by the existence and the reliability of data on production potentials and true land use. Areas believed to be surplus can in fact be lands that have been under communal tenure or traditional customary use and are vital for the livelihoods of small-scale farmers, pastoralists, women, indigenous peoples and the rural poor for food crops, livestock grazing or fuelwood collection (The Gaia Foundation et al. 2008). The lack of operational tools for full impact assessments is impeding the fulfilment of the agreed goal of sustainability in bioenergy development.

A negative socio-economic effect which may be associated with iLUC and a shift of agricultural production towards marginal lands is a large-scale privatization of lands by the most capitalized producers which may lead to the displacement of smallholder farmers and whole rural communities (Howarth et al. 2009; Beringer et al. 2011). An example for such a process is described by Jingura et al. (2011) for smallholder farmers living in those regions of Zimbabwe which are most likely to be available for the production of *Jatropha*. On those lower grade lands there is customary tenure, which gives very limited land rights to farmers; most of the land rights are held by traditional leaders. If decisions for the use of land for *Jatropha* production in these areas were to be made by people other than the smallholder farmers themselves, this could lead to displacement of people. Similar examples are known from *Jatropha*, soy and other energy plants in Latin America (Spangenberg and Settele 2009b).

Water footprint

A main reason for the marginality of agricultural areas is the lack of precipitation that lowers the yields and does not allow economically feasible agriculture. Consequently, a major constraining factor for cultivation of energy crops in such areas is water availability and the water footprint (Faaij and Domac 2006; Smeets et al.

2009). The issue is severe and Gerbens-Leenes et al. (2009) suggest extending the ethical discussion on whether food crops can be used for energy to a discussion on whether we should use our limited water resource base for food or for energy (a discussion best held on the basis of catchment areas). The deep roots and fast growth of perennial biomass crops result in high water uptake, and have been found to decrease effective rainfall by 50-60% compared with annual crops (Stephens et al. 2001). Productive use of degraded lands will often require substantial investment in irrigation which is a particular concern, as irrigation for agriculture already accounts for over 70 % of freshwater extraction globally (Howarth et al. 2009; UNESCO 2009). Additionally, processing of biofuels can also consume substantial quantities of water (NRC 2008). There are further concerns with regard to water quality, in particular when annual tillage crops are grown for bioenergy, including eutrophication from nutrient movement (dissolved and with soil), turbidity and excessive sedimentation from soil erosion (NRC 2008). Water footprints might thus arise from the use of an area for bioenergy and from feedstock processing, potentially leading to conflicts with other types of land use or (non-marketable) ecosystem services if water is scarce (Bhardwaj et al. 2011; Fritsche et al. 2010). Therefore, water-demanding energy crops should be allocated to regions with high effective water availability (Fernando et al. 2010).

Greenhouse gas emissions and loss of soil organic carbon

Growing energy crops on surplus land is only acceptable from a sustainability perspective if any land use and processing related greenhouse gas (GHG) emission increases are more than offset by reductions in fuel GHG emissions. In the EU, member states must meet binding, national targets for renewable energy. Only those biofuels with high GHG savings demonstrated by rigorous life cycle assessment (LCA) count towards national targets. Biofuels must deliver current GHG savings of at least 35% compared with fossil fuels, rising to 50% in 2017 and to 60%, for biofuels from new crops, in 2018 (Europa 2010). Similar legislation has been or is being enacted elsewhere. A problem of growing energy crops predominately in marginal areas might arise from their remoteness from markets or end-users. This could induce relatively long distance transport of the bioenergy feedstock in cases where processing plants are centralised and distant from production areas. Long transport distances of bioenergy feedstock could make net gains in energy and CO_2-neutrality disappear (Giller et al. 2007). In terms of transport for low-energy-density biomass, cost is the limiting factor and affects viability long before significant GHG implications are manifested. Also, cultivation in lower grade land may result in higher fuel consumption on machinery, due to hilly fields, for example, or to irrigate fields when needed, and on the production of fertilizers needed at higher rates to achieve adequate yields (Biewinga and van der Bijl 1996). As a consequence, costs and GHG emissions may increase.

Emission of reactive N, as oxides of N into the atmosphere caused by the combustion of N-rich grassland biomass, was identified as a disadvantage in deriving bioenergy from grasslands (Ceotto 2008), because of its contribution to acidification (Biewinga and van der Bijl 1996). This may not be the case if grass biomass is used in applications equipped with flue gas cleaning but this process may again impinge on the energy balance. Another argument against bioenergy is that emissions of the potent GHG N_2O stimulated by fertiliser application during cultivation offset displaced fossil energy GHG emissions. Reijnders and Huijbregts (2007) calculate that N_2O emissions of 0.2-1.0 t CO_2 equiv. ha^{-1} yr^{-1}, and soil carbon loss of 3.1 t CO_2 equiv. ha^{-1} yr^{-1} for wheat and sugarbeet production equate to GHG emissions of 2.0-2.5 kg kg^{-1}ethanol and 0.6-0.9 kg kg^{-1}ethanol, respectively, from the two crops. By comparison, N_2O emissions from perennial bioenergy crops are relatively low. Field data suggest that due to lower fertilizer requirements and higher N-use efficiency, these crops emit 40% to >99% less N_2O than conventional annual crops (Don et al. 2012).

To assess the net effect of biofuel cropping systems on climate change mitigation, Fargione et al. (2008) introduced the term "C debt". This term refers to the losses in soil C and aboveground biomass due to soil disturbance and clear cutting which have to be balanced before a newly established biofuel cropping system constitutes a net GHG benefit. Gelfland et al. (2011) widened this definition to include soil N_2O emissions and CO_2 emissions associated with the production of fertilizer and herbicides that are used in the newly established biofuel cropping system. N_2O emissions from bioenergy crops have to be quantified, in order to assess the net effect of bioenergy cropping systems on C sequestration and GHG emissions (Adler et al. 2007). Fargione et al. (2008) show that the 'payback period' (i.e. the time before the C debt is fully compensated by avoided fossil fuel C use following biofuel production) associated with the conversion of various native ecosystems to annual biofuel systems can last up to several centuries. The former land use is of critical importance in determining whether the production of energy crops turns soils into a net sink or a net source of carbon. (St. Clair et al. 2008). If conversion of land to energy crop cultivation would turn a carbon sink into a carbon source with a long payback period this would have to be considered a constraint for the achievement of bioenergy sustainability targets.

Socio-economic factors

As a consequence of lower yields from marginal or degraded lands (see also *Marginal yields from marginal or degraded land*) and higher initial investment costs (soil preparation, irrigation), lower margins can be expected. For industrial-scale bioenergy cropping in particular, this might necessitate cheap labour which in turn has consequences for the social structure of the local communities (Giller et al. 2007). Unregulated land ownership, fragmented property, low level of education, institutional constraints, low level of marketing opportunities, competition for land or biomass and poor or lack of infrastructure can both hinder land rehabilitation and increase production costs (Sugrue 2008). The type of employment in marginal areas may be related to the type of bioenergy chain, in turn associated with the productivity of a region and the spatial extent of the area, setting the potential scale of the bioenergy enterprise. Faaij and Domac (2006) distinguish between high-value employment and low value employment generated by bioenergy supply chains, noting that in developed countries wages for bioenergy workers are equivalent to other technical qualified workers, whilst in developing countries workers are often paid below average wages. The implementation of standards, such as those of the International Labour Organisation, may help to assure higher quality employment in developing countries. Nevertheless, high quality employment can only be financed through high economic viability of a production system. Meanwhile, from a social perspective, small scale decentralised bioenergy cropping on land marginal for food production could be operated at a subsistence level to support local communities in developing countries, as described in relation to the use of crop residues via small-scale gasification (Mendu et al. 2012). This would however result in a modest gain in global energy resources only.

The socio-economic implications of producing bioenergy on low quality lands requires further investigation. There are regional differences in production costs depending amongst others on costs of land and labour (Hoogwijk et al. 2009). For example, the costs of rehabilitation of degraded land by afforestation depends on the specific country and is in a range of 100 € ha^{-1} (China) to about 3,500 € ha^{-1} (Austria) with additional costs of 4 to 40 € ha^{-1} yr^{-1} (Metzger and Hüttermann 2009). Even considering the same production costs per hectare on degraded compared to non degraded land, the cost per ton of crop harvested could be up to 100 % higher if the yield level is decreased by 50 % (Hoogwijk et al. 2009). Currently there is no agreement on the economic viability of bioenergy production on marginal land. Soldatos et al. (2011) found that low-yield energy crop production on marginal lands is clearly uneconomic. Meanwhile, whilst van der Hilst et al. (2010) found bioethanol production costs from feedstock grown in the Netherlands to be uncompetitive with petrol, the cost of second generation ethanol production from *Miscanthus* grown on low grade agricultural land was calculated to be lower than the cost of ethanol production from sugarbeet grown on high grade agricultural land.

Options in the utilisation of surplus land for bioenergy production

In the previous section, we discussed the most important constraints for the development of bioenergy on surplus land. In this section we demonstrate that, if the constraints and their implications are assessed properly and accounted for, options for sustainable bioenergy production can be identified and developed. In that case, bioenergy production might mitigate or even reverse the constraining factors in the respective areas. In the following we will discuss a list of options we have identified.

Mitigating constraints through active planning

The multitude of constraints for bioenergy development in the respective types of surplus land makes it obvious that assessing the true availability and suitability of land for bioenergy is not a trivial task. The challenges of sustainability require making use of existing knowledge about feedstock management, feedstock type, feedstock location, feedstock extent, environmental attributes, original habitat conditions, use of water and mineral resources, soil quality and erosion, emission of minerals and pesticides to soil and water, waste generation and utilization, biodiversity, expected price and cost developments, and response of local farmers and society in general (Dale et al. 2010; Fernando et al. 2010). Given this long list of sustainability criteria and given the rapid pace of land-use change, development of future options requires preparation for uncertainty (Jackson et al. 2010). For several of the constraints listed above, active planning of land use could facilitate the mitigation of bioenergy impacts. Due to the high political and economic pressure on surplus land, strategies for simply sustaining the present conditions or systems through increased resilience do not appear feasible. Jackson et al. (2010) emphasized the importance of developing strategies for adaptive capacity and transformability that consider trade-offs at multiple scales.

If the allocation of land is left to the market and to commercial companies, in particular in countries where land-planning schemes and tools are weak, they will most likely choose the most profitable land for industrial size enterprises and there is no a priori reason to think that degraded, lower-grade or marginal land is most profitable for bioenergy production (Azar and Larson 2000; Johannson and Azar 2007). Indeed, cost-competitiveness of bioenergy crops under marginal production conditions presents a challenge for their economic viability since their cost frequently exceeds the market price of the energy they produce (Monti and Askew 2010). Economic forces and farmer flexibility considerations may favour planting of high yield annual crops on fertile soils, with poor environmental and socio-economic performance (Boehmel et al. 2008). Rapid expansion of sugar cane and biodiesel production in Columbia and Brazil provide possible examples of a trade-off between economic growth and employment on the one hand, and environmental pressure on the other (Faaij and Domac 2006).

Meanwhile, unchecked market-driven expansion of bioenergy production could culminate in industrial scale bioenergy chains involving thousands of hectares of cultivation centred on large processing and energy conversion plants, with negative environmental and socio-economic consequences. Human rights may also be adversely affected where bioenergy chains are developed rapidly in response to top-down targets and economic drivers (NCB 2011). Faaij and Domac (2006) report that bioenergy chains in Austria and Sweden developed by entrepreneurs in a bottom-up process lead to a more diverse pattern of development compared with patterns arising from development by mature industries (e.g. Finnish forestry industry), where large-scale centralised operations are preferred. Thus, bottom-up development of bioenergy chains may improve environmental and socio-economic performance, but ultimately such development will also need to be bounded within a framework of strategic land-use planning to avoid expansion into industrial scale mono-plantations. However, small-scale bottom-up bioenergy production can only be initiated and sustained within an attractive and relatively stable market context (based on energy and carbon prices, taxes and incentives). With premature development of bioenergy chains, a deterioration in market conditions could lead to failure and ultimately reduce confidence in bioenergy options. Thus bottom-up (supply) initiatives have to be accompanied by targeted and sustained initiatives to stimulate demand (e.g. renewable energy tariffs, grants for boilers) if sufficient demand is not already in existence.

As various stakeholders are commonly involved in the planning and establishment of biomass plantations, proper communication of bioenergy issues might be of equal importance. A questionnaire among various stakeholders in Sweden, which is leading in commercial plantations of willow SRC in Europe, revealed that many authorities, farmer and nature conservation organizations frequently base opinions or decisions regarding bioenergy on misconceptions or unjustified fears about what biomass crops are, how they affect environment and landscape, and what conditions are needed for growing these crops (Weih 2009).

Improving rural development

Perhaps the most promising option for bioenergy development lies in the potential for improving rural development, in particular in marginal areas where local farming systems and the associated biodiversity are threatened by abandonment. De Aranzabal et al. (2008) note that the constant reciprocal interaction between territorial and socio-economic structures behind the opposing processes of intensification in productive areas and land abandonment in less productive areas of Europe has given rise to negative cultural, economic and environmental impacts. The social effects of small and medium scale bioenergy production comprise the standard of living as well as social cohesion and stability (Domac et al. 2005). Energy crops provide an option for diversifying farm income from arable and pastoral agriculture. Lower inputs and lower agricultural labour requirements, in particular for perennial crops, may suit older or part-time farmers in developed countries (Valentine et al. 2012). Also bioenergy systems involving biomass processing and export from the site of production create additional jobs further down the supply chain, improving employment in those marginal areas (Valentine et al. 2012). Domac et al. (2005) report employment generation of between 25 (Croatia) and 81 (Bosnia and Herzegovina) total jobs per PJ annual fuel consumption for CHP (combined heat and power) and wood heat projects in Central Europe (ranging in capacity from 6.8 to 15 MW_{th}), between 44% and 64% of which were classified direct employment. Panoutsou (2007) calculate potential employment of 13 to 22 additional jobs per MW capacity of installed district heating fed by locally sourced cardoon and giant reed perennial crops in Greece, of which 85% were indirect jobs. Of the additional direct employment revenue, 79-89% was for skilled jobs, some of which may involve external (i.e. non-local) labour. In effect, substitution of fossil fuels with bioenergy may redirect income from large fossil fuel companies towards small and dispersed bioenergy enterprises, including farmers, as has happened in Austria and Sweden (Faaij and Domac 2006).

In low-input/low-output systems such as semi-natural grasslands, subsidy systems for bioenergy production from existing grasslands may be required to make their management economically viable for farmers, and thus prevent agricultural intensification and associated adverse biodiversity effects (Heinsoo et al. 2009). In Estonia for example, such subsidies cover losses in production amounting to ca. 65 GJ ha^{-1} placing the income from semi-natural grasslands in the same range as that from more intensively managed dedicated energy crops with an energy yield of ca. 100 GJ ha^{-1} (Heinsoo et al. 2009). The cost effectiveness of supporting low-input bioenergy systems compared with other potential public expenditure is difficult to ascertain, owing to the multiple functions being supported, and the range of alternative options that could support some of these functions. Marginal abatement costs for CO_2 are used to assess the cost effectiveness of measures to mitigate climate change (e.g. Nauclér and Enkvist 2009), and could be used to compare support for bioenergy with support for energy conservation measures or deployment of other renewable energies. However, such assessments fail to capture biodiversity and socio-economic goals, often involve contentious cost and scale assumptions (Ekins et al. 2011), and rarely consider indirect effects, such as trade balance and employment multiplier effects. When assessing bioenergy and alternative options at a climate-change policy level, consideration of the aggregated economic impact across supply chains at a national or regional level, including both end-users and suppliers, may be more relevant than user-oriented marginal abatement costs (e.g. Styles et al. 2008). Government financial support to encourage end-user uptake of bioenergy can leverage indigenous economic activity by diverting fossil fuel expenditure away from external energy suppliers to indigenous bioenergy supply chains (Mathiesen et al. 2011).

However, long-term planning may be required to ensure that possible socio-economic benefits arising from initial small-scale bioenergy production in the current market are not reversed by uncontrolled expansion. If bioenergy production moves from genuine surplus land to compete with food production, social cohesion can be damaged by the resulting upward pressure on commodity prices, including staple food (The Royal Society 2008). This is a major threat associated with unchecked market-led development of bioenergy chains leading to industrial scale mono-cropping that, in addition to ecological damage, could result in the displacement of indigenous populations and subsistence and smallholder food production, especially where land-tenure rights are poorly established, whilst providing relatively few employment opportunities or local economic benefits (especially where profits are expatriated by multinational companies).

Sustaining high nature value farming systems

By halting depopulation and generating income in rural areas, bioenergy production could contribute to the preservation of agricultural systems associated with high nature value (see *Improving rural development* and e.g. Eichhorn et al. 2006; Plieninger et al. 2006). Lambin and Meyfroidt (2010) emphasise the importance of profitable land-use options in combination with absolute protection of pristine areas to ensure enduring protection of valuable landscapes. Low-input perennial bioenergy crops such as SRC and grasses may be compatible with the maintenance of HNV farming, within the confines of viability according to land suitability and distance to market. In this vein, Dale et al. (2010) suggest that perennial bioenergy crops might be most appropriately considered as a component of conservation farming systems where their use is integrated with land-use planning and rotations that improve soil quality and reduce erosion and leakage of agricultural inputs. Such a development would require a well-designed approach for overall land use that would place each use in its most suitable location, considering the potential of the land for all human needs as well as for biodiversity protection while withstanding the economic drivers pushing the system to ever larger and more homogenous units to reduce cost and exploit the economics of scale.

Taking into account that ecosystems, both their health and their function, have adaptive capacity and transformability (Jackson et al. 2010), a bioenergy focused development of HNV farming systems might be feasible if we are willing to accept that they will change in character but not necessarily in biological value. This is in accord with the idea formulated by Bignal (1998) to characterize the system by functional parameters of their ecological, agricultural and social components and using this knowledge for a functional approach to nature conservation rather than trying to maintain or restore “historic” states of a system. These points correspond with the argument that conservation management must incorporate productive land use if it is to be socially acceptable and thus effective (Lambin and Mefroidt 2010).

Halting degradation and reclaiming land

According to Daily (1995), there has been a significant increase in the impact of soil degradation on agricultural productivity. There is evidence that this will increase further if no action is taken, having a direct effect on biodiversity and on the possibilities to mitigate the effects of climate change. Lambin and Meyfroidt (2010) report that institutional and technological innovations enable societies to work within the constraints of degraded natural ecosystems, so that degradation does not need to be a cause of abandonment. The question remains, how sustainable such innovative methods might be and in which time frame they could restore the productivity of the land to a level suitable for energy crop cultivation. Reclamation of productivity to support biomass cultivation increases production costs. Therefore, government support schemes should prioritize the use of degraded land for biomass production (Fritsche et al. 2010). Any scheme would however have to take into account that the time required to restore degraded lands varies considerably with ecosystem type, history and spatial pattern of land use and the degree of alteration of climatic factors (Daily 1995). It is argued, that cultivating dedicated perennial energy crops on degraded land could improve this land by restoring soil organic matter and soil fertility, stabilizing erosion, nutrient and contaminants leaching and run-off and improving moisture conditions (Hall et al. 1993; Fernando 2005). Studies have shown that SRC poplar and willow and *Miscanthus* plantations can increase soil organic carbon (SOC; Rowe et al. 2009; Zimmermann et al. 2012), improve soil fertility and reduced nitrogen leaching (Makeschin 1994). Agroforestry systems could be an interesting option for land reclamation after open-cast mining and for improving land after degradation by restoring soil properties and halting wind and water soil erosion (Quinckenstein et al. 2009). In reclaimed lignite mine sites of Germany for example, agroforestry systems with SRC were established successfully (Gruenewald et al. 2007). Owing to its shallow and extensive root network and its ability to accumulate heavy metals and other pollutants, willow and poplar SRC may be used for remediation of contaminated land and treatment of wastewater (Börjesson 1999a; Rosenqvist and Dawson 2005). The same was also reported for other energy crops, such as *Miscanthus*, giant reed, hemp, sorghum and sunflower (Fernando et al. 2010, and references within).

Mitigating climate change

Bioenergy crops can be important constituents in a portfolio of climate mitigation measures (Sims et al. 2006). This option however depends on the C debt of a biofuel cropping system which is partly determined by the land use it is replacing (e.g. Hillier et al. 2009; see also *Greenhouse gas emissions and loss of soil organic carbon*), and by the constraints elaborated above. Soils depleted to comparatively low levels of carbon content have the greatest carbon sequestration potential (Smith et al. 1997). Accordingly, energy cropping systems established on degraded and abandoned agricultural lands with relatively small initial C stocks in plants and soil will show comparatively short payback periods; even the C debt of annual biofuel cropping systems might be repaid within decades. The potential for soil C storage is however largest when perennial energy crops are established on former cropland (e.g. Hansen et al. 2004; Dondini et al. 2009a; Rowe et al. 2009). Due to a lack of continuing soil disturbance after their establishment and a high belowground biomass, perennial biofuel cropping systems incur little or no soil C loss at all, resulting in payback times of a few years or less (e.g. Zimmermann et al. 2012). Combining field data with spatial modelling, Dondini et al. (2009b) estimated soil C accumulation rates under *Miscanthus* between 2-3 t C ha^{-1} yr^{-1} for Ireland, depending on crop yields and initial soil C levels. However, the carbon mitigation potential of SOC sequestered by energy crops shows wide ranges, depending on former land use, farming practices, climate and soil conditions such as soil texture and water retention (Jug et al. 1999; Smith et al. 2000; Grogan and Matthews 2002; St. Clair et al. 2008). If bioenergy crops are being planted on permanent grassland, as might be the case in particular in marginal areas, there could be no change in net soil C contents (e.g. Schneckenberger and Kuzyakov 2007) or even a loss of 15% of SOC (Jug et al. 1999; St. Clair et al. 2008).

Mitigating impacts of transport distances

Biomass transport is a feature of all bioenergy supply chains as, in almost all cases, the production of biomass for energy generation will occur at a distance from population centres where the energy will be used. Surplus land will not necessarily be at a greater distance from the point of energy use than land already used for bioenergy production (e.g. for firewood). However, in cases where distances between biomass production and bioenergy use are great, local conversion of bioenergy into energy carriers such as electricity or biogas could be considered as a means of minimising the GHG footprint of bioenergy transportation. Marginal or degraded areas in particular can be remote from the markets or the end users of the feedstock, and therefore economic and environmental costs of transportation might reduce the climate change mitigation potential of energy crops (see *Mitigating climate change*). With transport cost a decisive factor and the land requirement as well as the transport distances increasing with heterogeneous planting systems, the most probable outcome of land-use decisions is large scale monoculture. An alternative scenario of development might be the decentralisation of energy production and consumption and/or adaptation of dimensions of bioenergy production to local demand. Environmental benefits are maximized when bioenergy feedstocks are used locally (e.g. Gmünder et al. 2010) and, consequently, initiatives to stimulate and maximize local demand should accompany decisions to promote bioenergy production in remote areas. Local demand can be satisfied by the use of biomass in small boilers, in biomass-CHP plants and in anaerobic digestion-CHP plants. Where the supply of locally produced bioenergy feedstock exceeds local demand, the excess should be converted into energy carriers which can be cheaply and easily used elsewhere.

Transport distances informed by information or assumptions on the spatial distribution of cultivation, conversion and final use locations are an important component of LCA necessary to assess the sustainability of bioenergy cultivation in a certain area. The same is true for biomass processing, such as pelleting, which is regarded as a simple and relatively efficient conversion pathway that enables complete and simple use of harvested woods and grasses. Pelleting improves energy density, and pellets may be transported long distances if production and use are located relatively close (10s of kms) to water transport hubs (Faaij and Domac 2006). Smeets et al. (2009) assumed a lorry-based transport distance of 100 km for pellets was economically viable. Primary energy consumption of 1.6 GJ per oven-dried tonne for pelleting is equivalent to 9% of biomass energy content (Smeets et al. 2009) – this is efficient compared with production of liquid biofuels that may use more energy than they produce (Pimentel

2003; The Royal Society 2008). As pellets could be used in small scale local heating systems as well as in medium size commercial power plants, this type of biomass processing is adaptable to a wide size-range of bioenergy enterprises. Smeets et al. (2009) concluded that bioenergy chains based on pelleting of perennial grasses can result in GHG reductions compared with fossil fuel chains when annual cropping or grassland is replaced and net GHG reductions when natural vegetation is considered as the reference land use.

Choosing the right crops

Productivity and environmental benefits of energy crops can be greatly optimized when appropriate site-specific choices are made (Zegada-Lizarazu et al. 2010). Such site-specific choices are of particular importance for surplus land which is often characterised by environmental constraints for energy crop cultivation such as soil fertility, water availability, soil carbon stocks, erosion or location within natural sensitive areas. Perennial crops offer numerous environmental advantages, and provide a wider range of ecosystem services, compared with annual crops. At a landscape level the planting of 10-20% of energy forestry in open farmland for example can have a considerable benefit for biodiversity and other ecosystem services such as erosion protection (Börjesson 1999b). This benefit is strongest where harvest times are varied across bioenergy fields (Weih 2008; Smeets et al. 2009). However, as both area limitation and harvest time variation reduce economic viability, careful ex ante planning is required. Perennial grasses such as *Miscanthus* and switchgrass for example have a considerably lower environmental footprint than annual crops (Faaij and Domac 2006; Boehmel et al. 2008; Smeets et al. 2009). High nutrient use efficiency translates into an optimum N application rate of just 1.9 kg per dry tonne harvested biomass for *Miscanthus* (Boehmel et al. 2008).

Many processes that provide essential services in natural systems, such as organic nutrient cycling, pollination, predation, etc., need to be artificially boosted in cropping systems to achieve adequate yield in cropping. The boosting actions, mostly the use of herbicides and pesticides, frequently result in negative impact on biodiversity. In perennial cropping systems, the need for boosting actions may be lower, because many of the processes providing these services are operating naturally and most perennial systems probably can utilize ecological processes more efficiently than annual systems (Jordan et al. 2007; Weih et al. 2008). It is therefore likely that perennial biomass crops may often be a better choice than annual crops to achieve reasonable biomass production along with maintaining high cropping security, enhancing energy and GHG balances and maximizing the positive effects on biodiversity (but see Spangenberg and Settele 2009b). For example, woody perennial biomass crops are likely to host diverse microbial communities including mycorrhizas, which can improve both biomass productivity and cropping security, and at the same time increase soil biodiversity (Rooney et al. 2009).

Meanwhile, there remains some uncertainty surrounding the overall environmental performance of perennial grasses compared with extensive grassland. Smeets et al. (2009) used the universal soil loss equation to estimate erosion rates for *Miscanthus* and switchgrass of 2.6 to 7.7 t ha^{-1} yr^{-1} at annual rainfall rates of 400 mm to 1200 mm. These erosion rates were less than one third of the rates calculated for annual crops, but twice those calculated for grassland, and over ten times those calculated for deciduous forest. They are also considerably higher than the upper limit for sustainable soil erosion in Europe of 1.4 t ha^{-1} yr^{-1} proposed by Verheijen et al. (2009). Nonetheless, the US Conservation Reserve Programme uses perennial grass to minimise soil erosion, and the UK's DEFRA classify *Miscanthus* as a moderately susceptible land-use type that can be planted in areas of high and very high soil erosion risk (Smeets et al. 2009). Van Dam et al. (2009) report that switchgrass cultivation on non-degraded grassland has a neutral effect on soil C stocks and a positive effect on biodiversity, estimated by 'Mean Species Abundance' (MSA; see http://www.globio.info/what-is-globio/how-it-works/impact-on-biodiversity for definition), in Argentina, compared with a small negative effect on MSA when displacing natural vegetation. In contrast, the cultivation of soybeans for biodiesel had a significant negative effect on soil C and species abundance. Van der Hilst (2010) suggest that there is a high potential for *Miscanthus* cultivation on grassland soils, in relation to economic competitiveness and land availability in the Netherlands, but that there is high uncertainty surrounding the economic performance of pasture land.

Plant breeding

In addition to improving crop performance by choosing the most appropriate crop types for the respective characteristics of surplus land, plant breeding is also of vital importance for the environmental benefits they have and for improving the yields they deliver. As most of the energy crops currently cultivated are largely undomesticated and at their early stages of development, plant breeding and identification of proper cultivars could significantly improve their productivity when grown under marginal conditions (Zegada-Lizarazu et al. 2010). Novel energy plants from plant breeding programmes (Schröder et al. 2008; Karp et al. 2011) or genetic engineering (Xie and Peng 2011) might need to be developed to improve yields of energy crops grown on lower grade lands (Karp and Richter 2011). Genetically modified crops might however be met by public discontent, posing a risk to the still positive image of bioenergy. Land may often be marginal for agricultural production because of environmental conditions which expose plants to abiotic stress from drought, flooding or extreme temperatures. An important breeding goal therefore is to increase the stress tolerance of species used for bioenergy production. Similarly, it will become increasingly important to identify species and varieties which can tolerate the changes likely to come as a result of climate change. Three principal challenges to achieving yield improvement in biomass crops were identified by Karp and Shield (2008) to be a reduction in thermal threshold in order to extend the growing season, an increase in above ground biomass without depletion in below ground biomass and without causing water depletion.

Historically, breeding goals most often target short-term events (e.g. single physiological processes) to enhance productivity or fight potential pests, and build on high-input systems along with the frequent application of chemicals for weed and pest control. Such conditions are likely to conflict with the environmental goals of bioenergy development, including enhanced biodiversity. Breeding strategies for biomass crops to be grown on lower grade land and in low-input systems thus need to build on low resource availability, high resource use efficiency, and also consider possible trade-offs between e.g. high productivity under optimum growth conditions and high stress tolerance (Weih 2003). Owing to the long life expectancy of perennial crops, the breeding process needs to integrate the relatively short-term events studied by geneticists and molecular biologists with the longer-term ecological information investigated by ecologists (Weih et al. 2008). Such an approach should improve the possibilities to utilize the ecological services that could be associated with increased biodiversity. In a systems approach, DeHaan et al. (2009) suggest that first biofuel crop breeding programs for low-input systems are likely to accelerate progress by focusing on grass–legume bicultures to maximize biomass yields. The level of intensification associated with the management of such bicultures in the low-input systems would however have to be assessed with regard to potential conflicts with nature conservation values of those systems, and the economic viability of the resulting cropping and processing systems.

Conclusions and policy recommendations

Bioenergy is increasingly developing into a significant part of agricultural land use, which in turn will require more integrated energy, agriculture and land-use policies to circumvent adverse impacts of competition for land (Smith et al. 2010). So far, estimates of availability and suitability of surplus land for development of energy crop production or use of existing biomass potentials are uncertain. The high level of uncertainty is on the one hand due to environmental, economic and social constraints not yet systematically taken into account and on the other hand due to not making the most out of the potentials and the elbowroom offered by novel crops and their production methods. A serious approach to factoring in the constraints, combined with creativity in utilizing the options provided, in our opinion, would lead to a more sustainable and efficient development of the bioenergy sector. Despite the advanced but not necessarily sustainable state of bioenergy development, we still see opportunities for designing and establishing sustainable bioenergy production systems with optimized production resulting in social, economic and ecological benefits. A question that needs to be solved is: how can policy levers and existing agricultural subsidy mechanisms be used to encourage spatially optimised bioenergy feedstock cultivation?

Strategies aiming in this direction should build from the scientific understanding of the effects of bioenergy choices at different scales and ways to deal with socio-economic and environmental trade-offs (Dale et al. 2010). Land-use decisions should be made on higher spatial scales, involving a full weighting of both benefits and trade-offs on non-surplus and surplus lands (c.f. Ceotto 2008). As a general rule, surplus land should only be used for bioenergy production if accompanied by an overall positive environmental effect across a range of environmental receptors. Policies intended to achieve enduring ecological and social benefits should allow or include incentives for productive utilisation of land in a manner compatible with the protection of high nature value, such as low input bioenergy feedstock production. In addition to incentives, rigorous and enforceable environmental compliance criteria are required in land-use policy, and bioenergy policy in particular. If such environmental compliances are not part of policy incentives for the development of bioenergy or if their compliance is not enforced, land of high environmental value might get lost. This is currently happening in Germany, where perennial grasslands in marginal areas, riparian habitats and even sites within protected areas (Natura 2000 sites) are increasingly transformed to cultivation of maize for biogas (Ammermann 2008). In appreciation of the pressure that bioenergy targets create for land use, the European Directive on Renewable Energy has recognised the need to comply with environmental and social sustainability objectives. As such, old forest, species rich grassland or land with a high C stock such as wetlands and pristine peatlands, do not count towards the renewable energy targets (COM 2008, Berry and Paterson 2009). Those sustainability objectives restrict the cultivation of bioenergy crops in many marginal areas of Europe which are often characterised by traditional and low-intensity managed grasslands of high nature value and/or are part of the Natura 2000 network (EEA 2006).

If coupled with active landscape scale planning for biodiversity conservation and sustenance of ecosystem services (see *Mitigating constraints through active planning*), in particular ecosystem services provided by natural or semi-natural habitats, sustainable intensification in marginal areas might be compatible with biodiversity issues through precision agriculture, multiple cropping or agroforestry systems (Brussaard et al. 2010; Greiff et al. 2010). Perennial crops, in this respect, are better bioenergy feedstock options from an environmental and socio-economic perspective than annual crops such as sugarbeet, maize or oilseed rape. In Northern America, land in the Conservation Reserve Program (CRP), an environmental programme for protecting biodiversity, reducing soil erosion, protecting freshwater, and providing natural flood control (FABRI 2007), is considered to potentially be available and suited for the production of drought resistant perennial biomass crops such as switchgrass or other grassy biomass crops (Cook and Beyea 2000). Those perennial grasses could even provide benefits to the environmental condition of those lands, if harvested and managed appropriately (Rosenberg and Smith 2009; Bhardwaj et al. 2011).

Recently, Finnan et al. (2012) showed how the net environmental benefits of bioenergy plans could be quantified using an approach based on the environmental receptors suggested in the strategic environmental assessment directive (2001/42/ec). In order to maximise net environmental benefit from surplus land, the first decision should be on how the land will be used for bioenergy production. Here, the choice is between using the vegetation already growing on the land as a bioenergy feedstock or cultivating the land for energy crop production. As such, most land could be considered as 'available' for bioenergy production as long as the caveats elaborated earlier are sufficiently taken into account, the choice then being how to best use the land for bioenergy production. Harvesting of the existing vegetation would allow the land to remain in communal ownership while providing an 'alternative' source of income for the community. This is a positive social effect as this alternative will not necessarily lead to large-scale privatization of surplus land for bioenergy. In some instances, a positive environmental effect may be achieved by using the vegetation already growing on the land for bioenergy rather than using the land for the cultivation of energy crops. Wachendorf et al. (2009) showed that semi-natural grassland in Europe can be used for bioenergy production by separating the silage harvested into a liquid fraction for biogas production and a solid fraction for combustion. Similarly, baler technology now exists for harvesting biomass from brushlands. Such harvesting is often beneficial for reducing fire hazards and herbicide usage and restoring wildlife habitats (Anderson group 2011). The use of grassland biomass already growing on CRP land, instead of converting the land to perennial grassy crops, might further minimize environmental degradation while improving the productivity of the land.

Those examples of bioenergy pathways illustrate that there is no silver bullet for land-use decisions which involve growing energy crops. Regional solutions, taking both constraints and opportunities into account, have to be developed. Bioenergy production is to a large extent driven by environmental goals and, as a consequence, bioenergy plans need to be optimised from an environmental perspective. For all bioenergy plans, the net environmental benefits of the plan should be positive across a wide range of environmental receptors (e.g. GHG, water, biodiversity, landscape, social factors etc).

Based on those findings, we recommend taking the following points into consideration when working on sustainable strategies of bioenergy development:

Slow down

Gawel and Ludwig (2011) suggested reducing the political pressure on bioenergy by reducing bioenergy targets and quots and by reconsidering funding and incentives until a full sustainability appraisal is established. Based on their scenario analysis of global implications of biomass and biofuel use in Germany, Bringezu et al. (2009) came to a similar conclusion. They found that Germany alone, already being a net importer of agricultural land, would require a net additional land area of 2.5–3.4 Mha by 2030, mainly driven by current policy targets on biofuel. They suggest that Germany should aim to decrease its overall global cropland requirement by revising policy targets with implications for direct and indirect LUC. A slowdown in the introduction of biofuels, at least until adequate and effective controls addressing effects such as displacement are implemented in bioenergy policies, would reduce the impact of dedicated energy crops on for example food commodity prices with their detrimental effects upon the poor (RFA 2008). In addition, there is an urgent need to consider how the threat of environmental and socio-economic damage associated with industrial scale bioenergy exploitation could be contained under a future scenario of strong market forces driven by high energy prices and more efficient bioenergy conversion processes.

Scaling of bioenergy issues

Once the pressure is reduced we can make up leeway in identifying key or focus areas of surplus land potentials. For this, valid information on current land use on spatial scales relevant for decision making processes is needed. Global scale data on land use, land property, climate and soil are often too coarse to provide reliable assessments that could be applied in local or regional land-use planning. They can only provide a rough idea on the potential locations of surplus land which need further assessment (ground truthing) on a regional or local scale.

Improving baseline knowledge and data bases

Further research and development is needed to accurately determine the environmental and socio-economic implications of developing surplus land for bioenergy use. Countries need to monitor their actual land use, and assess the potential of the land for agricultural production with a target of finding the most promising bioenergy feedstock with respect to productivity and sustainability. For this, the impacts of national resource consumption on the domestic and, where relevant, the global environment should be taken into account (incl. iLUC, subsequent GHG emissions; UNEP 2009). Water footprint analyses, for example, in combination with water availability mapping, might be used to identify water as a constraining factor and help to select the crops and areas that could produce bioenergy in the most water-efficient way (Gerbens-Leenes et al. 2009). Potential changes in hydrology and the impact of land and water use and management, need to be researched by integrated assessments at catchment scale to advance our understanding of how changes in water and land management may affect downstream users and ecosystems (Berndes 2008).

Ultimately, an understanding of, and influence over, socio-economic drivers of pressures such as land-use change that affect biodiversity will be essential if biodiversity loss is to be halted, or at least the rate of loss reduced. However, relating socio-economic factors to pressures is complicated by international trade and transboundary pressures. For most areas of potential study, there is a net import or export of food and energy that requires macroeconomic assumptions to attribute impacts. In addition, local socio-economic drivers are influenced by socio-economic drivers at regional and global scales that may also affect local biodiversity directly through pollution and GHG emissions (Haberl et al. 2009).

Overall, we support the idea of the development of a global high resolution knowledge base for the sustainable use and requirements of land as a tool for risk assessment and sustainability appraisal. At the same time, on a local scale, pilot projects and demonstration activities need to be implemented. Screening studies to determine energy crop responses and yields to different treatments and soil conditions as well as pilot studies prior to the field establishment of crops on marginal lands for example may give information related to the potential productivity as well as on the crop management options designed to increase productivity in a sustainable way (Fernando 2005).

Applying knowledge to appraisals and assessments

Based on sufficient knowledge and reliable data bases, comprehensive land-use management guidelines that consider agriculture, forestry, urban infrastructure, mining and nature conservation need to be implemented on the regional, national and international levels for sustainable resource use (e.g. UNEP 2009). However, due to the high political and economic pressure on surplus land, resulting in a rapid land-use change, waiting for the finalisation of such data bases might not be an option. We might have to learn to deal with uncertainty when developing strategies, by taking into account adaptive capacity and transformability of land-use systems (c.f. Jackson et al. 2010). Furthermore, we might have to find ways of better applying the knowledge we have already. For example, goals for the conservation of farmland biodiversity could be reconciled and harmonized with bioenergy targets, based on the existing ecological understanding of farmland and farming systems by setting limits of tolerance for a system with respect to proportions of land cover types including bioenergy crops (sensu Bignal 1998). Such an approach would allow a much higher precision in the assessment of available land for bioenergy production with respect to nature conservation constraints. In this respect, the Driver Pressure State Impact Response concept (DPSIR) might provide a useful approach to study the relationship between socio-economic factors and ecosystem impacts that has so far been little used to explore biodiversity pressures (Haberl et al. 2009).

Conflicts of interests between different stakeholders often result from a misconception of energy crops and their impacts (cf. Weih 2009 for willow SRC in Sweden). A key to addressing these problems is to increase the knowledge of the various stakeholder groups, and improve communication between them. Dissemination of relevant information should be made through guidelines or recommendations that stress the importance of the environmental and biodiversity aspects, and that give practical advice on how plantations should be located, designed and managed in order to promote the environment and biodiversity values (e.g. Weih 2008).

A full assessment of the socio-economic effects of bioenergy chains requires the consideration of macroeconomic effects and social effects in relation to alternative energy and land-use options, including factors such as subsidies (not forgetting "hidden" subsidies such as military protection of oil supplies), and externalities such as air pollution and climate change. Approaches have been developed to represent difficult to quantify impacts arising from the cultivation of energy crops, such as biodiversity loss or GHG emissions (e.g. Fargione et al. 2010; Urban et al. 2011), or integration of market models that quantify displacement and expansion effects (Reinhard and Zah 2009; Reinhard and Zah 2011), into consequential LCA models. Still more work is needed to further improve LCA, in particular as the reliability of data used in some LCAs is called into question (e.g. St. Clair et al. 2008).

Implementing planning and steering tools

Rapid bioenergy development driven by indiscriminate incentives arising from a top-down approach (e.g. political biofuels targets) can result in feedstock production that violates land rights and results in poor socio-economic and environmental performance. Encouraging smaller-scale bottom-up development of bioenergy chains instead can maximise socio-economic benefits, and could also help to achieve a more dispersed pattern of development. One barrier to the development of more sustainable bioenergy chains based on low-input perennial biomass crops is the cost of establishment combined with a long payback period, which could be overcome by diverse forms of financial support (Sherrington et al. 2008). But, a bottom-up approach can only be successful if there is sufficient demand, which may require top-down initiatives on the demand side of the bioenergy chain. Strong demand driven by subsidies and/ or future market forces may result in indiscriminate mass planting, at the aggregate regional or industrial level. In order to avoid such a response, some degree of top-down coordination or targeted incentives to encourage landscape scale planning is likely to be required. Local and regional bioenergy chains to generate heat, electricity and CHP would be more advantageous than globalised liquid biofuel chains. Caution is advised on the crude top-down targeting of ´surplus lands´ for development of bioenergy owing to difficulties associated with defining such lands and the danger of creating a perverse incentive for productive land to be classified as surplus land on paper in order to qualify for bioenergy development programmes (Dale et al. 2010). There may be a case for top-down incentives to target smaller scale bioenergy initiatives by, for example, placing a limit on energy capacity eligible for subsidies or feed-in tariffs.

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References

Adler PR, Del Grosso SJ, Parton WJ (2007) Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecological Applications 17: 675–691. doi: 10.1890/05-2018

Adler PR, Sanderson MA, Weimer PJ, Vogel KP (2009) Plant species composition and biofuel yields of conservation grasslands. Ecological Applications 19: 2202–2209. doi: 10.1890/07-2094.1

Alexopoulou E, Christou M, Eleftheriadis I (2010) Role of 4F cropping in determining future biomass potentials, including sustainability and policy related issues. BiomassFutures D3.2: 1–40. http://www.biomassfutures.eu/work_packages/WP3 Supply/D3.2 Role of 4F cropping in determining future biomass.pdf

Ammermann K (2008) Energetische Nutzung nachwachsender Rohstoffe – Auswirkungen auf die Biodiversität und Kulturlandschaft. Natur und Landschaft 83: 108–110.

Anderson Group: Harvesting Systems for Biomass and Forestry. http://www.grpanderson.com/en/biomass/biobaler-system

Azar C, Larson E (2000) Bioenergy and land-use competition in the Northeast of Brazil: A case study in the Northeast of Brazil. Energy for sustainable development 4: 64–72.

Baffes J, Haniotis T (2010) Placing the 2006/08 Commodity Price Boom into Perspective. The World Bank, Policy Research Working Paper 5371: 1–40.

Baldock D, Beaufoy G, Brouwer F, Godeschalk F (1996) Farming at the margins: Abandonment of redeployment of agricultural land in Europe. Institute for European Environmental Policy (IEEP)/Agricultural Economics Research Institute (LEI-DLO) (London/The Hague): 1–182.

Bauen A, Berndes G, Junginger M, Londo M, Vuille F (2009) Bioenergy – a Sustainable and Reliable Energy Source, IEA BIOENERGY, ExCo: 2009:06: 1–108. http://www.task39.org/LinkClick.aspx?fileticket=8IsypIOAwXs%3D

Baumann A, Beil M, Oppermann R (2010) Biomassenutzung. In: Oppermann R, Blew J, Haack S, Hötker H, Poschlod P (Eds) Gemeinsame Agrarpolitik (GAP) und Biodiversität. Bundesamt für Naturschutz, Naturschutz und Biologische Vielfalt 100, (Bad Godesberg): 282–295.

Beaufoy G (2011) HNV farming policy – progress to-date and future challenges. In: Ó hUallacháin D, Finn J (Eds) Conserving farmland biodiversity, Lessons learned & future prospects. Teagasc Biodiversity Conference, Wexford (Ireland), May 2011. Teagasc (Carlow), 10–14.

Beringer T, Lucht W, Schaphoff S (2011) Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. GCB Bioenergy 3: 299–312. doi: 10.1111/j.1757-1707.2010.01088.x

Berndes G (2008) Water demand for global bioenergy production: trends, risks and opportunities. WBGU (Berlin): 1–48. http://www.wbgu.de/wbgu_jg2008.html

Berndes G, Hoogwijk M, van den Broek R (2003) The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass and Bioenergy 25: 1–28. doi: 10.1016/S0961-9534(02)00185-X

Berry PM, Paterson JS (2009) Energy mitigation, adaptation and biodiversity: synergies and antagonisms. IOP Conference Series: Earth and Environmental Science 8: 012023. http://iopscience.iop.org/1755-1315/8/1/012023

BfN (2010) Energieholzanbau auf landwirtschaftlichen Flächen. Anbauanforderungen und Empfehlungen des BfN. Bundesamt für Naturschutz (Leipzig), 1–15.

Bhardwaj AK, Zenone T, Jasrotia P, Robertson GP, Chen J, Hamilton SK (2011) Water and energy footprints of bioenergy crop production on marginal lands. GCB Bioenergy 3: 208–222. doi: 10.1111/j.1757-1707.2010.01074.x

Biewinga EE, van der Bijl G (1996) Sustainability of energy crops in Europe. A methodology developed and applied. Centre for Agriculture and Environment (Utrecht), 1–209.

Bignal EM (1998) Using an ecological understanding of farmland to reconcile nature conservation. Journal of Applied Ecology 35: 949–954. doi: 10.1111/j.1365-2664.1998.tb00013.x

Bindraban PS, Bulte EH, Conijn SG (2009) Can large-scale biofuels production be sustainable by 2020? Agricultural Systems 101: 197–199. doi: 10.1016/j.agsy.2009.06.005

BMVBS - Bundesministerium für Verkehr, Bau und Stadtentwicklung (2010) Globale und regionale Verteilung von Biomassepotenzialen – Status-quo und Möglichkeiten der Präzisierung. BMVBS-Online-Publikation 27/2010: 1–127.

Boehmel C, Lewandowski I, Claupein W (2008) Comparing annual and perennial energy cropping systems with different management intensities. Agricultural Systems 96: 224–236. doi: 10.1016/j.agsy.2007.08.004

Börjesson P (1999a) Environmental effects of energy crop cultivation in Sweden—II: Economic valuation. Biomass and Bioenergy 16: 155–170.

Börjesson P (1999b) Environmental effects of energy crop cultivation in Sweden—I: identification and quantification. Biomass and Bioenergy 16: 137–154.

Borland AM, Griffiths H, Hartwell J, Smith JAC (2009) Exploiting the potential of plants with crassulacean acid metabolism for bioenergy production on marginal lands. Journal of Experimental Botany 60: 2879–2896. doi: 10.1093/jxb/erp118

Bringezu S, Schütz H, Arnold K, Merten F, Kabasci S, Borelbach P, Michels C, Reinhardt GA, Rettenmaier N (2009) Global implications of biomass and biofuel use in Germany – Recent trends and future scenarios for domestic and foreign agricultural land use and resulting GHG emissions. Journal of Cleaner Production 17: S57–S68. doi: 10.1016/j.jclepro.2009.03.007

Britt C, Garstang J (Eds) (2002) Bioenergy crops and bioremediation – a review. Report by ADAS for the Department for Food, Environment and Rural Affairs: 1–134.

Brussaard L, Caron P, Campbell B, Lipper L, Mainka S, Rabbinge R, Babin D, Pulleman m (2010) Reconciling biodiversity conservation and food security: scientific challenges for a new agriculture. Current Opinion in Environmental Sustainability 2: 34–42. doi: 10.1016/j.cosust.2010.03.007

Bühle L, Donnison I, Heinsoo K, Südekum K-H, Wachendorf M (2010) PROGRASS – Erhalt von Naturschutzgrünland durch eine dezentrale energetische Verwertung. Mitteilungen der Gesellschaft für Pflanzenbauwissenschaften 22: 275–276.

Campbell JE, Lobell DB, Genova RC, Field CB (2008) The global potential of bioenergy on abandoned agriculture lands. Environmental Science & Technology 42: 5791–5794. doi: 10.1021/es800052w

Ceotto E (2008) Grasslands for bioenergy production. A review. Agronomy for Sustainable Development 28: 47–55. doi: 10.1051/agro:2007034

Christersson L, Sennerby-Forsse L (1994) The Swedish programme for intensive short-rotation forests. Biomass and Bioenergy 6: 145–149. doi: 10.1016/0961-9534(94)90094-9

Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, Dong H, Gabrielle B, Goss Eng A, Lucht W, Mapako M, Masera Cerutti O, McIntyre T, Minowa T, Pingoud K (2011) Bioenergy. In Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlömer S, von Stechow C (Eds) IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press (Cambridge, UK/New York, NY), 209–331. doi: 10.1017/CBO9781139151153.006

Cofie O, Penning de Vries F (2002) Degradation and rehabilitation of land and water resources: examples from Africa. In Kheoruenromne I (Ed) 17th World Congress of Soil Science, Bangkok (Thailand), August 2002: 2287–1 - 2287–9.

COM – Commission of the European Communities (2008): Proposal for a Directive of the European Parliament and of the council on the promotion of the use of energy from renewable sources. http://ec.europa.eu/energy/climate_actions/doc/2008_res_directive_en.pdf

Cook J, Beyea J (2000) Bioenergy in the United States: progress and possibilities. Biomass and Bioenergy 18: 441–455. doi: 10.1016/S0961-9534(00)00011-8

Cotula L, Dyer N, Vermeulen S (2008) Fuelling exclusion? The biofuels boom and poor people's access to land. IEED (London): 1–72. http://pubs.iied.org/pdfs/12551IIED.pdf

Daily GC (1995) Restoring Value to the World's Degraded Lands. Science 269: 350–354. doi: 10.1126/science.269.5222.350

Dale VH, Kline KL, Wiens J, Fargione J (2010) Biofuels: Implications for Land Use and Biodiversity. Biofuels and Sustainability Reports: 1–13. http://www.esa.org/biofuelsreports/

Dauber J, Jones M, Stout J (2010) The impact of biomass crop cultivation on temperate biodiversity. GCB Bioenergy 2: 289–309. doi: 10.1111/j.1757-1707.2010.01058.x

Davis SC, House JI, Diaz-Chavez RA, Molnar A, Valin H, DeLucia EH (2011) How can land-use modelling tools inform bioenergy policies? Interface Focus 1: 212–223. doi: 10.1098/rsfs.2010.0023

De Aranzabal I, Schmitz MF, Aguilera P, Pineda FD (2008) Modelling of landscape changes derived from the dynamics of socio-ecological systems: A case study in a semiarid Mediterranean landscape. Ecological Indicators 8: 672–685. doi: 10.1016/j.ecolind.2007.11.003

DEFRA (2011) Agricultural Statistics and Climate Change (1st Ed). DEFRA (UK): 1–93. http://www.defra.gov.uk/statistics/files/defra-stats-foodfarm-enviro-climate-climatechange-110729.pdf

DeHaan LR, Weisberg S, Tilman D, Fornara D (2010) Agricultural and biofuel implications of a species diversity experiment with native perennial grassland plants. Agriculture, Ecosystems and Environment 137: 33–38. doi: 10.1016/j.agee.2009.10.017

Dimitriou I, Aronsson P (2005) Willows for energy and phytoremediation in Sweden. Unasylva 222(56): 47–50.

Domac J, Richards K, Risovic S (2005) Socio-economic drivers in implementing bioenergy projects. Biomass and Bioenergy 28: 97–106. doi: 10.1016/j.biombioe.2004.08.002

Don A, Osborne B, Hastings A, Skiba U, Carter MS, Drewer J, Flessa H, Freibauer A, Hyvönen N, Jones MB, Lanigan GJ, Mander Ü, Monti A, Njakou Djomo S, Valentine J, Walter K, Zegada-Lizarazu W, Zenone T (2012) Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon. GCB Bioenergy 4: 372–391. doi: 10.1111/j.1757–1707.2011.01116.x

Dondini M, van Groenigen KJ, Del Galdo I, Jones MB (2009a) Carbon sequestration under *Miscanthus*: a study of ^{13}C distribution in soil aggregates. GCB Bioenergy 1: 321–330. doi: 10.1111/j.1757-1707.2009.01025.x

Dondini M, Hastings A, Saiz G, Jones MB, Smith P (2009b) The potential of *Miscanthus* to sequester carbon in soils: comparing field measurements in Carlow, Ireland to model predictions. GCB Bioenergy 1: 413–425.

Dornburg V, van Vuuren D, van de Ven G, Langeveld H, Meeusen M, Banse M, van Oorschot M, Ros J, van den Born GJ, Aiking H, Londo M, Mozaffarian H, Verweij P, Lyseng E, Faaij A (2010) Bioenergy revisited: Key factors in global potentials of bioenergy. Energy & Environmental Science 3: 258–267.

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. Joint Research Center Scientific and Technical Reports EUR 24485 EN: 1–146. doi: 10.2788/54137

EEA (2006) How much bioenergy can Europe produce without harming the environment? European Environmental Agency Technical Report No 7/2006: 1–67.

EEA (2009) Distribution and targeting of the CAP budget from a biodiversity perspective. European Environmental Agency Technical Report No 12/2009: 1–85.

EEA (2010) The European Environment. State and Outlook 2010. Land use. European Environmental Agency (Copenhagen): 1–48. http://www.eea.europa.eu/soer

Eichhorn MP, Paris P, Herzog F, Incoll FD, Liagre F, Mantzanas K, Mayus M, Moreno G, Papanastasis V, Pilbeam DJ, Pisanelli A, Dupraz C (2006) Silvoarable systems in Europe – past, present and future prospects. Agroforestry Systems 67: 29–50. doi: 10.1007/s10457-005-1111-7

Ekins P, Kesicki K, Smith AZP (2011) Marginal abatement cost curves: a call for caution. UCL Energy Institute (London): 1–37. http://www.bartlett.ucl.ac.uk/energy/news/documents/ei-news-290611-macc.pdf

Emmerson M, Bourke D, Dauber J, O'Rourke E, Stanley D, Thompson R, Whelan P, Stout J (2011) The food versus fuel debate – what effect will replacing traditional crops with Miscanthus x giganteus have on farmland biodiversity? In: Ó hUallacháin D, Finn J (Eds) Conserving farmland biodiversity, Lessons learned & future prospects. Teagasc Biodiversity Conference, Wexford (Ireland), May 2011. Teagasc (Carlow), 58–59.

Europa: Commission sets up system for certifying sustainable biofuels. Press release 10 June 2010. http://europa.eu/rapid/pressReleasesAction.do?reference=IP/10/711&format=HTML&aged=0&language=en&guiLanguage=en

European Union (2009) Directive 2009/28/EC of the European Parliament and of the council on the promotion of the use of energy from renewable sources. Official Journal of the European Union L 140/16: 1–47.

Faaij A (2007) Biomass resource potentials; where are they? In: Haverkort A, Bindraban P, Bos H (Eds) Food, fuel or forest? Opportunities, threats and knowledge gaps of feedstock production for bio-energy. Plant Research International B.V., Report 142 (Wageningen), 13–19.

Faaij A, Domac J (2006) Emerging international bio-energy markets and opportunities for socio-ecnomic development. Energy for Sustainable Development X: 7–19. doi: 10.1016/S0973-0826(08)60503-7

FABRI (2007) Estimating Water Quality, Air Quality, and Soil Carbon Benefits of the Conservation Reserve Program. Food and Agricultural Policy Research Institute FAPRI-UMC Report #01–07, (University of Missouri-Columbia): 1–76. http://www.fsa.usda.gov/Internet/FSA_File/606586_hr.pdf

FACT (Ed) (2010) The Jatropha Handbook- From Cultivation to Application. FACT Foundation (Eindhoven): 1–172. http://www.snvworld.org/en/Documents/FACT_Foundation_Jatropha_Handbook_2010.pdf

FAO (2009) Global agriculture towards 2050. High-level expert forum, Rome, 12–13 Oct. 2009: 1–4. www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf

FAO (2011) The Global Bioenergy Partnership sustainability indicators for bioenergy. GBEP Secretariat (Rome): 1–223.

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. Science 319: 1235–1238. doi: 10.1126/science.1152747

Fargione JE, Plevin RJ, Hill JD (2010) The ecological impact of biofuels. Annual Review of Ecology, Evolution, and Systematics 41: 351–77. doi: 10.1146/annurev-ecolsys-102209-144720

Fernando ALAC (2005) Fitorremediação por Miscanthus x giganteus de solos contaminados com metais pesados, PHD Thesis Universidade Nova de Lisboa (Lisbon).

Fernando A, Oliveira JS (2005) Effects on Growth, Productivity and Biomass Quality of Miscanthus x giganteus of soils contaminated with heavy metals. In: Van Swaaij WPM, Fjällström T, Helm P, Grassi A (Eds) Biomass for Energy, Industry and Climate Protection: Proceedings of the 2nd World Biomass Conference, Rome (Italy) 10–14 May 2004, ETA (Florence) and WIP (Munich), 387–390.

Fernando AL, Duarte MP, Almeida J, Boléo S, Mendes B (2010) Environmental impact assessment of energy crops cultivation in Europe. Biofuels, Bioproducts & Biorefining 4: 594–604. doi: 10.1002/bbb.249

Field CB, Campbell JE and Lobell DB (2008) Biomass energy: the scale of the potential resource. Trends in Ecology and Evolution 23: 65–72. doi: 10.1016/j.tree.2007.12.001

Finnan J, Styles D, Fitzgerald J, Connolly J, Donnelly A (2012) Using a strategic environmental assessment framework to quantify the environmental impact of bioenergy plans. GCB Bioenergy 4: 311–329. doi: 10.1111/j.1757-1707.2011.01143.x

Fischer G, Prieler S, van Velthuizen H, Berndes G, Faaij A, Londo M, de Wit M (2010) Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios. Biomass and Bioenergy 34: 173–187. doi: 10.1016/j.biombioe.2009.07.009

Foley JA, DeFries RS, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK (2005) Global consequences of land use. Science 309: 570–574. doi: 10.1126/science.1111772

Fornara DA, Tilman D (2009) Ecological mechanisms associated with the positive diversity–productivity relationship in an N-limited grassland. Ecology 90: 408–18. doi: 10.1890/08-0325.1

Fresco LO (2007) Biomass, food and sustainability – is there a dilemma? Report to the Rabobank, Amsterdam, The Netherlands, 52pp. http://www.rabobank.com/content/images/Biomass_food_and_sustainability_tcm43-38549.pdf

Fritsche UR, Sims REH, Monti A (2010) Direct and indirect land-use competition issues for energy crops and their sustainable production – an overview. Biofuels, Bioproducts & Biorefining 4: 692–704. doi: 10.1002/bbb.258

Gawel E, Ludwig G (2011) Indirekte Landnutzungsänderungen durch Energiepflanzen. Naturschutz und Landschaftsplanung 43: 237–243.

Gelfland I, Zenone T, Jasrotia P, Chen J, Hamilton SK, Roberton GP (2011) Carbon debt of conservation Reserve Program (CRP) grasslands converted to bioenergy production. Proceedings of the National Academy of Sciences of the United States of America 108: 13864–13869. doi: 10.1073/pnas.1017277108

Gmünder SM, Zah R, Bhatacharjee S, Classen M, Mukherjee P, Widmer R (2010) Life cycle assessment of village electrification based on straight jatropha oil in Chhattisgarh, India. Biomass and Bioenergy 34: 347–355. doi: 10.1016/j.biombioe.2009.11.006

Gerbens-Leenes W, Hoekstra AY, van der Meer TH (2009) The water footprint of bioenergy. Proceedings of the National Academy of Sciences of the United States of America 106: 10219–10223. doi: 10.1073/pnas.0812619106

Giller K, van den Veen G, van Ittersum M (2007) Competing claims on natural resources: Food, fuel, fibre or forest? In: Haverkort A, Bindraban P, Bos H (Eds) Food, fuel or forest? Opportunities, threats and knowledge gaps of feedstock production for bio-energy. Plant Research International B.V., Report 142 (Wageningen): 37–41.

Graham RL (2007) Forecasting the magnitude of sustainable biofeedstock supplies: the challenges and the rewards. Biofuels, Bioproducts & Biorefining 1: 255–263. doi: 10.1002/bbb.33

Greiff KB, Weber-Blaschke G, Faulstich M, von Haaren C (2010) Förderung eines umweltschonenden Energiepflanzenanbaus. Naturschutz und Landschaftsplanung 42: 101–107.

Grogan P, Matthews R (2002) A modelling analysis of the potential for soil carbon sequestration under short rotation coppice willow bioenergy plantations. Soil Use and Management 18: 175–183. doi: 10.1111/j.1475-2743.2002.tb00237.x

Gruenewald H, Brandt BKV, Schneider BU, Bens O, Kendzia G, Hüttl RF (2007) Agroforestry systems for the production of woody biomass for energy transformation purposes. Ecological Engineering 29: 319–328. doi: 10.1016/j.ecoleng.2006.09.012

GTZ (Ed) (2008) Biofuels Development in Drylands - Panacea or Empty Promise? Proceedings of the Side Event COP 8 UNCCD, Madrid (Spain), September 2007. GTZ (Eschborn): 1–45.

Haberl H, Beringer T, Bhattacharya SC, Erb K-H, Hoogwijk M (2010) The global technical potential of bio-energy in 2050 considering sustainability constraints. Current Opinion in Environmental Sustainability 2: 394–403. doi: 10.1016/j.cosust.2010.10.007

Haberl H, Gaube V, Diaz-Delgado R, Krauze K, Neuner A, Peterseil J, Plutzar C, Singh SJ, Vadineanu A (2009) Towards an integrated model of socioeconomic biodiversity drivers, pressures and impacts: A feasibility study based on three European long-term socio-ecological research platforms. Ecological Economics 68: 1797–1812. doi: 10.1016/j.ecolecon.2008.11.013

Hall DO, Rosillo-Calle F, Woods J (1993) Biomass for energy: supply prospects. In: Johansson TB, Kelly H, Reddy AKN, Williams RH (Eds) Renewable energy – sources for fuels and electricity. Island (Washington, D.C.): 593–652.

Hansen EM, Christensen BT, Jensen LS, Kristensein K (2004) Carbon sequestration in soil beneath long-term Miscanthus plantations as determined by 13C abundance. Biomass and Bioenergy 26: 97–105. doi: 10.1016/S0961-9534(03)00102-8

Hastings A, Clifton-Brown J, Wattenbach M, Mitchell CP, Stampfl P, Smith P (2009) Future energy potential of Miscanthus in Europe. GCB Bioenergy 1: 180–196. doi: 10.1111/j.1757-1707.2009.01012.x

Heinsoo K, Melts I, Sammul M, Holm B (2010) The potential of Estonian semi-natural grasslands for bioenergy production. Agriculture, Ecosystems and Environment 137: 86–92. doi: 10.1016/j.agee.2010.01.003

Hellmann F, Verburg PH (2010) Impact assessment of the European biofuel directive on land use and biodiversity. Journal of Environmental Management 91: 1389–1396. doi: 10.1016/j.jenvman.2010.02.022

Hillier J, Whittaker C, Dailey G, Aylott M, Casella E, Richter GM, Richie A, Murphy R, Taylor G, Smith P (2009) Greenhouse gas emissions from four bioenergy crops in England and Wales: Integrating spatial estimates of yield and soil carbon balance in life cycle analyses. GCB Bioenergy 1: 267–281. doi: 10.1111/j.1757-1707.2009.01021.x

Hoogwijk M, Faaij A, Broek van den R, Berndes G, Gielen D, Turkenburg W (2003) Exploration of the ranges of the global potential of biomass for energy. Biomass and Bioenergy 25: 119–133. doi: 10.1016/S0961-9534(02)00191-5

Hoogwijk M, Faaij A, de Vries B, Turkenburg W (2009) Exploration of regional and global cost–supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. Biomass and Bioenergy 33: 26–43. doi: 10.1016/j.biombioe.2008.04.005

Howarth RW, Bringezu S, Bekunda M, de Fraiture C, Maene L, Martinelli L, Sala O (2009) Rapid assessment on biofuels and environment: overview and key findings. In: Howarth RW, Bringezu S (Eds) Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, Gummersbach (Germany), September 2008, Cornell University (Ithaca NY), 1–13. http://cip.cornell.edu/biofuels/

IEA - International Energy Agency (2010) World Energy Outlook 2010. OECD/IEA (Paris): 1–738.

IEA - International Energy Agency (2011) Key World Energy Statistics. IEA (Paris): 1–82.

Jackson L, van Noordwijk M, Bengtsson J, Foster W, Lipper L, Pulleman M, Said M, Snaddon J, Vodouhe R (2010) Biodiversity and agricultural sustainagility: from assessment to adaptive management. Current Opinion in Environmental Sustainability 2: 80–87. doi: 10.1016/j.cosust.2010.02.007

Jingura RM, Matengaifa R, Musademba D, Musiyiwa K (2011) Characterisation of land types and agro-ecological conditions for production of Jatropha as a feedstock for biofuels in Zimbabwe, Biomass and Bioenergy 35: 2080–2086. doi: 10.1016/j.biombioe.2011.02.004

Johannson DJA, Azar C (2007) A scenario based analysis of land competition between food and bioenergy production in the US. Climatic Change 82: 267–291. doi: 10.1007/s10584-006-9208-1

Jordan N, Boody G, Broussard W, Glover JD, Keeney D, McCown BH, McIssac G, Muller M, Murray H, Neal J, Pansing C, Turner RE, Warner K, Wyse D (2007) Sutainable development of the agricultural bio-economy. Science 316: 1570–1571. doi: 10.1126/science.1141700

Jug A, Makeschin F, Rehfuess KE, Hofmann-Schielle C (1999) Short rotation plantations of balsam poplars, aspen, and willows on former arable landing the Federal Republic of Germany. Soil ecological effects. Forest Ecological Management 121: 85–99. doi: 10.1016/S0378-1127(98)00558-1

Kamimura A, de Oliveira A, Burani GF (2011) Brazilian Family Farming Agriculture in the Biodiesel Production: A Portrait of Regional Possibilities. Low Carbon Economy 2: 7–14. doi: 10.4236/lce.2011.21002

Karp A, Shield I (2008) Bioenergy from plants with the sustainable yield challenge. New Phytologist 179: 15–32. doi: 10.1111/j.1469-8137.2008.02432.x

Karp A, Hanley SJ, Trybush SO, Macalpine W, Pei M, Shield I (2011) Genetic Improvement of Willow for Bioenergy and Biofuels. Journal of Integrative Plant Biology 53: 151–165. doi: 10.1111/j.1744-7909.2010.01015.x

Karp A, Richter GM (2011) Meeting the challenge of food and energy security. Journal of Experimental Botany 62: 3263–3271. doi: 10.1093/jxb/err099

Krasuska E, Cadórniga C, Tenorio JL, Testa G, Scordia D (2010) Potential land availability for energy crops production in Europe. Biofuels, Bioproducts & Biorefining 4: 658–673. doi: 10.1002/bbb.259

Lambin EF, Meyfroidt P (2010) Land use transitions: Socio-ecological feedback versus soicio-economic change. Land Use Policy 27: 108–118. doi: 10.1016/j.landusepol.2009.09.003

Lobley M, Winter M (2009) Introduction: Knowing the Land. In: Winter M, Lobley M (Eds) What is Land For? The Food, Fuel and Climate Change Debate. Earthscan (London): 1–362. http://www.earthscan.co.uk/?tabid=74738&v=31233

Lovett AA, Sünnenberg GM, Richter GM, Dailey AG, Riche AB, Karp A (2009) Land use implications of increased biomass production identified by GIS-based suitability and yield mapping for Miscanthus in England. Bioenergy Research 2: 17–28. doi: 10.1007/s12155-008-9030-x

Makeschin F (1994) Effects of forestry on soils. Biomass and Bioenergy 6: 63–79. doi: 10.1016/0961-9534(94)90086-8

Marland G, Obersteiner M (2008) Large-scale biomass for energy, with considerations and cautions: an editorial comment. Climatic Change 87: 335–342. doi: 10.1007/s10584-007-9386-5

Mathiesen B, Lund H, Karlsson K (2011) 100% renewable energy systems, climate mitigation and economic growth. Applied Energy 88: 488–501. doi: 10.1016/j.apenergy.2010.03.001

McLaughlin SB, De la Torre Ugarte DG, Garten CT, Lynd LR, Sanderson MA, Tolbert VR, Wolf DD (2002) High-Value Renewable Energy from Prairie Grasses. Environmental Science & Technology 36: 2122–2129. doi: 10.1021/es010963d

Mendu V, Shearin T, Elliott Campbell J, Stork J, Jae, J, Crocker, M, Huber, G, DeBolt, S (2012) Global bioenergy potential from high-lignin agricultural residue Proceedings of the National Acadrmy of Sciences of the United States of America. doi: 10.1073/pnas.1112757109

Metzger JO, Hüttermann A (2009) Sustainable global energy supply based on lignocellulosic biomass from afforestation of degraded areas. Die Naturwissenschaften 96: 279–288. doi: 10.1007/s00114-008-0479-4

Monti A, Askew MF (2010) Toward biofuels: an ongoing journey in the EU. Biofuels, Bioproducts & Biorefining 4: 583–585. doi: 10.1002/bbb.261

Nauclér T, Enkvist PA (2009) Pathways to a low carbon economy – version 2 of the global greenhouse gas abatement cost curve. McKinsey and Company: 1–19.

NCB (2011) Biofuels: Ethical issues. Nuffield Council on Bioethics (UK). http://www.nuffieldbioethics.org/chapter-downloads

Nijssen M (2010) Global bioenergy potentials of degraded lands. Master Thesis. University of Utrecht (Utrecht).

NRC (2008) Water Implications of Biofuels Production in the United States. The National Academies Press (Washington D.C.): 1–87. http://www.nap.edu/catalog/12039.html

OECD-FAO (2009) Agricultural outlook 2009–2018 - Highlights. OECD/FAO: 1–95. http://www.agri-outlook.org/dataoecd/2/31/43040036.pdf

OEKO (2006) Sustainability Standards for Bioenergy. Oeko-Institut (Darmstadt/Berlin/Frankfurt). http://www.oeko.de/service/bio/dateien/wwf.pdf

Offermann R, Seidenberger T, Thrän D, Kaltschmitt M, Zinoviev S, Miertus S (2011) Assessment of global bioenergy potentials. Mitigation and Adaptation Strategies for Global Change 16: 103–115. doi: 10.1007/s11027-010-9247-9

Panoutsou C (2007) Socio-economic impacts of energy crops for heat generation in Northern Greece. Energy Policy 35: 6046–6059. doi: 10.1016/j.enpol.2007.08.032

Paris P, Mareschi L, Sabatti M, Pisanelli A, Ecosse A, Nardin F, Scarascia-Mugnozza G (2011) Comparing hybrid Populus clones for SRF across northern Italy after two biennial rotations: Survival, growth and yield. Biomass and Bioenergy 35: 1524–1532. doi: 10.1016/j.biombioe.2010.12.050

Phalan B, Balmford A, Green RE, Scharlemann JPW (2011) Minimising the harm to biodiversity of producing more food globally. Food Policy 36: S62-S71. doi: 10.1016/j.foodpol.2010.11.008

Pimentel D (2003) Ethanol Fuels: Energy Balance, Economics, and Environmental Impacts are Negative. Natural Resources Research 12: 127–134. doi: 10.1023/A:1024214812527

Plieninger T, Bens O, Hüttl RF (2006) Perspectives of bioenergy for agriculture and rural areas Outlook on AGRICULTURE 35: 123–127. doi: 10.5367/000000006777641624

Plieninger T, Gaertner M (2011) Harnessing degraded lands for biodiversity conservation Journal for Nature Conservation 19: 18–23. doi: 10.1016/j.jnc.2010.04.001

Quinkenstein A, Wöllecke J, Böhm C, Grünewald H, Freese D, Schneider BU, Hüttl RF (2009) Ecological benefits of the alley cropping agroforestry system in sensitive regions of Europe. Environmental Science & Policy 12: 1112–1121. doi: 10.1016/j.envsci.2009.08.008

Reijnders L, Huijbregts MAJ (2007) Life cycle greenhouse gas emissions, fossil fuel demand and solar energy conversion efficiency in European bioethanol production for automotive purposes. Journal of Cleaner Production 15: 1806–1812. doi: 10.1016/j.jclepro.2006.05.007

Reinhard J, Zah R (2009) Global environmental consequences of increased biodiesel consumption in Switzerland: Consequential Life Cycle Assessment. Journal of Cleaner Production 17: S46-S56. doi: 10.1016/j.jclepro.2009.05.003

Reinhard J, Zah R (2011) Consequential Life Cycle Assessment of the Environmental Impacts of an Increased Rapemethylester (RME) Production in Switzerland. Biomass & Bioenergy 35: 2361–2373.

RFA (2008) The Gallagher Review of the indirect effects of biofuels production. Renewable Fuels Agency (St Leonards-on-Sea): 1–92. http://www.bioenergy.org.nz/documents/liquidbiofuels/Report_of_the_Gallagher_review.pdf

Rockström J, Steffen W, Noone K, Persson Å, Chapin FS III, Lambin E, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sörlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, Foley J (2009) Planetary Boundaries: Exploring the Safe Operating Space for Humanity. Ecology and Society 14(2): 32. http://www.ecologyandsociety.org/vol14/iss2/art32/

Rooney DC, Killham K, Bending GD, Baggs E, Weih M, Hodge A (2009) Mycorrhizas and biomass crops: opportunities for future sustainable development. Trends in Plant Science 14: 542–549.

Rosenberg NJ, Smith SJ (2009) A sustainable biomass industry for the North American Great Plains. Current Opinion in Environmental Sustainability 1: 121–132.

Rosenqvist H, Dawson M (2005) Economics of using wastewater irrigation of willow in Northern Ireland. Biomass and Bioenergy 29: 83–92.

Rösch C, Skarka J, Raab K, Stelzer V (2009) Energy production from grassland – Assessing the sustainability of different process chains under German conditions. Biomass and Bioenergy 33: 689–700.

Rounsevell MDA, Reginster I, Araujo MB, Carter TR, Dendoncker N, Ewert F, House JI, Kankaapaa S, Leemans R, Metzger MJ, Schmit C, Smith P, Tuck G (2006) A coherent set of future land use scenarios for Europe. Agriculture, Ecosystems and Environment 114: 57–68.

Rowe RL, Street NR, Taylor G (2009) Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. Renewable and Sustainable Energy Reviews 13: 271–290.

Rowe RL, Hanley ME, Goulson D, Clarke DJ, Doncaster CP, Taylor G (2011) Potential benefits of commercial willow Short Rotation Coppice (SRC) for farm-scale plant and invertebrate communities in the agri-environment. Biomass and Bioenergy 35: 325–336.

Russelle MP, Morey RV, Baker JM, Porter PM, Jung H-JG (2007) Comment on "Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass". Science 316: 1567.

Ruttan VW (1999) The transition to agricultural sustainability. Proceedings of the National Academy of Sciences of the United States of America 96: 5960–5967.

Schneckenberger K, Kuzyakov Y (2007) Carbon sequestration under Miscanthus in sandy and loamy soils estimated by natural 13C abundance. Journal of Plant Nutrition and Soil Science 170: 538–542.

Schröder P, Herzig R, Bojinov B, Ruttens A, Nehnevajova E, Stamatiadis S, Memon A, Vassilev A, Caviezel M, Vangronsveld J (2008) Bioenergy to Save the World. Producing novel energy plants for growth on abandoned land. Environmental Science & Pollution Research 15: 196–204.

Schroers JO (2006) Zur Entwicklung der Landnutzung auf Grenzstandorten in Abhängigkeit agrarmarktpolitischer, agrarstrukturpolitischer und produktions-technologischer Rahmenbedingungen. PhD Thesis, University of Giessen (Giessen). http://geb.uni-giessen.de/geb/volltexte/2007/4511/

Searchinger T, Heimlich R, Houghton RA, Dong FX, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu TH (2008) Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319: 1238–1240.

Selman P (2009) Planning for landscape multifunctionality. Sustainability: Science, Practice, & Policy 5: 45–52.

Sherrington C, Bartly J, Moran D (2008) Farm level constraints on the domestic supply of perennial energy crops in the UK. Energy Policy 36: 2504–2512.

Sieg K (2006) Jatropha curcas - an undemanding plant for biodiesel production: nut oil to biogas. Entwicklung + Ländlicher Raum 40: 25–28.

Sims REH, Hastings A, Schlamadinger B, Taylor G, Smith P (2006) Energy crops: current status and future prospects. Global Change Biology 12: 2054–2076.

Smeets EMW, Faaij APC, Lewandowski IM, Turkenburg WC (2007) A bottom-up assessment and review of global bio-energy potentials to 2050. Progress in Energy and Combustion Science 33: 56–106.

Smeets EMW, Lewandowski IM, Faaij APC (2009) The economical and environmental performance of miscanthus and switchgrass production and supply chains in a European setting. Renewable and Sustainable Energy Reviews 13: 1230–1245.

Smith P, Powlson DS, Glendining MJ, Smith JU (1997) Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. Global Change Biology 3: 67–79.

Smith P, Milne E, Powlson DS, Smith JU, Falloon P, Coleman K (2000) Revised estimates of the carbon mitigation potential of UK agricultural land. Soil Use and Management 16: 293–295.

Smith P, Gregory PJ, van Vuuren D, Obersteiner M, Havlik P, Rounsevell M, Woods J, Stehfest E, Bellarby J (2010) Competition for land. Philosophical Transactions of the Royal Society B 365: 2941–2957

Soldatos P, Lychnaras V, Panoutsou P, Cosentino LS (2010) Economic viability of energy crops in the EU: the farmer's point of view. Biofuels, Bioproducts & Biorefining 4: 637–657.

Spangenberg JH, Settele J (2009a) Biofuels: Steer clear of degraded land. Science 326: 1346.

Spangenberg JH, Settele J (2009b) Neither climate protection nor energy security: Biofuels for biofools? International Relations 5: 89–108.

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

Stephens W, Hess T, Knox J (2001) Review of the effects of energy crops on hydrology. Institute of Water and Environment, Cranfield University Silsoe (Bedford): 1–71. https://dspace.lib.cranfield.ac.uk/bitstream/1826/3368/1/Review%20of%20the%20effects%20of%20energy%20crops%20on%20hydrology-2001.pdf

Strijker D (2005) Marginal lands in Europe – causes of decline. Basic and Applied Ecology 6: 99–106.

Sugrue A (2008) Bioenergy production on marginal and degraded land: the potential social impacts. Draft paper for presentation to the joint international workshop on high nature value criteria and potential for sustainable use of degraded land. Paris (France) June and July 2008: 1–8. http://www.unep.fr/energy/activities/mapping/pdf/social.pdf

Styles D, Jones MB (2008) Life-cycle environmental and economic impacts of energy-crop fuel-chains: An integrated assessment of potential GHG avoidance in Ireland. Environmental Science and Policy 11: 294–306.

Tahvanainen L, Rytkönen VM (1999) Biomass production of Salix viminalis in southern Finland and the effects of soil properties and climate conditions on its production and survival. Biomass Bioenergy 16: 103–117.

Tang Y, Xie JS, Geng S (2010) Marginal land-based biomass energy production in China. Journal of Integrative Plant Biology 52: 112–121.

The Gaia Foundation, Biofuelwatch, The African Biodiversity Network, Salva La Selva, Watch Indonesia and EcoNexus (2008) Agrofuels and the Myth of the Marginal Lands. econexus: 1–8. http://www.econexus.info/publication/agrofuels-and-myth-marginal-lands

The Royal Society (2008) Sustainable biofuels: prospects and challenges. Policy document 01/08: 1–90.

The Royal Society (2009) Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture. Policy document 11/09: 1–72.

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

Tirado MC, Cohen MJ, Aberman N, Meerman J, Thompson B (2010) Addressing the challenges of climate change and biofuel production for food and nutrition security. Food Research International 43: 1729–1744.

UNEP (2009) Towards sustainable production and use of resources: Assessing Biofuels. United Nations Environment Programme: 1–119. http://www.unep.fr/scp/rpanel/pdf/Assessing_Biofuels_Full_Report.pdf

UNESCO (2009) Water in a changing world. The United Nations World Water Development Report 3: 1–76.

Urban B, von Haaren C, Kannig H, Krahl J, Munack A (2011) Methoden zur Bewertung der Biodiversität in Ökobilanzen am Beispiel biogener Kraftstoffe. Umwelt und Raum 3: 1–210.

Valentine J, Clifton-Brown J, Hastings A, Robson P, Allison G, Smith P (2012) Food vs. fuel: the use of land for lignocellulosic 'next generation' energy crops that minimize competition with primary food production. GCB Bioenergy 4: 1–19.

van Dam J, Faaij APC, Hilber J, Petruzzi H, Turkenburg WC (2009) Large scale bioenergy production from soybeans and switchgrass in Argentina Part B. Environmental and socio-economic impacts on a regional level. Renewable and Sustainable Energy Reviews 13: 1697–1709.

van der Hilst F, Dornburg V, Sanders JPM, Elbersen B, Graves A, Turkenburg WC, Elbersen HW, van Dam JMC, Faaij APC (2010) Potential, spatial distribution and economic performance of regional biomass chains: The north of the Netherlands as example. Agricultural Systems 103: 403–417.

van Vuuren DP, van Vliet J, Stehfest E (2009) Future bio-energy potential under various natural constraints. Energy Policy 37: 4220–4230.

Veen P, Jefferson R, de Smidt J, van der Straaten J (Eds) (2009) Grasslands in Europe of high nature value. KNNV Publishing (Zeist): 1–319.

Verheijen FGA, Jones RJA, Rickson RJ, Smith CJ (2009) Tolerable versus actual soil erosion rates in Europe. Earth Science Reviews 94: 23–38.

Vollrath B, Kuhn W (2010) Wildpflanzen für Biogas – Die Zukunft? Veitshöchheimer Berichte 141: 33–39.

Wachendorf M, Richter F, Fricke T, Grab R, Neff R (2009) Utilization of semi-natural grassland through integrated generation of solid fuel and biogas from biomass. I. Effects of hydrothermal conditioning and mechanical dehydration on mass flows of organic and mineral plant compounds, and nutrient balances. Grass and Forage Science 64: 132–143.

Weih M (2003) Trade-offs in plants and the prospects for breeding using modern biotechnology. New Phytologist 158: 7–9.

Weih M (Ed) (2008) Short rotation forestry (SRF) on agricultural land and its possibilities for sustainable energy supply. TemaNord 2008:543: 1–66. http://www.norden.org/pub/sk/showpub.asp?pubnr=2008:543

Weih M (2009) Willow short rotation coppice commercially grown on agricultural land in Sweden - possibilities for improvement of biodiversity and landscape design. IEA Technical Review No. 4: 1–36. http://www.shortrotationcrops.org

Weih M, Didon UME, Rönnberg-Wästljung A-C, Björkman C (2008) Integrated agricultural research and crop breeding: Allelopathic weed control in cereals and long-term productivity in perennial biomass crops. Agricultural Systems 97: 99–107.

WI (2006) Biofuels for transportation. Global potential and implications for sustainable agriculture and energy in the 21st century. Worldwatch Institute (Washington, D.C.): 1–38.

Wicke B (2011) Bioenergy production on degraded and marginal land – Assessing its potentials, economic performance, and environmental impacts for different settings and geographical scales. PhD Thesis. Utrecht University (Utrecht). http://nws.chem.uu.nl/publica/Publicaties%202011/Proefschrift_Wicke.pdf

Wiegmann K, Hennenberg KJ, Fritsche UR (2008) Degraded Land and Sustainable Bioenergy Feedstock Production. Issue Paper of the Joint International Workshop on High Nature

Value Criteria and Potential for Sustainable Use of Degraded Lands, Paris. Oeko-Institut (Darmstadt): 1–10.

Wright DH (1983) Species-energy theory: an extension of the species-area theory. Oikos 41: 495–506.

Xie G, Peng L (2011) Genetic Engineering of Energy crops: A Strategy for Biofuel Production in China. Journal of Integrative Plant Biology 53: 143–150

Yan LZ, Zhang L, Wang SQ, Hu L (2008) Potential yield of bioethanol from energy crops and their regional distribution in China. Transactions of the Chinese Society of Agricultural Engineering 24: 213–216.

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

Zhuang DF, Jiang D, Liu L, Huang YH (2011) Assessment of bioenergy potential on marginal land in China. Renewable & Sustainable Energy Reviews 15: 1050–1056.

Zimmermann J, Dauber J, Jones MB (2012) Soil carbon sequestration during the establishment phase of *Miscanthus x giganteus*: a regional-scale study on commercial farms using ^{13}C natural abundance. GCB Bioenergy 4: 453–461.