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FOOD SECURITY

Meeting the challenge of food and energy security

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Abstract

Growing crops for bioenergy or biofuels is increasingly viewed as conflicting with food production. However, energy use continues to rise and food production requires fuel inputs, which have increased with intensification. Focussing on the question of food or fuel is thus not helpful. The bigger, more pertinent, challenge is how the increasing demands for food and energy can be met in the future, particularly when water and land availability will be limited. Energy crop production systems differ greatly in environmental impact. The use of high-input food crops for liquid transport fuels (first-generation biofuels) needs to be phased out and replaced by the use of crop residues and low-input perennial crops (second/advanced-generation biofuels) with multiple environmental benefits. More research effort is needed to improve yields of biomass crops grown on lower grade land, and maximum value should be extracted through the exploitation of co-products and integrated biorefinery systems. Policy must continually emphasize the changes needed and tie incentives to improved greenhous gas reduction and environmental performance of biofuels.

Key words: Bioenergy, biofuels, biomass, land use, perennial crops.

Introduction

Three inter-connected challenges face humankind in the 21st century: food security, climate change, and energy security (Lal, 2010). The world population increased from 1 billion in 1800 to 6 billion in 2000, and is projected to reach ~9 billion by 2050. Despite large efforts to alleviate poverty, 1020 million people were chronically undernourished in 2009 compared with 850 million in 2004. This is partly a problem of distribution as dietary habits have changed, with a substantial rise in meat consumption. It is estimated that world food production will have to double by 2050 to meet these demands but strategies for increasing agricultural production will have to account for a changing climate. Carbon dioxide (CO_2) levels rose from 280 ppm in 1750 to 383 in 2008 and are increasing at a rate of ~2 ppm (4.2 picograms) per year. The projected 2 °C average increase in mean global temperature may reduce output from the main grain-producing areas of the world by about one-quarter (Lal, 2010).

Given these trends it is understandable that food security has once again risen to the top of government agenda. Nevertheless, it is energy security that is the focus of this paper. It is arguably an equally important challenge that impacts on food security and climate change. In the UK, agriculture itself accounts for only 2% of energy use. However, the energy input into food production throughout the whole chain comprises almost 20% of our total energy consumption (Barling *et al.*, 2008). Future fuel shortages and/or rising fuel prices are expected to impact on the cost of agricultural production and food. Potential conflicts over land use should therefore be considered within the context of the bigger framework of all the challenges that lie ahead.

Future energy challenges

Energy use has increased from ~11.5 exajoules (EJ) in 1860 to ~500 EJ today (Lal, 2010) and is projected to rise by 55% until 2025/30 if present trends continue (Umbach, 2010). The majority of energy usage is fossil fuel consumption by the domestic (~30%), industrial (~27%), and transport (~8%) sectors (IEA, 2009). Car ownership, in particular, has shown an unprecedented rise. In the UK, car travel increased from 215 billion vehicle km in 1980 to 378.7 billion vehicle km in 2000, and overall road traffic increased by 71% (ONS, 2010). The size of the global car and truck fleet is predicted to rise from an estimated 800 million to 1.6 billion vehicles by 2050, but an alternative view is of up to 3

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Abbreviations: DDGS, dried distillers' grains with solubles; dLUC, direct land-use change; ECS, Energy Crops Scheme; GHG, greenhouse gas; iLUC, indirect land-use change; LCA, life cycle analysis; LUC, land-use change; SRC, short-rotation coppice; RSM, rapeseed meal; RTFO, Renewable Transport Fuel Obligation; WUE, water use efficiency.

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billion vehicles by 2035 based on projected increases in national per capita income (Gott, 2008).

Although there are abundant reserves of oil, gas, and especially coal to meet demand at this present time, peak oil has been reached and oil will become increasingly expensive to extract. All fossil fuel reserves are finite resources with projected exhaustion periods of within 50–100 years for oil and gas and 100–200 years for coal (BP, 2008) Moreover, reserves are concentrated geographically, with 62% and 45% of all globally proven oil and gas reserves, respectively, located in the Middle East (Umbach, 2010). In the 1960s, the largest private energy companies (Exxon Mobil, Chevron, BP, Royal Dutch Shell, Conoco Philips, and Total) had access to 85% of the world's oil and gas reserves. A similar proportion is now controlled by state-owned energy companies. Saudi Aramco, for example, holds 20 times more oil reserves than the largest privately owned company Exxon Mobil. By 2050 an estimated 50% of total global oil demand will be produced by countries in which internal instability is seen as a high risk (Umbach, 2010).

Fossil fuel usage is also a key contributor to greenhouse gas (GHG) emissions. In 2004, 75% of global carbon emissions arose from the burning of fossil fuels, of which electricity accounted for 35% and transportation for 20% (EPI, 2004). As a result, and together with the increasing concerns over energy security, governments throughout the world are actively encouraging the development of low-carbon renewable alternatives. Among the different solutions being developed this paper focuses on plants, as it is the recent use of crop feedstocks for fuel that has caused concern over land-use conflicts with food production.

New expanding markets for crop production systems

The ability of plants to capture CO_2 from the atmosphere and convert it into harvestable biomass is the cornerstone of food-providing agriculture. Traditionally, however, plants have also been exploited as a source of fuel (and fibre). Today, the widespread non-industrial use of biomass for cooking and heating in developing countries, constituting two-thirds of current biomass use, is the greatest source of renewable energy (Heinimo and Junginger, 2009). The remaining third of biomass use for energy occurs in industrialized countries, where the potential for further exploitation is perceived to be huge (Ragauskas *et al.*, 2006). As a result of recent energy security and climate change drivers, three markets for crop feedstocks have been expanding: bioenergy (electricity, heat); biofuels (diesel, petrol, and aviation fuel substitutes); and biomaterials (feed, materials, chemicals). Different estimates exist for the potential global contribution of bioenergy and biofuels, but values of between 200 and 400 EJ year^{-1} (Jurginger *et al.*, 2006) have been proposed. Estimates of up to 1500 EJ year^{-1} have been given for the potential of biomass to help meet energy supplies in the future (Smeets *et al.*, 2007; IEA, 2009). Global estimates for biomaterials are more difficult to obtain but extraction from several data sources suggests that the total potential of this market could be 50 000 million tonnes [Adrian Higson National Non Food Crops Centre (NNFCC), UK, personal communication].

Of these new markets, bioenergy was the first to develop on an industrial scale, building on the traditional burning of wood and residues for heat and power. Plant biomass is currently utilized together with coal in large-scale co-generation (co-firing), or directly in dedicated biomass, gasification, or pyrolysis plants. In 2007, biomass contributed ~1% (6.4 EJ year^{-1}) to global power generation and other industrial applications (Heinimo and Junginger, 2009; Dornburg *et al.*, 2010). Projections are that renewables (in which biomass is seen as having a major role) could become the second largest source of electricity after coal, accounting for 43% of incremental electricity generation between 2005 and 2030 (Umbach, 2010). These figures do not include 'non-industrialized' use of biomass in developing countries.

A choice of renewables (e.g. wind, solar, hydro) exists for power generation but alternatives to liquid transport fuels are limited. Transport is also the sector in which emissions are increasing the fastest [by 24% in EU-25 between 1990 and 2001 (Eurostat, 2004)]. Targets for renewable fuel contributions have thus been set by governments worldwide: for example, the EU Biofuels directive and the UK Renewable Transport Fuel Obligation (RTFO). In 2007, biomass contributed 2.6 EJ year^{-1} to transport fuels (Dornburg *et al.*, 2010). In the USA alone, bioethanol production has increased from 3 to 12.1 billion gallons from 2005 until today (Service, 2010).

Several crop production systems have been brought into play to meet these expanding markets. In heat and power generation, feedstock requirements vary depending on the thermochemical process applied but a variety of biomass can be used. Materials should be supplied relatively cheaply, in large quantity, with a high calorific value and low moisture content. These industries thus developed utilizing agricultural, forestry, and municipal residues. To meet the increasing demand for feedstock, dedicated biomass crops, such as fast-growing trees (e.g. poplar, willow) and grasses (e.g. *Miscanthus*, switchgrass, giant reed), were introduced as novel (non-food) crops.

'First-generation' biofuels for transport are currently produced cost-effectively by conventional processes that depend on the edible, easily accessible fraction of the crop, which provides the substrates required for the conversion processes. Biodiesel is derived by transesterification of lipids (e.g. from algae) or oils from seeds/kernels of crops like oil palm, Jatropha, and oilseed rape (Canola). It is also derived from processed vegetable oil from the food industry. Bioethanol is produced by fermentation and distillation of sugars or starch (after a hydrolysis step) from grain (e.g. maize, wheat) or sugar crops (e.g. sugar cane, sugarbeet).

Biofuels can also be derived by more advanced ('second-generation') biological or thermochemical conversion from lignocellulose (cell wall constituents of biomass). Lignocellulose is the most abundant renewable source on earth but the cellulose and hemicellulose sugars are interlinked with

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lignin in the cell walls. Energy-intensive pretreatment steps are required to release the sugars for fermentation. Thermochemical routes are based on production of a syngas, which is converted to diesel (and any other product) through processes such as Fischer–Tropsch.

Rising concerns: food or fuel

Traditional use of biomass as a source of fuel is a cause of deforestation, but it has not conflicted with food production in industrialized economies because of the generally localized use of such resources. The use of large-scale renewable energy sources for heat and power generation in Europe was encouraged after the oil crisis of the 1970s. Brazil mandated the addition of ethanol to fuel in 1929 and started large-scale ethanol production in the 1970s. By 1990, 50% of all cars were running on bioethanol. Neither development raised alarm bells with respect to food security. When 'biofuels' was first re-introduced as a term, following the introduction of the 2005 Energy Act in the USA, they were heralded as 'green gold' (Pearce, 2006). All too quickly, however, they were quoted in much more negative terms, including 'the most destructive crop on earth' in the *Guardian* newspaper (Monbiot, 2005) and 'a crime against humanity' by UN expert Jean Ziegler (Ferrett, 2007). This controversy has challenged governments to reconsider policies and targets.

Five related elements are pertinent to the current controversy. Firstly, ambitiously set targets resulted in a major push for production of first-generation biofuels from food crops, as only these provide immediate solutions. For example, a record 92.9 million acres of maize (corn) were planted in the USA in 2007 alone, one-third of which was used for bioethanol. In the UK, the area of oilseed rape increased from 250 000 hectares in 1984 to 670 000 hectares in 2007. Of the 2 million tonnes of harvested seed, only 5% was converted into biodiesel (Twining and Clarke, 2009).

The second issue of producing biofuels predominantly from food crop systems is that these require intensive input. Among these, nitrogen fertilizer, in particular, requires energy to manufacture and results in GHG emissions (Horne *et al.*, 2003). When placed under the scrutiny of life cycle analysis (LCA) first-generation biofuels often show minimal GHG reductions or energy savings.

A third factor is that realism has set in. It has become clear that the considerable optimization of the enzymatic and physicochemical processes, required to improve the efficiency of second-generation conversion, will take longer to achieve than initially promised (Service, 2010). Lignocellulose is very resistant to breakdown and industrial production of lignocellulosic ethanol is currently limited to a few industrial operations (e.g. Iogen) or pilot facilities. Thermochemical production of diesel via syngas is similarly limited. The transport volumes required for these processes will also require major changes in the infrastructure of the supply chains (Richard, 2010).

A fourth issue concerns the land area calculated as necessary to meet biofuel targets. The UK National Farmers Union estimated that 1.2 billion litres of bioethanol and 1.35 billion litres of biodiesel are needed to meet the UK RTFO targets. For biodiesel, this would equate to 2.7 million tonnes of oilseed rape, resulting in an additional 800 000 hectares. Although Cottrill *et al.* (2007) revised this value to ~950 000 tonnes of oilseed rape, the planted area required (for biodiesel alone) would still be in the order of 340 000 hectares. Bioethanol production would require ~3 million tonnes of wheat using current technologies. This equates to 500 000 hectares, between 20% and 30% of the current wheat production area in England (Cottrill *et al.*, 2007). Based on these estimates, between 15% and 20% of the total UK arable agricultural area would be needed to meet the RTFO targets from home-grown first-generation biofuel crops. The current contribution to UK biofuels is only 8.5%, corresponding to 23 000 and 10 000 hectares of oilseed rape and sugar beet, respectively (RFA, 2010).

The fifth and final blow to the promise of biofuels was dealt by a series of publications on indirect land-use change (iLUC) (Searchinger *et al.*, 2008). Land use for energy crops (including biomass/lignocellulosic crops) is alleged to result in uncultivated land being converted to crop production elsewhere. This would cause loss of considerable carbon stocks in soils and, in many cases, an overall negative GHG balance as well as a reduction in other ecosystem services (Searchinger and Houghton, 2008; Searchinger *et al.*, 2010).

The multiple objections have led to a conundrum. On the one hand, agriculture causes GHG emissions, and bioenergy in general has the potential to help mitigate these. On the other hand, this potential could be negated if using land for energy crops results in yet more land being converted for food production elsewhere (Fig. 1). Although the subject of fierce scientific debate, the present situation has culminated in what essentially has become an ultimatum of food or fuel, with some arguing that biofuels in particular are damaging, there is not enough land to produce both food and fuel, food security is the more important challenge, and that using land to grow biofuels should be stopped. These views primarily escalated as a consequence of the extremely rapid rise in US bioethanol production from maize. For this reason biofuels have most emphasis in the sections that follow, although many of the principles apply to bioenergy in general.

Meeting the challenge of energy and food

Food production in the developed world is very energy intensive and contributes to its high energy consumption. Even a temporary shortage of energy supply would have multiple impacts on agriculture and society generally, and it is difficult to see what other contingency plans are in place, particularly for transport, should fuel supplies cease as a result of even a natural catastrophe. Whilst some competition over land use is unavoidable, the fact remains that alternatives to fossil fuels are needed. Biofuel is a new industry and offers farming a new avenue of income. It is unrealistic to expect that it will develop perfectly, without

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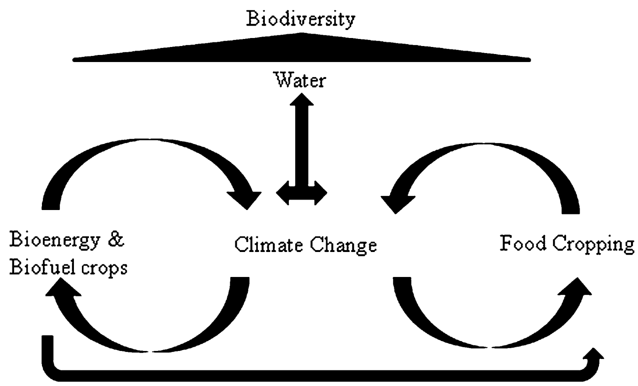

Fig. 1. Food cropping contributes to GHG emissions and in turn is impacted upon by climate change. Climate change also impacts energy crops, but energy cropping could mitigate climate change. However, if energy crops result in land conversion to food cropping this mitigation effect is weakened and some argue cancelled out. Both could impact on other ecosystem services, such as water use and biodiversity.

the need for improvement and optimization. Here, the view is presented that it is not helpful to focus on the food *or* fuel issue. Rather, what is needed is to focus on finding improvements to biofuels and land-based solutions to achieve the bigger challenge of meeting the demands for food *and* energy in the future. In doing so, a number of counter-considerations need to be taken into account in response to the concerns outlined above.

Several factors in the production systems affect energy and GHG balances

In highlighting aspects of the process that have the greatest impacts on energy and GHG balances, LCA can be useful in improving biofuel chains. For example, Horne *et al.* (2003) demonstrated that positive net energy and GHG balances were possible for biodiesel from oilseed rape and bioethanol from sugar beet or wheat. Electricity/steam in feedstock processing and the indirect energy requirements of nitrogen fertilizer manufacture were the main factors affecting their results. Avoidance or significant reduction of these factors could thus improve the energy savings and GHG reductions of even the 'worst' biofuel chains (Horne *et al.*, 2003).

LCA is also affected by its boundary definition. When corn for ethanol is grown in rotation with soybean in Iowa, 35% less GHG emissions result compared with when corn is grown continuously (Feng *et al.*, 2010). Corn ethanol's GHG benefits were lower in 2007 than in 2006 because of an increase in continuous corn in 2007. Using 2006 as a baseline and 2007 as a scenario, corn ethanol GHG benefits were 20% lower than those of gasoline but exceeded them if geographical limits were expanded beyond Iowa, due to the effects on the expansion of soybean outside of the Iowa area (Feng *et al.*, 2010).

LCA is product centred and estimates can vary due to variability in parameters, the LCA methodology used, and the way in which uncertainty due to parameters is accounted for (Whitaker *et al.*, 2010). If these sensitivities are not properly understood, LCA can lead to incorrect and inappropriate actions on the part of industry and/or policymakers (Singh *et al.*, 2010).

Using crop residues or perennial biomass crops gives higher GHG reductions

In comparison with first-generation biofuel crops, perennial biomass crops require lower fertilizer and cultivation inputs, resulting in much higher GHG reductions and energy savings (von Blottnitz and Curran, 2007; Gasol *et al.*, 2009; Hillier *et al.*, 2009). A corollary of this is that first-generation biofuel systems should be phased out and replaced with lignocellulosic biofuels from crop residues or perennial cropping systems (Farrell *et al.*, 2006).

A large body of evidence indicates that potentially high carbon savings and GHG reductions could be achieved if biofuel production was switched to biomass crops such as willows and poplars and the perennial grasses, *Miscanthus* and switchgrass (e.g. Foster, 1993; Adler *et al.*, 2007; Hastings *et al.*, 2008; Schmer *et al.*, 2008; Hillier *et al.*, 2009; Stephenson *et al.*, 2010). The use of crop residues, such as the corn stover and wheat or rice straw, either as co-products or, even better, instead of utilizing the grain, also provides improvements from straight first-generation biofuels. However, gains in terms of energy savings and GHG reductions are offset by the negative impacts of residue removal such as lower yields, change in N_2O and CH_4 emissions from land, and decline in soil carbon pools (Varvel *et al.*, 2008; Cherubini, 2010; Gregg and Izaurralde, 2010). As a result, ways of offsetting the disadvantages are required, such as the use of winter cover crops (Kim and Dale, 2005), or limits to the amount removed, e.g. up to 40% of wheat straw (Lafond *et al.*, 2009).

Co-products and integrated biorefining pave a better way forward

Overall GHG balances in LCA and land-use calculations are also affected by whether other materials that are co-produced or generated as by-products are included in the analyses. In the estimates of bioethanol production from sugar beet and wheat described earlier in relation to UK RTFO targets, it is important to note that 950 000 tonnes of oilseed meals (RSM) and 1 million tonnes of dried distillers' grains with solubles (DDGS, etc.) would also be generated for use as animal feed. In an evaluation of six representative analyses of corn ethanol fuel chains, the studies that reported negative net energy balances all ignored co-products (Farrell *et al.*, 2006). Taheripour *et al.* (2010) showed that models that omitted DDGS and RSM overstated cropland conversion from US and EU mandates by ~27%.

It has become increasingly apparent that the future lies not so much in biofuels but in integrated biorefining. In this way more value is extracted from fuel chains and there is simultaneous improvement of the economic, energy, and

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GHG balances. An impressive example of this can be seen in the sugar beet factory at Wissington, UK. In addition to sugar and bioethanol, the washed-off stones and soil are utilized, animal feed, betaine, raffinate, vinasse, and lime are also produced, and the CO_2 and heat are used for growing tomatoes under glass on an adjacent site. This concept is not restricted to biofuels but can be extended to heat and power production. Co-products and residues could be utilized on all scales from on-farm through to larger scale units with farmers encouraged to work in cooperatives where appropriate. Thus, bioresources, in general, should not be considered with regard to use for food or fuel but within the context of integrated, more efficient, farming systems. More effective and diverse use of the biomass and land resources would improve the carbon footprint of agriculture. Of course, this needs to consider the potential conflicts over different resource demands (sustainable soil management, animal feed and bedding, as well as food and energy).

Many variables affect LUC and land requirements

The 'payback period' describes the time required for biofuels to overcome the carbon debt that results from the release of GHG associated with direct land-use change (dLUC) and iLUC. Planting crops for biofuels is argued to have 'payback periods' of 100–1000 years (Kim *et al.*, 2009); however, these depend on the specific ecosystem affected and the methods of calculation. Accurate assessment of LUC impacts is subjected to even more problems regarding parameter uncertainties and boundaries than LCA (Mathews and Tan, 2009). Wicke *et al.* (2008) demonstrated that the GHG balance of palm oil biofuels can be negative where the production involves conversion of forests and/or peatlands but positive in other land-use cases. Some estimates do not consider all the potentially important variables of the crop management system that might affect the GHG emissions of biofuels (e.g. Kim *et al.*, 2009). In their modelling analysis using DAYCENT, these authors showed that conservation practices (no-till and no-till plus cover crops) could reduce payback periods significantly; from 100 and 349–1057 to 3 and 14 years for grassland and forest conversion, respectively (Kim *et al.*, 2009). Unfortunately, their modelling exercise was not evaluated against experimental evidence. Long-term experimental results show that conversion of grassland to arable causes substantial loss of organic carbon (e.g. Johnston *et al.*, 2009) and there is also doubt that no-till management results in increased carbon (Blanco-Canqui and Lal, 2008). Many of the controversial statements about payback times reflect the gap in knowledge and uncertainty that exists in this area. There is an urgent need to improve the evidence base and for model evaluation in order to more accurately assess impacts of LUC. Here, in particular, evidence-based quantitative estimates of GHG emissions and fractions of stabilized organic carbon in the soil under different first- and second-generation energy crops are needed.

Perennial energy cropping systems contribute many ecosystem services

Perennial biomass crops can contribute environmental benefits in addition to the improved energy savings shown by LCA. Growing *Miscanthus* and willow for bioenergy showed significant improvements for multiple environmental variables (nitrate leaching, eutrophication, and acidification) compared with food crop rotations, biogas from maize, and biogas from permanent grassland (Klägi *et al.*, 2008). Similarly, comparisons of poplar and willow, with oilseed rape, hemp, triticale, and rye showed that the mean annual N_2O emissions from the perennials were more than half those of annual crops as a result of reduced nitrification (Kavdir *et al.*, 2008). An evaluation of 14 bioenergy feedstocks revealed sugar cane to have the best land and nitrogen use efficiency; however, willow also ranked highly, whilst soybeans and oilseed rape ranked lowest (Miller, 2009). Perennial biomass crops increase carbon sequestration (Hunter *et al.*, 1996; Hansen *et al.*, 2004; Lemus and Lal, 2005; Sartori *et al.*, 2006; Varvel *et al.*, 2008) and improve soil ecology (Baum *et al.*, 2009*a*, *b*). Willow and poplar clones are also highly suitable for phytoremediation of contaminated soils (e.g. extraction of Cd, Zn, and degradation of organic pollution) due to their high biomass production and fine root density (Baum *et al.*, 2009*a*). An additional advantage of perennial energy crops is the soil improvement from carbon sequestration on marginal land (Varvel *et al.*, 2008).

These environmental benefits are much needed in combating climate change. In a presentation at the 2010 European Society of Agronomy conference, Bindi and Olesen (2010) summarized the impacts of climate change on food cropping systems and identified important mitigation and adaptation strategies. These included: more permanent crop cover and less intensive soil tillage, more perennial crops to sequester carbon and reduce N_2O, and diversification of land use to improve resilience and increase carbon capture. All of these could be effectively achieved through the planting of perennial biomass crops for biofuels.

Conversion of natural habitats to farmland has resulted in deforestation and loss of biodiversity. It has also been argued that biodiversity loss could be increased by planting biofuel crops (Fig. 1). However, impacts depend on what is being replaced with which bioenergy crop. Several ecological studies have shown that perennial biomass crops, particularly willow, are highly beneficial and could be used to enhance biodiversity in arable farmland (Baum *et al.*, 2009*b*; Karp *et al.*, 2010) although some faunal species, which prefer open farmland habitats, may be disadvantaged.

Water availability could become a major limitation of both food and energy crop production in the future, and improving water-use efficiency (WUE) of cropping systems is an important climate change mitigation and adaptation strategy (Bindi and Olesen, 2010). There have been concerns that biofuels will result in increased water demand, resulting in yet another conflict with food production. Using corn for ethanol production could result in a 6-fold increase in water

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requirements in the USA (Stone *et al.*, 2010). Water use will be lowest for crops without irrigation and high WUE. Perennial biomass crops establish extensive roots systems, which can help withstand water shortages. Grasses such as *Miscanthus* have the additional advantage of the C4 pathway of photosynthesis, which is associated with high WUE. While knowledge of the water balance of energy crops is limited (e.g. Dimitriou *et al.*, 2009) long-lasting and active canopies are likely to reduce ground water recharge between 10% and 70% depending on soil water availability and plant age (e.g. Busch, 2009). As for biodiversity, impacts on water availability will depend on the land cover that perennial cropping systems will be replacing (Karp *et al.*, 2010). Moreover, genetic diversity exists for this trait in perennial biomass crops and breeding programmes have already targeted improvements in WUE.

Improvements in yield and resource-use efficiency reduce land-use requirements

Assessment of land-use requirements generally should be based on current achievable yields. Yield estimates for perennial biomass crops, however, are based on a limited number of experimental trials, providing quasi-optimal conditions. Average yields of short-rotation coppice (SRC) willow and *Miscanthus* in the UK can range from 7 to 13 odt ha^{-1} $year^{-1}$ (Aylott *et al.*, 2008) and 8 to 16 odt ha^{-1} $year^{-1}$ (Richter *et al.*, 2008), respectively. Maximum yields can be as high as 18 odt ha^{-1} $year^{-1}$; however, there is a strong impact of environmental limitations, mainly water availability and temperature. Due to a lack of experience and the need for further optimization in commercial production, the yield gap is likely to be wider than for arable crops. On the other hand, technological and yield progress could be greater because these crops are relatively undomesticated. Future potential yields are difficult to predict with accuracy, due to the limited trial data available and the associated uncertainties over modelling crop–environment interactions. Many studies have used yield data from older varieties. Compared with the yields measured in countrywide trials of SRC (e.g. Aylott *et al.*, 2008), new varieties of willow show considerable yield improvement of ~0.1 tonne of dry matter per hectare annually over the past 30 years (Karp *et al.*, 2011). Further advances are to be anticipated from the considerable investment in genetic mapping and genomics of perennial trees and grasses over the past decade. As perennial biomass crops sequester carbon and are efficient in recycling nutrients, they have a strong potential for the improvement of degraded land. Genetic diversity exists for resource-use efficiency (water, nitrogen) within germplasm collections of biomass crops, and particular emphasis has been given to increase these even further. Given the advances being made in these crops, doubling yield on the basis of genotypic selection seems possible to achieve but unlikely to be realized on a large scale, due to resource limitations (water, nitrogen) where the crops will most likely be planted and their low input system of cultivation.

Marginal land and land availability mapping are proving instructive

Since the early 1990s, several initiatives, such as the Energy Crops Scheme (ECS), have encouraged the planting of a range of energy crops around the UK and other European countries, while in the USA traditional forage crops were considered for biofuel [maize contributes 44% of global ethanol (Yokoyama, 2007) and bioenergy (switchgrass: McLaughlin and Walsh, 1998)]. In contrast to other countries, like the USA or Germany, however, the UK is still debating further incentives for energy crops (Slade *et al.*, 2009). In 2006 only 64 000 odt of biomass were produced from ~5000 ha of *Miscanthus* (NNFCC, 2008). Although the area planted almost doubled by 2007 the 2010 area estimates for both willow and *Miscanthus* are in the order of only 18 000 hectares (Defra, 2009). The ECS has lost momentum due to unstable wheat prices and an uncertain policy framework influenced by concerns over food security and iLUC. This raises serious questions over the implementation of the theoretical production potentials of between 1.6 and 7 million tonnes of biomass proposed by the NNFCC (2008). A series of differentiated scenarios for the expansion of energy crops was suggested by the NNFCC that considered the areas of set-aside land (~300 000 hectares), unused arable land (150 000 hectares), and temporary grassland (133 000 hectares). New insights through more differentiated approaches, however, allow better assessment of the constraints, impacts, and benefits (Haughton *et al.*, 2009; Lovett *et al.*, 2009) and the production potentials and costs (Bauen *et al.*, 2010). Thus, decisions could be taken to further expand biomass crops to a scale where agronomic and technological progress would enhance economic and environmental returns. Lovett *et al.* (2009) used suitability mapping to optimally allocate land in England to *Miscanthus.* They used primary physical (e.g. soils, slope steepness) and socio-environmental constraints (e.g. areas of cultural and biodiversity value) together with hypothetical decision criteria (secondary constraints), such as avoidance of grassland and best land for arable crops. Examining a scenario to meet the government targets stipulated in the UK Biomass Strategy, they showed that an ~10% conversion of abundant lower grade land would not impact greatly on food production. Coincidentally, this area corresponds to approximately what was left fallow by farmers (NNFCC, 2008).

More realistic scenarios for global bioenergy potential that account for multiple demands on land use are also being developed. Dornburg *et al.* (2010) analysed a system at a global level that accounts for ecosystem functions and economic variables and services. They reported a wide range of potentials for energy production (200–500 EJ $year^{-1}$) based on different cropping choices (e.g. proportion of perennial energy crops) and assumptions over improvements in agricultural efficiency.

Key questions to address at the national economic, and, ultimately, at the farm management level are 'which land to use for each commodity (food, energy)' and 'how to

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integrate these commodities to maximize synergies'. Two classes of available land could be considered globally without major impact on current food production: marginal agricultural land (Cai *et al.*, 2010) and abandoned crop and pasture land (Field *et al.*, 2008). Cai *et al.* (2010) considered four different scenarios covering from 330 to 700 million hectares of degraded and abandoned cropland to 1 billion hectares when pastures were included. Their estimate of maximum energy contribution varied between 10% and 62% of current fuel demand, depending on the yield potential of the lignocellulosic crops implemented. Much less can be resourced using only low-input natural vegetation (3–10%) from degraded and abandoned crop land and estimates become more similar to the lower value of 5% reported by Field *et al.* (2008). The discrepancies between the two studies arise from differences in the assumptions regarding obtainable productivity, partitioning of net plant productivity into harvestable carbon, and the accessibility of the land/biomass resource in marginal areas.

Concluding remarks

Land-use conflicts need to be considered within the context of meeting all the challenges ahead (food security, climate change, and energy security). Intensification of food production will be limited if energy supply becomes restricted or significantly more expensive. Emphasis should shift from the dilemma of 'food *or* fuel' to delivering solutions to the challenge of how the increasing demands for 'food *and* energy' will be secured in the future. Perennial biomass crops offer many solutions to climate change mitigation and to the enhancement of other ecosystem services in farmland landscapes. To tackle the challenge of delivering food and fuel, cropping systems should utilize perennial biofuel crops that can be grown on lower grade land. Integrated biorefining approaches should also be encouraged that extract the maximum amount of carbon possible, producing not just fuels but co-products including for the food industry. Dale *et al.* (2010) explored multiple cropping and land usage to integrate biofuel and animal production. They showed that, from a fraction of the US agricultural land, large amounts of biofuel (ethanol) can be produced without decreasing domestic food production or agricultural exports. Their intelligent approach avoids iLUC and would also reduce GHG emissions by >10% of total US annual emissions, while increasing soil fertility and promoting biodiversity. However, these authors conclude that multiple drivers will be required to effect these changes. First of all, production systems must be economically attractive to farmers and the biofuel industry, and secondly, policy must continually emphasize the changes needed and tie incentives to improved environmental performance of biofuels and animal production

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