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Food vs. fuel: the use of land for lignocellulosic 'next generation' energy crops that minimize competition with primary food production

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Abstract

This review addresses the main issues concerning anticipated demands for the use of land for food and for bioenergy. It should be possible to meet increasing demands for food using existing and new technologies although this may not be easily or cheaply accomplished. The alleviation of hunger depends on food accessibility as well as food availability. Modern civilizations also require energy. This article presents the vision for bioenergy in terms of four major gains for society: a reduction in C emissions from the substitution of fossil fuels with appropriate energy crops; a significant contribution to energy security by reductions in fossil fuel dependence, for example, to meet government targets; new options that stimulate rural and urban economic development, and reduced dependence of global agriculture on fossil fuels. This vision is likely to be best fulfilled by the use of dedicated perennial bioenergy crops. We outline a number of factors that need to be taken into account in estimating the land area available for bioenergy. In terms of provisioning services, the value of biofuels is estimated at $54.7–$330 bn per year at a crude oil price of $100 per barrel. In terms of regulatory services, the value of carbon emissions saved is estimated at $56–$218 bn at a carbon price of $40 per tonne. Although global government subsidies for biofuels have been estimated at $20 bn (IEA, 2010b), these are dwarfed by subsidies for fossil fuel consumption ($312 bn; IEA, 2010b) and by total agricultural support for food and commodity crops ($383.7 bn in 2009; OECD, 2010).

Keywords: bioenergy, biofuels, ecosystem services, energy crops, food, land use

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Introduction

The scale of the challenges facing the world is unprecedented: we need to provide an increasing population, expected to reach 9 billion (bn) by 2050 (Cohen, 2005; UN, 2008; Lutz & Samir, 2010), with sufficient food, feed, fibre and fuel from finite land, water and mineral resources as lifestyle expectations increase and at a time of climate change. These challenges were expressed by John Beddington, chief scientific adviser to the UK government, as a 'perfect storm' of food shortages, scarce water and insufficient energy resources. By 2030, the world would need to produce 50% more food, 50% more energy and 30% more fresh water (Alexandratos *et al.*, 2006). If these needs are not addressed, this could cause public unrest, cross-border conflicts and mass migration as people flee from the worst affected areas (Beddington, 2009).

Such assertions may sound alarmist, but the spike in food and fuel prices attributed to shocks from the financial and commodities markets, extreme climate events and political turmoil resulted in the number of undernourished people in the world rising by 115 million (m) in 2006 to 963 m in 2008, reversing the previous downward trend. Food riots erupted in more than 30 nations in the first half of 2008 (World Food Programme, 2009). The trend now appears to be upwards, with the potential

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for further economic shocks and increased market volatility (OECD-FAO, 2010).

This review seeks to address the main issues concerning the use of land for food and/or fuel. It will consider the anticipated demands for food and fuel, the use of perennial energy crops for the production of lignocellulosic 'next generation' biofuels based on biological fermentation and what land could be devoted to energy crops without increasing the cost of food commodities and food security. In the last-mentioned, we take into account both supply and demand for food and fuel. In relation to energy crops, this takes into account that energy crops are deep-rooted perennials which may be more economic than food crops on marginal lands, the value of their reduced greenhouse gas emissions and other societal gains, and the scope for them replacing land currently used, for instance, for the nonsustainable over-consumption of meat or by reducing food requirements by reducing food waste. Finally, we will attempt to quantify the size of the biofuel resource and value in terms of their provisioning and regulatory ecosystem services.

Increased food security

Clearly food is one of the basics of life. Food production is the most important use of land. After decades in the dark recesses of governmental policies and research strategies, production in terms of yield is back on the agenda. The main pressures for increased food output are not only population growth, but also include rising affluence and the migration of people from rural to mega urban centres (Satterthwaite *et al.*, 2010). On the basis of increased market integration, globalization and rapid income growth over a number of years prior to the recent economic crisis, gains in agricultural output of over 40% are expected by 2019 in Brazil, with growth above 20% expected in China, India, Russia and Ukraine (Bullion, 2010; OECD-FAO, 2010). In contrast, net agricultural output in the EU-27 is only expected to increase by 4% at most. Less optimistic longer term insights into the different climate change-related challenges that the agricultural sector will face in developing countries are presented by Schmidhuber & Tubiello (2007) and Rosegrant *et al.* (2008).

Substantial increases in food production have been achieved in the last 50 years. Grain production has almost trebled and chicken and pig production has quadrupled and doubled, respectively, with much lower gains in millet, sorghum, cattle and sheep (Godfray *et al.*, 2010). A strong case has been put forward by the Royal Society (2009) that increase in production should be through 'sustainable intensification' of existing cultivated land rather than through an expansion of agricultural land area in order not to damage carbon sinks or biodiversity. Doubtless, we will have to continue and extend the use of the proven existing disciplines, such as plant breeding, agronomy and plant protection. We will also have to reap the benefits of new technologies, such as marker-assisted selection, genetic manipulation and machine imaging to develop agricultural systems which use less water, energy and fertilisers in the face of climate change and instability (for the most recent publications, see for instance, IAASTD, 2008; Lobell *et al.*, 2008; NRC, 2008; World Bank, 2008; Evans, 2009; Bullion, 2010; Gewin, 2010; Gilbert, 2010; Long & Ort, 2010; Potrykus, 2010). The socioeconomic and political dimensions and investment in infrastructure will also be hugely important. Many have pointed out that agricultural subsidies in richer countries and protectionism add to inequality and poverty in developing countries by undermining markets (Schultz, 1968; Johnson, 1973; Tyers & Anderson, 1992; Anderson, 2010). The technical ability to produce enough food will not alone alleviate hunger which is primarily a question of poverty: the problem is food accessibility rather than food availability (OECD-FAO, 2010). This has been encapsulated by OECD-FAO (2010) in terms of investments to promote income generating activities resulting in improved ability to purchase food. This will in turn result in substantial economic growth payoff, as illustrated by the 1990s, when the value-added per worker in countries where 2.5% of the population was undernourished was 20 times higher than in countries where more than 35% of the population was undernourished.

Increased food security has been dealt with in greater detail by Gregory *et al.* (2005), Defra (2006), Tudge (2007); Garnett (2008), Audsley *et al.* (2009), Evans (2009), Godfray *et al.* (2010) and others. The prospects for continued progress in increasing cereal yield and, moreover, closing the gap between attained and potential yields has been reviewed by Fischer & Edmeades (2010) and Jaggard *et al.* (2010). Both sets of authors are reasonably optimistic that the world could produce 50% more food by 2050, although this would not be easily or cheaply accomplished and there are no grounds for complacency.

So far, we have referred to food as if it was a single entity. An important aspect is the balance between primary and secondary food production. Globally, cereals are the most important food source in the world but human consumption of cereal products (*per capita*) is expected to decline as diets become more diverse with increasing prosperity (Kearney, 2010). It is generally accepted that as income grows, so does expenditure on livestock products (e.g. Delgado *et al.*, 1999; Steinfeld *et al.*, 2006). It is also important to include other factors particularly religion. For example, Muslims and Jews do not eat pork and Hindus do not eat meat.

Among other negative environmental effects, Steinfeld *et al.* (2006) have highlighted that the whole livestock supply chain accounts for an estimated 18% of total global greenhouse gas emissions. The main greenhouse gases (GHGs) are methane from the enteric fermentation of ruminants and from manures, and nitrous oxide from the nitrogenous fertilisers and manures. Production of meat from ruminants is also much more inefficient (6–8 to 1) in terms of energy input/energy output (due to a greater proportion of food eaten being used for maintenance rather than production) than production from poultry and pigs (3–4 to 1) (Wirsenius, 2003; Stehfest *et al.*, 2009; Gill *et al.*, 2010). This raises the question of whether it would be feasible to reduce meat consumption and replace it by the production of food or bioenergy crops.

This solution is, however, too simplistic. First, livestock production directly supports the livelihoods of 600 million poor smallholder farmers in the developing world (Thornton *et al.*, 2006). Certain areas can only sustain extensive grasslands where ruminants (cattle, sheep and goats) are efficient convertors of fibrous grass to human food. For centuries areas, such as the savannah grasslands of Africa, some of which is now desert, have been grazed by nomadic tribes of herdsmen. Such ecosystems can only support a limited population with such a nomadic lifestyle and are very susceptible to damage by over grazing. Although this lifestyle for an increasing population may be unsustainable, as it increases desertification and reduces the area available for overall food production, livestock are an important risk reduction strategy for such vulnerable communities and are important providers of nutrients and traction for growing crops (Randolph *et al.*, 2007; Thornton, 2010). Secondly, poultry and pigs consume grain and thus compete with humans for food crops. While cattle in some countries, such as Argentina and livestock areas of Europe, are largely grass-fed, this is not the case world-wide. Wirsenius *et al.* (2010) have demonstrated that on a global scale, cattle use similar amounts of edible crops as chickens in addition to their use of pasture and forage. They conclude a major option for better efficiency of food production and for reduction of greenhouse gas emissions would be to substitute beef by chicken: eat less beef not less meat. Alternatively, Newbould *et al.* (2010) have highlighted a number of approaches in which greenhouse gas emissions from ruminant production can be reduced. Thirdly, the use of ruminant products particularly milk may promote human health (e.g. Elwood *et al.*, 2010).

To sum up this section, the land devoted to food production will be determined by population growth, climate change, diet preferences as affected by affluence and other factors such as religion, and the capability of the land to produce food crops or whether it is only suitable for extensive pastures. The use of these factors to model food production regionally and globally is considered in a later section.

The need for bioenergy

Energy as a source of heating, lighting, cooking fuel and motive power is essential for modern civilizations. This review considers the scope and merit in using land for growing crops that can be used as bioenergy. The need for bioenergy is fuelled by the vision of four major gains for society.

A reduction in C emissions from the substitution of fossil fuels with appropriate energy crops

The use of fossil fuels (oil, coal and natural gas) for energy (including transportation) represents an estimated 61.4% of world greenhouse gas emissions (Herzog, 2009) that are acknowledged to be responsible to climate change that is often referred to as the greenhouse effect or global warming. The replacement of fossil by renewable biomass is one of several options that can contribute to stabilizing atmospheric CO_2 to a trajectory that avoids a doubling of the preindustrial concentration (Pacala & Socolow, 2004). Other forms of renewable energy, such as wind, tidal, wave and photovoltaics can also contribute but are intermittent and require energy storage or the use of other fuel technologies as back-up. Only bioenergy can deliver energy in the form of heat, liquid transport fuels, biorefining leading to plant-based equivalents of important petro-chemicals and the sequestration of soil carbon that open up the possibilities of negative carbon balances. Harper *et al.* (2010) have highlighted strategies for the capture and storage of carbon in soils, plants and products opening up the possibility of achieving a ‘sub-zero carbon Britain’ that ‘actively cleans up the atmosphere’.

In the EU, member states must meet binding, national targets for renewable energy. Only those biofuels with high greenhouse gas savings demonstrated by rigorous life cycle assessment (LCA) count towards national targets. Biofuels must deliver current greenhouse gas savings of at least 35% compared with fossil fuels, rising to 50% in 2017 and to 60%, for biofuels from new plants, in 2018 (Europa, 2010). Similar legislation has been or is being enacted elsewhere.

The indirect effects of bioenergy production also need to be considered. These can arise from the conversion of important carbon sinks, such as forests and grasslands

(Croezen *et al.*, 2010). This was the subject of a recent workshop hosted by the GHG Europe project in Dublin in October, 2010.

A significant contribution to energy security by reductions in fossil fuel dependence

Biomass can be used to replace fossil fuels, particularly coal, through thermal technologies, such as combustion to produce heat and/or power, gasification to produce syngas or pyrolysis to produce gas, liquid (including a heavy oil) and solid products with a diverse range of potential applications. Alternatively wet biomass, typically from waste products, can be subjected to anaerobic digestion to produce methane and possibly hydrogen.

From the viewpoint of energy security, we wish to largely confine ourselves in this section to a third main use of bioenergy, namely to produce biofuels for transportation in place of finite reserves of fossil liquid fuels. Liquid transport fuels can be either first generation vegetable oils, transesterified biodiesel or ethanol from fermented starch and sugar feedstocks, or second generation ligno-cellulose ethanol and biorefined oils or butanol from plant-based feedstocks.

While the IEA predicted that there are sufficient reserves of oil to meet demand until 2030 as long as investment in new production capacity is maintained, two recent reports (ITPOES, 2010; Joint Operating Environment, 2010) have expressed concerns about the effects of reaching peak oil, the point at which the rate of oil production starts to decline, or when demand outstrips the increase in production, within an earlier timeframe. Currently, oil demand is just matched by production capacity (Donnelly, 2011). If oil shale from the Green River Formation could be used to meet a quarter of the US demand for petroleum products, Bartis *et al.* (2005) have estimated that this would yield 800 bn barrels of recoverable oil which would last for more than 400 years. The financial and environmental costs of exploiting the huge reserves of unconventional oil found in Canadian tar sands and oil shales from the United States, which have to be mined rather than pumped, may be too high to bear (LeDoux, 2009; Bradbury, 2010; McRobie, 2010; Stockman, 2010). The well-to-wheels CO_2 emissions are also typically 5–15% higher than for conventional crude oils (IEA, 2010b). According to the values relating to the current size and demand for liquid fuels presented by ITPOES (2010), the level of exploitation of biofuels, for which no estimate of total resource is given, is 1.5 m barrels per day. This is above the output of Canadian tar sands of 1.2 m barrels per day.

Deutch *et al.* (2006) analyse the consequences of US oil dependency proposing forward planning that adapts to and also mitigates that dependency. Increasing the use of bioenergy is one of the mitigating strategies along with increasing the use of coal, nuclear and other energy sources and improving energy efficiency. Important sections of the US Energy Act of 2005 relate to biofuels: Section 932 authorising the Department of Energy's biomass and bioproducts programmes to partner with industrial and academic institutions to advance the development of biofuels, bioproducts and biorefineries; Section 941 amending the Biomass Research and Development Act to include four new technical areas for R&D activities: (i) develop crops and systems that improve feedstock production and processing, (ii) convert recalcitrant cellulosic biomass into intermediates that can be used to produce biobased fuels and products, (iii) develop technologies that yield a wide range of biobased products that increase the feasibility of fuel production in a biorefinery and (iv) analyse biomass technologies for their impact on sustainability and environmental quality, security and rural economic development; and Section 942 authorising the establishment of incentives to ensure that annual production of 1 bn gallons of cellulosic biofuels is achieved by 2015.

The mandatory addition of biofuels to transport fuels is enacted in law in EU nations by Directive 2009/28/EU, for example, in the United Kingdom with the Renewable Transport Fuel Obligations setting a target of 5% of all road transport fuels to be renewable by 2010. In the United States, it is also mandated by the Energy Policy Act (EPAct) 2005 to blend 7.5 bn gallons of renewable fuel into ethanol by 2012. This was further strengthened by the Energy Independence and Security Act of 2007 to include biodiesel and to use 36 bn gallons by 2022 with the provision that the LCA of the biofuel should demonstrate a lower C emission than the fossil fuel it replaces. The EU Commission has introduced sustainability criteria for industry, governments and NGOs to set up certification schemes for biofuels. Biofuels must deliver substantial reductions in greenhouse gas emissions alluded to in the previous section and should not come from forests, wetlands and nature protection areas (Europa, 2010).

Electric cars that use renewable or cleaner-generated electricity may only partially substitute for oil in the foreseeable future. In the United Kingdom, the electricity generating mix and capacity would have to change substantially for this to happen. Batteries have leapt ahead of expensive hydrogen fuel cells as the technology of choice for getting beyond oil, but getting there 'will not be easy' (Tollefson, 2008). From a fuel security viewpoint, concerns have been expressed that countries, such as the United States will simply trade their dependence on Middle Eastern oil for a reliance on Asian batteries (Tollefson, 2008).

New techniques to release natural gas from shale rocks (Kerr, 2010) also open up the possibility of compressed gas being more widely used as a transport fuel.

IEA (2010a) indicated that 20% of liquid fuel demand could be met by biofuels under its BLUE map/shift scenario for 2050. The rest of demand would be met by electricity, hydrogen, biogas and natural gas.

New options that stimulate rural and urban economic development

Energy crops provide new options for farmers wishing to diversify from arable and pastoral agriculture. In the United Kingdom, they have lower agricultural labour requirements than the latter enterprises (Thornley *et al.*, 2008) which may suit older or part-time farmers. This is likely to be the situation in most developed countries. Many more jobs are created further up the supply chain (Thornley *et al.*, 2008), more than for other renewable technologies (ADAS, 2003). Ideal energy crop species require low inputs and, by virtue of deep roots, are suited to land of low agricultural or biodiversity value or abandoned land no longer suitable for quality food production as well as being highly productive on good land. [We have avoided the use of the term 'marginal lands' in view of the objections raised by the African Biodiversity Network and others (2008).]

Elsewhere in the world, there is also a considerable potential for expanded as well as more efficient use of biomass. While Africa now uses substantial amounts of biomass in the form of wood and charcoal for cooking, traditional methods are often inefficient and cause health problems. Furthermore, in many areas in Africa, deforestation from unsustainable use of biomass and from land clearance leads to supply shortages (AEEP, 2010a). The benefits of bioenergy have been considered by Diaz-Chavez *et al.* (2010) for a number of different African countries. In Tanzania, for example, opportunities exist for income generation and diversification by producing and selling biofuel feedstocks. Employment opportunities will be created through agro-industrialisations. This will lead to improved standard of living and linkages with others sectors in the economy. Energy supply in rural areas will also stimulate rural development and reduce pollution caused by burning fire wood. Reduced time will be spent by women and children on basic survival activities (gathering firewood, fetching water, cooking, etc.).

Many of the world's poorest countries are well placed to become major producers of biomass for liquid fuels (FAO, 2008). The development of biofuel as a source of energy, when grown on a large scale, could represent a paradigm shift in agricultural development and stimulate urban economic development.

It is vitally important of course that bioenergy does not jeopardize food production leading to a greater number of undernourished people in the world. Higher prices and competition for inputs (e.g. land, water, fertilisers) leading to their diversion from food production to bioenergy might lead to a food crisis. In the case of Tanzania, there are fears that the sheer speed of biofuel expansion may generate new pressures on land tenure arrangements, jeopardizing access to land and food security unless a strong policy and legal framework is put in place (FAO, 2008, Diaz-Chavez *et al.*, 2010). Negative effects of biofuels on food prices are more likely for first generation biofuels that compete directly with food crops than for second generation lignocellulosic-based biofuels that are higher yielding, in which the whole crop is available as feedstock and can be grown on less favourable land (FAO, 2008). Types of biofuels will be dealt with in a later section.

Reduced dependence of global agriculture on fossil fuels

In the era of horse power, about 25% of the land in the United Kingdom was required to feed the horses. Now global agriculture is heavily dependent on fossil fuels (White & Grossmann, 2010). The rise in food prices in 2008 alluded to above can be attributed in part to the costs of oil and fertilizer, the manufacture of which is considerably energy intensive and emits N_2O. Food and fuel security are therefore inextricably linked. Important questions are whether agriculture can become less reliant on fossil fuels (Warwick HRI, 2007; Royal Society, 2009) and whether the generation and use of renewable fuels in agriculture can offset the high carbon footprint of food production. The former lies outside the scope of this review. In relation to the latter, stronger connections need to be researched and demonstrated between the production of biomass resources on-farm and different forms of bioenergy leading to reduction of greenhouse gas emissions which can be credited to the farm and be used as bioenergy sources (e.g. as biogas for heating or electricity generation or as liquid biofuels) to offset the high carbon footprint of food production. In other words, how can bioenergy be used in the growing and processing of food? Currently, bioconversions such as the production of biofuel from perennial lignocellulose crops or biogas from anaerobic digestion of farm wastes may require too high capital expenditure and large scale for a single farm. Policies are required which credit shared reductions in greenhouse gas emissions back to biomass producers. Renewable nitrogen fertilizers are another option (Gilbert & Thornley, 2010). Fertilizer production is a major source of agricultural greenhouse gas emissions. The manufacture of fertilizers using hydrogen derived from the electrolysis of water using electricity generated from biomass, or through anaerobic digestion, to produce ammonia in place of the energy intensive Haber-Bosch process would lead to major savings in greenhouse gas emissions.

In some cases, it could be argued that we are extremely profligate with energy, as demonstrated by lights in empty offices and the illuminations of Piccadilly Circus in London, Time Square in New York and Shanghai, vast mileages travelled for pleasure and by slow implementation of energy efficiency savings. Similar assertions could be made for the levels of waste (30–40%; Godfray *et al.*, 2010) arising from food production and consumption. Supermarket food supply chains in developed countries discard otherwise perfectly acceptable blemished or mis-shapen fruit and vegetables, and huge quantities of food are wasted before and after it has reached the table. Some of this type of food waste is used as animal feed, composted, used for bioenergy particularly anaerobic digestion or sent to landfill. In Africa and elsewhere, a similar amount of waste results from losses during transportation, storage and distribution. The problem is exacerbated by increasing urbanisation. Ironically, 1 bn people in the world are overweight, of which 300 million are obese (World Health Organization, 2003), whilst people starve in parts of Africa.

Bioenergy options

In the multifunctional use of agricultural land, there are a number of options relating to the production of biomass:

1. Food crops are used for bioenergy. Examples are maize (*Zea mays* L.), wheat (*Triticum aestivum* L.) and sorghum (*Sorghum bicolor* (L.) Moench), in which starch in the grains are converted to sugars and then to ethanol by simple fermentation, cassava (*Manihot esculenta* Crantz) and sweet potatoes (*Ipomoea batatas* (L.) Lam) in which the starch of tubers are likewise converted to ethanol, sugar cane (*Saccharum officinarum* L.) in which high yields of stem sugar are converted to ethanol, and oilseeds such as palm (*Elaeis guineensis* Jacq.), soya (*Glycine* max (L.) Merr.), oilseed rape (*Brassica napus* L.) and the recently introduced shrub *Jatropha curcas* L., in which the extracted oil is esterified and used as biodiesel.

Grain followed by sugar cane are the current main source of global bioethanol production (OECD-FAO, 2010, fig. 4.5) with edible vegetable oils the main source of global biodiesel production (OECD-FAO, 2010, fig 4.6).

Some use is also being made of oats (*Avena sativa* L.) as whole natural pellets in place of wood pellets for small-scale combustion (Bäfver *et al.*, 2009).

All three types of bioconversion discussed in this section are regarded as well-understood first generation technologies in which there is little scope for efficiency savings. The amount of extra energy generated compared with the energy used in production ranges from about 1 to 4 for annual crops (figure 7, FAO, 2008 sourced from Worldwatch Institute, 2006 and Rajagopal & Zilberman, 2007). Indeed, the carbon intensity (CI), the g CO_2 equivalent carbon emissions per MJ net energy, is higher in most cases than that of fossil fuels (Hastings *et al.*, 2010). Except for sugar cane from Brazil, which may have energy balances as high as 8, and palm oil, with an energy balance around 9 (figure 7, FAO, 2008 as before), these crops may not be very efficient in terms of energy balances and reduction of greenhouse gas emissions. It has been argued that there is some scope for greenhouse gas emission savings, for example, by reducing nitrogenous fertilizer application and transport and processing costs (Kindred *et al.*, 2008), and that they are a step to more efficient processes under development. It has also been pointed out that coproducts from the production of biofuels from wheat and rape are protein-rich and can be used to avoid the cultivation and import of animal feed (Lywood, Pinkney & Cockerill, 2009; Croezen *et al.*, 2010; Murphy *et al.*, 2011). Bioethanol from sugar cane is a more efficient combination of raw material and fermentation technology, mainly because this species is a high yielding tropical species and the bagasse is used to provide heat for all of the processes. This results in a CI that is about 30% that of petrol. The largest energy inputs for these fuels are in fertilizer manufacture and in fermentation or distillation processes.

The disadvantages of this scenario are that

(a) The use of the grain of these crops for bioenergy competes directly with their use for food. This is perceived as morally wrong and risks causing prices of food to rise as supplies tighten. Use of grain for bioenergy may be more acceptable where there are exportable surpluses such as in more well-off developed countries. Such use can become disastrous in developing nations with fragile farming systems and supply chains, in which cash-generating exports are given preference over securing cheap local food supplies. In South Africa, Parliament decreed in 2007 that maize would no longer be used for bioenergy as it was considered a staple food crop (Diaz-Chavez *et al.*, 2010). In the case of oats, it has been argued in Scandinavia that it is acceptable for surplus or damaged grains to be used (Bäfver *et al.*, 2009). We doubt that large quantities of damaged grain exist. Woods *et al.* (2009) have flagged up the flexibility of use of these food crops for food or for feedstock, highlighting the severe competition that can result when the 'signal for new demand (often policy instigated) exceeds the ability of producers to respond with increased production or when climate negatively affects yield in major supplying regions'.

(b) As many of these crops are annuals, they require large amounts of inputs in terms of energy to establish and manage and in terms of fertilizer and as shown above have low energy balances.

(c) The use of palm and sugar cane has, directly or indirectly, encouraged destruction of native forests with severe negative effects on carbon sequestration and biodiversity.

To ensure that supplies of raw materials are sustainable, the EU has set sustainability criteria in the Directive 2009/28/EU. These include the preservation of native ecosystems and minimum greenhouse gas emission savings of 35% compared with fossil fuels and should not be derived from raw materials obtained from land with high biodiversity or high soil carbon stocks.

2. The crop residues of annual staple cereals such as wheat, maize and sorghum consisting of stems, threshed ears or husks, and senesced leaves are used for bioenergy, whereas the grain is used for food, feed or bioenergy. This is largely the model used by the Elean dedicated power station near Ely in Cambridgeshire in the United Kingdom, the largest straw-burning power station in the world (http://www.eprl.co.uk/assets/ely/overview.html). Other residues include groundnut (*Arachis hypogaea* L), palm and rice (*Oryza sativa* L.) husks.

The disadvantages of this scenario are that

(a) The low bulk density of straw limits transport costs to a finite radius from the plant. In the case of the Elean power station, this radius is 60 km. To secure sufficient supplies, the area around the plant has to have a high density of cereal growing. The yield of harvestable residues at around 2–3 t ha^{-1} compares unfavourably with the yields that can be obtained from dedicated energy crops.

(b) The use of straw for bioenergy competes with other applications, such as the use of straw for animal bedding or for upgrading to feed for ruminants.

(c) From a resource viewpoint, it may be more sustainable to chop and plough the crop residue into the soil. The removal of straw represents a major loss of carbon and nutrients from the system. Incorporation will preserve 10–20% of the carbon in the soil organic matter and improve soil fertility.

3. Dedicated lignocellulosic 'next generation' perennial energy crops are grown for their high yields of biomass. Being perennial, these crops can be grown for 15–30 years without having to be re-established. Thus, the cost of establishment can theoretically be spread over a number of years although of course the money has to be invested 'up-front'. From a harvest point-of-view, the crops can be divided into those such as perennial grasses that need to be harvested annually and short-rotation coppice tree species such as willow and poplar which can be typically harvested at 2 or 3 years intervals.

These perennial crops are highly efficient in recycling nutrients. Perennial grasses include *Miscanthus*, an Asian grass in which *M. x giganteus* (Hodkinson & Renvoize, 2001) is widely grown in Europe, switchgrass (*Panicum virgatum* L.), a native prairie grass in the United States and reed canary grass (*Phalaris arundinacea* L.) adapted to northern latitudes. In autumn, these grass species senesce and nutrients are translocated to underground storage organs before the biomass is harvested. This minimizes the nutrient offtakes and thus increases the energy output/input ratio. In contrast, nutrients are stored in stems in deciduous tree species, such as willow (*Salix* spp) and poplar (*Populus* spp.).

Dedicated perennial energy crops can be used for bioenergy in many ways. This includes thermal conversions and biofuel production. The latter includes chemical and biological conversion of the cellulose and hemicellulose that make up 75% of the dry matter of these crops (Hoekman, 2009; Naik *et al.*, 2010; Sims *et al.*, 2010). Cellulose, like starch, is a polymer of glucose, but is 100 times less fermentable than starch. Glucose of course can readily be converted to ethanol. Hemicellulose is a polymer of xylose and arabinose. The most efficient use of these crops would be through the biorefinery concept, where chemicals from these renewable sources are derived much in the same way as petro-chemicals are produced in the petroleum supply chain. Biorefineries would bring considerable added value to the use of dedicated perennial energy crops. Biomass-based second generation ethanol and biodiesel are expected to make up 7% and 6.5%, respectively, of total world production of these fuels by 2019 (OECD-FAO, 2010).

The distinct advantages of perennial energy crops compared with food crops in terms of greenhouse gas emissions is dealt with in later sections of this review.

The disadvantages of dedicated perennial energy crops are:

(a) By definition, they have no other major use than for the production of bioenergy and biorenewable chemicals. In the United States, it has been suggested that hay production is an alternative use of switchgrass. This is less likely in *Miscanthus*, which is used in Europe, due to it having sharp serrated edges to the leaves. However, there are breeds of horses and cattle in Japan which graze *Miscanthus* (Hirata *et al.*, 2007).

(b) Like straw from cereals, low bulk density increases transport costs, making it more suitable for local use.

(c) Most of the crops are vegetatively propagated, which considerably increases costs of propagation. The two main energy crops in Europe, *Miscanthus* and short-rotation coppice willow, are propagated by rhizomes and cuttings, respectively. This deters uptake by farmers even when planting grants have been provided, and necessitates that the crop be kept for a number of years to spread the cost of establishment. Switchgrass is propagated by seed. Considerable research is being devoted to producing *Miscanthus* that can be propagated much more cheaply from seed (Clifton-Brown et al., 2011).

(d) Current farm-level constraints to the growing of energy crops include the perception of low financial returns and lack of robust supply chains (Sherrington *et al.*, 2009; Valentine *et al.*, 2009).

(e) Whereas the crops mentioned under option 1 produce substrates that are readily converted to biofuels, methods of production of biofuels such as bioethanol from lignocellulose substrates are not yet economic.

4. Multifunctional crops, that is, crops that can be used for bioenergy and other purposes. Ideally, these would be nonfood crops. The biorefinery concept would be as applicable to these crops as to dedicated perennial energy crops.

Two examples of multifunctional energy crops are

(a) High sugar perennial ryegrasses (HS PRG; *Lolium perenne* L.). These have been developed at IBERS for use in pastures for grazing by ruminants leading to more efficient production of milk and meat but they are also well suited for the production of biofuels through utilizing the sugars and the lignocellulose. An advantage of using existing grasslands for bioenergy is that there is no disturbance of carbon sinks.

(b) Jerusalem artichoke (*Helianthus tuberosus* L) can be used as a vegetable, extraction of inulin (a fructose polymer) to provide dietary health benefits for obesity, diabetes and several other conditions, and as a crop for biofuels. The crop produces fructose in stems and stores it in its tubers. It can grow in a variety of soils, and it is not demanding of soil fertility. Most of the fructose produced in the leaves is only translocated to tubers at a late stage of development, so it is possible to harvest stems annually as has been demonstrated in Spain by Curt *et al.* (2006), and produce ethanol with inulin adapted strains of yeast (Matías *et al.*, 2011). The yields are lower than those of the tuber, but the cost per tonne of fructose is less as lifting of tubers from the soil and annual establishment are avoided. Yields of up to 10.4 t ha^{-1} of total sugars (mainly fructose) have been reported.

Disadvantages of these crops include

(a) Alternative uses may compromise the value and use of these crops for bioenergy. Thus, HS PRG clearly could be used for animal production perhaps in response to fluctuating economic returns. This would make the availability of raw materials for bioenergy unpredictable.

(b) HS PRG requires high levels of N fertilizer which makes their energy balance less attractive. Growing them with legumes that fix N is currently being examined.

The use of forest plantations or seminatural woodlands, or thinnings or coproducts from these plantations and woodlands, will not be discussed as they are not part of the competition for agricultural land. Short-rotation forestry, in which the tree 'crop' is ready for harvest after say 8 years, can be regarded as an extreme form of short-rotation coppice used for willow and poplar. Furthermore, for the most part, the extent of forests and seminatural woodlands is fixed (or in the case of rain forests diminishing at alarming rates), and they are largely being used because 'they are there'. In our opinion, the wood may be too valuable, the long lead in time to harvest and high costs of extraction due to semimechanical harvesting are not favourable for sole use as bioenergy. Hedenus & Azar (2009) have shown that bioenergy plantations are a better mitigation strategy than long-rotation forests at higher carbon prices pursed under a stringent climate policy.

The use of perennial energy crops for the production of lignocellulosic 'next generation' biofuels

We consider that the dedicated crops described under three for the production of next generation biofuels as the best option as it does not compete directly for use for food, does not require large amounts of inputs in terms of annual cultivation and fertilizer application, nor involve the destruction of native forests with severe negative effects on carbon sequestration and biodiversity. (For the effects of perennial energy crops on biodiversity and other environmental aspects, see Semere and Slater, 2007a,b; Fry & Slater, 2008; Clapham & Slater, 2008; Bellamy *et al.*, 2009; Rowe *et al.*, 2009;

Haughton *et al.*, 2009). The advantages of high yields, high energy balances, concomitant reductions in greenhouse gas emissions and generally favourable effects on biodiversity and other environmental aspects are generally accepted to outweigh the disadvantages, in which there is considerable technology-driven scope for development of next generation biofuels (e.g. US DOE, 2006; Gomez *et al.*, 2008; Royal Society, 2008; Rubin, 2008; Woods *et al.*, 2009; IEA, 2010a; Murphy *et al.*, 2011).

It should be noted that although biorefining is not considered further, this option is not precluded by the production of biofuels since residues or a part of the cellulose and hemicelluloses fraction could be used to produce homologues of existing petro-chemicals and their derivatives.

There has been considerable investment worldwide focussed on the development of energy crop production and conversion from lignocellulose, with R&D funding from governments (particularly the Department of Energy in the USA and the Department of the Environment, Food and Rural Affairs in the United Kingdom), from the European Union (through projects such as New Improvements for Ligno-cellulose Ethanol; http://www.nile-bioethanol.org/), from oil companies notably BP and from research funders, such as BBSRC in the United Kingdom. This investment needs to be sustained and also focused on demonstration at scale (Murphy *et al.*, 2011). As for the development of food crops, the development of energy crop production will take a considerable research effort to come to fruition (Robertson *et al.*, 2008).

We would like to consider two aspects relating to the use of perennial energy crops for the production of lignocellulosic ‘next generation’ biofuels, namely their yields and their composition.

For yield, *Miscanthus* appears to be the energy grass most adapted to Northern Europe. It has also performed well in other areas such as Illinois, USA (Heaton *et al.*, 2004, 2008). Peak autumn yields of mature stands of *Miscanthus* range from 14 t ha^{-1} in United Kingdom to 50 t ha^{-1} in more southern warmer latitudes such as in the United States (Heaton *et al.*, 2008). The current practice is to delay harvest until the spring in order to obtain higher dry matter content (reduced moisture) and lower mineral content. Lower moisture content aids transportation and improves gross calorific value. Lower mineral content, arising through translocation to rhizomes, reduces nutrient offtake and the level of potentially corrosive minerals. Delayed harvest results in a reduction in yield of around 23–53% depending on location and harvest time (Lewandowski & Kicherer, 1997; Lewandowski *et al.*, 2003). Scope exists for selecting for traits that impact on nutrient mobilization, such as senescence (Robson *et al.*, 2011), which may have less impact on yield and improves chemical composition.

High productivity arises from a combination of characteristics: for example photosynthesis is of the C4 type with a maximum conversion efficiency of intercepted light (εc) into biomass that is potentially 40% higher than that of C3 photosynthesis (Monteith, 1978). Furthermore, *Miscanthus* is cold tolerant which is unusual in C4 species, which are mostly tropical and subtropical in origin and are therefore poorly adapted to cold, temperate environments. In side-by-side trials, *Miscanthus* was 59% more productive than grain maize (another C4 crop) in the Midwestern USA (Dohleman & Long, 2009) due to earlier emergence, later senescence and greater radiation interception through the growing season.

Field *et al.* (2008) dismissed increasing yield as a means of increasing the potential contribution of biomass, for instance, on the basis that average net photosynthetic productivity (NPP) in biomass energy plantations over the next 50 years is unlikely to exceed the NPP of the ecosystems that they replace and that modelled higher yield projections at the higher end of the range tend to be based as much on optimistic extrapolation as on analysis. The current authors refute this for two reasons.

First, we see no real reason why the average NPP in biomass plantations should not exceed the NPP of the ecosystems that they replace. In the wild, high biomass *per se* may not confer adaptive advantage. In many ecosystems, seed production may be more important than vegetative growth. Even in resource rich environments (e.g. with plentiful nutrients, water and solar radiation), plants either need to exploit a different niche or else out-compete their neighbours.

Secondly, we consider that there is real scope for improving the genetic potential of energy grasses. Half of the annual increase (2% per annum) in maize grain yields of Iowa (USA) in the last 30 years is estimated to be due to 12 days on average earlier planting than in 1979, thus allowing the crop to capture more radiation (Fischer & Edmeades, 2010). Greater rates of progress can be expected in the largely unimproved energy grass crop which has received very little breeding effort to date. Long *et al.* (2006), Zhu *et al.* (2010) and Heaton *et al.* (2008) have also identified scope for improving the rate of leaf photosynthesis in energy and food crops. The theoretical potential peak autumn yield based on photosynthetic rates for *Miscanthus* growing with ample water in England has been estimated at 32 t ha^{-1} (Long *et al.*, 1990). This would equate to a spring harvestable yield of ca. 25 t ha^{-1}, which is approximately twice the UK national harvested average yield of 12 t ha^{-1} (Clifton-Brown *et al.*, 2004) predicted by the MISCANFOR model (Hastings *et al.*, 2009b). We predict, by incorporating the physiological traits discussed before, that the national average harvestable yield could reach 18 t ha^{-1}

by 2030 if rainfall patterns remain fairly static. The recent analysis by Hastings *et al.* (2009b) took account of predicted changes in climate (IPCC, 2007) and these showed that the distribution of land areas suitable for production in Europe may shift northwards and eastwards during the next 20–40 years. Varieties with superior drought and frost resistance will be needed if the yield of *Miscanthus* in Europe is to be maintained.

The majority of energy stored in biomass from lignocellulosic grass species is contained within the dense polymers of the cell wall, the major component of dried biomass by weight. The concentration and composition of the cell wall are thus key factors affecting biomass quality, that is, its suitability for conversion to heat, power and chemical products. Typical published compositions for several spring harvested biomass crops are shown in Table 1. The differences in composition reported by Allison *et al.* (2010), Hodgson *et al.* (2010b) and Karp & Shield (2008) are most likely due to genetic and environmental effects. Biomass from tree species generally contains higher concentrations of acid detergent lignin (ADL) with softwood species, such as pine generally containing more lignin and less cellulose than hardwoods (McKendry, 2002) and values given for willow and poplar fall within these typical limits (Karp & Shield, 2008).

The concentration and composition of the cell wall affects the digestibility of plant material when fed as forage to cattle and sheep (Hatfield *et al.*, 1999) and also its utility for lignocellulosic fermentation (Grabber, 2005; Chheda *et al.*, 2007; Doran-Peterson *et al.*, 2008; Gressel, 2008; Pauly & Keegstra, 2010). Although the carbohydrate polymers of the cell wall are a rich source of fermentable sugars, in practice the utility of this reserve is limited by the lignin. High levels of lignin often require feedstocks to be subjected to aggressive pretreatment steps using heat, acid and alkali before effective deconstruction of the lignocellulose matrix with hydrolytic enzymes can be achieved (Lu & Mosier, 2008). This can result in the formation of compounds that inhibit microbial growth and subsequent fermentation (Tran & Chambers, 1985; Jung & Vogel, 1986; Klinke *et al.*, 2004). The reduction of lignin content in bioenergy crops would therefore be a strategy of biomass improvement for biological conversion (Chen & Dixon, 2007; Li *et al.*, 2008). In contrast, increasing lignin content would improve calorific value and energy density for thermochemical conversion processes, such as combustion and co-combustion with coal, fast pyrolysis to char and liquid oil products and gasification to synthetic gas, itself a feedstock for the production of many industrial platform chemicals (Fahmi *et al.*, 2008; Allison *et al.*, 2009, 2010; Hodgson *et al.*, 2010a).

In addition to the composition of the cell wall biomass the suitability of particular biomass feedstocks for some thermochemical processes may be compromised by unacceptably high concentrations of alkali minerals. This results in the formation of ashes with low-melting points and can lead to blockage and slagging of combustion equipment (Jenkins *et al.*, 1998; Allison *et al.*, 2010). Whilst this is often considered a problem primarily of energy grass crops (Lewandowski & Kicherer, 1997; Bakker & Elbersen, 2005; Monti, Di Virgilio & Venturi, 2008; Wrobel *et al.*, 2009), it may also be a factor to consider with coppice grown tree species. Biomass from short rotation coppice willow, for example, has been shown to contain high levels of bark compared with forest timber and as such may contain unacceptably high concentrations of alkaline metals (Adler *et al.*, 2005) and it may also be possible to improve composition by increasing the wood to bark ratio and optimizing stem thickness.

The improvement of biomass crops is therefore complex and requires thorough understanding of cell wall composition and plant architecture, and it will be necessary to understand how changing these parameters may affect plant physiology, development and disease resistance. At present, studies in model species, such as maize and poplar have indicated that lignin is the most realistic target for genetic improvement and many studies have shown that lignin concentration and composition can be altered by mutation (Vignols *et al.*, 1995;

Table 1 Concentration (%DW) of lignin (ADL), hemicellulose and cellulose for biomass crop species reported in the literature

Species	Lignin %	Hemicellulose %	Cellulose %	Source
Miscanthus	9.2	33.7	42.6	Allison *et al.* (2010)
	9.5–9.8	26.3–30.5	44.8–48.1	Hodgson *et al.* (2010a,b)
	10.5	15.9	57.6	Karp & Shield (2008)
Switchgrass	6.1	36.0	31.6	Karp & Shield (2008)
	5–20	10–40	30–50	McKendry (2002)
Softwood	27–30	25–30	35–40	McKendry (2002)
Hardwood	20–25	20–25	45–50	McKendry (2002)
Poplar	20	23	40	Karp & Shield (2008)
Willow	19	14	56	Karp & Shield (2008)

Halpin *et al.*, 1998; Barriere *et al.*, 2004), and transgenic intervention (Anterola & Lewis, 2002; Vanholme *et al.*, 2008). Progress with crop species is not so advanced. Whilst it is likely that manipulation of lignin in willow will benefit from the genetic resources available for poplar, very few resources are available currently for crop species, such as *Miscanthus* and switchgrass, which are relatively undomesticated. Although most efforts to improve crop species have focused on breeding, for example, Clifton-Brown *et al.* (2008), Bouton (2008) and Smart & Cameron (2008); it is likely that there will be considerable advancements in the genetic manipulation of energy grass species in the near future as resources become available (e.g. Fu *et al.*, 2011).

Land areas available for food and lignocellulosic 'next generation' perennial energy crops

Land availability depends upon a range of direct and indirect factors. Smith *et al.* (2010), in a recent review on factors affecting competition for land, categorized these drivers as pressures. *Pressures* represent *direct causes*, the visible motivations for competition for land, for example, urban development, floods, climate change, land degradation. *Drivers* (*underlying causes*) for competition are factors of higher causal order that determine the degree of the actual direct pressures, for example, population growth, changes in dietary preference, macroeconomic changes and unknown policies in relation to agriculture, biodiversity, carbon, etc. Consequently, land availability for energy crops cannot be predicted with certainty but can be studied through the construction of scenarios using projected changes in the drivers and pressures affecting land availability (van Vuuren *et al.*, 2006, 2008; Smith *et al.*, 2010). The range of scenarios used in modelling exercises to date generates a great diversity in projections of land availability for food and energy crops (van Vuuren *et al.*, 2008). The use of different land-use and land-allocation models adds further to the diversity of the projections. Projections of future policy impact will always contain a degree of uncertainty but improved models, data and more sophisticated scenarios will allow uncertainties to be reduced (although not eliminated) in the future (Smith *et al.*, 2010).

In identifying scenarios and collecting data for land-use models to project how we can sustainably produce both food and fuel in an ever changing climate, we believe it is important to take the following aspects into account.

1. The diet and prosperity of the world population defining the animal protein, vegetable and grain mix of food requirements.
2. The land left over, if any, when food and feed crop demand has been met, taking into account the predicted effects of climate change
3. Energy crops are deep rooted perennials which may be more economic than food crops on so-called marginal lands or on agriculturally degraded and abandoned lands (Tilman *et al.*, 2006; Campbell *et al.*, 2008).
4. Gains in productivity of crop (including food, feed and energy crops) and animal production. Hastings *et al.* (2009b) have modelled the effect of producing a 'hi-tech *Miscanthus* genotype with improved drought and frost resistance. Wirsenius *et al.* (2010) found that faster, yet achievable growth in animal food productivity than the FAO assumes would lead to global agricultural land use decreasing by about 230 million ha from current levels by 2030 or about 500 million ha lower than in the reference scenario, that is, the area implied in the FAO projections.
5. The extent to which global agricultural land use can be decreased by a reduction in nonsustainable overconsumption of meat, substitution of pig and/or poultry for ruminant meat in human diets, and lower food wastage. Wirsenius *et al.* (2010) found that 20% substitution of pig and/or poultry for ruminant meat in human diets would lead to global agricultural land use decreasing by 480 million ha, resulting in about 1000 million ha less than the reference scenario. In relation to a 25% decrease in meat consumption per capita and 15–20% lower food wastage at retail and household levels, agricultural land use decreases by about 15% in high-income regions.
6. The economic value of bioenergy production (provisioning ecosystem services), the associated value of reduced greenhouse gas emissions and carbon sequestration (regulatory ecosystem services) and other societal gains arising from biofuels.

Greenhouse gas emissions from food and lignocellulosic 'next generation' perennial energy crops

Agricultural lands occupy 37% of the earth's land surface (Smith *et al.*, 2008). Agriculture accounted for an estimated emission of 5.1–6.1 bn t CO_2-eq. yr^{-1} in 2005 (10–12% of total global anthropogenic emissions of GHGs). Methane (CH_4) contributes 3.3 bn t CO_2-eq. yr^{-1} and nitrous oxide (N_2O) 2.8 bn t CO_2-eq. yr^{-1}. Of global anthropogenic emissions in 2005, agriculture accounts for about 60% of N_2O and about 50% of CH_4. Despite large annual exchanges of CO_2 between the atmosphere and agricultural lands, the net flux is estimated to be approximately balanced, with CO_2

emissions around 0.04 bn t CO_2 yr^{-1} only (Smith *et al.*, 2007). Globally, agricultural CH_4 and N_2O emissions have increased by nearly 17% from 1990 to 2005, an average annual emissions increase of about 60 million t CO_2-eq. yr^{-1}. During that period, the five regions composed of developing countries showed a 32% increase, and were, by 2005, responsible for about three quarters of total agricultural emissions. The other five regions, mostly industrialized countries, collectively showed a decrease of 12% in the emissions of these gases (Smith *et al.*, 2007).

Greenhouse gas emissions from annual food crops are on average higher than emissions from 'next generation' perennial lignocellulosic energy crops, since almost all annual food crops (except legumes) require significant input of fertiliser nitrogen (Williams *et al.*, 2006; Hillier *et al.*, 2009a), leading to N_2O emissions. N_2O is a greenhouse gas around 300 times more potent than carbon dioxide (Smith *et al.*, 2008). It should be borne in mind, however, that higher yields since 1961, the start of the so-called Green Revolution, have also avoided emissions of up to 161 bn t of carbon, outweighing emissions from increased fertiliser application (Burney *et al.*, 2010). In contrast, perennial energy crops tend to require less nitrogen fertilizer less often (St Clair *et al.*, 2008). In addition to a reduction in N_2O emissions compared with annual food crops, perennial crops require the soil to be deep ploughed only once before crop establishment (St Clair *et al.*, 2008). In contrast, for annual food crops, the soil is usually ploughed at least once per year (except in zero tillage systems which still occupy limited areas globally; Smith *et al.*, 2008). This soil disturbance leads to loss of carbon from the soil organic matter. Perennial energy crops also tend to add more litter to the soil than annual food crops (since they are present all year round rather than during a specific crop season), and also tend to provide more recalcitrant, lignocellulosic litter (Dondini *et al.*, 2009; Hastings *et al.*, 2009a,b). These factors combine to give higher soil carbon stocks (and therefore reduced carbon dioxide losses) under perennial energy crops compared with annual food crops (Dondini *et al.*, 2009; Hillier *et al.*, 2009b).

For all crops, minimizing GHG emissions per unit of product is desirable, so increased productivity helps in this respect (Audsley *et al.*, 2009; Burney *et al.*, 2010; Godfray *et al.*, 2010; Smith *et al.*, 2010). Such is the negative impact of annual food cropping that Glover *et al.* (2010) have called for the development of perennial grain crops as a means of maintaining important ecosystem services. Although not mentioned explicitly, this would have a major effect on reducing greenhouse gas emissions.

St Clair *et al.* (2008) estimated annual GHG emissions for annual food crops (winter wheat and oil seed rape) and for two lignocellulosic perennial energy crops (*Miscanthus* and short-rotation willow). The energy crops under typical management resulted in GHG emissions of 0.4–0.5 t CO_2-eq. ha^{-1} yr^{-1}, compared with emissions in excess of 2 t CO_2-eq. ha^{-1} yr^{-1} for oil seed rape and winter wheat under typical management, that is, the GHG emissions from annual food crops were over five times higher than emissions from perennial energy crops (St Clair *et al.*, 2008). The actual emissions from any crop also depend upon where the crop is grown. If land use change from perennial vegetation is involved, the GHG balance can be unfavourable, even for perennial energy crops, but the impact of conversion of similar land to annual food cropping always results in higher GHG emissions (St Clair *et al.*, 2008).

The economic value of regulatory and provisioning ecosystem services from biofuels

The concept of ecosystem services is one that humankind has been aware of, albeit subconsciously, for millennia. It appears to have come into widespread use in the 1990s. The review by Rapport *et al.* (1998) refers to 'services' provided by ecosystems being extremely important to human welfare.

Four categories of ecosystem services were defined by the Millennium Ecosystem Assessment (MEA, 2005). These were provisioning services, such as food, timber, water and fibre; regulatory services, that affect climate, floods, wastes and water quality; cultural services that provide recreational, cultural and spiritual benefits and supporting services such as soil formation, photosynthesis and nutrient recycling.

The value of noncommodity outputs of multifunctional agriculture has also been considered in terms of economic market-led value and prices (IAASTD, 2008).

The value of biofuels' provisioning services can be directly priced in terms of its monetary value. We have expressed this in terms of barrels of oil equivalent.

The value of barrels oil equivalent for EU derived from Hastings *et al.* (2009b) (assuming use of 10% of arable land) is \$6.60 bn per annum at a price of crude oil per barrel of \$50, \$13.21 bn at a price of crude oil per barrel of \$100 and \$15.85 bn at the April 2011 price of crude oil per barrel of \$120 for the parameters for the genotype *M. x giganteus* assuming 1960–1990 climate, only \$1.93 bn at a price of crude oil per barrel of \$50, \$3.86 bn at a price of crude oil per barrel of \$100 and \$4.63 bn at a price of crude oil per barrel of \$120 for the parameters for M. *x giganteus* under the SRES A2 climate in 2080 (due to this genotype not being able to cope with the changed climate) and \$8.79 bn at a price of crude oil per barrel of \$50, \$17.58 bn at a price of crude oil per barrel of \$100 and \$21.10 bn at a price of crude oil per barrel of $120 for new parameters for new drought and frost tolerant hybrids under the SRES A2 climate in 2080. On a world level, ITPOES (2010) estimated current biofuels to account for 1.5 million barrels per day (Mb day^{-1}) out of total demand of 85 Mb day^{-1}. This would value biofuels' provisioning services as $75 million per day ($27.4 bn per annum) at a price of crude oil per barrel of $50 per barrel, $150 million per day ($54.7 bn per annum) at a price of crude oil per barrel of $100 per barrel and $180 million per day ($65.64 bn per annum) at a price of crude oil per barrel of $150 per barrel. Under the IEA BLUE map/shift scenarios for 2050 (IEA, 2010a; Murphy *et al.*, 2011), the use of biofuels could be 9 Mb day^{-1}, which would value biofuels' provisioning services as $165 bn per annum at a price of crude oil per barrel of $50 per barrel, $330 bn per year at a price of crude oil per barrel of $100 per barrel and $396 bn per year at a price of crude oil per barrel of $120 per barrel. The potential value of biofuels' provisioning services based on the land areas available for lignocellulosic 'next generation' perennial energy crops indicated by new land-use models could be much higher. These figures do not take into account the many benefits to rural and urban farmers arising from the use of bioenergy or biofuels.

Although it is more difficult to value ecosystem services (MEA, 2005) or noncommodity outputs of multifunctional agriculture (IAASTD, 2008) in terms of economic market-led value and prices (Heal, 2000), carbon sequestration can be valued, since carbon prices have been introduced. While these are currently at low, although not insignificant, levels (€14.35 t^{-1} Jan 2011 spot price on European Climate Exchange), much higher prices of carbon would drive carbon reduction and the development and uptake of 'game-changing' low carbon technologies (UKERC, 2009). Practical issues are how carbon mitigation is measured, particularly whether this can be done enterprise by enterprise or by broader brush which risks rewarding less efficient or bad practices. The value of carbon equivalents mitigated for EU derived from Hastings *et al.* (2009b) is $170.9 million per annum at a carbon price of $10 t^{-1} and $683.7 million per annum at a carbon price of $40 t^{-1} for the parameters for the genotype *M. x giganteus* assuming 1960–1990 climate, only $51.3 million per annum at a carbon price of $10 t^{-1} and $205.1 million per annum at a carbon price of $40 t^{-1} for the parameters for *M. x giganteus* under the SRES A2 climate in 2080, and $225.5 million per annum at a carbon price of $10 t^{-1} and $ 901.9 million per annum at a carbon price of $40 t^{-1} for the parameters for new drought and frost tolerant hybrids under the SRES A2 climate in 2080. The value of carbon equivalent mitigated for the world based on the potential contribution of energy cropping to future global energy supplies from various studies cited by Smith *et al.* (2007) ranges from $13.6 to $55.6 bn at a carbon price of $10 t^{-1} and $55.6 to $ 218 bn at a carbon price of $40 t^{-1}.

The values of biofuels' provisioning and regulatory services must be set against the extent to which they receive government supports, the complexity of which was reported by Koplow (2006). It is estimated that worldwide government support for biofuels is currently $20 bn (IEA, 2010b). If the potential of biofuels is realized, then the rewards are much higher and support can be justified given the likelihood of higher oil and carbon prices on the basis of the value of benefits in terms of fuel security, GHG mitigation and the pump priming of new technologies particularly cellulosic ethanol. In any case, the size of the support of biofuels is small in relation to the cost of fossil fuel consumption subsidies amounted to $312 bn worldwide in 2009 (IEA, 2010b), to the cost of getting on track to meet the 2 °C climate goal for 2030 which has risen by about a $1 trillion from 2009 to 2010 (IEA, 2010b) and to the cost of total agricultural support for food and commodity crops estimated at $383.7 bn in 2009 (OECD, 2010).

Conclusions

Major investment is needed to increase world food production. This should be through sustainable intensification rather than through an expansion of agricultural land in order not to damage carbon sinks or biodiversity (Royal Society, 2009). Increasing food production in the face of the challenges of finite land, water and energy at a time of climate change will require considerable research and well-funded implementation programmes. In addition, food accessibility as well as food availability is important (OECD-FAO, 2010). Investments promoting income generation are needed to improve the ability to purchase food. The negative effects of agricultural subsidies in richer countries on poverty in developing countries have been often highlighted over the last 50 years. The reduction of waste is also needed. There are few grounds for complacency in the achievement of any of these challenges.

However, food production cannot be the only driver of land management decision making (Winter & Lobley, 2010). Ecosystems provide many services (Rapport *et al.*, 1998; MEA, 2005) that are extremely important to human welfare.

In this review, we present the vision for bioenergy in terms of four major gains for society.

First, bioenergy mitigates carbon emissions through substitution of fossil fuels and soil sequestration. The potential economic value of regulatory ecosystem services from biofuels from energy crops has been quantified in terms of the value of carbon equivalent mitigated. Worldwide estimates from various studies cited by Smith *et al.* (2007) ranges from \$13.6 to \$55.6 bn at a carbon price of \$10 t^{-1} and \$55.6 to \$218 bn at a carbon price of \$40 t^{-1}.

Secondly, bioenergy can make a significant contribution to energy security through reductions in fossil fuel dependence. Biofuels represent a source of liquid fuel that can be counted as part of oil reserves, with obvious implications to fuel security. On a world level, ITPOES (2010) estimated current biofuels to account for 1.5 Mb day^{-1} out of total demand of 85 Mb day^{-1}. Under the IEA BLUE map/shift scenarios for 2050 (IEA, 2010a; Murphy *et al.*, 2011), the use of biofuels could be 9 Mb day^{-1}. From these consumption figures, we can estimate the current potential economic value of provisioning ecosystem services from biofuels (ITPOES, 2010) as \$75 m per day (\$27.4 bn per annum) at a price of crude oil per barrel of \$50 per barrel and \$150 m per day (\$54.7 bn per annum) at a price of crude oil per barrel of \$100 per barrel. Most of this derives from first generation biofuels. Under the IEA BLUE map scenarios, the economic value of provisioning ecosystem services from biofuels is predicted to be \$165 bn per annum at a price of crude oil per barrel of \$50 per barrel and \$330 bn per year at a price of crude oil per barrel of \$100 per barrel. The potential value of biofuels' provisioning services based on the land areas available for lignocellulosic 'next generation' perennial energy crops could be much higher.

Thirdly, biofuels provide new options that stimulate rural and urban economic development. Energy crops provide new options for farmers and create jobs further up the supply chain (Thornley *et al.*, 2008). Most food cannot be eaten raw, refrigeration helps stores food, transportation is the life blood of trade, mechanical power is needed for many uses including grinding food and pumping water, and telephones and computers are of growing importance in modern life (AEEP 2010b). Bioenergy will be able to meet some of these needs, particularly those which involve the use of biomass for cooking in place of traditional nonsustainable sources of biomass (e.g. from deforestation) and the use of liquid biofuels. The development of biofuels as a source of energy when grown on a large scale could greatly enhance rural and urban economic development.

Fourthly, bioenergy has considerable untapped scope to reduce the high carbon footprint of food production and to uncouple food production from the costs and risk arising from high and volatile oil prices. More research is needed to connect the production of biomass resources on-farm and different forms of bioenergy leading to reduction of GHG emissions which can be credited to the farm and be used as bioenergy sources to offset the high carbon footprint of food production.

The major question is how we can use bioenergy without jeopardizing food production, carbon sinks and biodiversity. A main tenet of this review has been that the use of dedicated perennial lignocellulose energy crops, such as *Miscanthus* and willow will reduce direct competition with food. Improved models, data and more sophisticated scenarios are therefore needed to determine how much food and fuel can be produced from a finite land resource. As Mark Twain neatly put it: 'Buy land. They're not making it anymore'.

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References

ADAS (2003) *Renewable energy and its impact on rural development and sustainability in the UK*. DTI Report. Available at: http://seg.fsu.edu/Library/case%20of%20the%20UK.pdf.

Adler A, Verwijst T, Aronsson P (2005) Estimation and relevance of bark proportion in a willow stand. *Biomass and Bioenergy*, **29**, 102–113.

AEEP (2010a) *Africa-EU Renewable Energy Cooperation Programme*. Available at: http://www.africa-eu-partnership.org/sites/default/files/aeep_recp.pdf.

AEEP (2010b) *The Energy Challenge: Access and Security for Africa and for Europe*. Available at: http://www.africa-eu-partnership.org/sites/default/files/energy_partnership_aeep_communication_paper_en_0.pdf.

African Biodiversity Network, Biofuelwatch, EcoNexus, the Gaia Foundation, Salva La Selva and Watch Indonesia (2008) *Agrofuels and the Myth of the Marginal Lands*. Available at: http://www.econexus.info/pdf/Agrofuels_&_Marginal-Land-Myth.pdf.

Alexandratos N, Bruinsma J, Bödeker G, Schmidhuber J, Broca S, Shetty P, Ottaviani MG (2006) *World Agriculture: Towards 2030/2050. Food and Agriculture Interim Report*. Organization of the United Nations, FAO, Rome. Available at: http://www.fao.org/economic/esa/esag/en/.

Allison GG, Morris C, Hodgson E *et al.* (2009) Measurement of key compositional parameters in two species of energy grass by Fourier transform infrared spectroscopy. *Bioresource Technology*, **100**, 2428–2433.

Allison GG, Robbins M.P, Carli J, Clifton-Brown J, Donnison IS (2010) Designing biomass crops with improved calorific content and attributes for burning: a UK perspective. In: *Plant Biotechnology for Sustainable Production of Energy and Co-Products* (eds Mascia P, Schefrran J, Widholm JM), pp. 25–56. Springer-Verlag, Berlin & Heidelberg GmbH & Co. KG.

Anderson K (2010) Policy reforms affecting agricultural incentives: much achieved, much still needed. *World Bank Research Observer*, **25**, 21–55.

Anterola AM, Lewis NG (2002) Trends in lignin modification: a comprehensive analysis of the effects of genetic manipulations/mutations on lignification and vascular integrity. *Phytochemistry*, **61**, 221–294.

Audsley E, Brander B, Chatterton J, Murphy-Bokern D, Webster C, Williams A (2009) *How Low Can We Go? An Assessment of Greenhouse Gas Emissions from the UK Food System & the Scope to Reduce them by 2050. Study for WWF-UK and the Food Climate Research network.* WWF-UK, Godalming.

Bäfver LS, Rönnbäck M, Leckner B, Cleesson F, Tullin C (2009) Particle emission from combustion of oat grain and its potential reduction by addition of limestone or kaolin. *Fuel Processing Technology*, **90**, 353–359.

Bakker RR, Elbersen HW (2005) Managing ash content and quality in herbaceous biomass: an analysis from plant to product. *14th European Biomass Conference*, pp. 210–213, Paris.

Barriere Y, Ralph J, Mechin V *et al.* (2004) Genetic and molecular basis of grass cell wall biosynthesis and degradability. II. Lessons from brown-midrib mutants. *Comptes Rendus Biologies*, **327**, 847–860.

Bartis JT, LaTourette T, Dixon L, Peterson DJ, Cecchine G (2005). *Oil Shale Development in the United States Prospects and Policy Issues*. MG RAND Corporation, Santa Monica, CA.

Beddington JR (2009) *Food, Energy, Water and the Climate: A Perfect Storm of Global Events? Speech to Sustainable Development UK 09*. QEII Conference Centre, London. Available at: http://www.govnet.co.uk/news/govnet/professor-sir-john-beddingtons-speech-at-sduk-09.

Bellamy PE, Croxton PJ, Heard MS *et al.* (2009) The impact of growing miscanthus for biomass on farmland bird populations. *Biomass and Bioenergy*, **33**, 191–199.

Bouton J (2008) Improvement of switchgrass as a bioenergy crop. In: *Genetic Improvement of Bioenergy Crops* (ed. Vermerris W), pp. 295–308. Springer- Verlag, New York.

Bradbury D (2010) Can tar sands really ever be sustainable? *Businessgreen*, 24 August 2010. Available at: http://www.businessgreen.com/business-green/news/2268616/tar-sands-really-green.

Bullion A (2010). Crop research essential for food security. *Comment and Analysis Agra Europe*, July, pp. 30–32.

Burney JA, Davis SJ, Lobell DB (2010) Greenhouse gas mitigation by agricultural intensification. *Proceedings of the National Academy of Sciences USA*, **107**, 12052–12057.

Campbell JE, Lobell DB, Genova RC, Field CB (2008) The global potential of bioenergy on abandoned agriculture lands. *Environmental Science and Technology*, **42**, 5791–5794.

Chen F, Dixon RA (2007) Lignin modification improves fermentable sugar yields for biofuel production. *Nature Biotechnology*, **25**, 759–761.

Chheda JN, Roman-Leshkov Y, Dumesic JA (2007) Production of 5-hydroxymethylfurfural and furfural by dehydration of biomass-derived mono- and poly-saccharides. *Green Chemistry*, **9**, 342–350.

Clapham SJ, Slater FM (2008) The biodiversity of established biomass grass crops. Biomass and energy crops III. *Aspects of Applied Biology*, **90**, 325–329.

Clifton-Brown JC, Stampfl PF, Jones MB (2004) Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. *Global Change Biology*, **10**, 509–518.

Clifton-Brown JC, Robson P, Allison G *et al.* (2008) Miscanthus: breeding our way to a better future. In: *Biomass and Energy Crops*, III (eds Booth E, Green M, Karp A *et al.*), pp. 199–206. Association of Applied Biologists (AAB), Warwick.

Clifton-Brown JC, Robson P, Sanderson R *et al.* (2011) Thermal requirements for seed germination in *Miscanthus* compared with Switchgrass (*Panicum virgatum*), Reed canarygrass (*Phalaris arundinaceae*), Maize (*Zea mays*) and perennial ryegrass (*Lolium perenne*). *Global Change Biology Bioenergy* (accepted).

Cohen JE (2005) Human population grows up. *Scientific American*, **293**, 48–55.

Croezen HJ, Bergsma GC, Otlen MB, Van Valkengoed MPJ (2010) *Biofuels: Indirect Land Use Change and Climate Impact*. CE Delft, Delft.

Curt MD, Aguado P, Sanz M, Sánchez G, Fernández J (2006) Clone precocity and the use of *Helianthus tuberosa* l. stems for bioethanol. *Industrial crops and Products*, **24**, 314–320.

Defra (2006) *Food Security and the UK: An Evidence and Analysis Paper*, Food Chain Analysis Group, December 2006. Available at: http://www.defra.gov.uk/evidence/economics/foodfarm/reports/documents/foodsecurity.pdf.

Delgado C, Rosegrant M, Steinfield H, Ehui S, Courbois C (1999). *Livestock to 2020: the next food revolution. Food, Agriculture, and Emvironment*. Discussion Paper No. 28. International Food Policy, Research Institute, Washington DC.

Deutch J, Schlesinger JR, Victor DG (2006) *National security consequences of U.S. oil dependency*. Task Force Report No. 58, Council of Foreign Relations Press, New York.

Diaz-Chavez R, Mutimba S, Watson H, Rodriguez-Sanchez S, Nguer M (2010) *Mapping Food and Bioenergy in Africa*. A report prepared on behalf of FARA. Forum for Agricultural Research in Africa, Ghana.

Dohleman FG, Long SP (2009) More productive than maize in the Midwest: how does Miscanthus do it? *Plant Physiology*, **150**, 2104–2115.

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

Donnelly J (2011) Editorial: performance statistics. *Journal of Petroleum Technology*, **63**, 1–8.

Doran-Peterson J, Cook DM, Brandon SK (2008) Microbial conversion of sugars from plant biomass to lactic acid or ethanol. *The Plant Journal*, **54**, 582–592.

Elwood PC, Pickering JE, Givens DI, Gallacher JE (2010) The consumption of milk and dairy foods and the incidence of vascular disease and diabetes: an overview of the evidence. *Lipids*, **45**, 925–935.

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

Evans A. (2009) *The Feeding of the Nine Billion: Global Food Security for the 21st Century*. A Chatham House Report, Royal Institute of International Affairs, London. Available at: http://www.chathamhouse.org.uk/publications/papers/view/-/id/694/.

Fahmi R, Bridgwater AV, Donnison IS, Yates N, Jones JM (2008) The effect of lignin and inorganic species in biomass on pyrolysis oil yields, quality and stability. *Fuel*, **87**, 1230–1240.

FAO (2008) *The State of Food and Agriculture 2008. Part 1. Biofuels: Prospects, Risks and Opportunities*. FAO, Rome.

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

Fischer RA, Edmeades GO (2010) Breeding and cereal yield progress. *Crop Science*, **50**, S85–S98.

Fry DA, Slater FM (2008) Theeffects on plant communities and associated taxa of planting short rotation coppice in Wales. Biomass and energy crops III. *Aspects of Applied Biology*, **90**, 287–293.

Fu C, Mielenz JR, Xiao X *et al.* (2011) Genetic manipulation of lignin reduces recalcitrance and improves ethanol production from switchgrass. *Proceedings of the National Academy of Sciences*, **108**, 3803–3808.

Garnett T (2008) *Cooking Up a Storm: Food, Greenhouse Gas Emissions and Our Changing Climate*. Food Climate Research Network, Centre for Environmental Strategy, University of Surrey. Available at: http://www.fcrn.org.uk/fcrnPublications/publications/PDFs/CuaS_web.pdf.

Gewin V (2010) Food an underground revolution. *Nature*, **466**, 552–553.

Gilbert N (2010) Food inside the hothouses of industry. *Nature*, **466**, 548–551.

Gilbert P, Thornley P (2010) Energy and carbon balance of ammonia production from biomass gasification. *Poster at Bio-Ten Conference*, Birmingham.

Gill M, Smith P, Wilkinson JM (2010) Mitigating climate change: the role of domestic livestock. *Animal*, **4**, 323–333.

Glover JD, Reganold JP, Bell LW *et al.* 2010. Increased food and ecosystem security via perennial grains. *Science*, **328**, 1638–1639.

Godfray HCJ, Beddington JR, Crute IR *et al.* (2010) Food security: the challenge of feeding 9 billion people. *Science*, **327**, 812–817.

Gomez LD, Steele-King CG, McQueen-Mason SJ (2008) Sustainable liquid biofuels from biomass: the writing's on the walls. *New Phytologist*, **178**, 473–485.

Grabber JH (2005) How do lignin composition, structure, and cross-linking affect degradability? *A review of cell wall model studies. Crop Science*, **45**, 820–831.

Gregory PJ, Ingram JS, Brklacich M (2005) Climate change and food security. *Philosphical Transactions of the Royal Society. B, Biological Sciences*, **360**, 2139–2148.

Gressel J (2008) Transgenics are imperative for biofuel crops. *Plant Science*, **174**, 246–263.

Halpin C, Holt K, Chojecki J *et al.* (1998) Brown-midrib maize (bm1) – a mutation affecting the cinnamyl alcohol dehydrogenase gene. *The Plant Journal*, **14**, 545–553.

Harper P, Wexler W, Kemp M, Perez-Minana E (2010) Land use in agriculture. In *Zero Carbon Britain 2030. A new energy strategy. The Second Report of the Zero Carbon Britain project* (ed. Kemp M), pp. 189–231. Centre for Alternative Technology, Machynlleth.

Hastings A, Clifton-Brown J, Wattenbach M, Mitchell CP, Smith P (2009a) Improved process descriptions for leaf area index development and photosynthesis rates in *Miscanthus x giganteus*: towards more robust yield predictions under different climatic and soil conditions. *Global Change Biology Bioenergy*, **1**, 154–170.

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

Hatfield RD, Ralph J, Grabber JH (1999) Cell wall structural foundations: molecular basis for improving forage digestibilities. *Crop Science*, **39**, 27–37.

Haughton AJ, Bond AJ, Lovett AA *et al.* (2009) A novel, integrated approach to assessing social, economic and environmental implications of changing rural land use: a case study for perennial biomass crops. *Journal of Applied Ecology*, **46**, 315–322.

Heal G (2000) Valuing ecosystem services. *Ecosystems*, **3**, 23–30.

Heaton EA, Flavell RB, Mascia PN, Thomas SR, Dohleman FG, Long SP (2008) Herbaceous energy crop development: recent progress and future prospects. *Current Opinion in Biotechnology*, **19**, 202–209.

Heaton EA, Voigt TB, Long SP (2004) A quantitative review comparing the yields of two candidate C-4 perennial biomass crops in relation to nitrogen, temperature and water. *Biomass and Bioenergy*, **27**, 21–30.

Hedenus F, Azar C (2009) Bioenergy plantations or long-term carbon sinks? – A model based analysis. *Biomass and Bioenergy*, **33**, 1693–1702.

Herzog T(2009) *World Greenhouse Gas Emissions in 2005*. World Resources Institute Working Paper, World Resources Institute. Available at: http://www.wri.org/publication/navigating-the-numbers.

Hillier J, Hawes C, Squire G, Hilton A, Wale S, Smith P (2009a) The carbon footprints of food crop production. *International Journal of Agricultural Sustainability*, **7**, 107–118.

Hillier J, Whittaker C, Dailey G *et al.* (2009b) Greenhouse gas emissions from four bioenergy crops in England and Wales: integrating spatial estimates of yield and soil carbon balance in life cycle analyses. *Global Change Biology Bioenergy*, **1**, 267–281.

Hirata M, Hasegawa N, Nogami K, Sonada T (2007) Tuft, shoot and leaf dynamics in *Miscanthus sinensis* in a young tree plantation under cattle grazing. *Tropical Grasslands*, **41**, 113–128.

Hodkinson TR, Renvoize SA (2001) Nomenclature of Miscanthus x giganteus (Poaceae). *Kew Bulletin*, **56**, 759–760.

Hodgson EM, Fahmi R, Yates N *et al.* (2010a) Miscanthus as a feedstock for fast-pyrolysis: does agronomic treatment affect quality? *Bioresource Technology*, **101**, 6185–6191.

Hodgson EM, Lister SJ, Bridgwater AV, Clifton-Brown JC, Donnison IS (2010b) Genotypic and environmentally derived variation in the cell wall composition of Miscanthus in relation to its use as a biomass feedstock. *Biomass and Bioenergy*, **34**, 652–660.

Hoekman SK (2009) Biofuels in the U.S. – challenges and opportunities. *Renewable Energy*, **34**, 14–22.

IAASTD (2008). *International Assessment of Agricultural Knowledge, Science and Technology for Development: Executive Summary of the Synthesis Report*. Available at: http://www.agassessment.org/docs/IAASTD_EXEC_SUMMARY_JAN_2008.pdf.

IEA (2010a) *Energy Technology Perspectives. Scenarios & Strategies to 2050. Executive Summary*. IEA, Paris.

IEA (2010b) *World Energy Outlook 2010 Factsheet. What does the Global Energy Outlook to 2035 Look Like?* Available at: http://www.worldenergyoutlook.org/docs/weo2010/factsheets.pdf.

IPCC (2007) Climate change 2007: impacts, adaptation and vulnerability. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE), 476 pp. Cambridge University Press, Cambridge, UK. Available at: http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg2_report_impacts_adaptation_and_vulnerability.htm.

ITPOES (2010) *The Oil Crunch. A Wake Up Call for the UK Economy. Second Report of the UK Taskforce on Peak Oil and Energy Security (ITPOES)*. Ove Arup & Partners Ltd., London.

Jaggard KW, Qi A, Ober AS (2010) Possible changes to arable crop yields by 2050. *Philosphical Transactions of the Royal Society. B, Biological Sciences*, **365**, 2835–2851.

Jenkins BM, Baxter LL, Miles TR Jr, Miles TR (1998) Combustion properties of biomass. *Fuel Processing Technology.*, **54**, 17–46.

Johnson DG (1973) *World Agriculture in Disarray*. Fontana World Economic Isses Series, 1. St.Martin's Press for the Trade Policy Research Centre, London, MacMillan; New York.

Joint Operating Environment. 2010. *Ready for Today. Preparing for Tomorrow*. U.S. Joint forces Command, Suffolk, VA.

Jung HG, Vogel KP (1986) Influence of lignin on digestibility of forage cell wall material. *Journal of Animal Science*, **62**, 1703–1712.

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

Kearney J (2010) Food consumption trends and drivers. *Philosphical Transactions of the Royal Society. B, Biological Sciences*, **65**, 2793–2807.

Kerr RA (2010) Natural gas from shale bursts onto the scene. *Science*, **328**, 1624–1628.

Kindred D, Mortimer N, Sylvester-Bradley R, Brown G, Woods J (2008) *Understanding and managing uncertainties to improve biofuel GHG emissions calculations*. HGCA Project Report 435, HGCA, London.

Klinke HB, Thomsen AB, Ahring BK (2004) Inhibition of ethanol-producing yeast and bacteria by degradation products produced during pre-treatment of biomass. *Applied Microbiology and Biotechnology*, **66**, 10–26.

Koplow D (2006) *Biofuels – At What Cost? Government Support for Ethanol and Biodiesel in the United States*. Global Subsidies initiative (GSI) of the International Institute of Sustainaable Development (IISD), Geneva, Switzerland.

LeDoux L (2009) Can oil shale be used as a power source? Why the U.S. hasn't tapped this resource for energy. *Scientific American*, 14 July 2009. Available at: http://www.scientificamerican.com/article.cfm?id=can-oil-shale-provide-power.

Lewandowski I, Kicherer A (1997) Combustion quality of biomass: practical relevance and experiments to modify the biomass quality of Miscanthus x giganteus. *European Journal of Agronomy*, **6**, 163–177.

Lewandowski I, Scurlock JMO, Lindvall E, Christou M (2003) The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. *Biomass and Bioenergy*, **25**, 335–361.

Li X, Weng JK, Chapple C (2008) Improvement of biomass through lignin modification. *The Plant Journal*, **54**, 569–581.

Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science* **319**, 607–610.

Long SP, Ort DR (2010) More than taking the heat: crops and global change. *Current Opinion in Plant Biology*, **13**, 241–248.

Long SP, Potter L, Bingham MJ, Stirling CM (1990) An analysis of limitations to the production of C4 perennials as lignocellulosic biomass crops, with reference to trials in E. England. In: *Biomass for Energy and Industry, 5th European Conference* (eds Grassi G, Gosse G, dos Santos G), pp. 1235–1241. Elsevier Applied Science, New York.

Long SP, Zhu XG, Naidu SL, Ort DR (2006) Can improvement in photosynthesis increase crop yields? *Plant Cell & Environment.*, **29**, 315–330.

Lu Y, Mosier NS (2008) Current technologies for fuel ethanol production from lignocellulose biomass. In: *Genetic Improvement of Bioenergy Crops* (ed. Vermis W), pp. 89–142. Springer-Verlag, New York.

Lutz W, Samir KC (2010) Dimensions of global population projections: what do we know about future population trends and structures. *Philosphical Transactions of the Royal Society B, Biological Sciences*, **365**, 2779–2791.

Lywood W, Pinkney J, Cockerill S (2009) The relative contributions of changes in yield and land area to increasing crop output. *Global Change Biology*, **1**, 360–369.

Matías J, González J, Royano L, Barrena RA (2011) Analysis of sugars by liquid chromatography-mass spectrometry in Jerusalem artichoke tubers for bioethanol production optimization. *Biomass and Bioenergy*, **35**, 2006–2012.

McKendry P (2002) Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*, **83**, 37–46.

McRobie H (2010) *Canada's Tar Sands: A Dangerous Solution to Offshore Oil*. Available at: http://www.guardian.co.uk/commentisfree/2010/may/11/alberta-california-tar-sands-oil.

Millennium Ecosystem Assessment (MEA) (2005) *Ecosystems and Human Well-Being: Synthesis*. Island Press, Washington.

Monti A, Di Virgilio N, Venturi G (2008) Mineral composition and ash content of six major energy crops. *Biomass and Bioenergy*, **32**, 216–223.

Monteith JL (1978) Reassessment of maximum growth rates for C_3 and C_4 crops. *Experimental Agriculture*, **14**, 1–5.

Murphy R, Woods J, Black M, McManus M (2011) Global developments in the competition for for land from biofuels. *Food Policy*, **36**(Suppl. 1), 552–561.

Naik SN, Goud VV, Rout PK, Dalai AK (2010) Production of first and second generation biofuels: a comprehensive review. *Renewable & Sustainable Energy Reviews*, **14**, 578–597.

Newbould J, Kim EJ, Scollan N (2010) Reducing animal greenhouse gas emissions. *IBERS Knowledge-based Innovation*, **3**, 9–15.

NRC (2008). *Emerging Technologies to Benefit Farmers in Sub-Saharan Africa and South Asia*. National Academies Press, Washington, DC, USA.

OECD (2010) *Producer and Consumer Support Estimates*. Available at: http://www.oecd.org.

OECD-FAO (2010). *Agricultural Outlook 2010-2019*. OECD Publishing, Paris.

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

Pauly M, Keegstra K (2010) Plant cell wall polymers as precursors for biofuels. *Current Opinion in Plant Biology*, **13**, 304–311.

Potrykus I (2010) Regulation must be revolutionized. *Nature*, **466**, 561.

Rajagopal D, Zilberman D (2007) *Review of environmental, economic and policy aspects of biofuels*. World Bank Policy Working Paper No. 4341, World Bank, Washington, DC.

Randolph TF, Schelling E, Grace D *et al.* (2007) Invited review: role of livestock in human nutrition and health for poverty reduction in developing countries. *Journal of Animal Science*, **85**, 2788–2800.

Rapport DJ, Costanza R, McMichael AJ (1998) Assessing ecosystem health. *Trends in Ecology and Evolution*, **13**, 397–402.

Robertson GP, Dale VP, Doering CC *et al.* (2008) Sustainable biofuels redux. *Science*, **322**, 49–50.

Robson PRH, Moś M, Clifton-Brown JC, Donnison IS (2011) Phenotypic variation in senescence in *Miscanthus*: towards optimising biomass quality and quantity. *Bioenergy Research* (doi: 10.1007/s12155-011-9118-6).

Rosegrant MW, Ewing M, Yohe G, Burton I, Huq S, Valmonte-Santos R (2008) *Climate change and agriculture. Threats and opportunities*. GTZ on behalf of Federal Ministry for Economic Cooperation and Development, Eschborn, Germany.

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

Royal Society (2008). *Sustainable Biofuels: Prospects and Challenges.* Royal Society, London.

Royal Society (2009) *Reaping the Benefits. Science and the Sustainable Intensification of Global Agriculture*. Royal Society, London.

Rubin EM (2008) Genomics of cellulosic biofuels. *Nature*, **454**, 841–845.

Satterthwaite D, McGranahan G, Tacoli C (2010) Dimensions of global population projections: what do we know about future population trends and structures? *Philosphical Transactions of the Royal Society. B, Biological Sciences*, **365**, 2809–2820.

Schmidhuber J, Tubiello F (2007) Global food security under climate change. *Proceedings of the National Academy of Sciences*, **104**, 19703–19708.

Schultz TW (1968) What ails world agriculture? *Bulletin of the Atomic Scientists*, **24**, 28–35.

Semere T, Slater FM (2007a) Ground flora, small mammal and bird species diversity in miscanthus (*Miscanthus× giganteus*) and reed canary-grass (*Phalaris arundinacea*) fields. *Biomass and Bioenergy*, **31**, 20–29.

Semere T, Slater FM (2007b) Invertebrate populations in miscanthus (*Miscanthus×giganteus*) and reed canary-grass (*Phalaris arundinacea*) fields. *Biomass and Bioenergy*, **31**, 30–39.

Sherrington C, Bartley J, Moran D (2009) Farm-level constraints on the domestic supply of perennial energy crops in the UK. *Energy Policy*, **36**, 2504–2512.

Sims REH, Mabee W, Saddler JN, Taylor M (2010) An overview of second generation biofuel technologies. *Bioresource Technology*, **101**, 1570–1580.

Smart LB, Cameron KD (2008) Genetic improvements of willow (*Salix* spp.) as a dedicated bioenergy crop. In: *Genetic Improvement of Bioenergy Crops* (ed. Vermerris W), pp. 347–376. Springer-Verlag, New York.

Smith P, Martino D, Cai Z *et al.* (2008) Greenhouse gas mitigation in agriculture. *Philosphical Transactions of the Royal Society. B, Biological Sciences*, **363**, 789–813.

Smith PD, Martino Z, Cai D *et al.* (2007) Agriculture. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA), pp. 499–540. Cambridge University Press, Cambridge, United Kingdom and New York, USA.

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

Stehfest E, Bouwmann L, van Vuuren D, den Elzen MGJ, Eikhout B, Kabat P (2009) Climate benefits of changing diet. *Climate Change*, **95**, 83–102.

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

Steinfeld H, Gerber P, Wassenaar TD, Castel V, de Haan C (2006) *Livestock's Long Shadow: Environmental Issues and Options*. FAO, Rome.

Stockman L (2010) *Tar sands in your tank. Exposing Europe's role in Canada's dirty oil trade*. Greenpeace Report. Available at: http://www.greenpeace.org/canada/en/campaigns/tarsands/Resources/Reports/tar_sands_in_your_tank/.

Thornley P, Rogers J, Huang Y (2008) Quantification of employment from biomass power plants. *Renewable Energy*, **33**, 1922–1927.

Thornton PK (2010) Livestock production: recent trends, future prospects. *Philosphical Transactions of the Royal Society. B, Biological Sciences*, **365**, 2853–2867.

Thornton PK, Jones PG, Owiyo T *et al.* (2006) *Mapping climate vulnerability and povery in Africa*. ILRI, Nairobi, Kenya. Available at: http://www.dfid.gov.uk/research/mapping-climate.pdf.

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

Tollefson J (2008) Car industry: charging up the future. *Nature*, **456**, 436–440.

Tran AV, Chambers RP (1985) Red oak wood derived inhibitors in the ethanol fermentation of xylose by *Pichia stipitis* CBS 5776. *Biotechnology Letters*, **7**, 841–845.

Tudge C (2007) *Feeding is Easy*. Pari Publishing, Pari.

Tyers R, Anderson K (1992) *Disarray in World Food Markets: A Quantitative Assessment*. Cambridge University Press, Cambridge.

UK Energy Research Centre (UKERC) (2009) *Making the Transition to a Secure Low-Carbon Energy System, Synthesis Report*. UKERC, London.

UN (2008). *World Population Prospects: The 2008 Revision Population Database*. Available at: http://esa.un.org/unpp/index.asp?panel=1.

US Department of Energy (US DOE) (2006) *Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda*. Available at: http://genomicscience.energy.gov/biofuels/2005workshop/b2blowres63006.pdf.

Valentine J, Duller CJ, Hinton-Jones M *et al.* (2009). *The development of sustainable heat and power fuelled by biomass from short rotation coppice in Wales*. Aberystwyth University Report of the Helyg i Gymru/Willow for Wales 2004–2008 Project. Available at: http://www.willow4wales.co.uk/.

Vanholme R, Morreel K, Ralph J, Boerjan W (2008) Lignin engineering. *Current Opinion in Plant Biology*, **11**, 278–285.

van Vuuren DP, Eickhaut B, Lucas PL, den Elzen M. (2006) Long-term multi-gas scenarios to stabilise radiative forcing – exploring costs and benefits within an integrated assessment framework. *Energy Journal (Special Issue)*, **3**, 201–234.

van Vuuren DP, Ochola WO, Riha S *et al.* (eds.) (2008) Outlook on agricultural change and its drivers. *International Assessment of Agricultural Science and Technology Development*, pp. 495–590. Island Press, Washington DC.

Vignols F, Rigau J, Torres MA, Capellades M, Puigdomenech P (1995) The brown midrib 3 (Bm3) mutation in maize occurs in the gene encoding caffeic acid *O*-methyl transferase. *The Plant Cell*, **7**, 407–416.

Warwick HRI (2007). *Final Report to DEFRA. Direct Energy Use in Agriculture: Opportunities for Reducing Fossil Fuel Inputs*. University of Warwick, Warwick, UK. Available at: http://randd.defra.gov.uk/Document.aspx?Document=AC0401_6343_FRP.pdf.

White RE, Grossmann R (2010) Food security: fossil fuels. *Letters in Science*, **328**, 173.

Williams AG, Audsley E, Sandars DL (2006) *Determining the environmental burdens & resource use in the production of agricultural & horticultural commodities*. Main Report, August 2006, Defra Research Project IS0205, Cranfield University and Defra, Bedford. Available at: http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0 and http://www.cranfield.ac.uk/sas/naturalresources/research/projects/is0205.html.

Winter M, Lobley M (2010) Conclusions: the emerging contours of the new land debate. In: *What is land for? The food, fuel and climate change debate* (eds Winter M, Lobley M), pp. 319–330. Earthscan, London.

Wirsenius S (2003) Efficiencies and biomass appropriation of food commodities on global and regional levels. *Agricultural Systems*, **77**, 219–255.

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

Woods J, Black M, Murphy R (2009) Future feedstocks for biofuel systems. *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 22–25 September 2008, Gummersbach, Germany* (eds Howarth RW, Bringezu S), pp. 215–232. CornellUniversity, Ithaca, NY, USA. Available at: http://cip.cornell.edu/biofuels/.

World Bank (2008) *Agriculture for Development*. The International Bank for Reconstruction and Development/The World Bank, Washington, DC.

World Food Programme (2009) *World Food Programme 2009 Annual Report*. World Food Programme, Rome, Italy.

World Health Organization (2003) *Obesity and Overweight*. Available at: http://www.who.int/dietphysicalactivity/media/en/gsfs_obesity.pdf.

Worldwatch Institute (2006) *Biofuels for Transportation: Global Potential, Implications for Sustainable Agriculture and Energy in the 21st Century*. Worldwatch Institute, Washington, DC.

Wrobel C, Coulman BE, Smith DL (2009) The potential use of reed canarygrass (*Phalaris arundinacea* L.) as a biofuel crop. *Acta Agriculturae Scandinavica, Section B – Plant Soil Science*, **59**, 1–18.

Zhu XG, Long SP, Ort DR (2010) Improving photosynthetic efficiency for greater yield. *Annual Review of Plant Biology*, **61**, 235–261.