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The new competition for land: Food, energy, and climate change ☆

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ABSTRACT

The paper addresses the new competition for land arising from growing and changing demand for food when combined with increasing global demand for transport energy, under conditions of declining petro-chemical resources and the urgent need to reduce greenhouse gas emissions. The paper starts from the premise of a 'food, energy and environment trilemma' (Tilman et al., 2009), where all demands to expand the area of cultivated land present high risks of increasing the carbon footprint of agriculture. Having reviewed the main drivers of demand for food and for liquid transport fuels, the paper weighs the controversies surrounding biofuels arising from food-price spikes, the demand for land, and consequent direct and indirect land-use change. It suggests that we need a more complex, and geographically differentiated, analysis of the interactions between direct and indirect land-use change. The paper then reviews evidence of land availability, and suggests that in addition to technical availability in terms of soil, water, and climate, political, social, and technological factors have significantly shaped the competition for land in different global regions, particularly the three major biofuel producing ones of the USA, Brazil and Europe. This point is further developed by reviewing the different innovation pathways for biofuels in these three regions. The main conclusion of this review is firstly that any analysis requires an integrated approach to the food-energy-environment trilemma, and secondly that strategic political direction of innovation and sustainability regulation are required to bring about major shifts in agriculture leading to sustainable intensification of cultivation (Royal Society, 2009), rather than the continued expansion of cultivated area. The consequent perspective is one of considerable global variety in technologies, agricultural productive systems, and use of natural resources. This contrasts sharply with the world of a dominant global and integrated technology platform based on petro-chemicals to which we have become accustomed.

Introduction: the new competition for land

During the 21st century, land as a global resource is likely to become the focus of intensified competition from a variety of uses. Moreover, the competing uses are likely to become subject to increasing controversy, in terms of the claims made by those promoting those uses, and in terms of potentially conflicting national, regional and global interests. The main focus of this paper is to consider these developments in the light of two underlying drivers for increased competition for land: the increasing demand for energy, particularly with respect to transport (terrestrial and air); and the increasing demand for food, both to meet growing world population and in meeting changes to, and improvements in, nutrition and quality of food.

Some recent debate has staked a primacy of claim over land use for production of food (World Bank, 2008; FAO, 2008; OECD-FAO, 2008). However, failure to address the demand for energy and materials, in particular to develop alternatives to counter the depletion of petro-chemical resources, will inevitably result in major economic and social disruption on a global scale. We restrict ourselves here to considering the implications for demand for land arising from developing alternatives to oil, rather than energy demand overall. Enhanced and sustainable social welfare will depend on developing new forms of agricultural production of both energy and food, highlighting the significance of 'the sustainable intensification of global agriculture' (Royal Society, 2009; Pretty, 2008; Godfray et al., 2010). We focus on issues raised by the new competition for land[1], particularly in relation to food, energy, and climate change, rather than the increasing demands for the production of food as such. This paper thus places the competition for land in the framework of the 'food, energy and environment trilemma'

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[1] For shorthand, when referring to land, the water resources required for the associated agriculture are taken as included.

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(Tilman et al., 2009). For this reason, it starts from a different premise than the Gallagher Report (Renewable Fuels Agency, 2008), with its focus more narrowly on climate change mitigation, biofuels, and land. The new competition for land arising from the trilemma is represented in Fig. 1, each component of which is then briefly described.

Food, land and climate change

Although much attention on reducing GHG emissions has concentrated on the use of fossil fuels, there has recently been growing recognition of land-use as a source of GHG. In overall terms, including both land conversion and current agricultural land use, contributions to greenhouse gas emissions (CO_2, CH_4, N_2O) are globally estimated to be at least two and a half times greater than the total emissions from global transport (IPCC, 2007; World Resource Institute, 2005). Consequently, any increased production from land to meet the double demand for food and energy/materials must do so sustainably, without further exacerbating anthropogenic climate change. 'Feeding the nine billion' faces a double challenge of restricting GHG emissions both from land-use change arising from expansion in cultivated areas, and a radical change in technology from that employed by current crops and cultivation (Royal Society, 2009; Godfray et al., 2010). For example, although much attention has been paid to the enhanced demand for meat as a source of greenhouse gases, it should also be remembered that rice is a major global contributor to emissions of methane, 20 times more powerful than CO_2 in its greenhouse effect (IPCC, 2007). There is thus a potentially vicious spiral of increased land use, increased global climate change risk, and decreasing availability of land cultivatable at high levels of productivity.

Oil, biofuels and biomass

The assumption that increased energy and materials demands will increase competition for land is based on the presupposition firstly that petro-chemical resources will become less available and at increasingly higher and volatile cost, and secondly that substitutes for fossil fuel transport energy and chemical building blocks for materials will be met in significant measure only by biofuels and industrial biotechnology. Liquid transport fuels are, and will continue to be, the only technology for aviation, now and in the foreseeable future. As will be shown below, they are likely to be the principal form of energy for terrestrial transport for decades to come, given the growing global vehicle fleets dependent upon them. Declining petro-chemical resources will increase the demand for biomass, and hence demand for land allocated to meet this demand.

The new competition

When increased demand for food and energy combine, pressure on land conversion is increased, leading to further climate change, which in turn may affect productivity and availability of land, so creating a potential vicious circle. That is the trilemma challenge.

Given the urgency and radical changes needed to meet the food-energy-environment trilemma, new modes of economic governance are emerging, but piecemeal and gradually, nationally, regionally, and internationally. Arguments will be presented that both 'business as usual' and, consequently, 'innovation as usual' are unlikely to adequately meet these challenges. A major shift in the political governance of market economies will be necessary. On the one hand, sustainability regulation, significantly pioneered with respect to biofuels, needs to be developed to encompass all land-based production and consumption, in order to avoid major distortions and deleterious consequences. On the other hand, the evidence is now overwhelming that strategic direction and orientation of innovation to meet these challenges requires the development of novel policy instruments to meet long term goals of transition from the fossil resource economy. This requires both prioritisation of developing the science base in strategically relevant areas, and strategic support for investments in innovation oriented to the sustainable intensification of agriculture for food, energy, and materials, biorefinery, and industrial biotechnology. Political governance requires both sustainability regulation and innovation orientation, in order to bring about long term structural change. The paper suggests that, in contrast to the petro-chemical epoch, the new world will be much more technologically diverse, different regions and nations following different courses, so presenting yet more challenging prospects for international consensus and coordination.

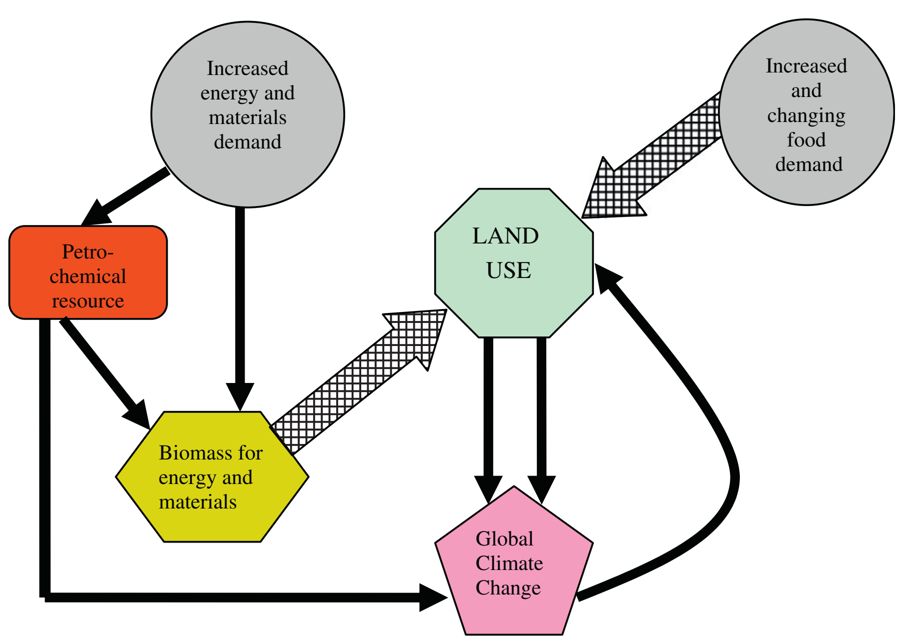

Fig. 1. The new competition for land use: interactions and feedbacks.

The paper will develop its argument firstly by exploring the drivers for the new competition for land from biofuels. It will then deal with the controversial issue of land-use change and especially extensification of land use, over which there is still much uncertainty and strong differences of opinion. Arising from this discussion, we develop a broader consideration of land as a global resource, with a particular focus on the three major biofuel producing regions of the world: Brazil, the USA and Europe. These three regions are then examined for the contrasting innovation pathways around biofuels, sustainability, and land use, emphasising the significance of political strategies. Finally, the paper draws out some policy implications for addressing the new competition for land, highlighting the need for a comprehensive and integrated approach, adequate to the dynamics presented in the model.

Drivers for increased competition for different uses of land

According to a number of recent reports, one of the main drivers for increased competition for use of land derives from the anticipated rise in world population from 6.5 billion to 9 billion by 2050, the changing demand for food, and the goal to reduce the scale of malnutrition (IAASTD, 2009; Evans, 2009; Royal Society, 2009; Pretty, 2008). The previous more-than-doubling of global population from 2.5 billion to 6.5 billion between 1950 and 2006 was achieved without any major increase (only approximately 10% or 1.4–1.5 million hectares) in total cultivated area of land, largely as a consequence of increases in agricultural productivity. However, since the mid-1980s, productivity growth has fallen below the rate of population growth, from 2.8% per annum, to 1.1%. Moreover, consumption per capita of three of the main grains (wheat, maize and rice) has increased at a faster rate, as has consumption of meat (IAASTD, 2009; Evans, 2009; Godfray et al., 2010). Without productivity growth commensurate with demand growth, pressures to increase the amount of land under cultivation for the production of food will increase. There is thus a major challenge to increase rates of productivity growth as the gains from the previous Green Revolution diminish.

Until quite recently, the International Energy Agency (IEA) had predicted that oil supplies could keep pace with rising global demand. However, in 2007–2008, their view changed, and, prior to the current recession, the IEA estimated that there was serious risk of an emerging energy gap of between 10% and 15% between supply and demand (IEA, 2008, 2009) in the next two decades. The revision of assessment arose both in terms of assumptions made about supply, especially from mature large fields in the Middle East, and in terms of assumptions made about demand, in particular the rate of growth in demand from China and India. More recently, the Uppsala model has challenged the current (2008) IEA assessment, suggesting that oil depletion is likely to be more rapid (Aleklett et al., 2010). Several analysts, moreover, argue persuasively that the main risk is not so much of a peak of physical production capacity followed by a decline, but that turbulence in oil prices will provoke successive waves of stuttering growth followed by severe depression (Hirsch et al., 2005; Cavallo, 2005; Sorrel et al., 2009; Lloyds, 2010).[2] There is a well established relationship between the price of a barrel of oil and GDP growth, with high prices and oil shocks contributing significantly to historical recessions (Jones et al., 2004; Bird, 2004). Less developed, oil dependent regions are particularly vulnerable. Sub-Saharan Africa suffered an increase in its oil import costs of $10.6 billion between 2004 and 2007, equivalent to 3% of the annual GDP, and 120% of their total annual international aid (Birol, 2008).

One of the key negative feedbacks of high oil prices concerns the reduction in agricultural productivity. The effects of high oil prices on the South, and globally on agricultural inputs (pesticides and nitrogen fertilizers), transport, tillage and irrigation systems, are likely to produce declines in agricultural productivity, so exacerbating the pressures to expand the area of cultivated land at lower levels of productivity (Overseas Development Institute, 2008; Murray, 2005; Burney et al., 2010). Industrialised farming systems require 50 (sometimes up to 100) times the energy input of traditional agricultural systems, and it is estimated that 95% of all our food products require the use of oil (Lucas et al., 2007).

As a consequence of diminishing fossil fuel energy supplies, in particular for transport, demand for alternative sources of liquid transport fuels is likely to increase. Although electric car alternatives to the internal combustion engine are strongly supported in some countries (King, 2007), and promise a minority market share, the global transport sector remains dominated by a future of the internal combustion engine powertrain for decades to come. The IEA has identified China and India as major economies predicated on the growth of liquid fuel driven cars. China's oil imports are predicted to reach 13 billion barrels per day in 2030, as car ownership rises from 20 to 140 per thousand population.

China is destined to be the largest source of demand for liquid transport fuels before the end of the second decade of this century. Having already overtaken Japan as a car market in 2005, China was predicted to overtake the USA by 2015 (IEA, 2008), but, partly as a consequence of the recession, had already done so by January 2010 (Financial Times, 21 October 2010).

For India, projections for continued and increasing dependency on the internal combustion engine powertrain also demonstrate a lock-into increasing demand for oil. The total vehicle stock in India increased from 19 million in 1990 to 68 million in 2004, and is projected to reach 295 million by 2030, overtaking the USA in 2025. These projections, however, were unable to take into account the significant innovation in the automobile industry in India, with a number of companies producing vehicles costing less than £1550 ($2500) per car in 2009.

Given the demand for liquid fuel and the depletion of global oil stocks, biofuels are likely to be promoted as a substitute for oil whether for objectives of energy security, economy, or sustainability. However, the demand scenario for biofuels is significantly determined by a combination of different political objectives and the price of oil as discussed below.

The controversy over direct and indirect land-use change

Taking into consideration the primary drivers for land use outlined in Section 2, an important issue arises concerning the competition between the driver for food and the driver for energy. Two papers, by Searchinger et al. (2008) and Fargione et al. (2008), have had a significant impact in Europe on the understanding of this competition, prompting the hasty response of the Gallagher inquiry and report (Renewable Fuel Agency, Gallagher, 2008). The papers made the assumption that there are alternatives to biofuels as a liquid transport fuel, and argued, from a sustainability criteria, that oil was better than most biofuels. Significantly, they used conventional extraction of oil as the benchmark, thereby ignoring the increasing carbon footprint arising from the extraction of non-conventional oil (oil sands, shale oil, deep ocean, etc.).

For present purposes, there are two connected arguments put forward by Searchinger, each of which have come under subsequent scrutiny: first, that biofuels provoked a rise in price of food, leading to the stimulation and expansion of food production; second, that the consequential displacement of production of food into new areas of cultivation (indirect land-use change) resulted

[2] "If we go one step further, if we see prices go much higher than that, we may see it slow down and strangle economic recovery." Fatih Birol, IEA Chief Economist, Financial Times, August 3 2009. Oil price at the time was $70 pb.

in a release of CO_2 into the atmosphere, so rendering biofuel production responsible for global climate change in ways not measured by previous life-cycle analysis models.[3] We shall briefly examine each of these in turn, inasmuch as they affect competition for land. More generally, however, the Searchinger analysis was helpful in highlighting the significance of land-use change as a major contributor to agricultural emissions of GHG. Nonetheless, it was unhelpful in isolating land-use change (correctly or incorrectly) attributable to biofuels production, portraying biofuels as the new, and possibly unnecessary, kid on the agricultural block. Thus, it is now evident that both direct and indirect land-use change *driven by whatever source of growing demand*, needs to be considered, and indeed, limited insofar as possible by intensification using sustainable technologies of crop and cultivation.

Searchinger argued that increases in the price of maize resulting from the switching of maize from production of food outputs (mostly animal feed) to production of biofuels in the USA, led to the expansion of demand for crops in other parts of the world, notably soya and wheat. As a consequence, previously uncultivated land was brought under cultivation. The effects of converting maize into ethanol therefore were deemed to induce 'indirect land use change' (ILUC). Early authoritative reports (World Bank, 2008; FAO, 2008) attributed a major role to biofuels in the increase in food prices, supporting this line of argument. The three main lines of criticism developed against biofuels have since been scrutinised: their role in the food-price spikes of 2007/2008; the nature and location of land-use change; and the specificity of effects of the US maize-to-ethanol biofuel.

The decline in agricultural productivity noted above, falling global stocks in grains, speculative trading, and erection of trade barriers, are now considered to be the major factors responsible for the food-price spikes of 2007/2008 (DEFRA, 2008, 2009a; Wiggins, 2008). Piesse and Thirtle (2009) particularly highlight the role of the declining stock-to-use ratios as responsible for the price spikes, as against long term causes arising from increased biofuel production. The rise in the price of oil, an effect of the emerging 'energy crunch', was also deemed to have had a more significant effect on food prices than any attributable to biofuels, which in turn have been deemed to have dampened the rise in oil prices by up to 15% according to Merrill Lynch (European Renewable Energy Council, 2008.). Furthermore, the most extreme price spike was in rice, where substitution effects for animal feed or other cereals are minimal.[4] For rice, any impact from biofuels lacks basis or evidence. Finally, any residual price effects that might be attributed to the diversion of maize from food to biofuel find no parallel in biofuels produced from other feedstocks, notably bioethanol from sugarcane or biodiesel from rapeseed oil. Piesse and Thirtle (2009), following Mitchell (2008), suggest that biofuels may in the long term arrest the decline in food prices, and even reverse it. However, this argument does not take into account the effects of continued and increasing dependency on oil, *in the absence of alternatives*, and the more extreme negative consequences on food prices that may flow from that. Overall, therefore, one of the key links to the Searchinger argument, the connection between biofuel production, food prices, and expansion of cultivated land, has been significantly weakened. Those other drivers of the food-price spikes are more important candidates for explaining land-use change, with markets for food directly stimulating new cultivation, so constituting direct land-use change. Nonetheless, given the complexity of the issues at stake, biofuels can be expected to continue to provoke controversies that shape policy-making (Bowyer, 2010).

The increased GHG emissions resulting from ILUC make assumptions as to both the location and nature of the land conversion in question (Liska and Perrin, 2009; Kammen et al., 2008). Thus, in terms of location, at one extreme, if primary Amazonian forest is cleared to produce soybeans as a replacement to US maize as animal feed, the effects of GHG emissions are considerable. At the other extreme, if land conversion occurs only within the USA, entailing a shift in production from one use of agricultural land to another, then effects of GHG emissions are minimal, even positive in some cases. In terms of the nature of land conversion, if the conversion is slash and burn, followed by cattle pasturage, then GHG disbenefits are large, but if the conversion is to low-tillage, mixed farming, disbenefits are considerably reduced. Kim et al. have argued that the maize-to-ethanol expansion in the US is likely to result largely in land conversion in the US (Kim et al., 2009), and Mathews and Tan (2009) have suggested that direct attribution of land-use change in one crop in any one country to land-use change in another crop in any other country is problematic, involving many complex factors. Paradoxically, in Europe where the impact of the Searchinger analysis has been most conspicuous, attention has been less sharply directed at the effects of substitution of rapeseed oil to biodiesel and consequent expansion of imports of palm oil production for food and cosmetics. The linkages between a biofuel production and indirect land-use change here seem more immediate, than the quite roundabout and mediated effects between maize in the USA and soya in the Amazon. According the FAO (2006), 2.5 million additional tonnes of palm oil were imported between 2002 and 2006, and a further 1.5 is projected up to 2010, as a consequence of European rapeseed oil being diverted into biodiesel. This additional tonnage equates to 500,000 ha for 2.5 million tonnes of additional production, given that productivity was stable over that period. In Europe, land under rapeseed had increased by 31% between 2002 and 2007, a quarter of which was used for biodiesel (Eurostat, 2007).

As the world's longest and most developed example of biofuel production, Brazil's sugarcane to ethanol production has been examined for its effects on indirect land-use change (Fischer et al., 2008; Nasser et al., 2009). The evidence strongly suggests that most of the expansion of sugarcane production has occurred in the South Central region, and has been achieved principally through increased productivity of sugarcane production and refining, and conversion of low intensity pasturage to sugarcane production. The result of this conversion has led to greater intensity of cattle raising in adjacent areas rather than expansion of pasturage. The main drivers for deforestation of the Amazon are direct land-use change for soybean production, timber, and cattle (Nepstad et al., 2006, 2008). The Brazilian example points to the need to address the land-use change question, direct and indirect, in a more systematic manner, at the local and regional level where impacts of different drivers for land-use change can be more reliably assessed.

Finally, the very indirectness of the effects of a novel or expanded production raises major methodological and regulatory problems. It could be argued, for example, that any ILUC carbon footprint of biofuels should properly be attributed to the price of oil, as the production of bioethanol, notably in Brazil, was a response to the rise in the price of petrol which then made bioethanol a strategic and market-competitive alternative. There are no logical grounds for restricting indirectness of effects within the agricultural sector: the carbon footprint of oil could be recalculated to include the land-use changes consequential upon high oil prices and the quest for oil-substitutes.

[3] In particular, the GREET model (Wang and Haq, 2008; http://www.transportation.anl.gov/modeling_simulation/GREET/index.html), or the model used in the CONCAWE assessment of greenhouse gas savings produced by the European Joint Research Centre (European Commission, JRC, 2008).

[4] From January 2007 to the height of the price spikes between April and September 2008, rice increased 224%, as against maize 77%, wheat 118%, soybeans 107% and sugar 111% (DEFRA, 2009a, Source UNCTAD commodity price statistics database). In the case of sugar, the major expansion of sugarcane ethanol does not coincide with the price fluctuations of sugar, except inversely.

Summing up the impact of the controversy over land-use change, the major lesson to be drawn is that the interaction between pressures for direct and indirect land-use change are complex, and difficult to disentangle. Any indirect land-use change for displaced production of food is currently occurring in the context of the much more significant drive for direct land-use change to expand food, timber or industrial production. The main objective must be to reduce the pressures to convert land from non-agricultural to agricultural uses of whatever kind, both to reduce greenhouse emissions from agriculture, and to protect biodiversity. Thus, reduction in pressures for land use expansion, from any source, must be sought in the direction of intensification and low-carbon cultivation technologies, for whatever agricultural output.

Land as a global resource?

With a focus on increasing competition for land, key questions are what land and where? Ultimately, these are complex political questions, as well as agronomic ones, as they concern more than issues of whether ecosystems can support cultivation, or are subject to barriers of biotic and abiotic constraints. Gross estimates of globally available land and biomass point to some useful parameters (IEA Bioenergy, 2009), but here we review some important geographical variation in potential and practice.

Focusing on the three major regions of current biofuel production and projected expansion, quite different issues of land competition and land availability can be discerned.

In the USA, there has been a decline in cultivated area of land from 1980 to 2010 from a peak of 300 million hectares to 240–245 million hectares in 2005, and is predicted to flatline until 2015, in spite of the increase in the area of corn (maize) planted for bioethanol (USDA, 2006). As the figure below indicates (see Fig. 2), expansion of corn demand for land has been accompanied by a decline in soyabean cultivated land, in part a result of the co-product from corn-bioethanol (Dry Distillers Grain with Solubles or DDGS) replacing soya for animal feed. As suggested above, the interactions between direct and indirect land-use change are complex, and if, within the USA, the corn-ethanol expansion led to reduced demand for land for soya, it is difficult to argue that it led to increased demand for soya elsewhere (Wescott, 2007). More broadly, the long term reduction of land use from increased productivity points to a potential reserve of previously cultivated land available for biomass for energy and materials. More importantly, the mandate from the Energy and Security Independence Act 2007 for two thirds of biofuels to be produced from non-food biomass by 2022 (ligno-cellulosic material from agricultural residue,

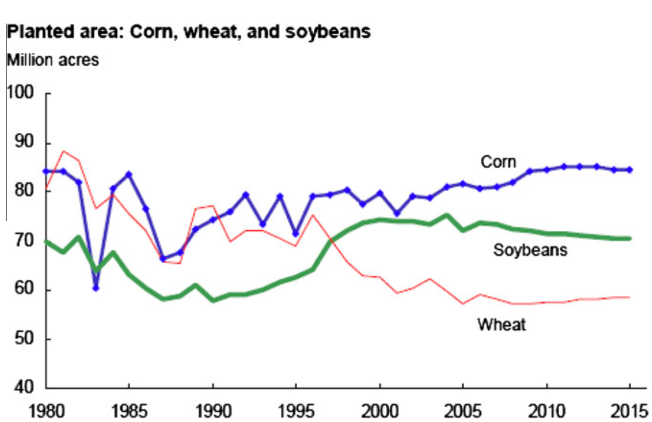

Fig. 2. Land use change of major crops in the USA. *Source*: USDA Baseline Projections 2006 (USDA, 2006).

energy crops such as miscanthus that can be grown on less productive or marginal lands, or carbon waste, or, indeed, algae) has the potential to lead to a marked reduction in competition for land between energy and food over the coming decade (Harvey and McMeekin, 2010).

For Europe, a recent assessment using the Agro-Ecological Zones (AEZ) methodology, where rain-fed areas suitable for cultivation and not currently used for food production are assessed, a large reservoir of available land is indicated (Fischer et al., 2009; European Commission, 2008). Of the current 164 million hectares (including Ukraine) of cultivated land, 76 million are under permanent pasture. The AEZ model suggests that between 44 and 53 million hectares will become progressively available by 2030, and *if* Europe changes its current trajectory, a further 19 million hectares would be available for ligno-cellulosic biomass. However, much depends on future political decisions concerning sustainability of crops, with revisions of sustainability criteria expected in 2013, and an increasingly high threshold for sustainability in 2017. More importantly, the relative lack of coherent political strategy in promoting and investing in biomass and agronomic innovation in Europe compared to the USA renders questionable whether 'technically available' land translates into a realisable renewable resource. In particular, a strategic issue concerns the continuing high dependency on biodiesel and its feedstocks, compared with bioethanol. There remains a concern that rapeseed will remain the major, path-dependent, and farmer interest-bound, feedstock. Relatively low in energy per hectare and in GHG savings, there is a risks a 'lock-in' to existing technology (Unruh, 2000) and that stimulation of second generation biodiesel, and/or a switch to alternative biofuels is not being considered with sufficient urgency (Porter et al., 2009).

In Brazil, there has been extensive examination of availability of land for expanding bioethanol production, both for the domestic and rapidly growing international market. As Fig. 3 below demonstrates, there has been ongoing expansion of area cultivated for sugarcane from under 1.5 million hectares in 1960 to 7 million in 2008, of which sugarcane for bioethanol grew from near zero in 1972 to 3.5 million in 2008. Projections suggest that the hectarage for sugarcane will nearly double in the coming years, primarily within agro-ecological zones in the Central South, replacing non-intensive pasturage (Smeets et al., 2008; Fischer et al., 2008; Goldemberg, 2008). Critically, the yield in litres per hectare has grown from 2000 in the year 2000 to 5917 l per hectare in 2004 (Goldemberg, 2008). Fischer et al. suggest that there is a further 5 million hectares of very suitable land available for conversion, not in competition with food production. The areas most at risk are the immediately surrounding savannahs (the Cerrado), and strong regulatory measures and enforcement will be necessary to ensure the prevention of encroachment.

However, given that Brazilian land resources are now extensively dedicated to producing bioethanol for the world market, one of the wider questions of land availability is how and in what manner land can be considered as a global as against national or local resource.

Extending the availability of land issue beyond the three regions so far discussed, an analysis has been undertaken to determine global land availability for sugarcane production across the sub-tropics. The AEZ methodology (Fischer et al., 2006) suggests that of the current 1550 million hectares of cultivated land, there are 120 million hectares that are very suitable or suitable for conversion to sugarcane production for bioethanol.[5] That is to say, global capacity for bioethanol from putatively available land is equivalent

[5] Of this global total, 48 million hectares in Africa, 69 million hectares in South America, and 7 million in Asia are deemed to be very suitable or suitable for sugarcane cultivation (Fischer et al., 2009, p. 54).

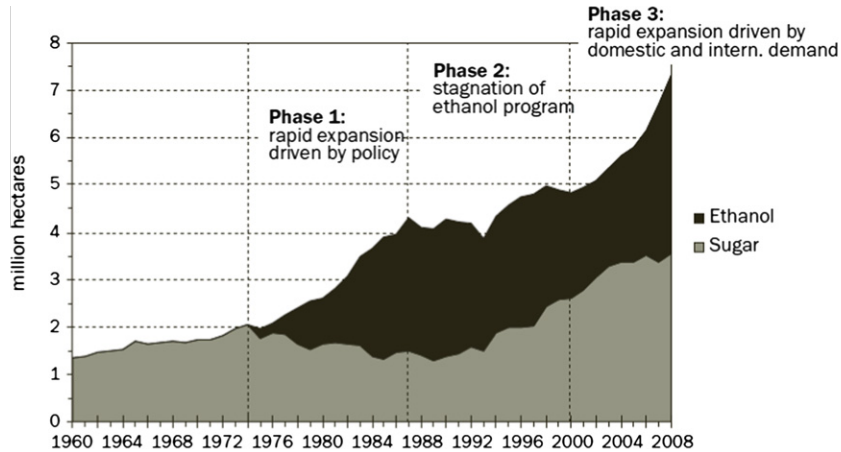

Fig. 3. Expansion of land cultivated for bioethanol, 1960–2008. *Source*: Fischer et al. (2008) and FAOSTAT (2008)).

to approximately 20 times the current capacity of Brazil. Mathews (2007) advanced an argument for a new global pact between North and South based on a similar analysis of potential sugarcane ethanol. Given the rate of increased productivity within Brazil, with new advanced hybrids and genetically modified sugarcane, new cultivation techniques, and new biorefinery technologies, he estimated that Brazilian capacity could quadruple without major impacts on land use beyond existing projections. An important component of this analysis, shared by Fischer and Mathews, is that the energy gain in the sub-tropics is significantly greater than any achievable in temperate zones. The fossil energy ratio (output of biofuel energy per unit of fossil fuel input energy) was 9.3 in 2006, compared with 2.1 for sugar beet in Europe, and 1.4 for corn-ethanol in the US (Goldemberg, 2007). The conversion of solar energy into biomass growth is significantly enhanced in sub-tropical compared with temperate zones (Woods et al., 2009). Moreover, the energy content of sub-tropical crops in general is significantly higher than those grown in temperate zones, so relatively limiting the amount of land required for the production of a given amount of energy, as shown in Fig. 4. Sugarcane and palm contrast quite significantly with corn, wheat and rapeseed as feedstocks for fuel. For this reason, the early-stage biofuel developments in sub-Saharan Africa point to gradual emergence of a South–North re-alignment in geo-energy, as well as developmental and market opportunities in that region (Mitchell, 2010; Sulle and Nelson, 2010; Nhantumba and Salamão, 2010). There is already evidence of a 'land-grab', or, more neutrally, land deals where national

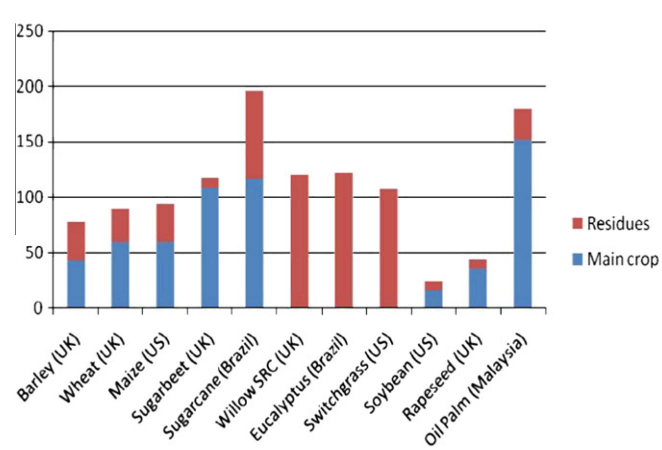

Fig. 4. Gross biofuel energy yields (GJ ha^{-1}) from conventional and advanced biofuel supply chains. *Source*: Woods et al. (2009).

interests and commercial interests are securing their own food and energy security by acquiring large tracts of 'available land' in Africa (Cotula et al., 2009; WWF, 2007; Greenpeace, 2007).

Whether for food or energy, an important distinction needs to be made between security of supply and sustainability of supply, with considerable implications for how to consider land as a global resource. If all energy and food has to be 'home grown' for reasons of security (possibly the US vision), then implications for competition for land are quite different than if primacy is given to renewability and sustainability. To give one current example, Sweden has been granted a dispensation by the EC from trade barriers to import Brazilian bioethanol as its main source of renewable transport energy, partly because of the climatic and agricultural constraints of cultivating biomass for energy within Sweden. This is a possible pioneer of a new North–South re-alignment. Many countries are never going to establish a position of energy or food independence, or anywhere near approaching it.

In summary, the fact that land is hypothetically and technically suitable and available for conversion to bioeconomy production of energy and materials without ecologically damaging consequences, does not mean that market forces will automatically lead to their effective and sustainable exploitation, or mitigate competition of land-use with food production. The Mathews and Fischer type of analysis significantly underestimates the political, economic and social complexity of such a geopolitical shift in the global use of land, at all levels of governance, local, regional and international. Similarly, analyses of 'agriculturally degraded' land available worldwide for potential use for producing biomass for energy or materials, useful though they are, only present arguments for technical feasibility (Campbell et al., 2008).

Three biofuel innovation pathways: Brazil, the USA, and Europe

There have been many reports on biofuels, analysing the technological advantages and disadvantages, GHG savings, and different benefits from different biofuels (e.g. Royal Society, 2008; Renewable Fuel Agency, 2008; European Commission, JRC, 2008). These reports also examine various technologies of biofuel, whether bioethanol or biodiesel, and so-called first and second generation biofuels. 'First generation' are biofuels, currently in widespread production and use, derived from a variety of feedstocks, mostly typical agricultural crops (maize, wheat, rapeseed, sugarcane, sugarbeet, palm oil, etc.). Second generation biofuels, only a few of which are close to commercialisation on a large scale, are derived from a multiplicity of feedstocks and refining technologies (dedicated energy crops such as miscanthus; algae; carbon waste; bacteria; jatropha; sweet sorghum, and many more; bio-fermentation, GM bacteria and enzymes; biomass-to-liquid (BtL) by thermo-chemical means such as Fischer–Tropsch for refining). Although a convenient and current form of labelling, in reality the distinction between first and second generation biofuels is quite misleading, particularly if it carries implications that the former are uniformly less effective than the latter for reducing GHG emissions or competition for land. With a focus on the developing competition for land, it is important to consider the innovation pathways in different regions as they can currently be discerned. These pathways are very different in different parts of the world, even when we consider the three major regions of biofuel production: the USA, Brazil and Europe. The most important consideration of these three trajectories, each with markedly different implications for land use, is the extent to which they are shaped not only by different political objectives, but also different natural resource endowments, and different future innovation potentials.

Two principal implications can be drawn from such regional differentiation. A single type of resource or technology for renewable transport energy and materials is unlikely to uniformly dominate the world as the petro-chemical technology platform has done since the middle of the last century. Consequently, different technologies will develop in different regions, including different transport and vehicle systems. It is misleading to assume that a 'second generation' biofuel technology will replace a 'first generation' biofuel by virtue of a technological superiority in GHG reduction, elimination of competition with food, or market opportunity. Secondly, how rapidly, and in what direction, these developments occur will continue to be driven as much by political strategies as by market forces. The three figures below summarise in broad terms the dominant innovation trends of biofuel production in the world. The first demonstrates how the USA and Brazil dominate bioethanol production; the second, how far Europe dominates the biodiesel production. The third figure in approximate terms illustrates the GHG savings of each of the crops, whether for bioethanol or for biodiesel. Significantly, the sub-tropical crops stand out for GHG savings in a way that mirrors their advantages in energy per hectare (Fig. 4), and consequent implications for land demand (see Fig. 5). We now briefly describe how each of the three regions has developed their biofuel innovation.

Brazil

Brazil has been the longest established major producer and user of bioethanol, under a strategic political direction of the ProAlcool programmes initiated as a consequence of the oil price shocks of the 1970s (Goldemberg and Guardabassi, 2008; Goldemberg et al., 2004). The driving force behind the innovation during the first 20 years was energy independence from reliance on imported petrol. From the beginning of this century, additional strategic goals have been to expand international markets for renewable fuel, to promote sustainability through greenhouse gas emission, and to sustain rural employment and eradicate poverty. The innovation strategy has been directed at all phases of the production of fuel. The government has supported the creation of improved varieties of sugarcane, including the development of GM sugarcane, with different inheritable traits. Mechanisation of harvesting is progressing to minimise the impact of pre-harvest burning of fields required for manual harvesting. Biorefinery has progressed through several stages of innovation, but currently is self-sufficient in energy through generating bio-electricity by using sugarcane residue (bagasse) as a fuel, now also contributing 1.5% of electricity supply to the national grid. Additionally, fertiliser co-products (vinasse) contribute to GHG savings and reduce pollution to the water table. Current state funded research programmes (the FAPESP BioEn programme) are supporting research into biopolymers and other chemical building blocks, on course for integrated biorefineries. The government initiated the development of the first transport fleet to run on 100% ethanol following the 1979 oil price shock, but more recently, Flex-Fuel Vehicles, capable of running on 100% bioethanol, petrol or liquid gas. Currently, bioethanol contributes 40% of transport fuels, and over 80% of new cars purchased are FFVs. The bioethanol industry supports 700,000 jobs directly and a further 200,000 jobs indirectly, 100 times greater employment by unit of energy than oil (De Almeida et al., 2007). It would be mistaken to describe sugarcane ethanol as first generation, given both the progressive stages of innovation already realised, and the projected increases in productivity at all phases of production. GHG savings of current generation sugarcane, with co-products, exceed those anticipated by 'second generation' ligno-cellulosic bioethanol, and the development of bio-ethylene as

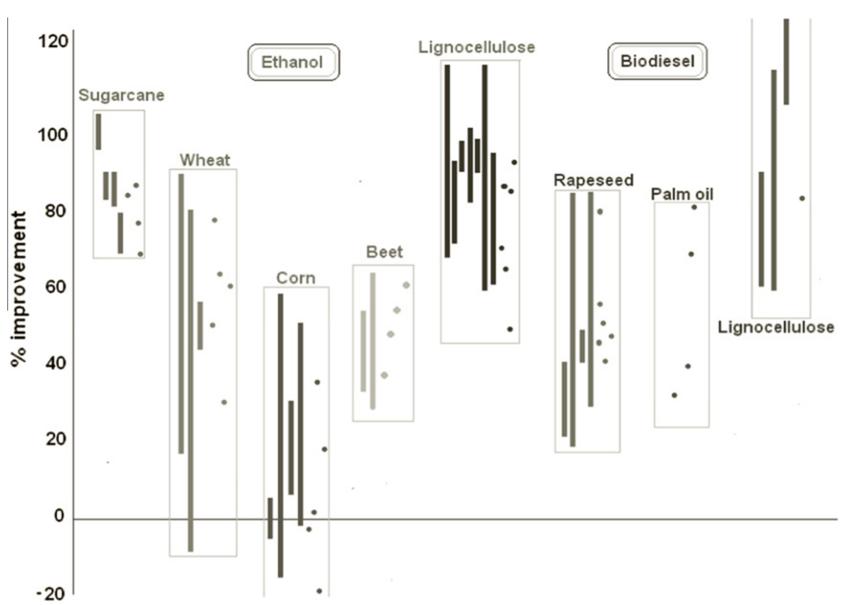

Fig. 5. Net life relative cycle GHG emission improvement of selected biofuel pathways as compared to gasoline and diesel fuels. Without land-use change. *Source*: OECD (2008) (see also Fritsche et al. (2008)).

a co-product will increase that advantage (Brehmer and Sanders, 2009; OECD, 2008). Brazil represents the most advanced country in the world for energy security and sustainability. It has achieved this position only as a consequence of political innovation strategies developed over the long term, encompassing funding of basic science, commercial R&D, and market shaping through use of incentives. Even if its political objectives have been primarily those of energy security and economic opportunity, Brazil has 'accidentally' achieved higher levels of renewable and ecologically sustainable transport energy than any other country or region.

The USA

As can be seen from Fig. 6 above, the main expansion of bioethanol production in the USA occurred later than Brazil, taking off around the turn of the century, although an earlier bioethanol industry had been promoted by the US government in response to the 1970s oil shocks, as with Brazil. The USA had passed its own peak oil in the early 1970s (Defeyes, 2001), and was becoming increasingly dependent on imported oil, thus raising issues of both energy security and availability. The annual trade deficit for oil had risen from $27 billion in 1987 to $100 billion in 2002 (IEA, 2006), and the costs and vulnerability of securing Middle East oil had escalated. The principal objective shaping the politically sustained innovation pathway in the USA was initially overwhelmingly that of energy security and independence, only more recently supplemented by objectives of GHG emissions reduction, and concerns over environmental sustainability. A succession of legislative and funding measures by the US government, led by the Departments of Energy and Agriculture, have established long term strategic goals, and significantly acted on both market demand and on development of supply for bioethanol. The 2000 Biomass R&D Act was followed by the Energy Policy Act of 2005, and the significantly entitled Energy Independence and Security Act, in 2007 (EISA). Mandates requiring substitution of petrol by bioethanol are ambitious – 20% reduction of petrol use in 10 years, and 30% biofuel for transport by 2020 of which two thirds are to be 'second generation' by 2022. Although below levels achieved in Brazil, these mandated markets are considerably above those aimed at in Europe. On the supply side, a multi-dimensional and large scale investment programme has been established in fundamental science, notably systems biology, and in technological development, both directly by government finance and by corporate-government alliances. A loan guarantee scheme underwrites risk on capital for new companies emerging in the production of ligno-cellulosic bioethanol, or in high risk areas, such as algal or bacterial derived biofuel. The Genomics Systems Biology Program for developing biofuel, biorefinery and plant technologies demonstrates a long term commitment to scientific and technological development. The Energy Bioscience Institute (EBI) comprising the Universities of Illinois, Urbana Champaign and the Lawrence Berkeley National Laboratory with BP, supported by $500 million from BP, and dedicated to developing second generation biofuels exemplifies the effects of the innovation environment created by current policy (Blaschek et al., 2008). As with Brazil, although the main stated objective of this strategic policy framework has been energy security and independence, the 'collateral benefit' especially from second generation biofuels has the potential to reduce competition for land with food uses, and result in significant GHG emissions reduction.

Europe

As can be seen from Fig. 7, Europe stands out as the major producer of biodiesel in the world, and Fig. 8 below demonstrates how far Europe contrasts with the other major biofuel regions in the

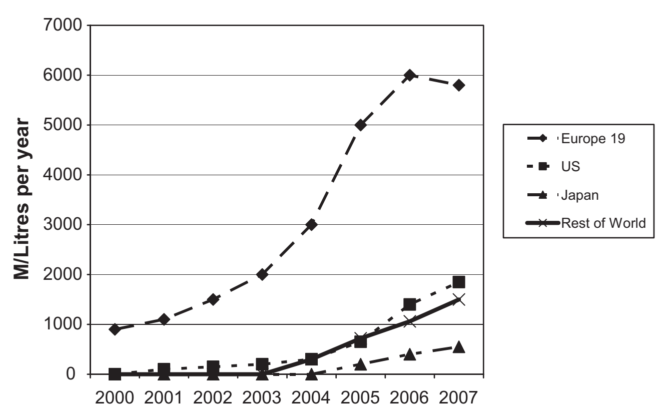

Fig. 7. World biodiesel production by region. *Source*: Adapted from IEA Bioenergy (2009).

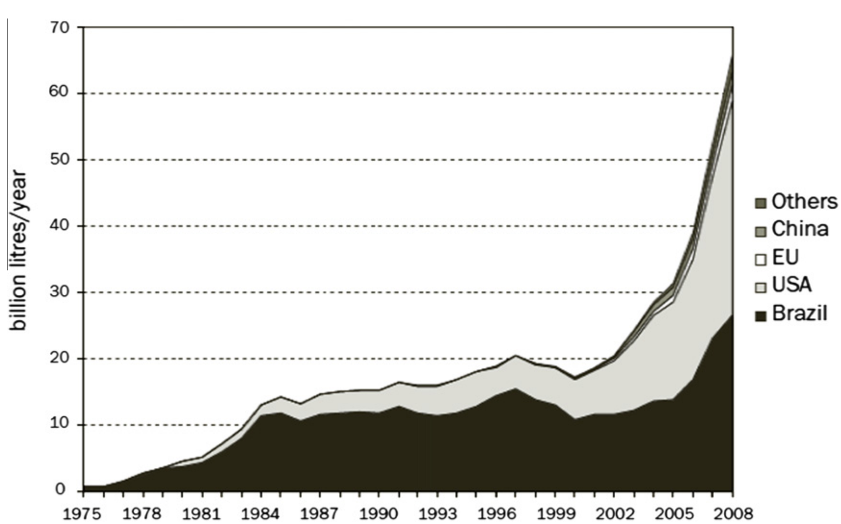

Fig. 6. World bioethanol production by region. *Source*: Lichts (2007, 2008).

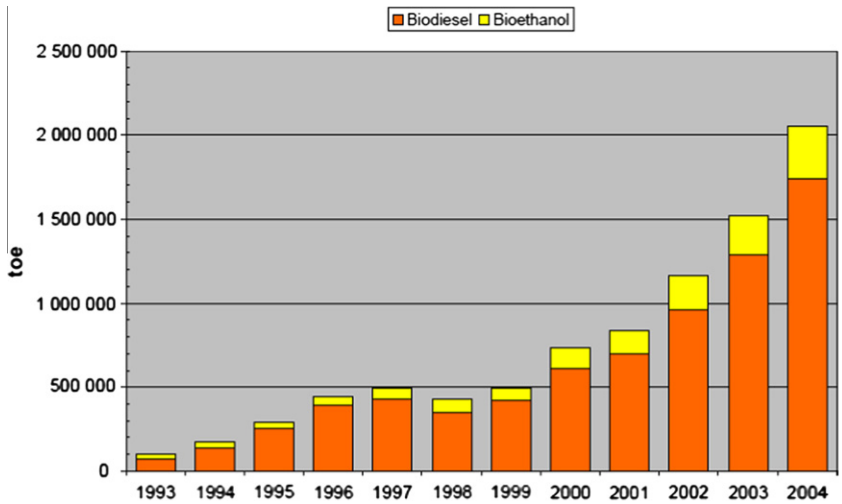

Fig. 8. The growth of biofuel production in Europe, 1993–2004. *Source*: Biofuels Research Advisory Council (2006).

dominance of biodiesel in terms of production and use (McMeekin et al., 2009). Of this biodiesel production, over 80% is derived from 'home grown' rapeseed. The principal explanation for the contrast with other regions is the rapid 'dieselisation' of the European vehicle fleet, with consumption of diesel rising from 45% of transport fuel in 1990 to 63% in 2005 (European Biodiesel Board). Currently, over 80% of all new vehicles purchased in Germany are diesel, with similar levels for many continental European countries.

As with the other two regions, the rapid growth in biodiesel production and use in Europe can be attributed to major policy initiatives taken at the European level, and then expressed in a variety of policy measures in different European countries. In contrast to the other regions, the principal policy objective guiding European strategy has been to address commitments made under the Kyoto Protocol by reducing GHG emissions (Londo and Deurwaarder, 2007). Policy at the European level sets long term targets, and mandates for levels of biofuel use, but considerably below those aimed at or achieved in the other regions. The first targets set in 2003 aimed at achieving 5.75% of biofuels for transport fuels by 2010. The actual level of UK replacement of petrol/diesel with biofuels stood at 2.6 per cent in 2009 (Renewable Fuel Agency, 2009), far below Germany (7.3 per cent; Government of Germany, 2008), France (3.57 per cent; French Authorities, 2008), and Sweden (4 per cent; Swedish Government, 2008). Following the Searchinger controversy, the 2009 Renewable Energy Directive and Fuel Quality Directive revised the targets to 20% of transport energy from renewable energy by 2020, with only 10% required to be supplied by biofuels or other 'green' transport energies. In marked contrast to the other regions, Europe has pioneered regulation for sustainability in its treatment of biofuels. The Renewable Energy Directive requires 35% GHG savings from now until 2017, and 60% GHG savings from new installations and processes thereafter. A review, and possible tightening of sustainability criteria, is projected for 2013. The Fuel Quality Directive requires the continued provision of petrol with a *maximum* of 5% ethanol blend until 2013, and the gradual phasing in of 10% bioethanol (E10) over the coming years. It also requires a 6% reduction in GHG emissions from units of energy supplied for transport fuels by 2020. Conveniently for the European rapeseed industry, RME biodiesel derived from rapeseed currently just achieves the required savings (according to current default values listed in Annex 5 of the Renewable Energy Directive), using measures that do not include indirect land-use change.

Policy measures adopted by different countries involve tax incentives for biofuel use and mandatory obligations, as with the Renewable Transport Fuel Obligation in the United Kingdom. But in contrast to both Brazil and the USA, on the supply side there has been no equivalent major strategic innovation programme for the development of future biofuels, in support of the relevant basic science or technologies. For example, given the current dependency on biodiesel, there has been no major programme for the development of second generation biodiesel, such as biomass-to-liquid (BtL) necessary to meet the more stringent GHG reduction requirements from 2017. Demand-side measures have not been complemented by adequate supply-side policies, leaving a considerable question mark on the achievability of either fuel-substitution or sustainability targets. Likewise with bioethanol, although there are some major bioethanol producers in Europe (British Sugar, Ensus, Tereos, Abengoa, CropEnergy), there is also heavy reliance on imported bioethanol, and little evidence of the strategic aim to move to second generation bioethanol similar to the USA. The policy direction of biofuel production and use towards sustainability of transport energy in Europe thus risks failure in these objectives, while not even addressing the major issues of energy security and availability.

Concluding this section, it can be seen that the demand for land to meet energy and materials demand is characterised by contrasting innovation bioeconomy pathways in three major regions. Each of the areas present different patterns of competition for land, different potentials for increased sustainability and renewability of energy, and different potential contributions to the use of land to meet global demand for energy and materials. This global landscape is one of diversity, not a uniform political, social or technological solution to economic stability or growth. Worldwide, biofuels as a substitute for petrol and diesel for transport energy are likely to become increasingly significant, given the limitations of alternative technologies and the projections of the growth of vehicles powered by internal combustion engines. But constraints on land-use, limitations on potential biomass, and technological opportunities suggest that, although "18 Brazils" (Mathews, 2007) may be a possibility, the world will not become "100% Brazil" with respect to transport energy. A new geopolitical framework for land resources could emerge, on condition that there is the international political will to achieve consensus on sustainable land use. Perhaps a more likely prospect is a patchwork of partial initiatives and lowest common denominator agreements based on narrow national interests.

Developing coherent international sustainability regulation

Biofuels have been a pioneer for sustainability regulation, particularly in the field of land use, and partly as a consequence over controversies surrounding ILUC (van Dam, 2010). Thus, in the US the State of California established a Low Carbon Fuel Standard in 2007, and in Europe, the Renewable Fuel Directive and Fuel Quality Directive of 2009, set the pace of sustainability regulation. As a pioneer, biofuel sustainability regulation has brought into focus some of the major complexities and challenges facing sustainability regulation in general, some technical, others political. The principal areas at stake are first, the coherence and scope of sustainability regulation; second, the complexity of setting boundaries, including or excluding indirect effects; and third, the establishment of political and scientific consensus on an international scale. In this respect, we shall briefly note the emergence of transnational, non-legally binding, self-regulation.

If biofuels have been a pioneer object of sustainability regulation, they have also been singled out for special treatment in ways that deflect attention from the wider issues of developing sustainable use of land. There are several distorting consequences from this uneven and partial regulatory development. First, the benchmark for assessing GHG savings continues to be conventional oil extraction, and although the carbon footprint of oil is primarily through emissions rather than through extraction and refining (Sperling and Yeh, 2009), that is much less the case with non-conventional oil from deep sea, oil sands or shale oil. These sources of oil are becoming more significant (IEA, 2009), and yet the benchmark remains unchanged. No sustainability regulation is being developed for oil extraction, including, for example, regulation to restrict flaring, still a widespread practice.

Second, the argument for regulating indirect effects of land-use change can be interpreted in part as a reflection of the absence of a comprehensive sustainability regulation regime. As Kim et al. (2009) have pointed out, even if the biofuel supply chain itself observed the best sustainability regulation practices from field to wheel, the indirect effects, if any, of land conversion elsewhere might involve the least sustainable use of land, such as slash and burn. Regulating the biofuel, and not regulating the agricultural products resultant from indirect effects, avoids regulating the actors directly responsible for detrimental environmental effects arising from high carbon-footprint agriculture. Apart from the major methodological difficulties of determining boundaries, what to include or exclude from indirect effects (Cooper, 2009), *sustainability regulation is more likely to be effective if applied to those directly engaged and responsible for any given production chain*. So rather than setting standards for biodiesel in Europe in order to indirectly regulate palm oil production in Indonesia (e.g. for product chains of cosmetics or food), regulation would be more effective if directly applied to those product chains too. By extension, that raises yet more testing questions of international regulation affecting major importers of Indonesian palm oil such as China.

Third, given the lengthy and complex process of developing formally binding international regulation, emerging forms of self-regulation involving a wide range of international and transnational actors, can be seen to be a preparatory phase leading towards that end, delivering some partial benefits in the meantime (Hall and Biersteker, 2002; Brunsson and Jacobsson, 2000; Broude and Shany, 2008). Thus, the Roundtable on Sustainable Palm Oil, the Roundtable for Sustainable Biofuels, and the Better Sugar Initiative are examples of self-regulation and certification, involving NGOs, producers, and retailers, developing standards for sustainability to which they commit to adhere. As with all forms of self-regulation, they are subject to the criticism that they are partial, including only those who voluntarily participate, and unenforceable, as they lack formal sanction. Nonetheless, in each case, they are engaged in standards development in the context of the absence of any standards. As such, these examples are evidence of a long and complex process of developing international standards for sustainability.

Conclusion. Sustainable intensification of agriculture and governance

We have attempted to explore the dynamics of competition for land, and identify some of the principal issues at stake for future sustainability of land use. Based on the model represented in Fig. 1, competition for land use in the coming decades was seen as being driven by two major objectives in achieving sustainable economic growth: the delivery of food and energy/materials in a post-fossil carbon economy. The paper has systematically attended to each of the elements of a complex interaction: growing and changing demand for food; demand for energy and materials derived from biomass in the context of oil depletion; GHG emissions from current agricultural practices and land-use change; and climate change itself as a constraint on land available for cultivation at high levels of productivity. The scale of the challenges was examined, as was the significance of current patterns of land-use in contributing to global warming. The growth of agricultural production cannot continue on current lines and practices without risking major crises, given its significance as a source of greenhouse gases. A key element of future development will be to meet increasing demands on land by intensification of low-carbon gas emitting agriculture, by all technological means possible.

The growth in demand for food (arising from the need to ‘feed the 9 billion’ and improve standards of nutrition) has been taken as given, resting on arguments and analysis more thoroughly developed elsewhere (IAASTD, 2009; Royal Society, 2009; Godfray et al., 2010; DEFRA, 2009b). In exploring the demand for land driven by biofuels and biomaterials, evidence was presented that suggests the need for a major shift in policy understanding of innovation. The shift to bioeconomy alternatives to petro-chemical technologies requires a pro-active, long-term, strategic political direction, promoting innovation from the basic science through to the delivery of goods. The broader challenge to deliver both food and energy calls for a combined new green and bioeconomy revolution. The political shaping of this process will require both sustainability regulation and strongly directed innovation, delivering the means to achieve the ends.

The shift to a bioeconomy and sustainable agriculture involves a paradigm change from the petro-chemical technological model of the world that has characterised the previous epoch. Land, water and climate as a global resource provides different regions with widely contrasted agricultural potentials. The shift to sustainable agriculture for food and energy is likely to re-shape the geopolitical environment of the world. Flows of food and energy/materials will be re-drawn, and different regions will pursue different innovation pathways as a consequence of their diverse political objectives and natural endowments.

In sum, two broad conclusions can be drawn from this paper. Firstly, however uncomfortable and challenging, mitigating the competition for land can only occur provided that the complexity of the dynamics is fully addressed. Each of the contributing factors explored above (energy and food demand; petro-chemical depletion; the various sources of anthropogenic climate change involved in land use) cannot be treated in isolation. Secondly, recent history and current developments strongly underscore the importance of long term political strategy driving forward the shift to a sustainable intensification of land use, combining regulation with effective long term, but urgent, promotion of science and innovation to deliver the goals of sustainability.

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