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Global developments in the competition for land from biofuels ☆

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ABSTRACT

The potential global demand for biofuels and the implications of this for land use and its interaction with food agriculture is reviewed. It is expected that biofuels will form an important element of global transport energy mix (in the order of 20–30% of total requirement) over the next 40 years and beyond. Over this time, there will be a transition from so called first generation biofuels, based on commodity agricultural crops with food/feed uses, to advanced biofuels, sometimes called second and third generation biofuels, based primarily upon lignocellulosic feedstocks. It remains unclear whether these advanced biofuels, based on lignocellulosic materials, will entirely replace first generation or if second generation will be supplemental to first generation. This expansion in biofuels will be coupled to a substantial increase in alternative fuels (electricity, hydrogen, biogas and natural gas) and modal shifts. Biofuel production from agricultural commodity crops that exhibit strong sustainability criteria will remain important (e.g. sugarcane) with supportive and competitive aspects for food security.

Land requirement projections estimated for a range of potential biofuel development trajectories range widely and are inherently uncertain. Under the most active scenario that delivers substantive greenhouse gas reductions in transport by 2050 (relative to 2005 levels), approximately 100 Mha of additional land is projected. In the 'business-as-usual' scenario, in which transport energy demand rises by 80% by 2050 from present levels, a land use requirement of 650 Mha is projected.

Significant potential exists for producing biofuels that possess high productivity and sustainability profiles through continued research, development and demonstration. Policy and regulation at a global level, that focuses biofuel development on these goals in ways that are synergistic with food agriculture, will simultaneously help to decarbonise transport and maintain a diverse and financially robust agricultural (and forestry) sector.

Introduction

This brief review considers biofuel production and its interaction with land use in agriculture for food production. The current state of development of biofuel technologies is presented and a view given on the potential future developments that can be expected over the next 20–40 years. Both the so-called 'first generation' (1G) biofuel technologies, based upon conventional agricultural commodity crops and the 'second generation' (2G) biofuel technologies utilising mainly (ligno)cellulosic feedstocks are analysed.

Biofuels are here defined as liquid transport fuels derived from biomass resources. The feedstocks for their production may include specifically grown crops or forestry resources (including short rotation coppice), residues from crops or forestry e.g. straw, corn stover, forest brash, or other sources of biomass wastes e.g. used cooking oils, food processing wastes, green wastes. The term 1G is used to denote the utilisation of specific agricultural commodities such as grains or oilseeds for biofuel production, usually by well-established sugar fermentations or oil processing techniques like trans-esterification, exploiting sugars, starch and vegetable oils as direct feedstocks to the conversion processes. The term 2G is used to denote biofuels produced from more recalcitrant biomass components, such as lignocellulosic material via pre-treatments and fermentations or thermo-chemical routes, including pyrolysis and gasification and fuel synthesis. 2G biofuels are sometimes referred to as 'advanced' biofuels along with 3G biofuels (see below) and this term will also be used here. It should not be confused with the specific use of the term 'Advanced biofuels' that has recently been applied in the USA Renewable Fuel Standard

☆ While the Government Office for Science commissioned this review, the views are those of the author(s), are independent of Government, and do not constitute Government policy.

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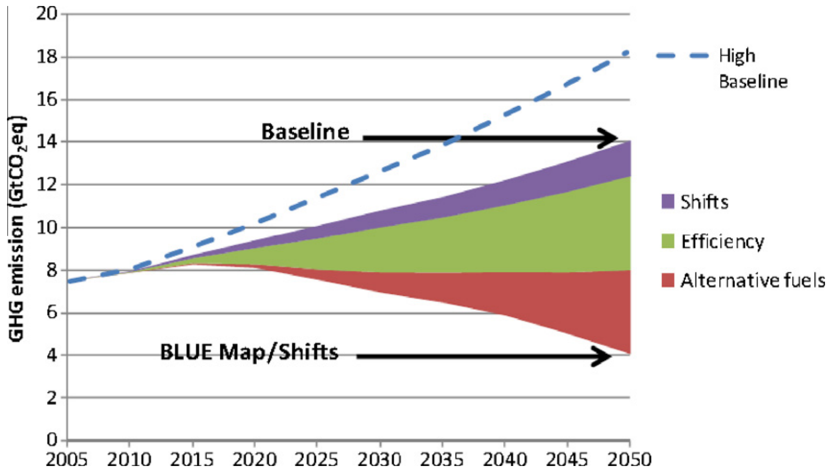


Fig. 1. Annual Global GHG emissions (GtCO2 eq.) from transport (2005–2050) under IEA Baseline and BLUE Map/Shifts scenarios. After IEA (2009) Transport Energy and CO_2: moving towards Sustainability International Energy Agency, Paris, France.

programme (RFS2) under the Energy Independence and Security Act (EISA) of 2007, to denote biofuels offering a 50% reduction or better, in life cycle greenhouse gas (GHG) emissions when compared to the 2005 gasoline or diesel baseline emissions (93 gCO_2eq/MJ gasoline, 92 gCO_2eq/MJ diesel). At present, a single universal terminology for biofuel sources, processing or type classification is lacking.

The main biofuels and feedstocks under consideration in this review are ethanol from carbohydrate fermentations and biodiesel from the trans-esterification of various plant oils (sometimes termed fatty-acid methyl esters or FAME). This is not intended to be exclusive and other biofuels such as biobutanol, straight plant oils, syn-fuels (from Fischer–Tropsch syntheses from syn-gas) and biogas are included within the scope of the review.

The review does not consider biofuels derived from algae which are sometimes referred to together with some other feedstocks and processes as 'third generation' biofuels (3G). Both gasoline and diesel substitutes and a variety of co-products are potentially available from algae and there is substantial renewed interest in such possibilities, as indicated in recent reviews by Rosenberg et al. (2008) and Greenwell et al. (2010).

Global demand for biofuels

The current and future demand for biofuels varies significantly between countries and regions. Drivers for demand include the economic, energy security and climate change policies of national governments; business opportunities in the energy and agricultural sectors; technological innovation in the automotive and wider transport sectors and, not least, social and environmental concerns. A number of these are considered further in relation to interactions with agricultural systems in other FORESIGHT Food and Farming Futures reviews (Smith et al., 2010; Woods et al., 2010).

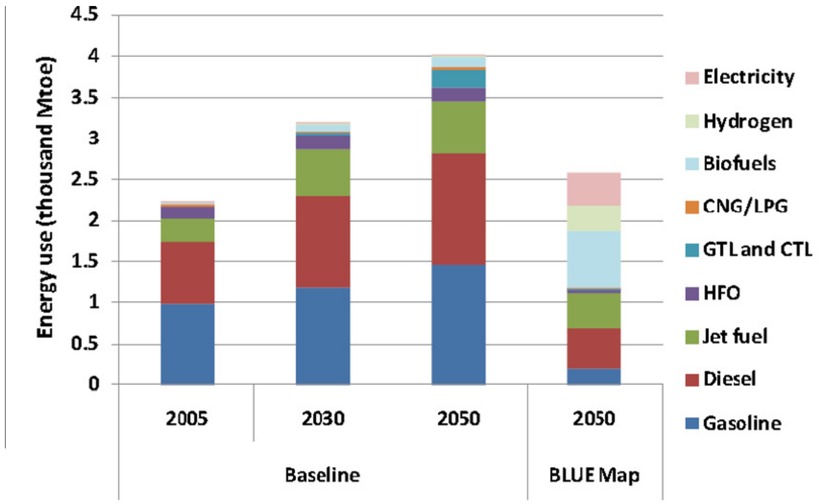
Substantial regional differences exist in the relative shares of diesel and gasoline in the transport fuel mix. For example, the IEA/WBCSD (2004), has projected that 74% of North America's transport energy will be derived from gasoline with the remaining 26% being derived from diesel, whilst in Europe, 60% will be derived from diesel and 40% from gasoline. Given the scale of investment in the fuel supply and power-train manufacturing infrastructure and the relatively long life-spans of the vehicle stock (e.g. 15+ years), even with very substantial policy intervention, diesel and gasoline will remain the dominant fuels over the next 20 years. This has important implications for alternative transport fuel development and also, in part, explains the emphasis there has been on ethanol (primarily from corn) in the USA as a gasoline substitute and on biodiesel (primarily from oilseed rape) in Europe as a diesel substitute.

The basing of biofuel mandates on either volumetric substitution or energy substitution for petrol and diesel by ethanol and biodiesel respectively, also has major implications for crop and feedstock choices and the associated land demands that arise for biofuel production. Because the energy densities of ethanol and biodiesel are lower than their fossil fuel alternatives, and ethanol has a significantly lower energy density than biodiesel and gasoline, the share of the fossil fuel-based market occupied by petrol or diesel vehicles affects the projected demand for ethanol and biodiesel crops, i.e. for starch/sugar or oil crops and feedstocks. Oil crops also tend to have significantly lower productivities on a volume or energy basis per unit area than starch or sugar crops.

Recent assessments of global primary energy demand from now to 2050 have been given by the International Energy Agency (IEA) in their 'Baseline' and BLUE Map scenarios. Under the Baseline scenario, world primary energy demand expands by 45% from approximately 12,000 million tonnes of oil equivalent (Mtoe) currently to approximately 17,000 Mtoe (714EJ) in 2030. Fig. 1 shows that under the Baseline scenario, the GHG emissions from transport would increase by nearly 50% from 2005 levels by 2030 and over 80% by 2050, due to increased consumption of fossil fuels (IEA, 2009). In contrast, the IEA BLUE Map/Shift[2] scenarios show options to achieve an overall reduction in transport GHG emissions of 40% in 2050 relative to 2005 emission levels.

The IEA Blue Map/Shifts for 2050 are striking in that, even with increased global transport energy demand (to approximately 2500 Mtoe (105EJ) by 2050) from world population growth and development, the overall levels of GHG emissions from transport are reduced to well below 2005 levels. This is achieved by increased fuel/energy efficiency in transport (approximately 50% of the 'gain'), deployment of low-carbon electrical and hydrogen energy carriers in light passenger and delivery vehicles after 2030

[2] The IEA's Blue Map, Blue Shift and Blue Map/Shift scenarios are CO_2 reduction scenarios developed based on halving global energy-related CO_2 emissions by 2050 using CO_2 reduction measures costing up to USD 200/tonne. These scenarios will require strong policies to achieve. BLUE Map for transport: achieves CO_2 emissions by 2050 that are 30% below 2005 levels by greater use of biofuels, deployment of electric vehicles, fuel cell vehicles etc. BLUE Shifts for transport: No advanced technology deployment, gains achieved through modal shifting only which results in a 20% reduction in energy use and CO_2. BLUE Map/Shifts (Blue Map + Blue Shifts) for transport: results in a 40% reduction in CO_2 below 2005 levels by 2050.



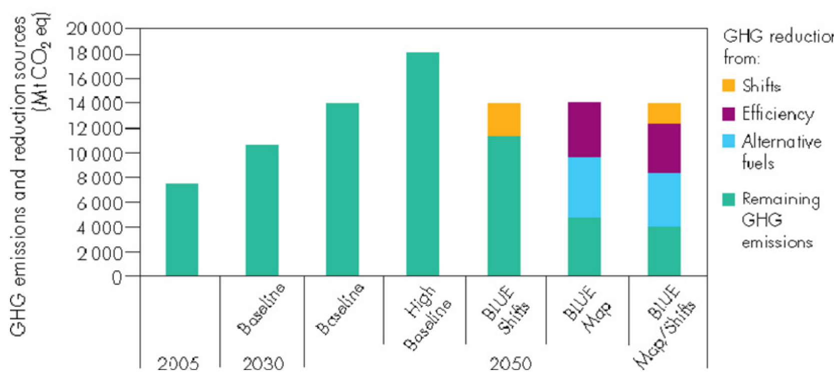


Fig. 2. Transport fuel energy use by composition (Mtoe × 103) (upper graph) and resulting GHG emissions and sources of reduction) under IEA Baseline and BLUE Map/Shifts scenarios 2005–2050 (lower graph). After IEA (2009).

Table 1
Summary of policies and assessment of the biofuels component of transport fuel requirements – 2010 to 2050.

Publication date	Reference	Biofuel proportion in transport fuel
2005	Perlack et al. (2005)	Biomass resource sufficient to replace 30% of US gasoline
2006	Biofuels Research Advisory Council – EU Vision	25% of transport fuel in EU by 2030
2009	EC – Renewable Energy Directive	10% of transport energy as renewable by 2020[a]
2009	EC – Fuel Quality Directive	Potentially increases biofuel to 15% of transport energy by 2020[a]
2007	Energy Independence & Security Act 2007 (EPA, 2010a)	7% of expected gasoline & diesel consumption in USA in 2022[a]
2008	Gallagher Review	5 to 8% of transport energy recommended, potentially 10% by 2020[a]
2009	UK Renewable Energy Strategy (Anon, 2009)	10% transport energy by 2020[a]
2008	IEA, 2008 Energy Technology Perspective	26% of total transport fuel demand in 2050
2010	IEA, 2010 Energy Technology Perspective	20% of total liquid fuel demand in 2050

[a] Mandated dates.

and by the use of advanced biofuels. Biofuels are important energy providers to reduce GHG emissions in the BLUE Map scenario, needed both in the short term, in light vehicles, and in the longer term, in freight, shipping and aviation (see Fig. 2). The IEA report notes that "*About a 20-fold increase in biofuels is needed to achieve the outcomes envisaged in the BLUE Map scenario by 2050. If done wisely, this should be possible using only a small share of global agricultural land.*" (IEA, 2009).

The most recent estimates by IEA in their Energy Technology Perspectives (IEA, 2010) indicate that 20% of liquid fuel demand by 2050 could be met by biofuels and that, together with low-carbon hydrogen and electricity for vehicles, these will represent approximately 50% of total transport fuels. It should also be noted that this is a downward revision of the previous 2008 IEA ETP (IEA, 2008) which indicated that some 26% of transport fuel demand by 2050 could be from 2G biofuels (IEA, 2008). This downward revision occurred due to emerging concerns over land use and conflicts with food agriculture and land use change (LUC) and the net GHG balances of biofuels, especially those that rely on 1G feedstocks (Searchinger et al., 2008; Fargione et al., 2008; Gallagher Review, 2008). These concerns have been the subject of intense scrutiny since 2008 and are discussed further later in this review.

The IEA BLUE Map figures for the biofuel component of world transport fuels of 20–25% by 2030–2050 are consistent with several of the current policy directions and assessments (see Table 1and Bacovsky et al., 2009).

Biomass productivities and production potentials

Projecting the impacts of future biomass production for biofuels has been and remains highly controversial. A wide range of issues remain uncertain and a number of variables and assumptions that underpin estimates of future yield increases are sensitive to management, national and international policies, economics and climate change. In projecting the land demand and associated bio-physical impacts of future biofuel demand, this uncertainty is

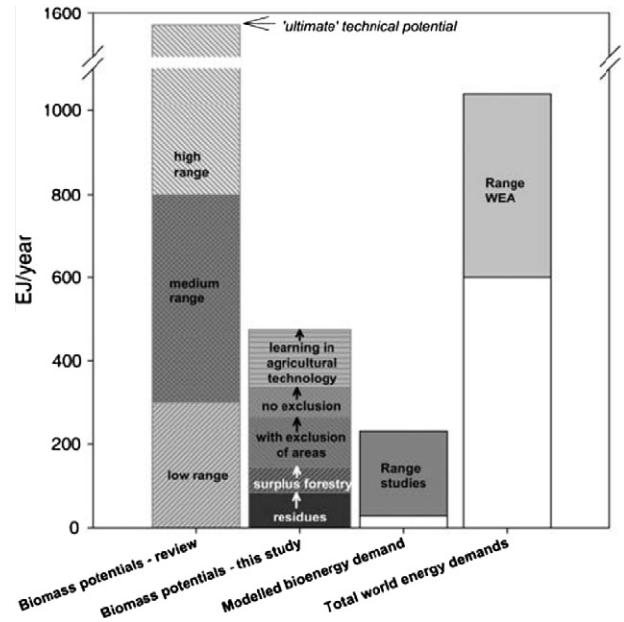


Fig. 3. Comparison of the range of biomass energy supply potentials (1st bar from left), lignocellulosic biomass supply potentials (2nd bar), modelled primary bioenergy demands included in the review (3rd bar) and estimated range for the total global primary energy demand from the World Energy Assessment (2000; 4th bar), all by the year 2050. From Dornburg et al. (2010).

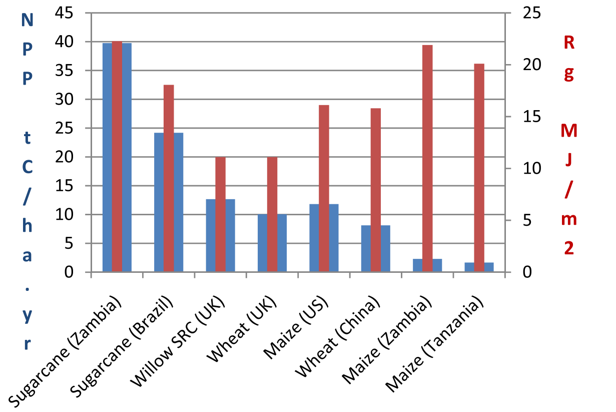


Fig. 4. Solar radiation versus Net Primary Production (NPP) for a range of crops and locations.

exacerbated because of the need to predict the future yields of novel crops, in particular perennial lignocellulosic crops, where little or no data is available about historic yields. Despite these uncertainties, simplified assumptions can be made based on assessing a broad range of factors that will impact on future yields and by comparison with fundamental limits to photosynthetic efficiencies.

Jaggard et al. (2010) review the main bio-physical issues that are likely to affect arable crop yields to 2050. They identify carbon dioxide fertilisation, ozone (ground-level), changed climate (temperature and water), improving technology (plant breeding, crop nutrition, crop protection) and 'the yield gap' as key variables in understanding and projecting crop yields by 2050. The authors conclude that 'there is a good prospect that crop production will increase by approximately 50% or more by 2050 without extra land;' i.e. sufficient to meet future food demand for the 2050 population. However, they highlight the need to factor-in bioenergy, which they were unable to do.

Rokityanskiy et al. (2006) and Dornburg et al. (2010) reviewed a range of studies assessing the energy production potentials and associated land demands of bioenergy (heat, electricity and transport), and integrating future food demands and technology changes. Fig. 3 (Dornburg et al., 2010), highlights both the scale and range of bioenergy potential assessments versus total primary energy demand in 2050. Whilst the range in estimates is very large, virtually all studies show the bioenergy potential to be substantial compared to projected primary energy demand.

The key question remains however, will bioenergy, and in particular biofuels, be competitive for land and resources to the food, materials and biochemicals sectors, or will the investment in new technologies, human capacity and infrastructure lead to a sufficient expansion in total biomass productivities that new land demand is curtailed or that adverse impacts on new land are ameliorated?

Radiation use efficiency

The solar radiation use efficiencies (RUE) of three conventional and one perennial lignocellulosic crops are used in Fig. 4 as a proxy to assess the 'yield gap' as defined by Jaggard et al. (2010).[3] The three conventional crops, sugarcane, wheat and maize are the predominant feedstocks for fuel bioethanol currently but are also food crops and can therefore be used to help understand the possible influence of bioenergy cropping on closing that yield gap, particularly in developing countries. Where investment occurs and modern agricultural techniques and inputs are used, RUE's of c. 1% or more are achieved. Where farmers are unable to access sufficient inputs, supporting infrastructure and vigorous varieties, RUE's of about 0.1% are achieved e.g. maize production in Zambia and Tanzania in Fig. 4.

In practice, a multitude of factors affect crop yields, as discussed above, however, a crop's ability to intercept the energy in sunlight and use it to capture and convert carbon into the complex polymers that make up biomass ultimately defines its yield potential. For example, very high levels of solar radiation imply low cloud coverage and therefore potentially lower rainfall. Farmers can either locate their crops to balance RUE with water use efficiency (WUE) or provide water to the crop e.g. through irrigation. Sugarcane production in Zambia, with an estimated RUE of 1.8%, has been located to facilitate irrigation which constrains the scale of production. In Brazil, however, sugarcane production is predominantly rainfed but still achieves an RUE of 1.4% compared to wheat in the UK (0.9%) and maize in the US (0.8%), which are also mainly rainfed.

It is likely that the high RUE of sugarcane in Brazil has resulted from long-term investment in combinations of research, development and deployment capacity and also in the matching of varieties to local soils and climate. In turn, the continued ability to fund the development of sugarcane over the last 40 years may have resulted from the industry's ability to access both crystalline sugar and emerging fuel ethanol markets and to switch sugar between these two markets depending on the prevailing market conditions. More recently, improvements in the efficiency of conversion of bagasse (sugarcane residue) to electricity at sugar/ethanol mills has led to greater returns per ha from sugarcane due to increasing revenues from electricity exports to the local grid. Bioenergy has therefore supported long term stability of markets for sugarcane producers and increased their confidence to invest in yield improvement instead of simply relying on area expansion.

How applicable are these positive interactions between food production (crystalline sugar) and bioenergy (ethanol and electric-

[3] Theoretical maximum efficiencies of photosynthesis for capturing and converting sunlight into fixed carbon are about 5%. However, in practice, temperature, water, nutrients, pests and diseases can severely reduce this potential to the point where crops typically only reach ~0.1–0.8% RUE determined as biomass produced per unit of intercepted radiation (MJ).

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ity) in Brazilian sugarcane to other conventional food crops that could also be used for bioenergy in other locations? Furthermore, how will the technologies to exploit lignocellulose from dedicated crops (2G) and residues from food and materials crops interact with food production?

Interactions between the biofuels and food

Over the last decade, Europe has seen stagnating demand for food crops due to a stable and aging population but continued, albeit moderating, improvement in crop yields. The result has been a decline in the area of arable crops in Europe. A set of modelling studies commissioned and published by the European Commission has evaluated the potential impacts of the biofuel component of 2020 renewable transport fuel targets within the Renewable Energy Directive (2009). The different modelling approaches and underlying assumptions used have led to very substantial differences in the estimated land demands for EU biofuels. However, in general, they project either a halt in the decline in arable crop land or a significant decrease in the rate of decline in that cropland (DG-Energy, 2010). It remains less clear what the international impacts of biofuel production will be in terms of land demand and therefore land use change or how renewed profitability for conventional biofuel crops, particularly rape and wheat, will affect future yields in Europe.

Expanding biofuel production around the world will increase the demand for a range of intermediate feedstocks including starch, sugars, vegetable oils and shortly cellulose. Many, if not virtually all, countries will consume biofuels over the next decade and many will produce the feedstocks and convert those feedstocks to biofuels with some countries becoming very significant exporters of either biofuels or the feedstocks needed to produce biofuels. A similar situation is emerging with regards to feedstocks required to produce electricity and heat.

Increasing biofuel demand will result in increased returns to feedstock suppliers and biofuel producers which in turn will result in increased investments in infrastructure, research and human capacity in the agricultural and forestry sectors. In parallel, the emergence of lignocellulosic conversion technologies and their deployment at scale will provide land users with new, often perennial, crops to manage watersheds, soil erosion, nutrient leaching, carbon stocks and biodiversity.

New biofuel markets, internal and export, offer a range of important opportunities to resolve existing problems with intensified agricultural and forestry production. However, they also may increase the pressure on vulnerable ecosystems and communities and compete with alternative uses of land e.g. food production and recreation. Policies will need to be developed to control the rate of expansion of biofuels and other forms of bioenergy, the location of their feedstocks and to ensure that local communities and their resources are not detrimentally exploited.

Current 1G biofuel technologies

The available technologies for ethanol production by fermentation of sucrose or starch from 'sugar' crops (sugarcane, sugar beet) or grain crops (maize, wheat, etc.) or production of biodiesel from plant oils are well established. Typical yields of biofuel in litres per hectare (l/ha) are given in Fig. 5 for a representative range of 1G crops.

Fig. 5 illustrates the relatively high biofuel yields that are available from the harvested components of three of the conventional 1G feedstocks – sugarcane, sugarbeet and oil palm – and their 'parity' with predicted 2G biofuel yields, using both hexose and pentose conversion from dedicated lignocellulosic feedstocks. It should also be noted that different biofuels are yielded – soybean, rapeseed and oil palm produce plant oils for biodiesel fuels and the other crops produce largely sugars for conversion to bioethanol for gasoline substitution. As both fuel types are needed biofuel crop cultivation is driven by both these qualitative requirements and the solely quantitative, yield-based requirements (e.g. interest in rapeseed for local biodiesel production within the EU). The addition of a 2G capability to biofuel yields from the conventional 1G crops (assuming residue collection) increases biofuel yields by some 10 to 35% for most 1G crops, although sugarcane shows significant increases and is the leading biofuel volume producer at approximately 9000 l/ha. These estimates assume: in-field residue removal rates @ 50% of total residue available (Woods and Hall, 1994; Bauen et al., 2004); lignin and currently un-fermentable sugars are not converted to biofuel (these are then available for electricity/heat production but could also form significant waste streams).

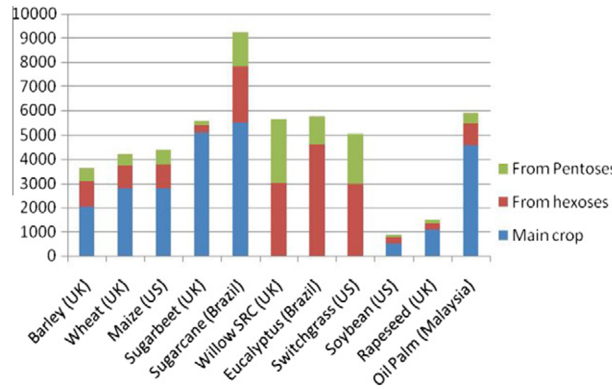

Fig. 5. Typical yields of 1G biofuels (l/ha) shown as Main crop derived from grains, seed oils, juice, etc. Potential additional biofuel yield from hexoses (sugar molecules containing six carbon atoms as found in e.g. cellulose, starch) and pentoses (sugar molecules containing five carbon atoms as found e.g. in some plant storage compounds and as hemicelluloses in plant cell walls) from 1G crop residues or from dedicated 2G biomass crop examples of Willow, Eucalyptus and Switchgrass are shown for reference as 1G + 2G or 'pure' 2G potentials. After Woods et al. (2009).

Only partially apparent in Fig. 5 is the importance of the 'co-product' value of all the currently harvested components of the feedstocks. Co-products arising from main crop processing to biofuels are highly significant differentiating factors for all the 1G crops, when evaluating their GHG, energy and land use requirements. Typical co-products from representative biofuel crop processing and their uses and market substitutions are shown in Table 2.

All the feedstocks in Table 2 generate co-products with fossil fuel substitution potentials (subject to regional effects such as electricity grid mix). However, 1G biofuel crop processing generates co-products, such as animal feeds, that also have important land use implications. These have been the subject of several studies and assessments (e.g. Arora et al., 2008). Liska et al. (2009) estimate that the GHG emissions 'credits' attributable largely to Distillers Grains with Solubles (DGS) from maize ethanol are equivalent to between 19% and 38% of total life-cycle GHG emissions respectively. In a detailed examination of the feed value of DDGS in swine diets in the USA using a least-cost optimization approach, (Fabiosa, 2009) considers the land-use credits to be equivalent to 0.37–0.6 ha of corn land per hectare of corn used for ethanol production. Lywood et al. (2009) have calculated that Dried Distillers Grains and Solubles (DDGS) co-product credits from animal feed uses are highly significant and that whilst the gross land area per tonne of bioethanol production from feed wheat (NW Europe) is 0.404 ha, the net land area becomes just 0.026 ha per tonne ethanol (only 6% of the gross land area) when co-product credits

Table 2
Examples of co-products from 1G and 2G biofuel crops.

Biofuel crop	Co-product	Use	Substitution
Maize, wheat, cereals	Distillers Grains with Solubles (DGS) (also dried as DDGS)	High-protein component in animal feeds also potential as solid fuel	Soy meal, other protein feeds Electricity, heat
Sugar beet	Sugar beet pulp	High energy component in animal feeds	Feed wheat, other feeds
Rapeseed	Rape meal	Animal feeds	Soy meal, other animal feeds
Oil palm	Empty fruit bunches	Animal feed, solid fuel	Other animal feed, electricity/heat
	Palm kernel expeller (PKE)	Solid fuel	Electricity/heat
	Palm oil mill effluent (POME)	Anaerobic digestion	Electricity/heat Fertiliser
Sugar cane	Bagasse	Solid fuel	Electricity/heat
Lignocellulose 2G crops e.g. willows, switchgrass	Lignin	Solid fuel, chemicals	Electricity/heat, petrochemicals

Note: soybean not included as a main biofuel crop because soybean meal is effectively the main product, the oil is a co-product (see Schmidt and Weidema, 2008).

are applied. Similar, though not as dramatic, net land area requirements of between 26% and 39% of gross land area requirement for biofuel production were calculated for maize, sugar beet and rapeseed crops.

The credit for co-products seen in these and other studies e.g. Gallagher Review (2008) is a key element that results both in reductions in life-cycle GHG emissions of the biofuel and in the net land use requirement for the biofuel crop via 'avoided' crop cultivation for feed crops. Such co-product considerations illustrate well the multi-purpose nature of these and other 1G crops. It also points out the lack of clear distinctions between the 1G and 2G 'classifications' (vis the sugarcane main crop 1G biofuel product plus the potential for a 2G biofuel product from bagasse and other residues).

The issue of indirect land use change (iLUC) caused by displaced production when crops are used for biofuel production has also been under intensive debate and analysis for the last 2–3 years. The debate has focussed on the development of robust methodologies for representation of iLUC effects and on the incorporation of these into whole life cycle assessments (LCAs) of biofuel GHG balances (see for example Searchinger et al., 2008; O'Hare et al., 2009; Hertel et al., 2010). iLUC 'factors' to account for international land use change are now included in the US EPA's RFS2 standard (e.g. 31.8 gCO_2eq/MJ corn ethanol, 4.1 gCO_2eq/MJ sugarcane ethanol, 40.32 gCO_2eq/MJ soy biodiesel). Importantly, as the science and modelling is far from finalised and remains contentious, the EPA's iLUC factors and their derivation and incorporation into biofuel life-cycle GHG balances are being kept under continuous review (see EPA, 2010b). The European Commission will publish its methodology for iLUC incorporation into biofuel GHG calculations for compliance with its Renewable Energy and Fuel Quality Directives in December 2010.

2G biofuel options and opportunities

Fig. 6 provides a comparison between 1G and 2G feedstocks based on the gross energy content of the biofuels produced per hectare. Conventional biodiesel production from Malaysian oil palm provides the greatest gross energy productivity (150 GJ/ha). However, when residues and co-products arising at the mills are included, sugarcane achieves a gross biofuel energy yield of nearly 200 GJ/ha. For sugarcane and oil palm in particular, other residue and waste streams could also be used for biofuel, heat and/or electricity production including in-field residues (e.g. tops and leaves or palm fronds).

This analysis illustrates the beneficial potential of dedicated cellulosic crops which can provide good gross energy yields with sub-

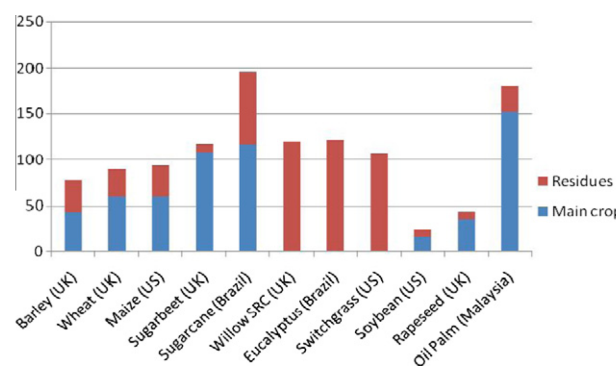

Fig. 6. Biofuel energy yields (GJ/ha) from 1G and 2G feedstocks [for simplicity the dedicated biomass crops (willow, eucalyptus and switchgrass) are shown as being residue only – no 'main crop' starch, oil or sucrose yield]. After Woods et al. (2009).

stantially lower energy and GHG input 'costs' compared with the 1G crops such as maize or wheat. The 2G dedicated lignocellulosic feedstocks are considered to offer substantial potential for development as biofuel feedstocks and several international initiatives are in place to develop this potential. Much of the current interest in 2G biofuel crop feedstocks is focussed on the following opportunities/challenges:

- Developing traditional and marker assisted breeding and GM approaches to crop improvement for applications including the development of novel crops for biofuels and biorefining (see Boerjan, 2005; Rae et al., 2008; Brereton et al., 2010).
- Matching biomass quality parameters to novel processing technologies.
- Maximising the efficiency of conversion and/or minimising inputs e.g. through combined or entrained pentose (C5) and hexose (C6) fermentations (see Figs. 5 and 6), and biorefining (Fig. 7).

Karp and Shield (2008) suggest that 2G perennial energy crops (trees and grasses) have inherent advantages over annual crops in terms of the ability to recycle nutrients and to more fully exploit the growing season. Crucially, they conclude that many of the traits that need manipulating to improve yields are unlikely to be amenable to simple genetic modification and will require a combination of approaches including conventional and quantitative trait loci (QTL) assisted breeding. The possible impacts of enhanced breeding through the use of molecular markers (i.e. QTL) and

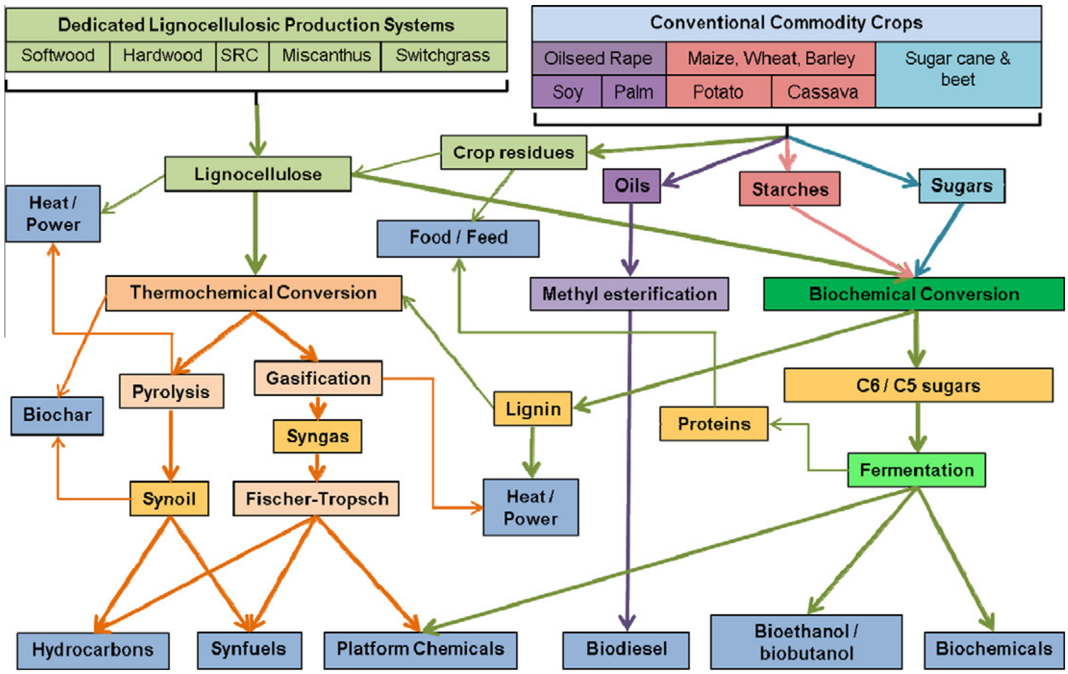

Fig. 7. Examples of biorefining routes to biofuels and co-products for selected 1G (conventional commodity crop) and 2G (dedicated lignocellulosic) feedstocks. Blue boxes indicate delivered products, orange boxes primary intermediates from bio-feedstocks) (modified after Woods et al. (2009)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

through novel gene discovery (i.e. GMO) suggest yield improvements in willows allowing 30–40 oven-dry tonnes per hectare per year are possible. However, the direct application of novel gene discovery to yield improvement is considered controversial in Europe and yields of between 20 and 30 oven-dry tonnes per hectare are considered more likely by 2030 with the effective application of QTL to conventional breeding.

Future scenarios for biofuel development

The potential routes and opportunities for biofuels outlined above are summarised in Fig. 7. This illustrates the multi-product and processing potentials for the transformation of biomass into biofuels and other products – a process usually referred to as 'biorefining'. The biorefining concept denotes a materials- and energy-integrated system for processing biomass with low or zero waste generation and conversely maximising carbon use efficiency (Ragauskas et al., 2006).

The pathways in Fig. 7 do not specifically point to 3G technologies, such as algae or synthetic biology and its prospects (see Kirby and Keasling, 2008). Substantial improvements in supply chain, energy and carbon efficiencies are likely to result from these novel technologies.

For the current 1G and near-future 2G biofuel pathways, the likely future feedstock crops and their biorefining potential can be characterized by two basic emerging research, development and implementation strategies:

1. The development and implementation of lignocellulosic crops, offering the potential to focus on indigenous woody and grass species best adapted to local conditions.
2. The development and implementation of conventional crops (often food crops) or crops with specialized outputs (e.g. high value chemicals), where high value or multi-product strategies dominate, including food and fuel pathways. A broadening out of breeding targets is already emerging as a result of these multi-product strategies.

Crop yield increases globally are likely to come mainly through simple, low cost agronomic management gains in conventional cropping. Such gains, as well as capacity investment to ensure long term viability of yield increases, are likely to be particularly important in sub-Saharan Africa, which must also find practical ways to transition from subsistence agriculture to appropriate and equitable modern production systems. If multi-product strategies in biorefineries prove to be an economically effective, flexible, and robust way of improving biofuel yields, then the need to expand cultivated land area for biofuel production is likely to be minimised. On the other hand, if advanced lignocellulosic biofuel production technologies prove to be cost-effective, then the first option of developing and implementing lignocellulosic crops is likely to dominate. In this case, the implications for land use change, particularly in terms of carbon emissions and loss of natural habitats with high biodiversity will need to be assessed more intensively. Whilst perennial lignocellulosic biomass crops, particularly those that are indigenous e.g. switchgrass in the USA, willows in UK, offer several potential environmental protection benefits (Karp and Shield, 2008; Tilman et al., 2010) capturing these in parallel with high harvestable biomass yields will require skilful and balanced management.

While fundamental yield improvement through increased radiation interception and radiation use efficiency is a major driver in the medium to long term (10–30 years), in the shorter term, gains will be achieved primarily by closing the 'yield gap' in developing countries and in the former Soviet Union states. A greater ability to use increasing fractions of the total aboveground biomass of biofuel crops through biorefining has implications for carbon stocks, particularly soil organic matter (a proportion of crop residues contribute to soil carbon maintenance), and therefore impacts long-term yield stability, as well as nutrient and water use efficiency and potentially biodiversity. Careful regulation and possibly novel monitoring and reward systems will be required to ensure 'good' long-term management practices are put into practice.

It is possible to estimate the land requirements for biofuel feedstocks under the scenarios discussed earlier in this review, taking

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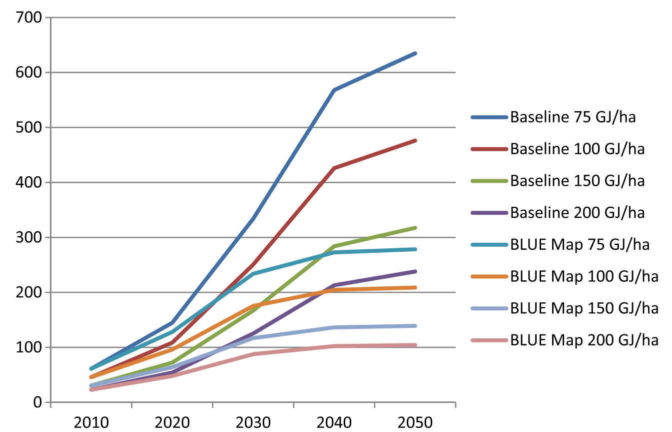

Fig. 8. Estimates for land use requirement (million hectares) for biofuel use in liquid transport applications 2010–2050 at varying biofuel yields per hectare under IEA Baseline (BAU) and BLUE Map scenarios (*based on yields in* Fig. 6). [Assumptions for global transport fuel demand and (biofuel proportions%): Baseline – 2010 91.9 EJ (5%), 2020 108.6 EJ (10%), 2030 125.3 EJ (20%), 2040 142.0 EJ (30%), 2050 158.7 EJ (30%). BLUE Map – 2010 91.9 EJ (5%), 2020 96.0 EJ (10%), 2030 100.2 EJ (15%), 2040 102.3 EJ (20%), 2050 104.4 EJ (25%). 75 GJ/ha represents a pessimistic scenario using 2010 maize or wheat main crop biofuel yields and lower than projected yields for 2G biofuels; 150 GJ/ha is a 'likely' 2G and best crops 1G biofuel scenario and 200 GJ/ha is a 'best technology' scenario assuming deployment of advances in biofuel crop breeding and technologies. *Note*: algal biofuels not included, biofuel limited to only marginal/less productive lands not included.]

account of the potentials discussed above. These are shown in Fig. 8.

The land requirements for biofuels to meet 20–30% of the IEA predicted transport fuel demands to 2050, range from 100 million hectares up to about 650 million hectares (Fig. 6). 100 Mha represents about 7% of current global arable cropland and 650 Mha about 45%. These proportions clearly span a land area requirement that, at the low end, would be feasible, given the potential that exists for up to 250–800 Mha of 'available' additional cropland globally (FAO, 2008); to, at the other extreme, an unfeasibly large requirement given the expected global needs for population growth and nutrition (Godfray et al., 2010). It should be noted that the land requirements estimated here are biased towards somewhat 'conventional' assumptions on crops and land 'take'. In fact, a very large range of options exist for how biofuel production may develop, including the land types that may be utilised (e.g. marginal or idle land, forest land) and how residues, 'new' crops and waste biomass (e.g. municipal solid waste (MSW)) may be used as feedstocks.

Several studies have noted that conflicts with food production may also be minimised by the use of marginal, idle and degraded land for biofuel production (Campbell et al., 2008; Fargione et al., 2008; FAO, 2008; Gallagher Review, 2008; Millbrandt and Overend, 2008). This offers a potential route to minimising conflicts with food production and, at its best, a means of enhancing carbon sequestration on land (e.g. sugarcane crops on degraded pasture in Brazil (EPA, 2010b)) and restoring land back to agricultural use for food production. Estimates of the global stocks of less-favoured lands (marginal/idle/degraded ands), range from around 400 to 600 Mha dependent upon methodology and definition. It is likely that novel 2G (and 1G) crops, such as *Jatropha curcas, Buddleja davidii*, and bamboos, which have good adaption to growth on less favoured land will also find use, although crop yields will need to be above a minimum threshold to enable positive carbon balances over a number of years (Schlamadinger and Marland, 1996; Jongschaap et al., 2007; Hallac et al., 2009, 2010).

In addition to biofuel production on less-favoured lands, intensification of agriculture on current arable land is needed and likely to occur for both food and biofuel crops (Pretty, 2008). Intensification of agriculture can have substantial positive benefits on GHG emissions as a recent analysis by Burney et al. (2010) has demonstrated. Furthermore, improved productivity via improved practices can be compatible with protection of other sustainability and biodiversity benefits (Pretty et al., 2006).

These pathways to biofuel development up to 2050 and their interaction with agricultural commodity crops and land are summarised in Fig. 9.

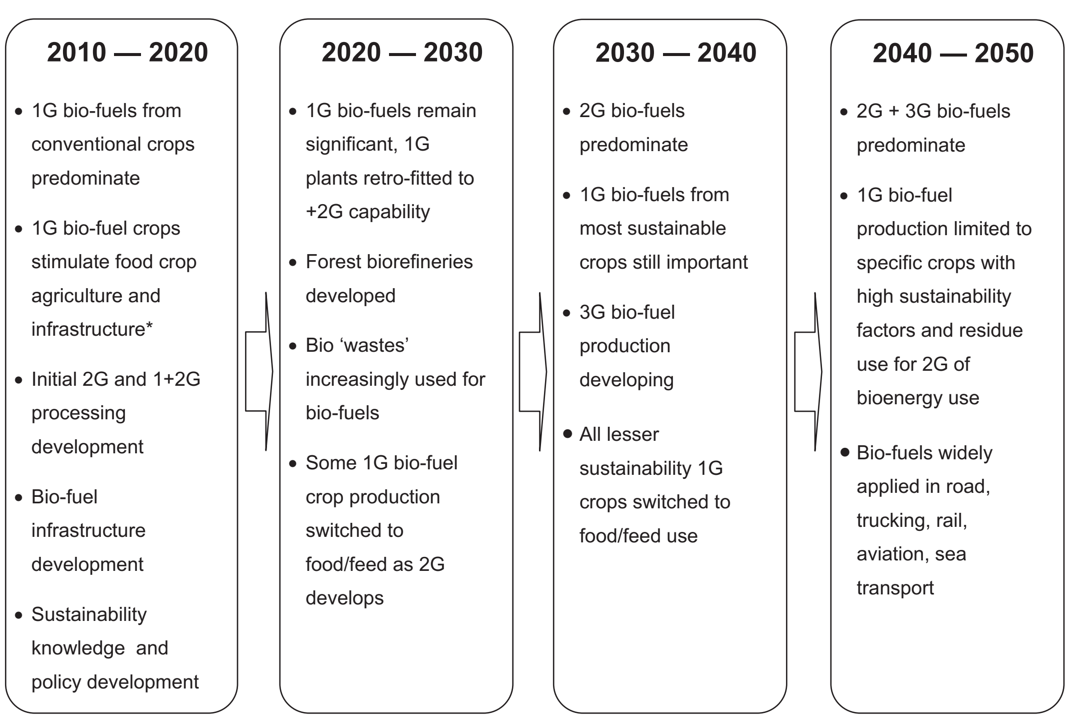

Fig. 9. Summary development of biofuels 2010–2050.

Discussion: peaceful co-existence or permanent strife between the biofuels and food sectors?

Despite the recent controversy surrounding the expanding role of biofuels in the transport sector, it is not obvious that the use of food crops for 1G biofuels is an automatic cause of conflict. In a best case scenario, energy demand could dispose of unwanted surpluses, keeping crop prices stable and high enough to warrant the investment that has been lacking in the past decades. Agricultural production of energy could then be highly complementary to agricultural food production, by preventing or ameliorating the rises in fertiliser and fuel prices that have occurred in the recent boom. If biofuels cannot fill the gap, as oil stocks come under increasing pressure, the next decades may witness a boom and bust cycle as each spurt in industrialisation is halted by a spike in energy prices. The rapid increase in demand for conventional (food) feedstocks for biofuels, driven by direct economic competitiveness with oil would also be likely to put pressure on food stocks, particularly cereals and vegetable oils; exacerbating price volatility in food markets. Managing the interaction between food and conventional biofuels, therefore, represents a huge opportunity for, just as much as a threat to, food security and bioenergy as a whole (Woods et al., 2010).

Whilst food security issues have only recently emerged, the key concern that has engaged biofuels researchers, developers and policy makers over the last 3 years has been to develop sufficiently robust methodologies that permit reasonable, evidence-based assessment of the potential GHG and wider sustainability impacts of specific biofuel supply chains; see for example, the UK's Renewable Fuels Agency web-site, US Environmental Protection Administration's Renewable Fuels Standard – 2 (RFS2), the renewable transport fuels component of the European Union's Renewable Energy Directive (RED), European Commission's JRC assessment (in 2010), Kammen et al., 2007; Hammond et al., 2008a,b; The Royal Society, 2008, 2009; UNEP, 2009.

Significant research, development & demonstration (RD&D) efforts are also occurring to develop 2G, 3G and refinements to 1G biofuel prospects (see BP's Energy Bioscience Institute, US DoE Bioenergy Centres, UK's BBSRC-BSBEC, EC FP7 EnergyPoplar programme, etc.). These initiatives also usually include significant commitments to develop the science and technology base for environmental, social and economic assessment of biofuels. However, a consequence of uncertainty over policy and governmental support for biofuel developments, coupled with the recent global financial crisis, has been to constrain the rate at which, particularly the advanced biofuel technologies, are being moved towards demonstration at scale. Without such demonstrations of operation at scale for process efficiencies, feedstock conversion rates and process economics, the rate of introduction of 2G technologies is and will inevitably suffer from continued lack of investment.

If the benefits of fossil fuel substitution and GHG emission reductions from advanced biofuels are to be realised within the timeframes and at the scales envisaged in the IEA Blue Map (between now and 2050), then action is needed urgently to sustain the current R&D efforts and to enable the several examples of success and promise reviewed here to be implemented rapidly. It is to be hoped that the important clarification steps recently taken in policies, such as the US Renewable Fuel Standard and the EU Renewable Energy Directive and Fuel Quality Directive, will now establish a stable environment in which biofuel supply chains that offer strong, assured GHG savings, coupled with important ecosystem and social protections, can develop. In particular, success with this is already going a long way towards realising Robertson et al.'s (2008) summary of the potential for sustainable cellulosic (2G) biofuels "*Sustainable biofuel production systems could play a highly positive role in mitigating climate change, enhancing environmental quality, and strengthening the global economy, but it will take sound, science-based policy and additional research effort to make this so.*"

Good agricultural practice (GAP) standards and their forestry equivalents, verified by credible assurance and certification schemes, will play a major role in the development of biofuels and bioenergy as a whole. These are emerging now as evidenced by the number of regional and global initiatives that are currently underway e.g. the Global Roundtable for Sustainable Biofuels (RSB), the Roundtable for Sustainable Palm Oil (RSPO), developing ISO and CEN standards and the existing FSC, PERC and other forestry schemes. These are informed by a rapidly-developing, though presently incomplete, basis of scientific knowledge and modelling tools. Clearly, both competitive and synergistic interactions between agriculture for food and agriculture (and forestry) for biofuel are possible. It is imperative therefore that well-informed policies and regulations are implemented that minimise detrimental competition, enhance the synergies and capture the global sustainability benefits available from beneficial biofuel uses.

Biofuels have focussed attention on a vast range of sustainability, policy and science & technology issues that will apply to all future land uses. The biofuels debate is a paradigm shift in how we evaluate the human appropriation of land for our purposes and sustainable intensification of land use will only become possible when we are able to reconcile all these issues across all forms of production (food, energy, materials).

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