SCIENCE INSIGHTS *for Biofuel Policy*

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LCA^{works} and Porter Institute (Imperial College London)

Welcome to the second issue of *SCIENCE INSIGHTS for Biofuel Policy*. This series explores issues of interest to stakeholders in the European biofuel debate and strives to provide an impartial and concise analysis of the scientific and policy context in which the debate takes place. In doing so, SCIENCE INSIGHTS for Biofuel Policy draws on the expertise of LCA^{works} and the Porter Institute (part of Imperial College London), as well as pertinent contributions in scientific journals, reports, and issue papers. This issue focuses on Biomass Potential and carries out a meta-analysis of published scientific work in the open literature to answer the question: is there sufficient sustainable biomass potential for biofuels at 10%, 20% or 30% biofuel penetration into the fuel mix, taking into account future food demand, resource constraints (e.g., availability of water for irrigation), social structures and wellbeing, and whilst protecting habitats, forests, carbon stocks, diverse ecosystems, biodiversity and air, water and soil quality.

Meta-analysis of Biomass Potentials for Biofuel Production

Authors: Mark Akhurst, Nicole Kalas and Jeremy Woods

Summary

The potential for sustainable biofuels* is currently the topic of a fierce global debate. In this paper, we draw together a high-level synthesis of the most recent, most rigorous research into the potential for biomass production globally, as a source of feedstock for sustainable biofuels.

Theoretically, the potential for biomass is enormous. Each year, biomass primary production globally amounts to 4,500 EJ globally (i.e., the total amount of biomass produced on all land) [1]. Meanwhile, transport fuel demand is currently around 90 EJ [2]. Therefore, a 2% increase in global biomass primary production would be energetically equivalent to all current transport fuel.

Clearly though, this is a hypothetical scenario, because only a fraction of global biomass production can be accessed and influenced (e.g., a significant share of forest and wilderness land cannot and should not be accessed or more intensively exploited). Also, realisation of this potential may not be technically or economically viable in many cases [3]. Furthermore, conversion of the biomass into useable transport fuels is much less than 100% energy efficient.

Methodologies for estimating the global potential for bioenergy are maturing, particularly by distinguishing between gross theoretical solar energy capture potential, technologically accessible potentials and economically feasible potentials. The overall scale of the potential, range and uncertainty increase with each level of assessment.

Several recent studies have modelled biomass potential from surplus / abandoned / degraded farmland. Two studies [14, 15] suggest that using surplus / abandoned / degraded land available today, the technical global potential for woody / lingo-cellulosic (LC) biomass, is around 50 EJ. A broader range of studies [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 16, 17] suggest, this could rise to 100 – 150 EJ by 2050, of which about half is likely to be economically viable.

Surplus forest products are another potential source of biomass for the future. Recent studies [8, 9, 14, 18] suggest that technical potential by 2050 is in the region of 100 EJ, of which, less than half e.g. up to 40 EJ, may be economically viable.

Several studies have modelled the potential of farming, forestry, organic and municipal waste as a source of biomass [5, 8, 9, 14]. The results suggest that in the region of 50 - 100 EJ of biomass could be technically available from this source by 2050, and again we assume that around 40 EJ may be commercially viable.

In total, by 2050, there is technical biomass potential of up to 350 EJ with around 150 EJ from crops on surplus farmland, 100 EJ from surplus forest products and 100 EJ from wastes and residues. Of this, about 100 to 150 EJ may be economically viable although a wider range is possible.

Future technology options for conversion of LC biomass into biofuels are expected to achieve 70% conversion efficiency (energy in biomass to energy in biofuels) by 2050. The economic potential of biofuels from LC biomass by 2050 is therefore in the range of 70-100 EJ, which would be sufficient to replace most of current global transport fuel demand, or around half of the IEA World Energy Outlook 2050 demand.

This analysis assumes that 100% of economic potential is used for biofuel production. Inevitably, the destination of future biomass crops will be dictated by a combination of policy and market forces. The correct policies therefore need to be implemented to ensure that future biomass production is employed in the most effective manner. Assuming that 50% of economic biomass potential was used for biofuels feedstocks, then by 2050, sufficient potential could exist to replace up to 25 - 30% of global transport fuel demand.

Introduction

Several studies have been carried out in recent years to assess biomass potential, mainly with a view to establishing whether sufficient resources could exist to contribute materially to the global energy mix [4–19], either through biofuels or as a fuel for power / heat. In many cases, the focus is on the greenhouse gas (GHG) savings potential and many studies have been published exploring the GHG

* *'biofuels' is the conversion of raw biomass into energy carriers suitable for transport / mobility applications*

impacts, with many concluding that biomass used to replace fossil fuels would, for the most part, bring GHG savings [3, 20, 21]. Since 2008, much of the research community has turned its attention to the indirect impacts of using biomass to replace fossil fuels (mainly biofuels), reaching a consensus that important indirect impacts on GHG balance of biofuels are likely to result from expansion of biofuel supply, although the absolute level of those impacts (and indeed whether impacts would be positive or negative for individual biofuels) is still unclear [22, 23, 24, 25]. This portion of the literature, addressing the Indirect Land Use Change (ILUC) impacts of biofuels is based on modelling the market mediated effects of using existing cropland to grow biofuel feedstocks. Such studies mainly conclude that the direct use of land for biofuels production will cause wider land use change as global production increases to meet the demands of the new and existing markets.

In the current paper, we look beyond ILUC, and focus on that portion of the literature which has recently researched the potential for increased biomass supplies, without disturbing existing farming (for food, fodder and fibre). We have identified five important sources of additional biomass supply in this respect:

- Ligno-cellulosic crops (e.g., energy grasses and fast growing trees) grown on abandoned / fallow / degraded land
- Low Input, Highly Diversity (LIHD) grasses grown on marginal grassland, savannah and shrub land
- Increased production from agricultural learning
- Surplus Forest Products (difference between projected forest productivity and industrial demand for forest products)
- Farming, forestry and municipal wastes and residues.

This paper summarizes the main findings of published research for each of these categories, and, where possible also reviews the economic viability of each option.

Figure 1. Global Technical Biomass Potentials from Surplus / Abandoned Land (EJ)

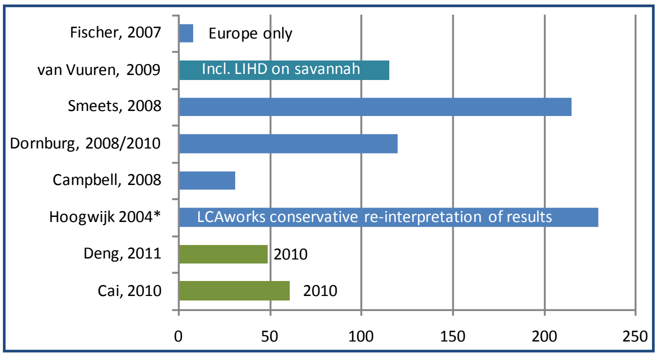


Figure 1 shows a summary of the most conservative estimates of each study (i.e., the results with the strongest sustainability criteria applied). These results, although all constrained by sustainability criteria, still show a wide range of outcomes. This is partly due to the different scenarios explored.

Abandoned/Fallow/Degraded/Surplus Agricultural Land

A significant fraction of recent studies of biomass potential focus upon this option [5, 6, 9, 10, 12, 13, 14, 15, 16, 17]. Table 1 (see pp 7-8) summarises the most recent and most comprehensive studies. In most cases, a range of biomass potentials is derived, based on a range of sustainability criteria and other constraints (e.g., water availability and environmental constraints). These studies all assume that the crops to be grown on the available land will be perennials (e.g., grasses and other woody crops) and all take great care to model the biomass potentials under a range of constraints.

Cai (2010) [15] and Campbell (2008) [12], both model the theoretical potential of currently available abandoned / degraded / marginal land for production of biomass, whereas Hoogwijk (2005) [5], Dornburg (2008) [9], Smeets (2008) [8], van Vuuren (2009) [10] and Deng (2011) [14] all model the potentials for this land in 2050, at which point it is assumed that a significant increase in abandoned or "surplus" crop land will exist, owing to yields on arable land and productivity on livestock–rearing land having increased more quickly than population / food demand. Also, van Vuuren [10] includes some natural grassland planted with Low Input, High Diversity (LIHD) grasses. Harberl et al [16] take an overview of other modelling studies, whilst Beringer et al [17] models the potential for bioenergy including significant conversion of natural vegetation. Neither of these studies is included further in the analysis here. Taking an average of the other six results which model global potential on degraded / abandoned / surplus land, gives 117 EJ/yr. If the highest (Hogwijk) and lowest (Campbell) results are excluded, the average of the remaining four results is 112 EJ/yr. For 2050 only, the average of the five global results is 142 EJ/yr, or 150 EJ/yr if the highest and lowest results are excluded. Based on this recent sample of the most comprehensive modelling reported in the literature, we therefore conclude that globally, there is a range of potential for 100 – 150 EJ of biomass energy, from degraded / marginal / abandoned / surplus agricultural land by 2050, with a midpoint of about 130 EJ.

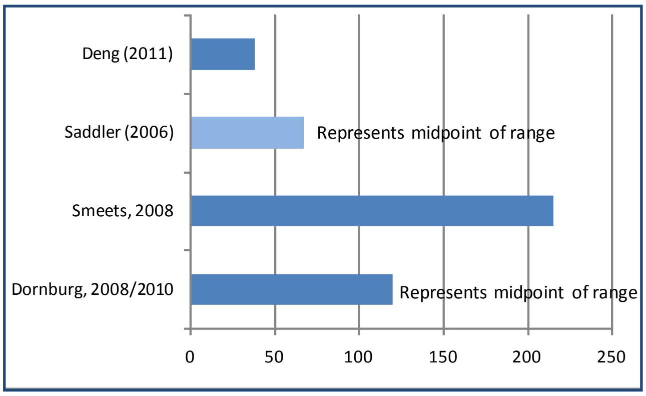
Economic Viability of Biomass Production on Abandoned/Fallow/Degraded/Surplus Agricultural Land

Few studies model the economics of potential biomass production, most preferring to focus attention on theoretical physical potentials. However, the studies by van Vuuren [10] and Dornburg [9] do look at production costs. Both studies suggest that around 35% of the theoretical (sustainable) biomass potential could be produced at a cost below $2/GJ feedstock. With crude oil at $100/barrel, and allowing for transport and refining costs of approximately 3%, fossil fuels production costs are in the region of $17/GJ. Allowing for conversion costs for LC feedstocks into biofuels of around $10 - $15/GJ in the near future, it can be seen that, at feedstock costs of $2/GJ or below, LC biofuels would be competitive in the current oil price environment. Van Vuuren concludes that with a carbon price of $150/tonne, and $40/barrel oil prices, biomass at $4-5/GJ would be competitive, suggesting that by 2050, 120 EJ of LC crop-derived biomass could be economically viable. Therefore, we can conclude that a minimum of 40 EJ, and perhaps 70-80 EJ of sustainable, economically viable biomass is likely to be available for biofuels by 2050. This analysis assumes that advanced conversion technologies will exist to allow the conversion of LC feedstocks into biofuels by 2050. In Box 3, we explore an alternative scenario, where surplus / abandoned land in 2050 is used to produce feedstock for "conventional" biofuels. This analysis demonstrates that even with currently available conversion technology, around 50EJ of biofuels could be available from this land. In practice, any potential biomass would not all be available for biofuels given likely increasing competition with other uses. Government policy and market forces will determine the fraction that is used for biofuels, versus these other uses e.g., power generation, biomaterials production.

Surplus Forestry Products

Four of the studies reviewed explore the potential of surplus forest products, defined as the difference between projected 2050 forest potential production and 2050 projected industrial demand for forest products. Managed plantations are excluded as they are included within the potential on surplus agricultural land [6, 9, 14, 18]. The results are summarized in Figure 2. The results show technical potentials for surplus forest products taking into account future forecast demand for other wood products. Key variables included the demand for industrial round-wood and wood fuel. The results suggest a technical potential around 100 EJ by 2050.

Figure 2. Global Technical Biomass Potentials from Surplus Forest Products (EJ)

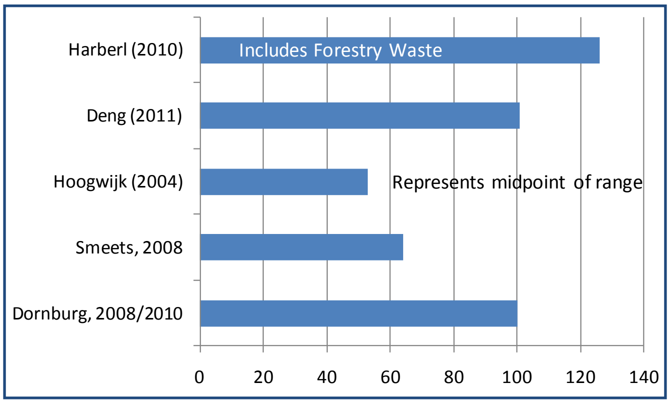


Smeets' analysis and modelling suggests that economic potential is 15 EJ, but after full ecological constraints have been overlaid, demand would exceed supply by 8 EJ, leaving no potential for biomass. Deng updates Smeets' work and concludes that 38 EJ of economic potential exists. Clearly, considerable uncertainty remains about the likely scale of this resource.

Farming, Forestry and Municipal Wastes and Residues

Five of the studies reviewed carry out detailed modelling of biomass potential from wastes and residues, including figure closer to 100 EJ is "fairly certain". No assessment

Figure 3. Global Technical Biomass Potentials from Wastes and Residues (EJ)



was made of the sustainability impacts of using wastes and residues at such a scale for fuels. The Dornburg [28] study goes on to explore the economic viability of wastes and residues concluding that less than 50% is likely to be available below 2€/GJ.

Summary of Biofuel Potentials

Recent studies modelling biomass potential from surplus / abandoned / degraded farmland suggest that technical potential for woody / lingo-cellulosic biomass, in the form of grasses, is around 50 EJ currently, rising to 100 – 150 EJ by 2050. However, the fraction of this technical potential which is commercially viable may be lower than 50%, possibly as low as 35% implying that in the region of 40-80 EJ could be commercially available by 2050, with a midpoint of 60 EJ.

Recent studies modelling surplus forest products suggest a technical potential by 2050 in the region of 100 EJ. However, one of the studies [6] finds that with full economic and ecological constraints, there is no potential surplus of forestry product by 2050. Another study [14] updates the earlier work and finds that approaching 40 EJ of this technical potential is economically viable. Based on these results, LCA[works] analysis suggests that around 40 EJ may be economically viable by 2050.

Recent studies modelling the potential of farming, forestry, organic and municipal waste as a source of biomass suggest that in the region of 50 - 100 EJ of biomass could be technically available from this source by 2050. Sustainability implications have not been extensively modelled. One study [9] has carried out economic modelling and finds that less than 50% of this biomass may be commercially viable; suggesting that economic potential from this source is likely to be in the range approaching 25 - 50 EJ, with a midpoint of approaching 40 EJ.

In total, by 2050, there is technical biomass potential for up to 150 EJ from crops on surplus farmland, 100 EJ from surplus forest products and 100 EJ from wastes and residues, giving a total of 350 EJ. Of this, we estimate 100 to 150 EJ is likely to be economically viable.

Technology options for conversion of lingo-cellulosic biomass into liquid fuels include enzymatic digestion followed by fermentation, or gasification, followed by various conversion options e.g. Fischer-Tropsch. These technologies are currently capable of converting up to 50% of the biomass energy into liquid fuels such as ethanol and biodiesel, increasing to perhaps 70% by 2050 [3].

The economic potential of biofuels from LC biomass by 2050 is therefore in the region of 100 EJ, which would be sufficient to replace more than 100% of current transport fuel demand, and more than 50% of 2050 transport fuel demand.

This analysis assumes that 100% of economic potential is used for biofuel production. Inevitably, the destination of future biomass crops will be dictated by a combination of policy and market forces. The correct policies therefore need to be implemented to ensure that future biomass production is employed in the most effective manner. Assuming that 50% of economic biomass potential were to be used for biofuels feedstocks, then by 2050, sufficient potential could exist to replace up to 25-30% of global transport fuel demand, or almost 100% of the IEA Blue MAP scenario transport fuel demand by 2050 (see Box 1).

Key Issues Impacting Biomass Potential

Population and Forecast Food Demand: The different studies all carry out detailed modelling of future food demand. All the models included in the study reported here take account of future forecast human food demand. Many different scenarios have been modelled. The most optimistic scenarios from a biofuels perspective i.e., less meat intensive diets, moderate population growth, lead to biofuel potential scenarios where biofuels could more than replace fossil fuels in the future. In most cases, where possible the scenarios leading to projected potentials towards the midpoint of the overall range of projections have been used. Box 3 presents a potential approach to mixed cattle and arable production which could potentially result in larger amounts af surplus land availability in future with no impacts on food production.

Biodiversity Impacts: Most of the studies reviewed as part of this meta analysis have taken into account a wide range of issues which may impact the scale of potential biomass production in the future and the possible impacts of scaling up such production, including biodiversity impacts. The recent study by Dornburg et al [28] reviews potential biodiversity impacts of increased biomass production, concluding that many studies have attempted to assess the biodiversity impacts of biomass production [29-35]. These studies give a wide range of results, explained by the studies' use of different time horizons, spatial resolution and biodiversity indicators. Biodiversity is often not explicitly defined in the studies. Bioenergy production is likely to lead to trade-offs on biodiversity.

At the local level, biodiversity effects depend on crop choice, agricultural management, former land use, and

Box 1. Transport Fuel Demand

Current (2010) transport fuel demand is around 90 EJ[2]. The future demand for road transport fuel is very uncertain, and will be critically dependent upon the world economy, the pace of technology and changes in government policy. However, demand needs to be modelled so that we can evaluate the quantity of biofuel required to displace e.g. 10%, 20% or 30%. The International Energy Agency (IEA) 2008 Energy Technology Perspectives'[3] base case forecast is that global transport fuel demand will reach 3,400 MToe by 2030 and 4,700 MToe by 2050. This is equivalent to 142 EJ in 2030 and 197 EJ in 2050. The quantities of biofuel required to replace 10%, 20% and 30% of transport fuel demand would therefore be as shown in the table below:

Mtoe	10%	20%	30%	100%
2030	340	680	1020	3400
2050	470	940	1410	4700
EJ	10%	20%	30%	100%
2030	14.2	28.4	42.6	142
2050	19.7	39.4	59.1	197

It is important to note that these figures represent all transport fuel demand, of which road transport fuel demand represents approximately 70%, with the remainder accounted for by aviation, shipping and rail[3].

In the IEA "Blue MAP" scenario[3], transport fuel demand in 2050 is 105EJ, with biofuels contributing 20-30%, equating to 21 – 32 EJ of biofuel[24].

spatial planning. Local biodiversity may benefit from the growing of biomass; for example, when intensive agricultural practices are replaced by low-intensity biomass production systems. In general, mixed cropping will increase rather than decrease biodiversity compared to conventional annual cropping systems [36]. At the global level, agricultural lands may only become available for biomass production when food production shifts to other areas. Such land churn could lead to biodiversity losses due to changes in land cover [36]; thus, short-term global biodiversity effects are intimately related to global land-use dynamics. In the long term, biomass production will contribute to lower emissions of GHGs and, therefore, to a reduction in the adverse effects of climate change on biodiversity.

Water Use: Most of the studies referenced have made detailed reference to water availability during their modelling of biomass potential (see pp 7-8). In some areas of the world, water is abundant and poses no threat to realization of the full technical biomass potential, but in other regions, technical potential is severely constrained by water scarcity. Climate change will tend to increase the variability of rainfall patterns and the rate of transpiration in future. Regional variations in the impacts of climate change are expected making the impacts on biomass potential very difficult to model accurately.

Other Issues Impacting Biomass Availability for Biofuels: There are many other issues which may impact the availability of biomass as a feedstock for biofuels production. In the future there may be greater competition with other sectors for water resources. Changing world political and economic balances are already leading to changing human dietary trends, including an increasing demand for meat, which is significantly more land intensive to produce than arable crops. At the same time, alternative protein chains and animal production systems are being developed, utilizing new technology, which may, in future, reduce land demand. Large scale biomass production, may give rise to major impacts on prices and subsequent availability of land and food, which have not yet been modelled adequately. It is also likely that increases in agricultural and livestock yields required to supply food demands in future, will lead to significant increases in agricultural energy inputs. Bioenergy and biofuels are likely to play an increasingly important role in the provision of this energy. Finally, the impacts of emerging sustainability objectives, as increasingly promoted by regulators, particularly in the West, has not been factored into models to any significant extent, but these impacts are likely to be significant unless managed carefully [26, 28].

IPCC - Special Report on Renewable Energy Sources (SRREN)

The IPCC has recently published a special report on renewable energy sources and climate change mitigation. The report estimates the global bioenergy potential to be in the range of <50 to >1,000 EJ [38]. This very wide range of potentials is much larger than the range cited in the current study, and pertains to a very broad range of input assumptions. The studies cited in the review reported here all lie well within this range.

The SRREN concludes that "historically, economic development has been strongly correlated with increasing energy use and growth of GHG emissions, and RE can help decouple that correlation, contributing to sustainable development (SD). Though the exact contribution of RE to SD has to be evaluated in a country-specific context, RE offers the opportunity to contribute to social and economic development, energy access, secure energy supply, climate change mitigation, and the reduction of negative environmental and health impacts. Providing access to modern energy services would support the achievement of the Millennium Development Goals."

Conclusions

- The global biomass resource base is currently under-utilised
- The scale of the biomass resource is significant in terms of current global energy consumption
- Fuller exploitation of this resource has major implications for energy, climate and food security
- It will also have significant impacts on the global bio-physical cycles e.g. water, nitrogen, phosphorous, potassium; and also on social factors
- Some positive outcomes can occur by default i.e. without substantive policy intervention e.g. energy security, others will require enhanced policies and regulation
- Current trends in fossil fuel prices mean that a reliance on status-quo is not tenable and intervention coupled to support for innovation is required
- Lignocellulosic technologies will enable more of the biomass resource to be accessed- this brings with it many benefits but also a number of threats
- A very recent IPCC report estimates the global bioenergy potential to be in the range of <50 to >1,000 EJ [38]
- Through this meta-analysis we derive a rough estimate of the technical potential for bioenergy up to 350 EJ, or roughly 2/3 of the current global primary energy demand.

Box 2. Mixed Crop-Livestock Agricultural Systems

As future demand for land increases, rather than extensifying agriculture unsustainably, another option is to utilise existing agricultural land more effectively. Currently, around 1.56 Bha of land is used for arable farming, whilst 3.4 Bha is used for permanent pasture.

Sparovek et al (2007) [27] present an integrated sugarcane and cattle production model in which hydrolysed bagasse is used as animal feed. The additional feed would allow more cows per hectare, freeing up part of the pasture land for sugarcane. As a result, sugarcane production is expanded on pasture areas without displacing the original cattle production.

Whilst pasture land will not all be suitable for sugarcane, as an illustration of the potential, pasture in South America amounts to over 450 Mha, with 200 Mha in Brazil (FAO 2009). If a 20% intensification of cattle could be achieved the Brazilian pasture, then an additional 40 Mha of sugarcane could be cultivated, with no reduction in cattle production and no net expansion in land area. This would represent a 6-fold increase in Brazilian sugarcane area (currently 8 Mha produces around 30 B litres, or 0.6 EJ). With the integrated production model, ethanol production could be increased to something approaching 4EJ, with no loss of cattle production, representing approximately 5% of global transport fuel demand. The Sparovek et al analysis suggests that the approach would be economically viable at current market conditions.

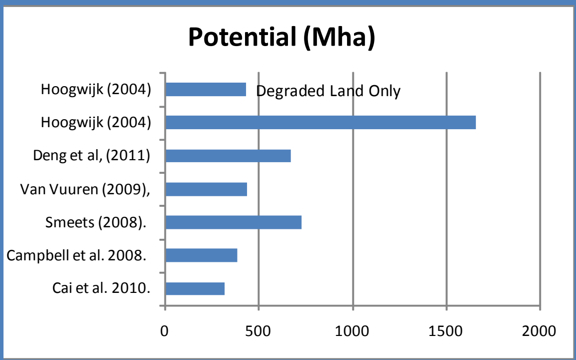
The approach would not be without risks. The integration model requires close interaction between two very different sectors. Diverting part of the bagasse from electricity generation to animal feed would have only a minimal impact on the direct emissions of the sugarcane to ethanol chain (<1% reduction in the GHG-savings compared to fossil fuels.)

This is just one example of how land use efficiency could be improved, and is, to some extent, already built into some of the modelling studies described here. However, this example illustrates just how much potential exists for improving land use efficiency.

Box 3. The Relevance of Advanced Biofuels.

Advanced biofuels (sometimes referred to as “second generation, 2G” biofuels), aim to convert a larger fraction of the plant material into biofuels. This is achieved by breaking down the lignocellulosic (LC) part of the plant into fermentable sugars and lignin, or by gasifying the LC material and usually using a catalyst, to create fuel molecules. The vision is that by using these processes to produce biofuels, a much wider range of crops will be available as feedstocks, including woody and grassy crops, which can produce greater yields per hectare than conventional (food) crops, such as wheat and oilseeds, with fewer inputs of irrigation and fertilizer, or make better use of lower quality soils.

Figure 4. Global Potential Surplus/Abandoned Farmland in 2050



In practice though, no commercial processes are yet available for 2G biofuel production. Furthermore, some existing biofuels i.e., sugarcane ethanol and palm oil biodiesel, are capable of producing yields as high, or higher than is likely to be achievable with LC biofuels. Also, conventional biofuels, such as wheat ethanol and oilseed biodiesels create valuable co-products which, if used as protein animal feeds, may displace areas of other protein crops e.g., soy, comparable with the area needed to grow the biofuel feedstock crop in the first place [37]. To illustrate the potential of conventional biofuel pathways, we carry out modelling to compare production on potentially surplus/abandoned farmland with that of LC biofuels.

Figure 4 shows the potential surplus/abandoned farmland, globally, from the different studies reviewed here. Based on these results, a conservative estimate of land potential in 2050 is 500 Mha. For illustrative purposes, we have assumed that 35% of this land could be used to grow sugarcane, and the remainder to grow wheat in rotation with oilseed rape. The results of our modelling (described in note 1) show that technical potential would be 31.6 EJ of sugarcane and 20.2 EJ of wheat ethanol/rapeseed biodiesel (RME), giving a total of 51.8EJ. This compares favourably with many of the studies on LC biofuel potential using the same land, as summarized in Figure 1. In reality, biofuel yields for sugarcane and wheat ethanol/ RME may not be as high as modelled. However to balance this, the conventional biofuel production modelled would produce around 700 million tonnes/year of high protein animal feed, which could displace around 170 Mha of soy production, although inputs of water and fertilizers would be higher.

Notes - Modelling of 1G biofuel potential on surplus land

Based on Figure 4, assume 500 Mha of surplus land available in 2050.

Of this, we assume 35% (175Mha) is used for sugarcane.

IEA ETP report [3], Table 9.11, gives a projection of 6,140 litres gasoline equivalent/ha in 2050 for Brazilian sugarcane ethanol, with other world yields projected at 5,600 litres/ha. We use 5,600 litres/ha, giving a potential ethanol production in 2050 of 175M * 5,600 = 980 billion litres gasoline equivalent.

Gasoline lower heating value is 32.2 MJ/litre [3]

Sugarcane ethanol potential = 980E9 * 32.2E6
= 31,556E15 J = **31.6 EJ**

Assuming that the remaining 325 Mha is used to grow wheat and oilseed rape (OSR) in rotation.

IEA ETP report [3], Table 9.11, gives a projection of 2,260 litres gasoline equivalent/ha in 2050 for grain ethanol in Europe, with other world yields projected at 2,070 litres/ha for sugarcane ethanol. We use 2,070 litres/ha, and assume a 3:1 rotation with OSR, giving a potential ethanol production in 2050 of 325M * 2,070 * 0.75 = 505 billion litres gasoline equivalent.

Gasoline lower heating value is 32.2 MJ/litre [3]

Wheat ethanol potential = 505E9 * 32.2E6
= 16,261E15 J = **16.3 EJ**

In every 4^{th} year, OSR will be grown on the 325 Mha.

IEA ETP report [3], Table 9.11, gives a projection of 1,480 litres gasoline equivalent/ha in 2050 for OSR biodiesel in Europe. No data is given for other world regions, so we use 1,480 litres/ha, giving a potential ethanol production in 2050 of 325M * 1,480 * 0.25 = 120 billion litres gasoline equivalent.

Gasoline lower heating value is 32.2 MJ/litre [3]

OSR biodiesel potential = 120E9 * 32.2.5E6
= 3,864E15J = **3.9 EJ**

Total potential is therefore: 31.6 EJ of sugarcane ethanol, plus 16.3 EJ of wheat ethanol, plus 3.9 EJ of OSR biodiesel, making a total of 51.8 EJ in 2050.

Table 1a, Comparison of Published Literature on Biomass Potentials

Authors	Type of model	Databases Used	Estimated land available for bioenergy (Mha)	Land classification	Year	Yields / yield increases	Estimated biomass potential (EJ)	Geographical coverage	Sustainability Impacts	Water	Production Costs / Economic Considerations
Cai et al. 2010. Land Availability for Biofuel Production	Fuzzy logic modelling	Soil Rating for Plant Growth (SRPG), from USDA-NRCS. Harmonized World Soil Database; Global Terrain Slope (GTS) Database; Shuttle Radar Topography Mission (SRTM)	320-702	marginal mixed cropland; abandoned cropland; degraded cropland	Technical potential based on 2011 land availability	60 - 140 GJ/ha for 2G biofuel crops	61 - 143 EJ Net Energy Gain (NEG)	Africa, China, Europe, India, South America, and the continental Africa, China, India, South America, continental United States	Not modelled. 320 Mha involves planting 2G biofuel crops, so sustainability impacts would be expected.	All areas assumed rain fed only	
			405	marginal grassland, savanna and shrubland planted with LIHD crops	Technical potential based on 2011 land availability	NEG = 17.8 GJ/ha for LIHD;	72EJ		Not modelled. LIHD should have low sustainability impacst and potentially sequester carbon in the soils.	Rain fed only.	Not modeled, but challenging economics are anticipated
Dornburg (2008, updated 2010). Assessment of Global Biomass Potentials and their links to food, water, biodiversity, energy demand and economy.	MARKAL, TIMER, IMAGE, LEI-TAP, GLASOD	Data from 8 previously published studies of biomass potentials. Data from the models used. OECD Environmental Outlook, UNEP-WCMC maps.		Surplus arable and pasture land, incl. Abandoned and degraded	2050		120EJ	Global	extensive account has been taken of food demand, competition for water, protected areas. Excludes marginal and badly degraded land, excludes water scarce areas and protects areas	Rain-fed only. Production in areas of water scarcity, marginal and degraded land could add a further 70 EJ	Currently: ~55 EJ/yr at <$2/GJ, increasing to ~100 EJ/yr at <$2/GJ by 2050.
				Residues from forestry, agriculture and organic waste	2050		40 - 170 EJ, with a mean value given of 100 EJ	Global			
				Surplus Forestry	2050		60 - 100 GJ/year	Global			
				Agricultural learning (incl yield increases above BAU)	2050		140 EJ	Global			
Smeets (2008). Possibilities and Limitations for Sustainable Bioenergy Production Systems.	Quickscan model	IMAGE	729 Mha	surplus arable land	2050	16 ODT/ha/yr	215 EJ		Modelling allows only land which is currently arable land (in 1998), and will not be needed in 2050 for food production. Biodiversity impacts are not modelled.	Rain fed only.	
				Surplus forest products	2050		59 - 103 EJ, with 74EJ most likely outcome		only considered wood harvestable without leading to deforestation or reducing standing stock.		15EJ is economic potential, reduced to minus 8EJ if full ecological constraints are applied
				Residues and wastes	2050		76 - 96 EJ theoretical potential, 64 EJ technical potential				

Table 1b. Comparison of Published Literature on Biomass Potentials (cont).

Authors	Type of model	Databases Used	Estimated land available for bioenergy (Mha)	Land classification	Year	Yields / yield increases	Estimated biomass potential (EJ)	Geographical coverage	Sustainability Impacts	Water	Production Costs / Economic Considerations
Campbell et al. 2008. The Global Potential of Bioenergy on Abandoned Agricultural Lands	History Database of the Global Environment (HYDE).	HYDE, Centre for Sustainability and the Global Environment (SAGE)	385 - 472 Mha	Abandoned agricultural land	Technical potential based on 2008 land availability	7 - 20 t/ha/yr for tropical grassland; 4.3 t/ha/yr global average which @ 20 GJ/tonne = 86GJ/ha	32 - 41 EJ AGB/yr	Global	Low sustainability impacts if land is used for rain fed, low input perennials.	All areas assumed rain fed only	
Van Vuuren (2009), "Future Bioenergy Potential under various natural constraints"	IMAGE, TIMES	IMAGE	435 Mha	Abandoned agricultural land plus a fraction of natural grassland (allowing for overlays of water scarcity and accessibility)	2050		120 - 300 EJ Technical potential, of which 115EJ remains after overlay of land degradation, water scarcity and other sustainability considerations	Global	An accessibility factor has been applied to protect biodiverse areas, forest, and agricultural land, thus ensuring the the modelled potential has very low sustainability impacts.	Assumes rain fed conditions. Water scarcity has been fully modelled.	Costs for 115 EJ, would average ~$3.5/GJ. At < $2/GJ, potential is limited to 40 EJ
Deng et al, (2011), The Ecofys Energy Scenario	Ecofys	IIASA	673 Mha	Land suitable for rain-fed agriculture, which is not required for other uses	Technical potential based on current IIASA database		49 - 70 EJ (from 250 Mha)	Global	Full sustainability criteria applied.	Assumes only rain-feed agriculture. Water scarcity has been fully taken into account	
		Literature		Surplus forest products	2050		38 EJ	Global	Full ecological constraints applied. Model excludes 25 EJ of unsustainable, traditional biomass		Economics taken into account.
		Literature		Residues and wastes	2050		101 EJ	Global	Full sustainability constraints. Only fully sustainable biomass has been included		Not modelled
Fischer et al (2007)	IIASA-LUC methodology, 'ABioE'	Several databases for different inputs, incl., GIS, CORINE, CRU Global Climatologies, VASCLimO Global Precipitation.	65 Mha	Arable and pasture land "freed up" by 2030 as a result of improved yields and efficiencies	2030		4EJ (for 1G biofuel crops), OR 8EJ for 2G crops.	EU27 + Norway, Switzerland and Ukraine	Not explicitly modelled. Demand for food, feed and export have been fully considered.	Assumes rain fed agriculture	Not modelled
Saddler (2006),	Comparative	Open Literature			2010, 2050		2010: 5.7 - 33 EJ, 2050: 13.3 - 119.8 EJ	Global	Model incorporates sustainability considerations of input studies.	Not explicitly addressed	Not modelled
Hoogwijk (2004)	Comparative. IMAGE	Open Literature	up to 3,700 Mha, with 2,600 Mha based on moderate assumptions	Surplus agricultural land	2050	10 - 20 ODT/ha	up to 988 EJ, with 694 EJ based on moderate assumptions. LCAworks analysis: for a scenario based on Hoogwijk's data, medium population growth, moderate diet, and most sustainable production system (LEI), potential = (1/1.3)*5,000 Mha*10 ODT/ha * 20GJ/the = 230 EJ	Global	Full account taken of future food demand. Protected areas excluded.	Mainly rain fed, with some irrigation	Not modelled

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