

BOOSTING BIOFUELS

Sustainable Paths
to Greater Energy Security



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Sugar cane in the field

EXECUTIVE SUMMARY

Substantial potential exists to expand both food and fuel supply in a sustainable fashion. Sustainable biofuel pathways examined in this report include:

- » boosting yields of food crops and associated residues on existing farmland;
- » freeing up existing farmland for biofuel crops through further yield improvements;
- » reducing losses and waste in the food chain to free up additional farmland for biofuel crops; and
- » improving livestock management to free up pastureland for biofuel crops.

The report also examines biofuel potential from:

- » afforestation using fast-growing tree species; and
- » cultivation of algae from organic waste streams or carbon dioxide.

As agricultural production expands to meet the world's growing food needs through 2050, the supply of associated harvest and processing residues will also expand. If sustainable shares of these residues were fully collected, the resulting biofuel could displace about a third of the transport fuel consumed today – even while allowing for some residues to be fed to animals for meat and dairy production.

Accelerating yield growth through modern agricultural practices should allow the same amount of food to be grown on less land. The land released could be planted with fast-growing, short-rotation trees and grasses. If the gap between current and potential food yields were fully closed, biofuel from trees and grasses could displace another third of today's transport fuel.

The amount of farmland needed for food production could be further decreased by reducing waste and losses in the food chain. Globally, a third of all food is lost or wasted. If food losses were eliminated, enough additional land would be available for advanced biofuel production to displace the final third of the fuels used in transport today.

In addition, there is significant potential to grow biofuel crops by raising the efficiency of livestock production on pasture land. There is evidence that fast-growing grasses could enhance biodiversity on such land. Recent trends in Brazil suggest the efficiency of livestock production on pasture land can be

quadrupled. If so, the land released could provide half of the world's current liquid transport fuel from second-generation biofuel, or else all such fuel through first-generation biofuel crops.

There is also great potential to increase biomass production in forests. Much larger amounts of forest residues could be harvested sustainably for energy purposes. Cultivation of fast-growing trees on degraded forest land or other marginal land could provide significant amounts of fuel and timber while sequestering large amounts of carbon in the wood and soil. These forests could displace yet another half of current liquid transport fuel.

Part of this potential can be harnessed through current "first-generation" technologies that produce biofuel from crops like sugar cane, maize and palm oil. Part can be harnessed through "second-generation" technologies that convert lignocellulose from farm and forest residues, grasses and wood. Such technologies are being demonstrated at commercial scale and should be cost-effective by 2030, if not sooner. A further part could be harnessed through "third-generation" technologies, now under development, which would produce biofuel from algae.

What share of the potential can be realised, or how soon, is unclear. Yet policies to encourage higher farm yields, promote sustainable forestry, and demonstrate cost-effective conversion technologies should boost biofuel production substantially. Together, these policies should encourage sufficient biofuel production to enhance global energy security, boost economic development, and contribute to success in limiting global climate change.

Policies and Measures for Promoting Sustainable Biofuels

- » **Demonstrate cost-effective technologies** for production of biofuels from lignocellulosic feedstocks (grasses, wood, farm and forest residues) and from algae.
- » **Accelerate improvement of crop yields** by expanding capacity building and extension services to promote modern farming techniques in developing countries, and by enhancing access to fertiliser and water storage.
- » **Improve understanding of logistics** for cost-effective harvesting of farm and forest residues.
- » **Collect comprehensive data** on land that could be used for sustainable biofuel crops, including achievable yields.
- » **Conduct in-depth research** on practices for cultivating fast-growing trees and grasses on pastureland that could sequester carbon and enhance biodiversity.
- » **Reduce food waste and losses** through more flexible labelling and investment in refrigeration and transport infrastructure to bring more food to market fresh.
- » **Accelerate afforestation** through incentives to cultivate trees on degraded lands and through sharing best practices for sustainable forest management.
- » **Expand registers of origin** to include sustainable feedstock sourcing and promote expanded trade.
- » **Strengthen land tenure** and improve land governance in developing countries to provide incentives for more intensive land management.
- » **Develop new business models** that focus on sustainable feedstock supply, supported by policy instruments such as biofuel targets, feed-in tariffs, and carbon value.

INTRODUCTION: TECHNOLOGY PATHWAYS

There are several opportunities to expand the use of bioenergy around the world, which correspond to different feedstocks and technology pathways. This report assesses how much biomass could be sustainably produced to reduce petroleum or other fossil fuel use and associated greenhouse gas emissions. The main focus is on liquid biofuels for transport, since transport accounts for the bulk of global petroleum use and since air, marine and heavy freight transport require the high energy density that liquid fuels provide. A secondary focus is on bioenergy for combined heat and power applications, which sustainable biomass can also supply.

Most biofuels today use agricultural crops as feedstocks. These “first generation” biofuels use available technologies to convert sugar or starch to ethanol and lipids to diesel fuel. Globally, some 95 billion litres of bioethanol and 30 billion litres of biodiesel were produced in 2014, equating to roughly 3.6% of petrol (gasoline) supply and 1.5% of diesel supply or about 3% of all liquid fuel used for transport. Most of this production is due to biofuel targets and incentives that Brazil, the United States and European Union countries have set up to diversify transport fuel supplies and improve energy security.

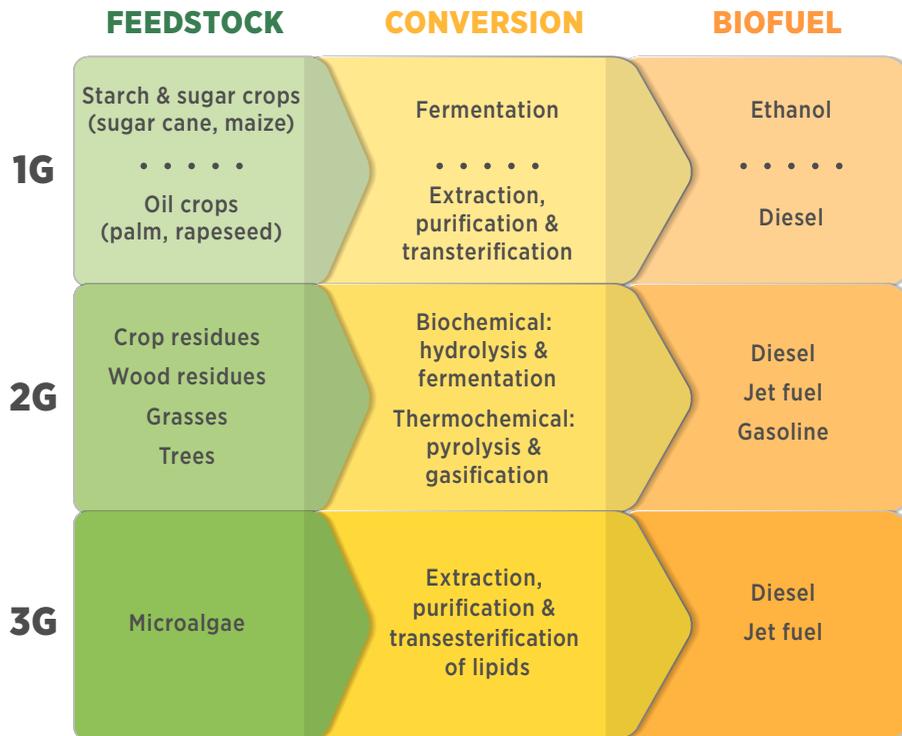
“Second-generation” biofuels use lignocellulosic feedstocks like farm and forest residues, grasses and trees. Some such feedstocks can have high yields, sequester carbon, and grow on land poorly suited for food crops. They are converted to biofuels using biochemical and thermochemical technologies that are now in a pilot or demonstration phase.

“Third generation” biofuels, from algae, are at an early stage of development and are not yet cost-effective. But they could grow on much less land while producing a variety of useful co-products. Because of their technical, economic and environmental promise, both second- and third-generation biofuels are the focus of intense research and development in several countries.

Cars can run on renewable hydro, wind or solar power as well as electricity from biomass. But for heavy freight trucks, ships and jets, which cannot be practically electrified, biofuel is the best available alternative to petroleum fuels.

Biomass carries considerable sustainable resource potential, whether converted to liquid biofuel for transport, used to help power electric vehicles, or combusted to produce heat and power for a variety of industrial, residential and commercial applications. Appreciating the extent of this potential is important

Figure 1: Some Typical Biofuel Technology Pathways



when considering practical policies and measures that could help to develop it over time. This report aims to provide the essential knowledge.

Biofuels have been criticised on the grounds that they may compete with food production or increase greenhouse gas emissions. In fact, the picture is somewhat more complicated: Some key biofuel crops (like corn) have protein components that remain available to the food chain when fuel is produced. And other biofuel crops (such as sugar cane and grasses) can sequester significant amounts of carbon in the soil. But in assessing the amount of biofuel that can be produced sustainably, it makes sense to give priority to approaches that complement rather than compete with food production, and which use available land without direct or indirect land use change. Such approaches, including higher farm yields, more intensive use of pastureland, more thorough harvesting of farm and forest residues, and reduction of land required for food production by cutting food losses and waste, are the focus of this report.

BIOFUEL FROM AGRICULTURAL RESIDUES

While food and fuel production have often been seen as being in conflict, there is actually substantial potential to boost food and fuel production simultaneously. This is because as food production expands to meet the nutritional needs of growing populations, there is also increased production of agricultural residues. For every tonne (t) of crop produced, an amount of residues is available in the field after harvest, of which a fraction can be practically and sustainably collected, typically assumed to be between a quarter and a half so enough is left to regenerate the soil.¹ In addition, a share of residues is attached to crops when they are processed, most of which can also be collected.

Multiplying the tonnes of each crop in each country (FAOSTAT, 2015), by tonnes of harvest and processing residue per tonne of crop (Smeets, Faaij and Lewandowski, 2004), some 161 exajoules (EJ) of agricultural residue was generated worldwide in 2010. Taking 25% to 50% of harvest residue and 90% of processing residue, 55-90 EJ could have been used. With projected growth in food supply,² assuming that the mix of crops is constant, available agricultural residue could reach 79-128 EJ by 2050.

However, much of this residue would be likely to be used for animal feed. Dividing the supply of meat between traditional grazing systems and higher-yield “mixed” systems in each country, and multiplying by the amount of residue used to produce each tonne of meat, 19 EJ of residue is seen to have been used for feed in 2010. With projected growth in meat consumption,³ 33 EJ of residue could go to feed by 2050, leaving 46-95 EJ for biofuel use.

¹ Zhao et al. report that 75 kilograms per hectare (kg/ha) of nitrogen fertiliser allows 25% of residues or more to be sustainably collected on half of Australian croplands, reaching 50% of residues in the southeast and 75% in the southwest. Villamil and Nafziger (2015) found that removing 50% or 90% of residue with no-till planting reduces solid carbon and nitrogen stocks by only 6% to 7%. Muth Jr., Bryden and Nelson (2013), found that if sustainability is defined to require that soil loss from wind and water erosion is within tolerable limits and soil organic matter is not depleted, some 2.25 t/ha of residue can be removed for each crop under land management practices in 2011, or 25% of 9.17 t/ha total residue (weighing residue t/ha for each crop in table 5 by crop shares in table 7). Projecting to 2030, table 6 shows that no-till practices raise sustainable collection by 43%, i.e. to 35%. The World Bioenergy Association (2015) claims 50% of residue can be sustainably collected. A hectare (ha) is a unit of land equal to 10,000 square metres (m²) or 0.01 square kilometres (km²).

² According to FAO (2012; table 4.3), yearly growth in food supply is taken to be 1.3% globally through 2030 (ranging from 0.8% in developed countries to 2.4% in Sub-Saharan Africa) and 0.7% globally from 2030 through 2050 (ranging from 0.3% to 1.9%).

³ According to FAO (2012; table 4.17), annual growth in meat consumption is taken to be 1.4% globally through 2030 (ranging from 0.6% in developed countries to 2.7% in Sub-Saharan Africa) and 0.9% globally from 2030 to 2050 (ranging from 0.2% to 2.6%).



Corn stover: a crop residue

Photograph courtesy of National Renewable Energy Laboratory (NREL)

With 40% efficiency in a lignocellulosic conversion process, this residue would yield 18 EJ to 38 EJ of biofuel. That is roughly 20% to 40% of all the liquid fuel used for transport in 2012, potentially nearly twice the fuel used for marine shipping and aviation.⁴ It also represents 10% to 30% of projected transport energy demand in 2050.⁵ At 80% efficiency in a combined heat and power plant, the same residue could generate 36-76 EJ of usable energy.

Various policies and measures can enhance skills and incentives to collect residues for bioenergy. Best practices on logistics for cost-effective, sustainable residue collection can be disseminated. Investment in cogeneration plants, with agricultural residues as feedstock, can be promoted through standardised feed-in tariffs and power purchase agreements, which help ensure a steady stream of revenue without a lengthy negotiating process. If these are clearly set forth and well enforced, potential investors can have confidence in their returns and assemble the needed capital.

In rural areas of developing countries, where much of the residue potential is located, revenue sharing schemes can help ensure that farmers and villagers receive a portion of the revenue from electricity and heat sales to encourage their collection efforts. Capacity building efforts can also play an important role by providing skills to carry out feasibility studies for finance and engineering studies to design the plants, as well as skills to build, operate and maintain the steam turbines, boilers and gasifiers.

National bioenergy policies, with clearly defined and realistic targets for producing electricity or biofuel from residues, as well as financial incentives to collect residues for energy purposes, can help ensure that cogeneration plants and biorefineries are well supplied with a steady, reliable flow of residue feedstock (Global Network on Energy for Sustainable Development, 2011).

⁴ IEA (2012) indicates 97.46 EJ for transport of which 21.95 EJ for marine and aviation (2.17 EJ for domestic navigation, 7.91 EJ for marine bunkers, 4.12 EJ for domestic aviation, and 6.75 EJ for aviation bunkers).

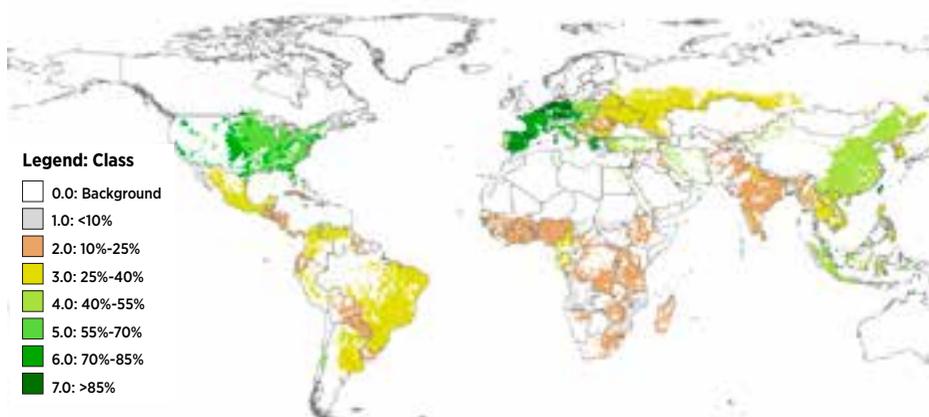
⁵ World Energy Council (2013) projects total final energy consumption (TFEC) for transport under different assumptions, ranging from 121 EJ in the "Symphony" scenario to 173 EJ in the "Jazz" scenario.

BIOFUEL POTENTIAL OF HIGHER CROP YIELDS

Growth in yields per hectare is responsible for some 80% of the increase in food production and residue potential implicit in Food and Agricultural Organization (FAO) projections.⁶ But yields could grow faster if greater efforts were made to expand extension services that let farmers in countries with lower crop yields adopt the practices that produce higher yields elsewhere. With higher yields per hectare, less land would be needed for food and more could be used for biofuel feedstock.

FAO projects that global average major crop yield will rise from 4.2 t/ha in 2010 to 5.1 t/ha in 2050. But applying the trend in yield growth by crop type from 1961 through 2013, the average could reach 6.6 t/ha in 2050 (FAOSTAT, n.d.).⁷ While 1,079 Mha would have to be planted in 2050 to meet world food needs at projected yields, just 839 Mha would be needed at the higher yields, releasing 240 Mha for biofuel crops. At a yield of 150 gigajoules (GJ) per ha, second-generation biofuel crops, like grasses, could provide 14 EJ of biofuel through a 40% efficient process, while first-generation biofuel crops, like maize or oil palm, could yield 29 EJ of biofuel at 80% efficiency.

Figure 2: Ratio of Actual to Potential Yield for Maize (Year 2000)



Source: *Global Agro-Ecological Zones* (FAO and IIASA, 2011-2013)

⁶ FAO (2012; table 4.4), notes another 10% is due to increased cropping intensity where multiple crops are planted on the same land each year. Only 10% of increased food production comes from expanding arable land.

⁷ Average annual yield growth by crop group from regression analysis of global data from FAOSTAT (n.d.).

Going further, FAO has assessed the gap between current and potential crop yields, assuming the current mix of irrigated and “rain-fed” land.⁸ For maize, a leading cereal feedstock in biofuel production, actual yield is less than 25% of potential yield for most of Africa and India, and less than 40% for most of Latin America and Former Soviet Union. Similar disparities exist for other crops.

To close the gap would entail raising average global crop yield to 10.4 t/ha in 2050 so that only 527 Mha would be needed for food rather than the 1,079 Mha projected by FAO, leaving 552 Mha for biofuel crops.⁹ If this land were planted with perennial grasses yielding 150 GJ/ha, converted at 40% efficiency, it would bring forth 33 EJ of biofuel, about a third of current transport fuel use. If the land were instead planted with conventional biofuel crops, like sugarcane or rapeseed oil, and converted to biofuel with a first generation process at 80% efficiency, 66 EJ of biofuel could result. Perhaps a practical target could be to close half the gap.

There could be still further potential biofuel production if more land were irrigated. FAO notes that “yields of irrigated crops are well above those of rain-fed ones,” that land equipped for irrigation has doubled since the 1960s to 300 M ha, and that “there remain some 180 Mha in developing countries that offer possibilities for irrigation expansion (FAO, 2012).” Since the yield is 50% higher on irrigated than on rain-fed land (FAO and IIASA, 2011-2013), realising these possibilities could free up 60 Mha of land¹⁰ for 4 EJ of biofuel using a second-generation or 8 EJ using a first-generation process. Since irrigation has been increasing by 3 M ha/year in developing countries (FAO, 2012), another 105 Mha could be irrigated by 2050 without accelerated effort, delivering over half this potential.

Several courses of action could help to raise agricultural yields. Capacity building and extension services could be expanded to spread modern farming techniques in developing countries. Fertiliser and water storage could be made more widely available. Agroforestry strategies for growing a mix of high-yielding food and fuel crops could be encouraged, based on successful country

⁸ FAOSTAT (2015) reports that globally, the average gap is 62.1 t/ha for sugars, 3.9 t/ha for cereals, 12.7 t/ha for root crops, and 0.6 t/ha for oil crops.

⁹ For each country, taking the land to meet food demand with current yields for each crop type and dividing by the ratio of actual to potential yield, finds the land area required to meet food needs if the yield gap were closed. As agricultural harvest area in 2010 was 981 M ha, 454 Mha could be available for biofuels without expanding land use from 2010.

¹⁰ Taking the yield ratio for each crop in each region, and weighting by crop shares, an overall yield ratio for each region is obtained; weighting by the available potential in each region, a global yield ratio is found.



Switchgrass in the field

Photograph courtesy of National Renewable Energy Laboratory (NREL)

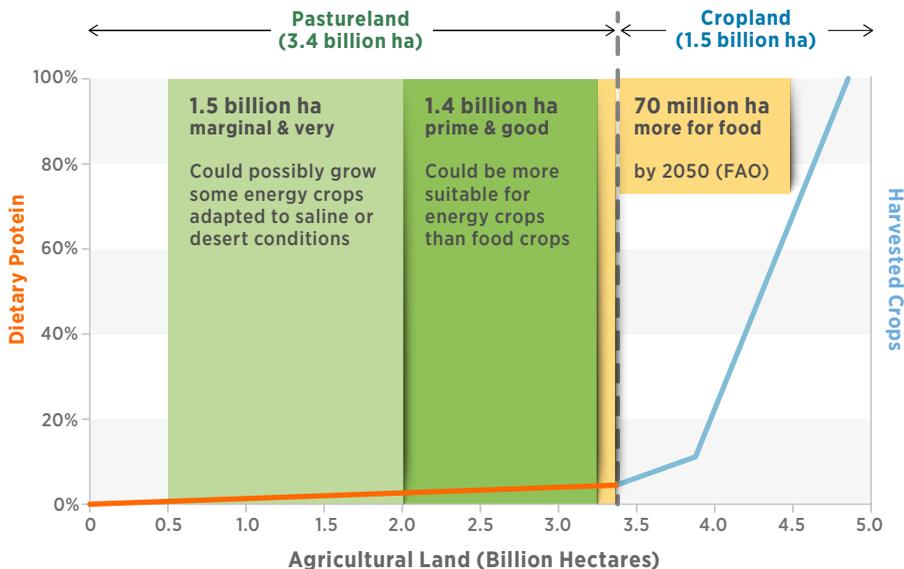
experiences. Neem oil trees, in India, provide diesel fuel for farm equipment and oil cake for fertiliser, while repelling insects so that food yields increase and villages become more prosperous (Puri and Panwar, 2007). Gliricidia, a fast-growing nitrogen-fixing fertilizer tree, boosts yields of coconut in Sri Lanka and maize in Malawi and Zambia (Evergreen Agriculture Partnership and World Agroforestry Centre, 2015). Secure land tenure and effective land governance, in countries that do not have them, are key to providing financial incentives for investment in intensive, sustainable land management.

SUSTAINABLE BIOFUEL FROM PASTURE LAND

Some 7.0 Gt of biomass was used to feed livestock in year 2000, of which 3.8 Gt was from grazed land (Krausmann *et al.*, 2008). If this pasture land were systematically harvested, assuming grass yields of 10 t/ha, the livestock raised on grazed land could be fed from just 380 M ha. Subtracting this from 1,330 Mha of prime and good pasture land available for farming in 2050 beyond anticipated food needs,¹¹ 950 Mha could be released to biofuel crops. If this fertile land were planted with trees or grasses yielding 150 GJ/ha, it could provide 142 EJ of biomass for 57 EJ of second-generation biofuel. A practical aspirational goal could be to get half of this by 2050.

Miscanthus x giganteus could be an excellent candidate for such intensification. It grows well in nearly all countries and regions with abundant available pasture land.¹² It has very high yields without fertiliser due to nitrogen-fixing bacteria in its roots. It is sterile and thus non-invasive to native species (SCOPE – Scientific

Figure 3: Pastureland for Energy Crops



Courtesy of Lee Lynd, Dartmouth University

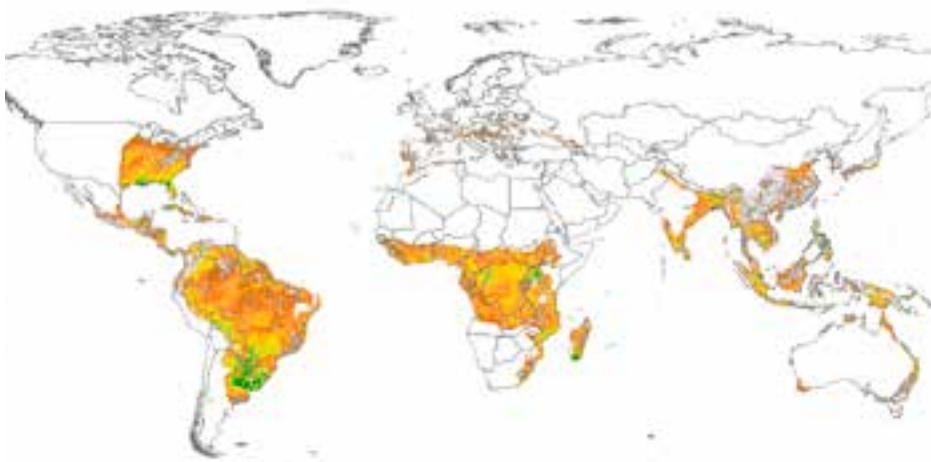
¹¹ FAO (2012; figures 1.6 and 1.7) shows 1,413 Mha of spare prime and good land in 2010, 1,334 Mha in 2050 – with 485 Mha in developed countries, 400 Mha in Sub-Saharan Africa, 314 Mha in Latin America, 94 Mha in East Asia, 37 Mha in the Near East, and 4 Mha in South Asia.

¹² FAO (2012) notes that countries with the greatest amounts of available pasture include Australia, Canada and United States among developed countries; Democratic Republic of the Congo, Madagascar, Mozambique and Sudan in Africa; Argentina and Brazil in Latin America; and China in East Asia. FAO and IIASA, *Global Agro-Ecological Zones (GAEZ 3.0)* shows nearly all of these to be within the climatic boundaries for effective cultivation of *miscanthus* (as shown in figure 4).

Committee on Problems of the Environment, 2015).¹³ It enhances biodiversity by providing cover for a variety of shade-tolerant plants, invertebrates, woodland bird species and butterflies (Donnelly *et al.*, 2011). Finally, *Miscanthus* may well sequester large amounts of carbon in the soil.¹⁴ Sugarcane, bamboo and switchgrass are other high-yield options.

In fact, the sustainable intensification of pasture land, with more efficient mixed and landless feeding systems, is well underway. In the past 30 years, world production of ruminant meat and milk has increased by about 40% while the global area of pasture has increased by only 4% (Bouwman *et al.*, 2005). Brazil, the world's leading country with regard to available pasture land and the second largest beef producer, increased carcass weight per ha by 3.5-fold in a 21-year period, 1985-2006 (Martha Jr., Alves and Contini, 2012). The stock of grazing animals per unit of land could more than double if the least productive pastures were brought up to half of their attainable density and nearly quadruple if average pastures were stocked as densely as the most productive 5% (Sheehan *et al.*, forthcoming).

Figure 4: Global Range of Suitable Conditions for *Miscanthus*



Source: *Global Agro-Ecological Zones* (FAO and IIASA, 2011-2013)

¹³ SCOPE (2015) notes yields of 193 GJ/ha of cellulose, plus 132 GJ/ha of combustible residue are reported from ten-year trials without fertiliser in Illinois (Arundale *et al.*, 2013). Twenty years of trials in England and Denmark showed no significant response to fertiliser.

¹⁴ Anderson-Teixeira *et al.* (2009) suggest 1.0 tonne of carbon per ha per year (tC/ha/yr) could be sequestered. Dunn *et al.*, shows sequestration of 0.4-0.5 tC/ha/yr for grassland and 0.55-0.65 tC/ha/yr for cropped land/pasture in Agro-Ecological Zones 7 and 10.

BIOFUELS ON LAND FROM REDUCED FOOD WASTE

Large amounts of food are lost in production and distribution, or wasted at the point of consumption. The FAO has found that one third of food produced for human consumption is lost or wasted globally, amounting to 1.3 billion tonnes per year. Production and distribution losses have similar proportions in developed and developing countries, amounting to 31%-33% in Europe and North America (280-300 kg out of 900 kg of food produced per capita per year) and 26%-37% in sub-Saharan Africa and South/Southeast Asia (120-170 kg out of 460 kg of food produced per capita per year). But consumer food waste is much higher in developed countries (11%-13%) than developing ones (1%-2%). For each major region and food group, FAO data show percentage losses in agricultural production, postharvest handling and storage, processing and packaging, retail distribution, and consumption (FAO, 2011).¹⁵

Using the available data, the total percentage and tonnage lost or wasted can be calculated for each food group. For crops directly consumed, the tonnes lost or wasted can be divided by the average yield in tonnes per ha to calculate the number of ha that could be liberated by eliminating the losses and waste. For meat and dairy products, the amounts of different kinds of feed to produce each tonne must first be calculated; then the area used to produce the feed can be found; finally this area can be multiplied by share of product lost to derive potential land saved.

By this calculus, 442 Mha of land could be freed up in 2050 by eliminating losses and waste from crops directly consumed as food, and another 340 Mha could be made available by eliminating losses and waste of meat and dairy products. With 782 Mha freed up in all, biofuel crops yielding 150 GJ/ha would provide 117 EJ of biomass, converting at 40% efficiency to 46 EJ of advanced biofuel, enough to displace over two-fifths of current liquid fuel use in transport. If the yield gap were closed, land released by eliminating waste and losses would decline to 553 Mha (table 1) and biofuel potential to 33 EJ. (Using first-generation processes for fuel or combined heat and power, end-use bioenergy potential would be twice as great.)

The portion of this potential that might be obtained through international best practices is interesting to consider (table 2). At the consumption stage, the region with the lowest share of food waste is Sub-Saharan Africa. Production

¹⁵ Regions are Europe, North America and Oceania, industrialised Asia, sub-Saharan Africa, North/West/Central Africa, South/Southeast Asia, and Latin America. Food groups are cereals, roots and tubers, oilseeds and pulses, fruits and vegetables, meat, fish and seafood, and milk.

losses are generally lowest in the industrialised countries of Asia. Post-harvest storage losses are most often lowest in North America. At the processing and distribution stages, industrialised regions achieve the lowest losses for three food groups (cereals, fruits and vegetables, and milk), whereas developing regions achieve the lowest losses for three others (roots and tubers, oilseeds and pulses, and meat).

Table 1: Land Released by Eliminating Losses and Waste in the Food Chain (Mha)

Region	All Stages Combined	Agricultural Production	Post-harvest Handling & Storage	Processing and Packaging	Distribution: Supermarket Retail	Consumption
Europe	74	13	5	16	8	32
Africa	67	25	12	15	11	4
Asia	224	48	36	50	39	51
OECD Pacific	23	3	1	5	4	10
North America	70	13	3	16	7	31
South America	94	26	8	24	17	19
World	553	129	65	126	87	147

Source: Based on FAO and IRENA research

Table 2: Best Practice Losses and Waste by Food Type and Stage of Food Chain

Food Type	Agricultural Production	Postharvest Handling & Storage	Processing and Packaging	Distribution: Supermarket Retail	Consumption
Cereals	2%	2%	3.5%	2%	1%
Roots & Tubers	6%	7%	10%	3%	2%
Oilseeds & Pulses	6%	0%	5%	1%	1%
Fruits & Vegetables	10%	4%	2%	8%	5%
Meat	2.9%	0.2%	5%	4%	2%
Milk	3.5%	0.5%	0.1%	0.5%	0.1%

Source: FAO, IRENA

With best practice reducing the levels of waste and losses, potentially available land is roughly half of the theoretical potential (table 3). This equates to the total land encumbered by waste and losses (table 1) less the land still encumbered by waste and losses if best practice for waste and loss reduction were implemented everywhere. The 269 Mha of land made available could provide 16 EJ of advanced biofuel.

Table 3: Land Released by Implementing Best Practices in the Food Chain (Mha)

Region	All Stages Combined	Agricultural Production	Post-harvest Handling & Storage	Processing and Packaging	Distribution: Supermarket Retail	Consumption
Europe	39	4	2	4	>0	28
Africa	36	16	9	7	4	1
Asia	105	15	27	14	12	37
OECD Pacific	11	<1	<1	1	1	8
North America	37	4	1	4	0	27
South America	41	11	6	6	4	13
World	269	52	46	37	22	114

Source: Food and Agricultural Organization, IRENA

A variety of measures could help to reduce food losses and waste so that part of this biofuel potential can be realised. In developing countries, improved harvesting techniques, storage and cooling facilities, solar or geothermal food drying, and better packaging can reduce food spoilage. Expanding the transportation infrastructure can bring more food to market while it remains fresh and saleable. Agricultural extension services and capacity building could help improve harvesting techniques; local health regulations could require better packaging; and development assistance could help build better infrastructure to support these services (FAO, 2011).

Indeed, as reduced food waste enables biofuel production, biofuel can serve as an agent of change in reducing food waste. Local bioenergy production at village scale, in areas with limited energy access, can power harvesting machinery to limit food production losses and refrigeration facilities to limit food distribution losses. So biofuel production and reduced food losses in developing countries can reinforce each other in a virtuous circle. Reduced food waste should then



Tomatoes drying in the sun

lower food prices and improve nutrition (PANGEA – Partners for Euro-African Green Energy, 2012).¹⁶

In developed countries, waste can be reduced by differentiating prices to encourage sale of food items that are not perfect in shape or appearance, modifying labels so that “best-before” dates do not encourage consumers to discard food prematurely, and raising awareness of possible uses for safe food that is thrown away. Regulations to allow the sale of lower quality food items that meet health guidelines, engagement by food distributors and retailers to make food labels more informative, and advertising to change consumers’ attitudes, can all play helpful roles (FAO, 2011).

¹⁶ PANGEA cites the “low and declining productivity of Sub-Saharan African agriculture” as a key driver of high food prices.

EXPANDING BIOFUELS BY CULTIVATING FORESTS

A large potential also exists to obtain more biofuel feedstocks from forests. Part of the potential comes from more efficient use of firewood for traditional heating and cooking. A second part comes from more thorough collection of wastes and residues in commercial managed forests and wood product processing plants. A third part comes from higher wood yields on existing forest land. Finally, there is potential to generate biomass by afforestation of land which is poorly suited to food crops, which will also help the environment by enhancing carbon sequestration.

FAO has noted that over half of harvested wood is used for low-efficiency heating or cooking in developing countries (FAO, 2010). Such traditional bioenergy represents about 15% of global energy use and half of current bioenergy use. Yet wood fires and traditional stoves have a conversion efficiency of 10% to 20%. Modern wood stoves could cut their energy use by 30% to 60%, freeing up 8-17 EJ of bioenergy potential annually for other uses.

Wood harvest residues include twigs, branches, tops and stumps left over after logs are cut from trees. Process residues include wood chips and sawdust from converting logs to timber and timber products. Waste includes waste paper and wood from demolished buildings. By collecting a quarter of harvest residues and three quarters of process residues and waste, a study finds 30 EJ of bioenergy could be obtained (Smeets *et al.*, 2007). Perhaps half this (15 EJ) could be practically and economically collected by 2050.

The same study notes that 2.6 billion hectares of existing forest land accumulates some 3.4 cubic metres (m³) per hectare, or a total of 8.9 billion m³ of wood yearly. This would yield about 103 EJ of bioenergy if it could all be harvested. Planted forests, which yielded 400 M m³ of wood with 5 EJ of bioenergy from 124 Mha in 1995, could yield 9 EJ on the same land by 2050 as they mature and become more productive, bringing potential wood production to 112 EJ. With wood demand projected to rise from 3.2 billion m³ (37 EJ) in 1998 to a range of 3.6-5.7 billion m³ (42-66 EJ) in 2050, the remaining bioenergy potential would be 46-70 EJ (Ibid.). But a more recent study finds that only 27 EJ per year of additional bioenergy could be obtained from existing forest lands if protected, inaccessible and undisturbed forests are excluded from consideration (Cornelissen, Koper and Deng, 2012).



Hybrid poplar stand

Photograph courtesy of NREL

Further potential biomass could become available through afforestation or reforestation efforts. The “Bonn Challenge” calls for 150 Mha of degraded and deforested land to be restored by 2020 (Global Partnership on Forest Landscape Restoration, 2012), and the New York Declaration calls for another 200 Mha by 2030 (Institute for Advanced Sustainability Studies (IASS), 2015). Efforts might focus on the 394 Mha of land around the globe that has been degraded by soil erosion or other factors and is not in use as farmland, pastureland, or forest (Nijsen *et al.*, 2012). If such land were planted with fast-growing tree species like poplar or willow in temperate climates and acacia or eucalyptus in tropical climates, the land could be converted to a productive managed forest. Since such species yield around 10 t of wood¹⁷ or 190 GJ/ha/year under average water conditions,¹⁸ meeting these goals could provide 67 EJ of bioenergy. But since degraded forests often have hard or eroded topsoil, lower yields could be more typical. To estimate from yields in China’s ongoing efforts to use degraded soils, perhaps just half this amount (33 EJ) would materialise.¹⁹

Taking this together with the potential of more efficient traditional use (8-17 EJ), wastes and residues (15-30 EJ), and higher yields in managed forest (27 EJ), forests could sustainably provide an additional 83-141 EJ of primary bioenergy. This could convert to about 33-56 EJ of advanced biofuel, or a mix of some 66-112 EJ of first generation biofuel, heat and power.

Afforestation would also sequester substantial carbon in the initial decades of rapid wood growth prior to harvest, and it would permanently sequester substantial amounts of carbon in the soil. Afforestation is one of the most cost-effective means of sequestering carbon from the atmosphere,²⁰ and the greenhouse gas balances from forestry play a vital role in keeping global emissions in check. Carbon is emitted in the manufacture of wood products, and methane is released from wood and paper in landfills. But emissions are avoided through recycling, the substitution of wood for other materials in building construction, and the substitution of electricity from pulp and paper

¹⁷ The German Poplar Commission (2012) noted poplar yields of 10 t/ha under average water conditions, ranging from 6 t/ha with poor water supply to 20 t/ha with high rainfall. Aylott *et al.* (2008) report mean yields of 4.9-10.7 t/ha, but also note varieties with mean yields up to 13.3 t/ha in the second planting rotation. The Intergovernmental Panel on Climate Change (IPCC) (2003) suggest yields of 6-15 t/ha for pine, 10-15 t/ha for acacia, and 11-26 t/ha for eucalyptus if ranges of growth in table 3A.7 are multiplied by densities in table 3A.9.

¹⁸ The Biomass Energy Centre (n.d.) notes energy content of 19.0 GJ/t at 0% moisture.

¹⁹ Jiang and Zhang (2003) report that 13.33 Mha of plantation forests yield 130 Mm³ of wood or around 10 m³/ha. For the species planted, weights of 530 kg/m³ for fir, 350-560 kg/m³ for pine, 590 kg/m³ for larch, 670 kg/m³ for birch and 420 kg/m³ for willow are given at www.simetric.co.uk, implying typical yields of 3.5-6.7 t/ha.

²⁰ Winsten *et al.* (2011) indicate afforestation is economic on pasture at 10 USD/Mt CO₂ equivalent and on cropland at 40 USD/Mt CO₂e

mills for electricity generated from coal or gas.²¹ By providing economic incentives to maintain and expand forests, production of biofuels along with wood products can enhance carbon sequestration while displacing oil and boosting energy security.

Sustainable agroforestry can be supported by a variety of national and international policy mechanisms. Certification of biomass origin can help governments give incentives to crops produced sustainably and help biofuel refiners source biomass responsibly. Support prices for reforestation, as implemented in Madagascar, or tree planting subsidies, as tried in Chile and Uruguay, can provide direct financial incentives for individuals and corporations to engage in afforestation efforts that meet sustainability criteria. Forest funds, as set up by Burkina Faso, Cameroon, Congo, and Mali in Africa, and Forest Replacement Associations, as set up by Brazil and Nicaragua in Latin America, can provide additional financial support for afforestation, with a mix of royalties, taxes, concession fees and forest replacement fees paid by businesses. Master plans for wood fuel supply, as in Chad, Niger and Senegal, can guide private actors on what to provide. Designated forest plantations, as in Brazil, Chile, Madagascar, Mozambique and Rwanda, can help to implement such plans or meet biomass goals.

Clear land tenure, where lacking, will be at the heart of effective initiatives for afforestation and forest management, as well as for sustainable intensification of agriculture; there is little financial incentive to plant and nurture biofuel crops over time without it. This is especially critical for high-yield perennial crops with multi-year growth cycles, such as grasses and short-rotation coppice. Regulators have awarded tenure to private enterprises in the Philippines and Uruguay, to households in China and Vietnam, and to individuals in Madagascar. Devolution of land use authority to regions or to regional authorities within the central government, as in Chad, Niger, Mali, Nepal and South Korea, may encourage stronger land tenure for villages, households and individuals, as regions are in closer touch with the needs of local populations.²²

²¹ FAO (2010) details greenhouse balances of forestry in 2006-2007. Gross emissions of 890 Mt CO₂e included 490 Mt in manufacturing (due to fuel combustion and electricity purchases), 238 Mt from the end of wood product life cycle (almost all methane emissions from rotting wood and paper in landfills), and 162 Mt from wood production, chemicals and fossil fuels upstream of manufacturing plants, and transport of wood products to market. These emissions were countered by 424 Mt sequestered in forest products, leaving 467 Mt CO₂e of net emissions from forestry. There were also avoided emissions of 809 Mt outside of forestry, including 300 Mt from recycling (avoided landfill methane emissions) and 483 Mt from substitution of wood for other building materials, resulting in net sequestration of 342 Mt even without considering avoided emissions from substituting electricity in pulp and paper mills for fossil-fuelled electricity and from keeping land in forest.

²² GIZ (2015) cites Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security, developed with stakeholders by FAO, as a basis for action.

ADVANCED BIOFUELS FROM ALGAE

Microalgae use energy from the sun or organic waste streams to create biomass from water and carbon dioxide (CO₂). Because of their simplified cellular structure, they convert energy to biomass much more efficiently than larger-scale plants.²³ And once their oil is extracted, it is easily converted to diesel fuel for trucks or jets.

The potential advantages of microalgal biofuels for the environment are substantial. They could help to remediate carbon emissions from fossil-fuelled power plants, converting the carbon dioxide in flue gas, provided it proves feasible to cultivate species that can survive the high concentrations of nitrogen oxide and sulphur dioxide that are present, or scrubbers are used to reduce those concentrations (Brown, 1996). As they can be cultivated in brackish water and non-arable land and have much lower land requirements than other biofuels, they can treat organic waste while avoiding carbon releases from land use change. And each kilogram of algae sequesters twice its weight in carbon dioxide.²⁴

But at present, biodiesel is much more expensive to produce from algae than from feedstocks like oilseed, and equally more expensive to produce than diesel from petroleum. In early 2015, the price of conventional jet fuel was 0.48 USD per litre (USD/L). By comparison, renewable jet fuel from algae and other organic oil was procured by the U.S. military from 2007 through 2012 at an average cost of 10.99 USD/L (Deane, O Shea and Ó Gallachóir, 2015). A study in the Netherlands found that bio jet fuel from algae cost 28 EUR/L in 2011, or 60 times as much as conventional jet fuel (Hulsman, Reinders and van Aalst, 2011).²⁵

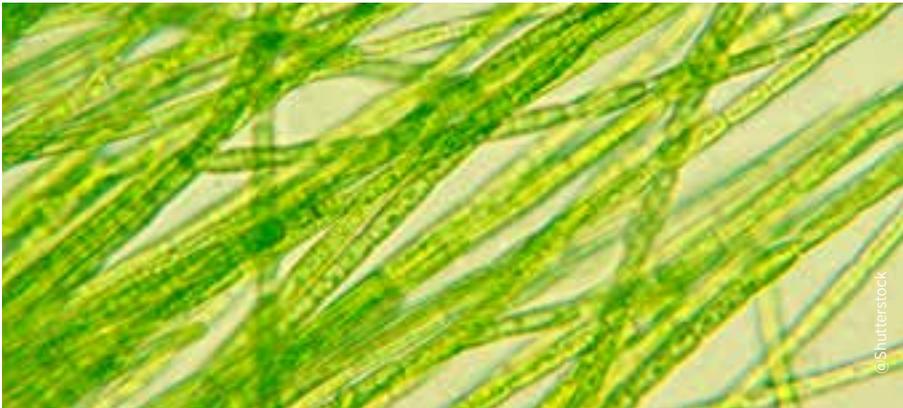
Fortunately, it should be possible to reduce the costs through technology development and economies of scale. Most production of algal biofuels to date has been in experimental facilities of low capacity for fuel production. With annual production capacity increased to 10,000 tonnes, the cost of oil from algae could drop below 1.20 USD/L with technology available today.²⁶ This could

²³ Darzins, Pienkos and Edye (2010) report yields of 450 L/ha/yr. for soybeans, 560 L/ha/yr. for camelina, 955 L/ha/yr. for sunflower, 1,890 L/ha/yr. for jatropha and 5,940 L/ha/yr. for oil palm. These contrast with reported algae yields of 3,800 L/ha/yr., potentially increasing to 10,200 L/ha/yr. through higher oil content and 50,800 L/ha/yr. with higher productivity.

²⁴ Chisti (2007) reports that some 1.83 kg CO₂ is sequestered per kg of algae.

²⁵ At an average exchange rate of 0.718 EUR/USD in 2011, this equated to roughly 39 USD/L.

²⁶ Ribeiro and da Silva cite estimates by Chisti (2007) that cost per kg of algae could decline to USD 0.47 for algae produced in photo-bio-reactors and to USD 0.60 for algae produced in raceways. Since algae contain about 30% oil by weight, a kg of oil from algae would then cost USD 0.47/0.3 = USD 1.40. Since the specific gravity of diesel fuel is between 0.81 and 0.96, a litre could then cost as little as USD 1.40 x 0.81 = USD 1.13.



Microorganism algae

make algal biodiesel roughly competitive with other biodiesel by 2020, when the International Energy Agency (IEA) Bioenergy Agreement has projected a cost of 1.20-1.45 EUR/L for jet fuel from forest wood (IEA Bioenergy, 2012) and a European Commission paper has projected a cost of 1.20 EUR/L for 2 Mt of sustainable bio jet kerosene.²⁷ With further advances and market-based credits for environmental benefits, algal biodiesel might compete with conventional jet fuel, for which a 2020 price of 0.54 EUR/L has been projected.²⁸

The economic case for algal biofuels may well be assisted by the development of technologies and markets for various valuable co-products. Several of these are environmental, such as treatment of waste water, remediation of contaminated ponds and streams, and capture of carbon dioxide from fossil-fuelled power plants. Others are more directly commercial, such as plastics, chemicals, protein for food, and “neutraceuticals” like omega-3 fatty acids.²⁹ Bio-refineries with a mix of biofuels and other products appear to be the most promising path to ultimate commercial success.

An optimistic view is that some 90 EJ of oil could be produced from algae grown in open ponds on non-arable land filled with salt water. This assumes 80% conversion efficiency from algae to finished fuel, taking account of process heat and electricity inputs, with the non-oil portion of algal biomass providing energy for cultivation and processing (Florentinus *et al.*, 2008). But algal bioenergy is still at too early a stage of development to estimate its realistic potential.

²⁷ Reported in Maniatis, Weitz and Zschocke (2011). At an average 2011 exchange rate of 0.718 EUR/USD, this equates to around 1.67 USD/L.

²⁸ Per U.S. Energy Information Administration (2014). At an average 2014 exchange rate of 0.753 EUR/USD, this equates to around 0.72 USD/L.

²⁹ See for example www.biofuelsdigest.com/bdigest/?s=algae

DEVELOPING SUSTAINABLE BIOFUEL POTENTIAL

The analysis above shows a large bioenergy potential (table 4). With second-generation conversion processes, lignocellulosic feedstocks such as agricultural residues, forest wood, and grasses and short-rotation coppice planted in pastures and on land made available through higher crop yields and reduced food waste, might yield 114 EJ of advanced biofuel by 2050 from a theoretical limit of 219 EJ. Alternatively, while waiting for such technologies to mature, residues and forest wood could be combusted to provide 102 EJ of heat and power from a theoretical envelope of 188 EJ, while pasture and land released due to higher yields and reduced waste could be planted with conventional biofuel crops yielding 126 EJ of biofuel from a theoretical potential of 250 EJ (with 228 EJ of energy in all extracted from an envelope of 438 EJ). In either case, the biofuel produced could exceed projected liquid transport fuel needs. Bioenergy from algae could provide a bonus over and above this.

Table 4: Bioenergy Potential in 2050: Aspirational Targets and Theoretical Potential (EJ)

Category	Primary Biomass Energy Content	End-use Bioenergy with 1G Biofuel or Combined Heat and Power (80% Efficiency)	End-use Bioenergy with 2G Biofuel Conversion (40% Efficiency)	REmap Assumptions for Primary Biomass Energy in 2030 (Reference)
Agricultural Residues	46 - 95	36 - 76	18 - 38	19 - 48
Higher Crop Yields	47 - 88	37 - 70	19 - 35	0 - 0
Pasture Land	71 - 142	57 - 114	28 - 57	33 - 39
Reduced Food Waste	40 - 83	32 - 66	16 - 33	18 - 18
Cultivating Forests	83 - 141	66 - 112	33 - 56	41 - 58
Total	287 - 549	228 - 438	114 - 219	112 - 162

EJ= Exajoules

For the range of potential shown in each column, the left-hand (smaller) value represents an aspirational target, while the right-hand (larger) value represents theoretical potential.

The estimate of theoretical primary biomass energy potential, 549 EJ, exceeds most other estimates in the literature. This is mainly because most other estimates do not consider (or fully consider) the potential of pasture land or

of land that could be made available by closing the agricultural yield gap and eliminating losses in the food chain. Considering only agricultural residues and forest cultivation, the primary energy potential would be just 236 EJ, which is within the range of values indicated in other studies.

In fact, there is a wide range of estimates on the amounts of biomass that could be sustainably grown and collected for conversion to biofuels. Recent studies that consider a range of environmental constraints have arrived at estimates of potential ranging from less than 50 EJ/year to more than 1000 EJ/year by 2050. But many studies agree that the technical potential in 2050 is “at least approximately 100 EJ/year”; a review article by 22 experts with a wide range of views found “high agreement” on sustainable potential of up to 100 EJ as well as “medium agreement” on potential of 100-300 EJ per year (Creutzig *et al.*, 2014).

Indeed, several studies with rigorous assessment of sustainability criteria come up with results towards the upper end of the range. The Global Energy Assessment by the IIASA gives a range of 160-270 EJ per annum (Johansson *et al.*, 2012). Carefully excluding all land that is protected, barren, covered by water or occupied by cities, all agricultural cropland (assumed to be needed for food production), all unprotected forest land (to maintain forest biodiversity and carbon stocks), all land poorly suited to rain-fed agriculture (to avoid new irrigation systems that might affect water supply), and further land that might be needed for food production or development or biodiversity protection, Ecofys finds a land-based bioenergy potential of some 250 EJ annually in addition to the algal potential cited above (Cornelissen, Koper and Deng, 2012). A paper whose co-authors include some noted bioenergy sceptics finds a similar potential for bioenergy on land, suggesting an “upper biophysical limit” of 190 EJ for bioenergy from intensified land use and 60 EJ for bioenergy from farm and forest residues, also totalling 250 EJ excluding algae (Haberl *et al.*, 2013).

Even at the lower end of the range identified, sustainable biofuels could greatly enhance energy security. If most of the biomass came from wood, grasses and residues, converting it to biofuel through a second-generation thermochemical or biochemical process at 40% efficiency – just half the usual efficiency for production of first-generation biofuels from sugar, starch, or oil crops that have dominated the biofuels industry to date – could displace more than a third of the oil that is currently used for transportation fuel. At the upper end of the range suggested, biofuels could displace nearly all today’s oil use for transport.



Newly harvested field

What portion of the world's theoretical bioenergy potential might practically be harnessed? In view of the great uncertainties about current and future land use, crop yields, and evolving costs of biofuel conversion, it is hard to know.

But steps can be taken so that bioenergy production expands substantially and sustainably. Best practices can be spread to boost both food and fuel production through higher yields. Forests and degraded lands can be planted with fast-growing trees to produce fuel while sequestering carbon. Advanced technologies can be developed and scaled to produce biofuels at lower cost.

Individually and collectively, we can act so that biofuels and carbon sequestration, food production and development all advance hand in hand.

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