Crops for Biofuel: Current Status and Prospects for the Future

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Introduction

Plants provide the energy for maintenance, growth, reproduction, and locomotion of almost every living organism on our planet. That energy, originating from the sun, flows from plants through a web of consumers and decomposers and gradually returns the carrier molecule CO_2 to the atmosphere. Fires, occurring naturally from lightening strikes or provoked by man's activities, are a more sudden but chemically similar, release of solar energy accumulated by plants. Humans and some other animals use plant material for construction but humans alone have combusted biomass under controlled conditions to provide heat for warmth, cooking, and both stationary power and traction.

Biomass accumulated by plants during previous geological periods formed coal and oil (fossil fuels), which have driven industrial development and transportation during recent centuries. Oil is clearly a finite resource and although proven reserves keep increasing (from 3.9 zettajoules (ZJ) in 1980 to 8 ZJ in 2008; EIA 2009), a more industrially developed, better fed, and still expanding world population is now consuming the resource at an increasing rate. At the present annual rate of extraction of 192 EJ (31.5 billion barrels), known reserves are sufficient for a little over 40 years (IEA 2008). Concern about the inevitable exhaustion of oil, high energy prices, energy security for individual countries, and global warming, are encouraging a search for alternative sources of energy.

One focus of the search is liquid energy for transportation, which consumes around half of total petroleum use. Biofuels from crops have been identified as a major possible alternative to fossil transportation fuels, though their use as transportation fuel is not new. Diesel engines were initially designed to run on vegetable oil and after the first major

Connor, D.J. and C.G. Hernandez. 2009. Crops for biofuels: current status and prospects for the future. Pages 65-80 in R.W. Howarth and S. Bringezu (eds) Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, 22-25 September 2008, Gummersbach Germany. Cornell University, Ithaca NY, USA. (http://cip.cornell.edu/biofuels/)

petroleum price rise in the 1970's there was much interest and analysis of energetic efficiency of agriculture in general and production of biofuel in particular. That period did not lead to a sustained increase in the use of biofuels, however, because the price of petroleum fell and with it the pressure to develop alternative sources. Now, the situation is more complex and petroleum prices are rising because demand exceeds production. There is already significant diversion of crop production to biofuel that will likely increase, at least in the medium term.

This chapter details which crops are currently used as biofuel feedstocks and in what quantity they are used relative to demand for fuel, as well as prospects and limitations for further expansion. We explore key issues of crop growth, choice and productivity of crops currently used, prospects for new sources, and competition for land for food and environmental conservation.

Plant growth and chemistry of plant products

All green plants capture solar energy by a common process of photosynthesis to construct simple C3 compounds from CO_2 and H_2O; the former absorbed by leaves from the atmosphere and the latter by roots from soil. Photosynthesis is limited by the low concentration of atmospheric CO_2. To get around this, one group of plants, mostly tropical grasses, have evolved a mechanism that utilizes C4 compounds to concentrate CO_2 at the sites of photosynthetic fixation. Under appropriately warm conditions, C4 plants commonly exhibit greater growth rates than the more common C3 plants. In both plant types C12 sugars, principally sucrose (= glucose + fructose), are translocated from leaves to become the energy currency and, with inorganic elements also absorbed by roots from soil, chemical building blocks of plant growth.

Plant growth is more than photosynthesis, however. It requires formation of vegetative and reproductive organs that increase in size and mass by accumulation and transformation of photosynthetic products. In annual crops, accumulation of biomass depends largely upon filling vegetative storage tissues (tubers, stems, and roots) or reproductive organs (seeds and fruits). In perennial plants, secondary thickening of stems (wood) provides additional sites for accumulation of biomass. Plant growth is, therefore, a chemical and physical expression of captured and transformed solar energy.

Most energy fixed by plants remains in structural compounds (cellulose, hemicellulose etc.) that are relatively chemically inert. Other classes of compounds (sugars, starches, proteins, fats/oils) are part of metabolism or storage. Energy for construction of these compounds is provided by chemical breakdown (respiration) of sugars releasing CO_2 in the process. Thus, energy retained by plants is less than that fixed by photosynthesis. It is also not proportional to accumulated biomass because proportions of major chemical forms differ in energy density and between species and stages of growth. These are important issues in the energetics of plant growth and suitability of crops for food, feed, and fuel production. Energy content (per unit dry mass) of chemical forms relevant to this discussion are as follows: sugars, starches, cellulose, and hemicellulose 14–16 megajoules per kilogram (MJ kg^{-1}); vegetative biomass ~ 17 MJ kg^{-1}; proteins and lignin 25 MJ kg^{-1}; and fats/oils 38–40 MJ kg^{-1} (Loomis and Connor 1992).

The efficiency with which crops capture incident solar energy in biomass is well known (Loomis and Connor 1992). The highest short-term rates for crops well supplied with water and nutrients are ~5% but most systems run at lower efficiency. Good crops, for example, have maximum lifetime rates ca. 2% because of the time spent establishing ground cover and slow growth rates during stages of maturation. Over an annual cycle, rates are even lower unless crops are combined (e.g. winter cover crops). Perennial crops can do better if they maintain leaf area, especially in the tropics where growing conditions can be favorable year-round for C4 plants.

Types of biofuel and feed stock requirements

Currently, biodiesel and bioethanol from a small range of crops provide essentially all renewable liquid transport fuels. Other liquid fuels, such as synthetic gasoline and diesel, play minor roles. However, non-liquid transport fuels, including biogas, hydrogen, and electricity, can also be produced from biomass.

Biodiesel (~34 MJ L^{-1}) is formed chemically by trans-esterification of vegetable oils obtained by physical and/or chemical separation from oilseed crops. The process reduces long branched molecules (less suitable as fuel) to short straight-chained fatty acid methyl esters of lower viscosity and higher cetane number, which are more easily combustible. Trans-esterification uses methanol (or ethanol) and produces glycerine as a co-product.

Bioethanol (~21 MJ L^{-1}) is produced by fermentation of glucose and fructose, which are easily obtained from sucrose crops such as sugarcane or sugar beet. Glucose and fructose can also be formed by hydrolysis of starches [(C12)n] from grains, tuber crops (e.g. potato and cassava). Fermentation is followed by distillation and dehydration (both energy-demanding steps) to produce fuel grade alcohol. Burning biomass residues or byproducts, as commonly done in sugarcane refineries, can supply some of the energy required in processing. Fermentation produces organic co-products that find use as animal fodder.

Bioethanol can also be made from cellulose, also [(C12)n] but with a different chemical bonding to starch (Badger 2002). Cellulosic ethanol can be formed by two methods. The first produces ethanol by fermentation as described above, following depolymerization of cellulose by various physical, chemical, and enzymatic treatments. In principle, any plant material can be used, but unlike sugar and starch, cellulosic material is variable in chemical content, especially in woody plants that contain large quantities of lignin compounds. This variation complicates commercial production. The second pathway is a set of processes that convert biomass to liquid fuels thermochemically, by fermentation of synthesis gas (H_2, CO, and CO_2) produced by catalytic conversion, or from bio-oil *via* pyrolysis (chapter 3, Brown and Wright 2009).

It is convenient to describe ethanol biofuels by their crop product of origin, sugar-, starch-, and cellulosic-ethanol, respectively.

Current biofuel crops, relative productivity, and land requirements to meet mandated targets

Maize (USA), and sugarcane (Brazil) provide the bulk of feedstock for bioethanol production, currently at 1090 petajoules (PJ) per year or 52 billion liters (FAO 2008a). Other

Table4.1. Average energy yield of the best two producers of bio-ethanol and biodiesel in various countries. [f] fruits harvested fresh; [s] aboveground material harvested fresh; [r] roots harvested fresh; [g] grain harvested at low water content; [e] energy contents: ethanol 21.1 MJ L^{-1}, biodiesel 32.9 MJ L^{-1}.(adapted from Liska and Cassman 2008)

Crop	**Country**	**Yield ($t\ ha^{-1}$)**	**Product**	**Biofuel ($L\ ha^{-1}$)**	**Energy[e] ($GJ\ ha^{-1}$)**
oil palm[f]	Malaysia Indonesia	20.6 17.8	Biodiesel	4736 4092	155.8 134.6
sugarcane[s]	Brazil India	73.5 60.7	Bioethanol	5475 4522	115.5 95.4
maize[g]	USA China	9.4 5.0	Bioethanol	3751 1995	79.1 42.1
cassava[r]	Brazil Nigeria	13.6 10.8	Bioethanol	1863 1480	39.3 31.2
rapeseed[g]	China Canada	1.7 1.5	Biodiesel	726 641	23.9 21.1
soybean[g]	USA Brazil	2.7 2.4	Biodiesel	552 491	18.2 16.1

crops (e.g. sugar beet, wheat, barley, cassava, potato, and rice) are also used in various countries. The dominant crop for biodiesel production, currently 340 PJ per year or 10 billion liters (FAO 2008a), is rapeseed (i.e. canola) (EU), although oil palm (Malaysia and Indonesia), soybean (USA and Brazil), and sunflower (Eastern Europe) are gaining importance. Peanut, cotton, sesame, and coconut are also used as feedstock. Most countries use locally produced crops. The EU is an exception to this.

A view of productivity of individual biofuel crops is presented in Figure 4.1 and Table 4.1. Figure 4.1 compares productivity for average (FAO 2008b) and high, but not highest recorded, crop yields for countries where individual crops are well adapted. Average crop yields (in tons per hectare dry matter for all crops except sugar beet and sugarcane, which are harvested fresh) are 8.0 wheat (UK), 9.4 maize (USA), 78 sugar beet (France), 74 sugarcane (Brazil), 2.7 soybean (Argentina), 2.1 sunflower (Czech Republic), 1.7 rapeseed (Canada), and 21 oil palm (Malaysia). The analysis expresses biofuel productivity in gasoline equivalents (35 megajoules per liter) and discounts (10%) annual yields of oil palm for an unproductive initial period after establishment and sugarcane for a proportion of crop that grows for more than one year before harvest. Table 4.1, adapted from Liska and Cassman (2008), provides a more specific analysis of current best practices for a range of crops in various countries.

Both sets of data illustrate large differences between crops reflecting differences in feedstock characteristics and environment (e.g. climate, management and irrigation), as well as previous achievements in crop improvement. Oil palm and sugarcane perform best because of their year-round growing environments. Maize and sugar beet also perform well in warm and cool climates, respectively. Except for oil palm, oil crops

Figure 4.1. Biofuel productivity of various feedstock crops (Source: FAO 2008b).

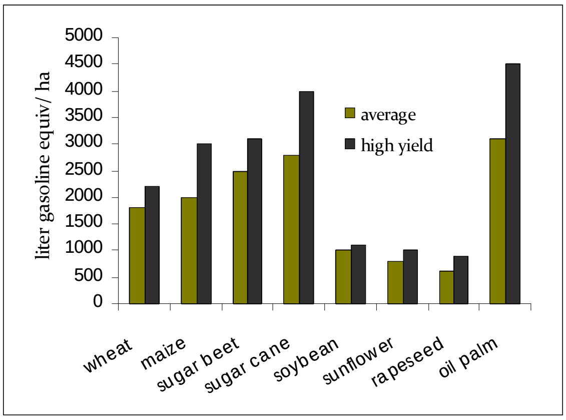
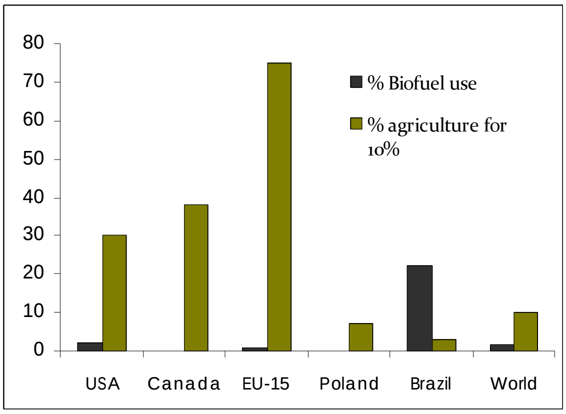


Figure 4.2. Proportions of biofuel use and crop area for 10% gasoline replacement. (Source: von Lampe 2006)



(e.g. soybean, sunflower, and rapeseed) produce small yields.

Data in Figure 4.1 reveal important characteristics shared by two productive crops – C4 sugarcane for warm and C3 sugar beet for cool growing conditions. Both are long season crops, both have vegetative storage organs (e.g. stem (sugarcane) and primary root (sugar beet), and both store sucrose. These characteristics have physiological implications for yield. First, vegetative organs are able to accept assimilate for storage over longer periods than grain crops, which depend on flowering and successful fruit set to provide storage capacity. Vegetative storage also reduces the opportunity for 'feed-back' restriction to yield accumulation during environmental stress, which may reduce grain set in cereal crops. Finally, sucrose is the least transformed storage product of photo-synthesis and therefore subject to smallest losses by subsequent metabolism.

Significant production of biofuel requires large areas of cropland. De la Torre Ugarte (2006) presents an extreme scenario to indicate the magnitude of the challenge. The author considers replacement of the total daily world transport fuel use in 2006 (~224 PJ or 7 billion liters) equally distributed between gasoline and diesel. According to the author, to replace that motive power with biofuel would require 100 PJ (4.8 billion liters) bioethanol and 124 PJ (3.7 billion liters) biodiesel per day. At high crop yields, the bioethanol demand could be met by either 300 Mha sugarcane or 590 Mha of maize; in other words, 15x the current global sugarcane crop area, or 5x the current global maize area. The biodiesel could be produced by 264 Mha of oil palm, or 20x its current area. Net gain would be considerably less because those numbers do not account for support energy on farm or in subsequent processing. However, this analysis does not apply to individual countries.

Opportunities to divert cropland to biofuel production, including that of fuel or feedstock for export, depend on the interplay among population, purchasing power, public and private investment, the national agricultural resource base, and government. These differences explain why, as shown in Figure 4.2 from von Lampe (2006), Brazil could meet 10% of transportation fuel from sugarcane on only 3% of total current agricultural land area. Current replacement is close to 22%, using 60% of the sugarcane area. Brazil scores high on land area, moderately on population, and low on purchasing power. The EU is close to the other extreme. It has a large population with high purchasing power, an agricultural area that is almost totally in intensive use while still requiring net importation of food and feed. Based on this analysis, the EU-15 would have to divert 70% of its agricultural area to meet its 10% biofuel for transport by 2020 mandate. Facing a 5.75% mandate by 2010, member countries have thus far achieved replacements around 1–2%, and that with significant contributions from imported grain.

Support energy and energy efficiency

The energy content in crops (mean 17 MJ kg^{-1}) that is captured from the sun in photosynthesis requires support energy, most of which is supplied by fossil fuels. It is best to consider support energy in two parts: 1) energy consumed independent of crop yield (e.g. for tillage and sowing); and 2) energy applied at levels related to expected yield (e.g. for fertilization, pest control, irrigation, and harvest). Support energy has, along with additional energy in transport and processing, direct relevance to the energetic efficiency of biofuel production. While the energy content of a biofuel can be readily measured, the support energy used in its production can at best be estimated. There are many steps to be considered, including embodied energy as well as that used directly. There is also a vexatious matter of what energy cost to allocate to co-products, which are increasingly important in closely integrated production systems (e.g. biofuel-livestock production). These issues contribute to variation in available estimates of the ratio of energy produced in biofuels to total (mostly fossil) energy used in production, or net energy ratio (NER),

Table 4.2 Ranges of net energy ratio (NER) reported for various biofuels. NER is calculated as biofuel energy/support energy (FAO 2008a)

Crop	Biofuel	NER
sugar beet	bio-ethanol	1.2 - 2.2
sugarcane		2.2 - 8.4
wheat		1.2 - 4.2
maize		1.2 - 1.8
oil palm	bio-diesel	8.6 - 9.6
soybean		1.4 - 3.4
rapeseed		1.2 - 3.6

The data in Table 4.2 illustrate a range of values for biofuel NERs on which discussion can be based. In studying the table, three points stand out. First, NERs are small except for palm oil and sugarcane. Second, among bioethanol crops, those that produce sugar are the most efficient. Third, NER is equally variable among crops that produce bioethanol or biodiesel. High values for sugarcane and oil palm are easily explained by the high productivity of year-round tropical environments and low support energy in processing. Palm oil benefits from small energy cost of expressing oil from seed. Sugarcane fermentation benefits not only from relatively little pre-treatment required to enter fermentation, but also from energy obtained by burning residual biomass to fuel processing (i.e. substituting fossil fuels in support energy).

Clearly, it is important to include NER in considerations of utility of biofuel production but it is rarely done. Production figures for biofuels are usually presented only as replacement values, which can be misleading. In the case of ethanol, because NERs are small (1.3 for maize ethanol), the gain on energy invested in production is just 30%.

That liquid fuel has special importance for today's transportation system is undeniable but energy can be used more efficiently in various ways, including for transport (see chapter 3, Brown and Wright 2009).

Future options and potential for expansion

Options to increase biofuel production include increasing crop area and/or crop yields; using crop residues and dedicated energy crops; and employing more efficient extraction and conversion methods. As explained previously, countries can find different solutions, but at a global level, expansion of biofuel production must be achieved in the context of a 50% increase in food production by 2030. That explains existing concern with moral, food security, agronomic, and ecological issues associated with biofuel production (Thompson 2008).

Greater crop area but mostly greater crop yields. Expansion of crop area beyond the current 1500 Mha in use is limited, although no-till production methods do now allow more intensive cropping (less fallow) and expansion into previously topographically unsuitable areas. Over much of the globe, unsuitable terrain, soils, and climate (Fischer et al., 2000), as well as lack of irrigation, remain the greatest limitation to expanding crop production. Table 4.3 presents total land area and part of total land area not limited by slope, soil quality, and low rainfall (FAO-AGL 2003). It reveals that only a small proportion of land does not suffer extreme limitation for rainfed cropping, as well as important differences between regions. While the total area land capable of supporting agriculture (2500 Mha) is greater than the current world cropping area (1500 Mha), it is important to remember that there are many other claims on land not accounted for in this analysis (e.g. urban land, conservation areas, etc.). Further, this analysis does not extend to the productivity of land with severe limits. Most productive land is already under cultivation and the opportunities on open land are rapidly being exploited (e.g. potential conversion of Brazilian Cerrado to mixed livestock cropping, extensive conversion of rainforest and peat lands to palm plantations in Indonesia). Such land use conversions threaten important ecosystem services and directly compete with the land's other potential values. Consequently, a sustainable increase in production must come from greater productivity of existing land. This can be achieved by site-specific combinations of improved production methods, better-adapted cultivars, and in most cases greater inputs of fertilizer and irrigation.

It is important to note, however, that while investment in productivity gain will remain an important component of the quest for food security, the gains will unlikely be sufficient to allow significant diversion to biofuel. To understand the reason why, it is necessary to understand the relationship between attainable, potential, and actual yield. Attainable yield is that obtained at any site using best technology to minimize limitations of water or nutrients and without losses due to pests, diseases, or competition from weeds. The maximum yield biologically obtainable in the most favorable environment is the yield potential of that crop. Actual yield is that achieved in practice. The difference between actual and attainable yields is the yield gap, which farmers can seek to reduce. The Green Revolution provided a substantial increase in potential yield of dwarf cultivars of cereals that were able to respond with greater harvest indices (grain yield/total biomass) to nitrogen fertilizer without lodging. Widespread increases of up to 60% in attainable yield have been attributed to this single advance (Evans 1998). Since then, gains in yield potential have been small. For example, no recent rice cultivar exceeds potential yield of 'IR8', the flagship rice cultivar of the green revolution in Asia (Cassman et al. 2003). Crop productivity has increased over recent decades by increasing attainable yields. Reductions in the yield gap by better and timelier operations, more fertilizers, and better weed, insect and pest control have also played a part. Plant breeding has contributed better-adapted cultivars, resistance to diseases, and more recently, with biotech methods, resistance to insects (e.g. cotton, maize) and improved weed control through herbicide resistance.

Cassman et al. (2003) revealed that relatively constant yield gains were achieved over the last four decades. As an example, world average yields of rice, wheat, and maize have increased at a rate of 53 kg ha^{-1} annually since 1960. Thus, while the annual rate of increase was 4.1% (mean yield 1.3 t ha^{-1}) in 1960, that rate has now fallen to 1.6% (mean yield 3.4 t ha^{-1}). Without a substantial increase in potential yield, the rate of progress in crop productivity must slow, as each increment is more difficult and costly to achieve (Duvick and Cassman 1999). Combinations of unforeseen circumstances that might provide a second new green revolution are unknown. Some would argue that the combination that provided the Green Revolution was unique.

A consistent yield gain on current agricultural area of 2% annually, which is beyond recent experience, would increase production by 22%, less than the expected 50% increase in demand. It would not provide extra grain for biofuel production. Further, the additional cars that are expected by 2030 (predictions suggest 2 billion) could add an equivalent of 1 billion people to global agricultural demand, even if annual biofuel contribution to each vehicle were limited to 100 L (<10% of a small annual fuel use). This assumes the standard nutritional unit of 500 kg grain to estimate the equivalent production required to maintain one person for a year (Loomis and Connor 1992). The 500 kg grain allows some production to be used as seed for the next crop, some to be fed to animals, and some land to be diverted to fruit and vegetable crops.

The requirement to increase global food production will place a serious limit on land available for conventional feedstock production, but could double the amount of residues available for conversion to biofuel. Further gains in food supply may also allow intermittent contributions from grain surplus.

Sustainable use of residues

The commercial reality of this option depends upon economic viability of cellulosic ethanol production, which has yet to be established. Fermentation plants are currently in early stages of commercial production. Abengoa Bioenergy has a large plant (5 ML y^{-1}) at Salamanca, Spain, and Iogen Corporation has a plant (3.5 ML y^{-1}) in Ottawa, Canada, both for wheat straw. Those and other companies, together with USA DOE, are planning other ventures, including some for maize. Cellulosic ethanol will be able to make a significant contribution only

Table 4.3 World distribution of total land area and the part (P), with percentage, that does not suffer from extreme limitation to rainfed cropping due to low rainfall, poor soils, or steep topography (adapted from FAO-AGL 2003)

Region	Total area	Area w/o severe limitation		Region	Tot. Area	Area w/o severe limition	
	Mha	Mha	%		Mha	Mha	%
North America	2183	371	17	Eastern Africa	640	235	37
Eastern Europe	171	103	60	Middle Africa	657	142	22
Northern Europe	173	37	21	Southern Africa	794	56	8
Southern Europe	132	68	52	Western Africa	633	164	21
Western Europe	110	53	48	Western Asia	433	50	26
Russian Fed	1674	261	16	Southeast Asia	445	172	39
Caribbean	23	8	23	South Asia	672	196	29
Central America	248	64	26	Central Asia	414	32	8
South America	1778	526	30	Japan	37	15	41
Oceania	740	88	12	**World**	**13390**	**2557**	**19**
Polynesia	56	24	42				

if residues are available in sufficient quantities without deleterious effects to environment or elsewhere. These are important questions for agronomists, foresters, and other ecologists.

Availability of biomass is highly site specific because residues from crops and forests are not ‘wastes left to rot’, but fodder for farm animals, as well as a web of consumers and decomposers that play a major role in the maintenance of soil fertility. Residues also protect soils from erosion and maintain the physical structure of soil, thus playing an important role in minimizing contamination of surface waters. Gross removal is impossible without impact. Crops of the highest yield will contribute most. Low yielding crops, such as those grown over wide areas in semi arid zones, are likely to contribute very little because the stubble produced is needed to protect soil and provide fodder for grazing animals. Countries that wish to consider residues and waste biomass options will require regional inventories of resources that can identify areas by level of biomass availability, vulnerability to removal, and cost of transportation.

The U.S. has a county-level biomass database and estimates that agriculture and forestry could supply 786 Mt residues on a sustainable basis (crop 428 Mt and forestry 358 Mt) (Perlack et al. 2005). An associated analysis (Graham et al. 2007) estimates that maize, the most widespread crop, could contribute 100 Mt residues (~55% of the corn stover produced) without irreversible effects, provided no-till production methods were applied. Fertilizers would be needed to amend any resulting loss of nutrients. The U.S. biomass analysis also includes surplus grain (87 Mt), animal wastes (106 Mt), and a proposal for 377 Mt from dedicated energy crops (see below). They estimated 1.3 Gt y^{-1} biomass that could be harvested sustainably is sufficient, at 379 liters ethanol per ton, to replace 30% of national liquid fuel requirement (Perlack et al 2005). However, this is not a net energy gain, as it does not account for the support energy in collection, transport, or processing.

It is difficult to estimate what contribution residues might make to biofuel production in terms of availability and competition from other energy extraction chains. Biomass already contributes around 10% of total world energy use and is the next most important energy source after fossil fuel, which dominates at 80% (FAO 2008a). Large differences in biomass use between countries are important considerations. While it contributes 3–4% of total energy use in developed countries, the corresponding values are higher elsewhere: 25% in Latin America, 34% in Asia, and 60% in Africa (MAPA 2006). Of the 3-4 Gt (52-69 EJ y^{-1}) of crop residues annually produced worldwide, approximately 30% is burnt on the field (Smil 1999). A future scenario of crop production might increase residues by 50%. If 30% of that potential 4.5 Gt residues were available for removal, that would correspond to 10.7 EJ, or 512 GL of ethanol (at 400 L t^{-1}). This is seven times the current world ethanol production of 91 GL y^{-1} from grain crops. Again, however, the net contribution, accounting for support energy, would be smaller in absolute terms and less again, relatively, to a greater fuel demand in 2030.

Two centuries ago, the world ran on biomass but residues can now contribute only a small part to our modern energy-demanding world. Technologies for conversion have yet to be evaluated and the economics of collection of residues and distribution of products are unknown, as are consequences of residue removal. The biological world would be a very different place if all ‘spare’ biomass were returned directly to the atmosphere through exhausts of internal combustion engines and not left as food for a web of consumers and decomposers.

Dedicated energy crops. Concern about diverting food crops to biofuel has placed dedicated energy crops towards the center of the debate about future biofuel options. Many crops are proposed (Table 4.4) and three major types are distinguishable: non-edible oil plants, short rotation trees, and perennial grasses. Justifications for developing special energy crops include less intensive production requirements, use of poorer quality land, and intrinsically greater efficiency of dedicated energy crops relative to food crops. The reasoning behind these motivations, however, does not withstand scrutiny.

The proposal that energy crops can be grown with less intensive production methods on land unsuitable for food crops is largely untrue. To start, there is a major problem with terminology in this part of the debate. The descriptors ‘abandoned’, ‘waste’, and ‘marginal’ land are commonly used without qualification and contribute to confusion. An agronomic assessment of productivity requires a description of topography, soil, climate and the availability of resources that could be applied to improve and sustain productivity. Once assessed, it is inescapable that as demand for food increases, any land that can be made productive will also be sought for food crops. Further, under all circumstances, efficient and continuing production will require substantial inputs of fertilizer, and irrigation if available, to justify effort and investment. Using perennial crops to protect soils in areas that are not currently arable is commendable, though the differentiation between arable and non-arable land has lessened over the past decade due to the introduction no-till production methods.

Dedicated energy crops must always compete with food crops for land, nutrients, and/or water. Unfortunately, attention to the inputs required to show adequate and sustainable productivity are absent from most studies. For example, The Tilman et al. (2006) conclusion that unfertilized, low-input, high-diversity prairie grassland on 'degraded' land produces more net energy than fertilized

Table 4.4 Some crops favored for investigation as dedicated energy crops. Data from EMBRAPA (2006), DOE (2008), and EEA (2007a).

Cellulose Crops		**Non-edible oil crops**	
Short rotation trees and shrubs	Eucalyptus (various) (*Eucalyptus* spp.)	Field Crops	Castor oil (*Ricinus communis*)
	Poplar (*Populus* spp.)		Physic nut (*Jatropha curcas*)
	Willow (*Salix* spp.)		Oil radish (*Raphanus sativus*)
	Birch (*Betula* spp.)		Pongamia (*Pongmia* spp)
Perennial grasses	Giant reed (*Arundo donax*)	Trees and shrubs	Souari Nut (*Caryocar brasilensis*)
	Reed canary grass (*Phalaris arundinacea*)		Buruti palm (*Mauritia flexuosa*)
	Switch grass (*Panicum virgatum*)		Grugri Palm (*Acronomia aculeata*)
	Elephant grass (*Miscanthus* hybrids)		Neem (*Azadirachta indica*)
	Johnson grass (*Sorghum halepense*)		Various native (brazilian spp.)
	Sweet sorghum (*Sorghum bicolor*)		
Aquatic Plants		Various algae	

corn grain ethanol systems while sequestering significant amounts of carbon in soil organic matter is invalid because nutrient losses at the commercial scale are not considered. Tilman et al. (2006) calculate energy yield from samples of aboveground plant biomass taken in August each year. The samples removed less than 3% of standing biomass. The remaining biomass stayed on the field until it was burnt in spring, thus returning most essential nutrients (other than nitrogen and sulfur) to the soil as ash. On the sandy soil in question, these nutrient inputs would represent a substantial proportion of available nutrients. In a real-world biomass system, however, all above-ground biomass, and thus nutrients, would be harvested. It is improbable that the net productivity of the system could be maintain-ed at an industrial scale. The same applies to short-term rotation crops. Yields of trees and shrubs are relatively small on a per year basis (4–8 t ha^{-1}) and the nutrient requirements for continuing productivity are undefined.

Of a wide range of non-edible oil crops, Jatropha (*Jatropha curcas* L.), *Euphorbiaceae*, a perennial frost-sensitive shrub native to N.E. Brazil, is attracting the most attention as a non-food biofuel crop in tropical and subtropical zones. The seed contains 30–35% extractable oil that is suitable as a fuel even before trans-esterification to biodiesel. The plant itself is unpalatable to stock and the seed, oil, and seed meal are toxic to humans. Its main uses to date have been as hedgerow plants in dry regions and for the local production of soap and medicines elsewhere. Currently, it is promoted as a drought-resistant feedstock crop that will yield well on poor soils with low inputs and as crop that can reclaim 'degraded' land. Current expansion of the crop is substantial. Planted area is currently 0.9 Mha in Asia, Africa, and Latin America and is set to increase to 5 Mha by 2010. A further increase to 13 Mha is expected by 2015 (GEXSI 2008); the bulk of the growth is in Asia (65%). Across all regions, jatropha is mostly grown on large plantations, (> 1000 ha). Just 26% of the global crop area is in plantations less than 5 ha.

Available physiological information reveals no special productive capacity or water-use efficiency and provides little data on which to evaluate productivity of the crop (Jongschaap et al. 2007). Large yields have been claimed, including in areas of low rainfall and on 'wasteland' soils (Francis et al. 2005), but plans of major projects are more modest in their assessments (GEXSI 2008). Yields for established (8 y old) plantations in favorable rainfall environments (> 600 mm y^{-1}) and on good soils, some with supplemental irrigation, are expected to range, between 5 to 10 t seed ha^{-1} (i.e. 1.8–3.5 t oil ha^{-1}). Yields in low rainfall environments and on poor soils remain to be established with confidence (Jongschaap et al. 2007).

The projected rapid expansion will likely test the potential of Jatropha in many environments. Where it is successful, there will be pressure for crop improvement and detoxification. Diversity, however, is the key to successful selection and breeding and recent studies revealed small genetic diversity in plant material from Asia and Africa (Jongschaap et al. 2007). Two possibilities for detoxification exist: 1) to breed cultivars without toxic constituents, and 2) to develop techniques to detoxify seed meal. Both small- and large-scale farmers would benefit from co-products of value for animal fodder or human food. Detoxification of crops for agricultural production is a well-established pathway to domestication (e.g. olive, lupin, vetch, and canola).

Algae secrete oils that can be easily scooped from their aquatic environment (Nature 2006a), though published yields may be overstated. Nature (2006b) claims algal annual yields of 12,000 L ha^{-1} biodiesel, twice that achieved consistently by oil palm, but the study does not define the data source. The Higher Education Section of The Australian newspaper (July 23, 2008) reported enthusiastically that a nationally funded bioresearch project was on track to develop a system to provide all Australia's transport fuel needs from 13,000 ha of algal ponds. A simple calculation demonstrates that this is impossible, because it would require the algae to fix more energy than the sun provides. A later admission, but with little publicity, admitted an error and re-estimated the required area at 1.69 Mha assuming a 4% conversion of solar energy to oil. Based on experience with crops, attaining that level of fixed energy would be a challenge. Even if realistic for primary productivity (assimilates from photosynthesis), some of the fixed energy must be used for cell growth and maintenance, as well as oil metabolization. It takes 2.5 units by mass of photosynthetic assimilate to make one unit of oil. The reports contained nothing about support energy or NER.

Biotechnology is promising much and attracting attention and investment (e.g. Nature 2006b, b; EERE-OBP 2008; Carr 2008). Readers of such reports should ignore the phrases 'smart breeding', 'novel crops', 'innovative cropping systems', 'high energy grasses' and look for defensible quantitative results. They should also be aware that the similar promises for major productivity gains in food crops have remained unfulfilled during recent decades. The most valuable contributions from biotechnology have been in manipulations of end products (e.g. oil and starch chemistry) and crop disease and herbicide resistance, which is controlled by one or a few genes. This aspect of genetic crop improvement can help with closing the yield gap. However, there has been no contribution to a greater efficiency of photosynthesis. Evolution has been working on that for millennia. Gains in crop yield have arisen mainly from changing partitioning patterns: less stem and more grain. Biotechnology will likely have success in biological transformation steps from biomass to biofuel, but it is the sustainable production of biomass that will restrict dedicated biofuel crops to a small and contentious role in world energy production.

With the exception of Jatropha projects described earlier, other major proposals that are now forming policy on dedicated energy crops reveal uncertainty. The USDA favors switchgrass as a dominant component of their biomass mix and has identified a range of lines suited to regions within continental USA (EERE-OBP 2008). Reported annual yields are reasonable but not large; 7–16 t ha^{-1} in the southeast, 5–6 t ha^{-1} in the western corn belt and 1–4 t ha^{-1} in N Dakota and again there are insufficient data on nutrient and other management inputs required for sustainable production. In contrast, the European proposal concentrates on re-organization of land use (currently includes 4 Mha energy crops) to make 20 Mha available for dedicated energy crops by 2030 (EEA 2007a). That greater area, together with concentrated effort to improve productivity could, it is proposed, produce 350 Mt biomass. With an additional 148 Mt from forestry (EEA 2007b) that is still well below the 'billion ton vision' for the USA (Perlack et al 2005). In the proposed strategy, reliance on a range of bioengineered dedicated energy crops with predicted annual yield gains of 2.5% for the decade from 2020 contrasts with inclusion of 30% low yield ‘ecologically oriented agriculture’ in the accompanying strategy for food crops. Recent analyses (e.g. Cerdá et al. 2008) emphasize that the expanded European Union (EU25) cannot meet the proposed 10% replacement of liquid fuel by 2020 without substantial importation or establishment of cellulose-based transformation facilities, which are not yet commercialized.

Clearly, designs for optimum biomass energy crops have yet to be formulated and their contribution yet to be established. From this survey, we support a focus of effort on perennial grasses but without emphasis on cellulose production alone. That, we interpret as a misdirected result of avoidance of crops also suitable for food. Perennial grasses will likely best succeed as energy crops when emphasis moves from cellulose production to that plus sugar content. If such analogues of sugarcane can be successful for cool environments, they would be potential food crops also.

Finally, it is important to stress that crop adaptation and breeding is a prolonged process as exemplified by successes with relatively few food crops that feed our world, and the continuing effort required to maintain them. Genetic potential for productivity must be matched with an understanding of water and nutrient requirements, and pests and diseases, as well as development of production systems appropriate for mechanization. Special ‘bioengineered’ energy crops will unlikely appear within the next few decades and more slowly unless clear specifications for ideal energy crops emerge. Concentration on few crops without rejection of existing food crops will increase the chance of success.

Conclusions

1. The use of food crop species to produce biofuels will remain problematic as the world struggles to increase food production to better feed an increasing population that currently includes roughly 1 billion who are severely underfed. Special energy crops are not an effective way to avoid competition with food production, because they too require land, water, nutrients, and other inputs and thus compete with food production. There is no evidence that non-food crops can be grown efficiently for energy production on land that could not also grow crops for food.

2. Greater production of food crops will require significant productivity gains because limited land is available for expansion of agriculture. Concentration of research and development on food production increases the chance to feed the world and provide residues for biofuel production. Development of new crops for biofuels will be a long-term venture and will best succeed if an optimal design can be established to focus research and development on a few options

3. Residues from agriculture and forestry are important potential sources of biofuel. Processes through which this biomaterial will be transformed into fuel are not yet established. Likewise, the amount of residues that could be sustainably utilized is unknown in most cases. Resolving this issue of availability

of residues is an equally important research activity as the development of transformation pathways.

4 Evidence suggests biofuels can make a modest (10%) contribution to national transportation fuel supply in countries with large cropland resources relative to population size. However, few countries will be significant exporters of biofuels. Clearly, biofuels cannot be a major source of transportation fuel in a highly populated and energy demanding world.

Acknowledgements

Drs Ken Cassman, Antonio Hall, Maria Ines Minguez and Ingr. Cristina Touchard offered valued comments on the manuscript.

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