chapter 10

Feedstocks for Biofuels and Bioenergy

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Highlights

- Currently only a few crops supply the bulk of biofuel and bioenergy production globally, however many crops and even as yet undomesticated plants have the potential to become important feedstocks, with major opportunities to offset greenhouse gas (GHG) emissions from the use of fossil fuels.
- It is important that expansion of any existing or newly developed crop for feedstock production does not lead to unacceptable socioeconomic or environmental consequences. However, holding bioenergy feedstocks to higher standards than existing food and forestry crops will delay major opportunities to realize important renewable energy opportunities and mitigation of current GHG emissions.
- Increasing the productivity of current and emerging bioenergy crops per unit land area is not only critical to economic viability, but also to biodiversity by minimizing the total land area needed. Land sparing is found far more effective than land sharing in strategies to realize bioenergy.
- Organic post-consumer waste and residues and by-products from the agricultural and forest industries, which contribute a major part of biomass for energy today, will not suffice to meet the anticipated levels of longer term biomass demand. Thus, much of the bioenergy feedstock will have to come from dedicated production.
- Global demand for wood has been increasing by 1.7% per year. Meeting future demands will require investment in energy tree breeding and enabling policies that tackle the environmental concerns surrounding forest management, new plantings and residue removal.
- Maize ethanol, often portrayed as the villain of the piece in the food versus fuel debate, may in fact have been key in stimulating yield improvement, including through genetically modified (GM) traits, that has resulted in increased exports of grain from the USA while providing a buffer in drought years.
- Of the four largest sources of biofuels: maize, sugarcane (bioethanol), soybean and rapeseed (biodiesel), only sugarcane appears to have a secure future although in the case of maize this will depend on the rate of yield improvement that could be achieved.
- With the exception of oil palm, the yields of biodiesel crops (soybean and rape/canola) are too low to contribute significantly to future energy supply. However,

breakthroughs in engineering accumulation of oil in vegetative tissues may provide an alternative with the potential of developing a sugarcane that accumulates oil in place of sugar.

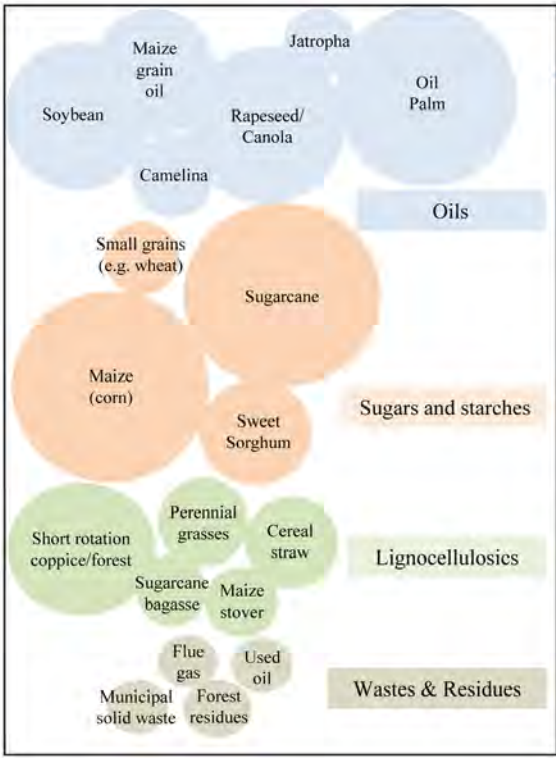
- The claims that large-scale microalgae production will meet future energy needs have not been substantiated and at best, these systems could contribute to high value products or have value when combined with wastewater treatment.
- Using high productivity perennial feedstocks, a substantial contribution to global energy needs, can be made using land unsuited to food crop production. This will require a large expansion of trials on marginal land, and coupled agronomic research and breeding on land unsuited for food crop production, as well as improved definition of land unsuited to food crop production.

Summary

Bioenergy and biofuels are recognized globally as crucial elements of the future energy matrix, without which the reduction in greenhouse gases needed to reduce the acceleration of global warming and climate change will not be achievable. Yet, in 2012 the oil equivalent production of biofuels was less than 2% of the amount of oil produced from geological reserves. The bulk of these biofuels came from two countries; USA and Brazil and from two crops; maize and sugarcane, respectively. Perennial lignocellulosic feedstocks provide an important opportunity to meet further growth in demand in more sustainable ways, compared to maize and other food crops. Similarly, less than 10% of the world energy use for heat and power is bioenergy, most of which is wood-based, although other crop wastes and residues, particularly sugarcane bagasse, are also used. Future supplies will be increasingly from managed (and planted) woodlands and fast-growing energy trees to relieve pressure on existing natural forests. There are many energy crops that are currently grown in low amounts that will be an important part of the future feedstock mix. However, exploitation of these emerging feedstock crops will require investment in breeding and agronomy to further enhance yields and adapt varieties to a wider range of environments, including future climates. Many concerns surrounding biofuels, in particular, relate to feedstock production. However, with improved knowledge of the different crops and where these crops should be grown and with improved varieties and management practices, these concerns can be addressed. By utilizing and developing the full range of feedstocks available, the challenge of increasing feedstock supply in sustainable ways can be met but only with secure, consistent and sensible policies that will achieve both environmental and economic sustainability.

Abbreviations and definition of key terms in the context of this Chapter and derived in part from Karp and Shield (2008): Bioenergy - any form of renewable energy from biological sources; Biomass – biological mass from which energy can be produced, including residues; Bioenergy crops - a generic term embracing crops grown for

heat, power and transport fuels; Biofuel, Biopower, and Biomass Crops –subsets of Bioenergy crops grown for liquid transportation fuels, heat and power, and any renewable use, respectively; Bl - billion liters; C3 photosynthesis – basal form, in which the first product of CO_2 assimilation is a C3 compound; C4 photosynthesis – the first product of CO_2 assimilation in the light is a C4 compound, this avoids photorespiration; CAM photosynthesis – CO_2 is assimilated into C4 acids at night, which are decarboxylated to provide an internal supply of CO_2 to photosynthesis during the day; EJ - 10^{18} J; Feedstocks – specific sources of bioenergy; GHG - greenhouse gases; GJ – 10^9 J; Lignocellulose – a subset of plant biomass that comprises the structural components, primarily the cell wall polymers cellulose, hemicelluloses, lignin and pectins; Mt - million metric dry tons; SRC - short rotation coppicing, SRF - short rotation forestry; t – dry metric tons.



Usage	Technical costs	Development time	Sustainability
Transport Fuels	L	L	L-M
Transport Fuels	L	L	L-H
Heat & Power	L	H	M-H
Transport Fuels	H	H	M-H
Heat & Power	L	L	M-H
Transport Fuels	H	L	M-H

Figure 10.1. Summary diagram of the major crop feedstocks, their uses, technical costs, development time and sustainability. H=high; L=low. Circles are indicative of relative importance of different feedstocks at the present time. For details see Table 10.1.

10.1 Introduction

Biofuel production in 2012 in oil equivalent was 52 Bl , or 2.2 EJ, compared to 3534 Bl, or 118 EJ of oil from geological reserves. The three largest producers of these biofuels were USA, Brazil and Germany at 45%, 23% and 5% of this total, respectively (BP 2013; EIA 2014). Despite the seemingly small amount, just under 2% of oil equivalent for the globe as a whole, biofuels represented almost 10% of the volume of gasoline used in vehicles in the USA and about 40% in Brazil, showing that large-scale displacement is possible within major markets (RFA 2013). While the bulk of production in the USA and Brazil is ethanol from maize and sugarcane respectively, most German production is of biodiesel from rapeseed. Globally, in 2012, ethanol represented 69% of the total and biodiesel 31% (BP 2013), with maize and sugarcane accounting for most ethanol and rapeseed/canola and soybean accounting for most biodiesel.

Biopower is predominantly from wood, which accounted for circa 36.2 EJ of the world energy needs in 2007; ~30EJ from traditional fuel, 3EJ from charcoal and only 1EJ from modern solids (pellets and chips). Proportions of usage and contribution to energy differ greatly between countries and continents (Asikainen et al. 2010). In Africa 90% of total roundwood production was used for biopower, whereas only 21% was used in Europe (Asikainen et al. 2010; see also Chapter 13, this volume). Net global bioenergy trade in wood grew six fold from 56.5 PJ (3.5 Mt) to 300 PJ (18 Mt) between 2000 and 2010 (IEA 2014) and global demand for wood has been increasing by 1.7% annually (Fenning and Gershenzon 2002). Wood pellets are the dominant commodity. Trade streams for wood waste, roundwood and wood chips are smaller and mostly limited to Europe. Europe remains the key region for international solid bioenergy trade, accounting for two thirds of global trade in 2014 (IEA 2014).

Table 10.1 gives the biomass, biofuel and bioenergy yields per hectare of the different feedstocks considered here in major regions of current and potential production. Much attention has been given to use of biodiverse systems for expansion of bioenergy production, with the concept that they could serve both biodiversity and production (Tilman et al. 2006). However, analysis of this land sharing concept finds that because of the large areas required by these less productive systems (Heaton et al. 2008), for most areas of the globe, high productivity monocultures are ironically more effective for biodiversity by sparing land through high productivity (Anderson-Teixeira 2012). For example, mixed-grass prairie would require 6x the land area of an unfertilized Miscanthus system to deliver the same amount of bioenergy (Heaton et al. 2008; Table 10.1). A particular focus of this article is therefore high yielding feedstocks and opportunities to increase production, as well as sustainability.

In this Chapter we examine existing feedstocks for bioenergy including biofuels, and those that may be emerging. The first sections deal with the two current major biofuel feedstocks - maize and sugarcane, followed by emerging perennial grass feedstocks, oil crops, woody feedstocks and algae.

Table 10.1. Overview of amounts of biofuel and bioenergy that could be produced per unit land area, based on current yields of each crop in specific regions.

Feedstock Common and latin binomial name (region of measurement)	Total Dry Biomass Yield (t/ha)	Grain/ seed/sugar yield (t/ha)	Easily accessed biofuel (GJ/ha)	Cellulosic (GJ/ha)	Combustion of residue (GJ/ha)	Sum of previous three columns	Combustion of Total Biomass (GJ/ha)
Annuals							
Maize *Zea mays* (USA)	18.4	9.2	72.8a	40.4	27.6	140.8	331.2
Wheat *Triticum aestivum* (EU28)	8.8	5.3	34.9a	19.4	13.2	67.6	159.0
Rapeseed *Brassica napus* (EU28)	5.6	2.8	33.2b	12.3	8.4	53.9	112.9
Soybean *Glycine max* (USA)	4.7	2.8	21.2b	20.5	5.6	47.3	96.1
Herbaceous perennials							
Sugarcane *Saccharum officinarum* (Brazil)	38.0	12.0	156.8a	167.0	113.9	437.7	684.0
Napier Grass *Pennisetum purpureum* (El Salvador)	84.0	0.0	0.0	738.2	503.5	1241.7	1512.0
Miscanthus *Miscanthus x giganteus* (Illinois)	22.0	0.0	0.0	193.3	131.9	325.2	396.0
Switchgrass *Panicum virgatum* (Illinois)	10.0	0.0	0.0	87.9	59.9	147.8	180.0
Reed Canary Grass *Phalaris arundinaceae* (Denmark)	12.0	0.0	0.0	105.4	71.9	177.3	216.0
Mixed Grass Prairie (Minnesota)	3.7	0.0	0.0	32.5	22.2	54.7	66.6
Agave *Agave americana* (Arizona)	8.0	0.0	33.0a	35.2	24.0	92.1	144.0
Woody perennials							
Oil Palm *Elaeis guineensis* (Indonesia)	34.0	17.0	128.8b	149.4	50.9	329.2	685.4
SRC Willow *Salix* “hybrids” (Sweden)	10.0	0.0	0.0	43.9	30.0	73.9	180.0
SRC Poplar *Populus* “hybrids” (Italy)	14.0	0.0	0.0	61.5	42.0	103.5	252.0
SRF Eucalyptus *Eucalyptus* “hybrids” (Brazil)	18.2	0.0	0.0	80.0	54.5	134.5	327.6

Yields of sugarcane, maize, wheat, rapeseed, soybean and oil palm, are averages for the stated country in 2011 (FAOStat, 2013). Miscanthus and switchgrass yields are averages for 7 unfertilized sites in Illinois over 8-10 years (Arundale et al. 2013a). Mixed grass prairie yields are from Tilman et al. (2006). Napier grass, Reed Carnary Grass and Agave yields are from Beale & Long (1985); Kandel et al. (2013); and Davis et al. (2014), respectively. Yields of SRC and SRF are averages for specific countries of existing commercial trials (from de Wit et al. 2013). It should be noted that yield ranges for all crops are very large and are variety, site and management dependent. It is assumed that 536, 380 and 342 liters of ethanol can be produced from 1 tonne of sucrose, lignocellulose and maize grain, respectively, and that dry sugarcane stem and agave shoot is 33% sugars. The oil contents of rapeseed, soybean and oil palm are assumed to be 36%, 23% and 30%, and that 80% of the lipid can be recovered as biodiesel. Cellulosic fuel is assumed to be manufactured from the cellulosic residue in the case of seed, grain and sugar crops, and from the total biomass in the case of trees and perennial grasses, other than sugarcane. It is then assumed that the residue (lignin) at 30% of the lignocellulose can be combusted to provide heat energy. The final column gives the bioenergy combustion value of the total annual biomass yield for each crop.

10.2 Maize and Other Grains

Currently, maize in the USA provides more than half of all fuel ethanol produced in the world (IEA 2013). In the last few decades maize in the USA has seen a larger increase in yield per hectare than any other major crop (Long and Ort, 2010; FAOSTAT 2013; USDA-NASS 2013; Figure 10.2). Production in 2013 is estimated at 335 Mt compared to 70 Mt in 1953, and yet the total area planted to the crop has changed little (USDA-NASS 2013; Figure 10.2). Although earlier increases in yield corresponded to increased fertilizer rates, particularly nitrogen (N), the average rate of N application to maize in the USA has remained constant at about 140 kg ha^{-1} since 1979 (USDA-ERS 2013), yet average yields per hectare have increased more than 80% over this period. In effect the amount of N used to produce a metric ton of maize grain has declined from 0.75 kg t^{-1} to 0.42 kg t^{-1}. Further, over most of the cornbelt, soybean is rotated with maize, to which no N is typically added, the soybean crop being supported by residual N from the preceding maize crop and its symbiotic relationship with N fixing rhizobia. In effect, this average 140 kg ha^{-1} of N application supports two years of crop production. The continued increase in yields approaching 30% per decade inevitably drove down prices, in real terms; in turn driving down the area planted to maize in the early 1980s (Figure 10.2). Beginning at this time, ethanol production as a petroleum oxygenate was incentivized with a blenders' credit in the USA. This also served as a means to give price support to maize by removing some of the surplus production relative to demand (Ferris 2013). Over the past two decades ethanol production has consumed a significant portion, but not all, of the continued increase in yield achieved by US farmers (Figures 10.2 and 10.3).

Today the world produces more maize than any other grain or seed. Of the global 880 Mt of production, the USA accounts for just over 40%, but grown on just 20% of the land planted to this crop globally (FAOSTAT 2013; USDA-NASS 2013). US production of maize grain from 2006-10 averaged 311 Mt yr^{-1}, of which 94 Mt yr^{-1} was used for ethanol production and 54 $Mtyr^{-1}$ exported (Figure 10.3). This compares to 207 Mt yr^{-1}, 11 Mt yr^{-1} and 45 Mt yr^{-1}, respectively in the first half of the 1990s (calculated from: USDA-NASS 2013; USDA-ERS 2013). In addition, 26 Mt yr^{-1} of dried distillers grains (DDGS) were produced on average between 2006 and 2010, compared to just 2 Mt yr^{-1} between 1990 and 1994 (USDA-ERS 2013). So while ethanol production now accounts for a large proportion of the total US maize crop, it has not prevented a 20% increase in exports and a 24% increase in use by all other domestic uses. Indeed the increase in exports of 8 Mt yr^{-1} over this period accounts for most of the 10 Mt yr^{-1} net increase of total US exports of primary foodstuffs, making the USA by far the largest net exporter of all primary foodstuffs at almost 110 Mt yr^{-1} (FAOSTAT 2013). Over the same period the EU28's deficit has almost doubled resulting in it becoming a net importer of over 20 Mt yr^{-1} (FAOSTAT 2013). These facts have to bring into question the media blame that has been placed on US maize ethanol production as the cause of increased global costs of primary foodstuffs (RFA 2013). Indeed, maize ethanol may have acted as a buffer to grain prices during the severe drought across the corn-belt in 2012 which lowered production by 40 Mt compared to 2011 (USDA-NASS 2013). Substantially less maize was used for domestic ethanol production following the drought with many

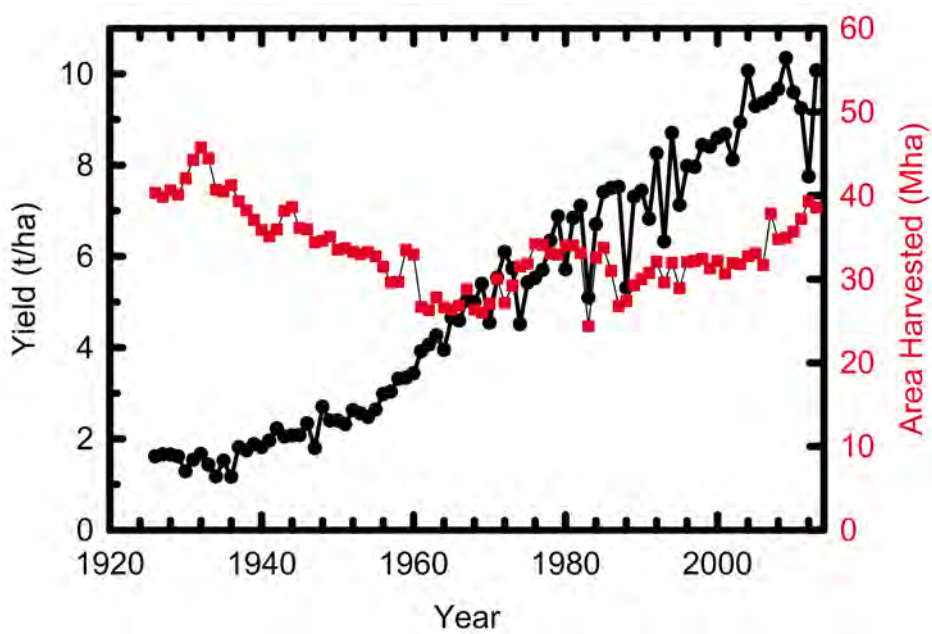


Figure 10.2. Historical progression of the yield of maize grain per unit land area in the USA and the area of the country committed to the crop. Data source: USDA-NASS (2013).

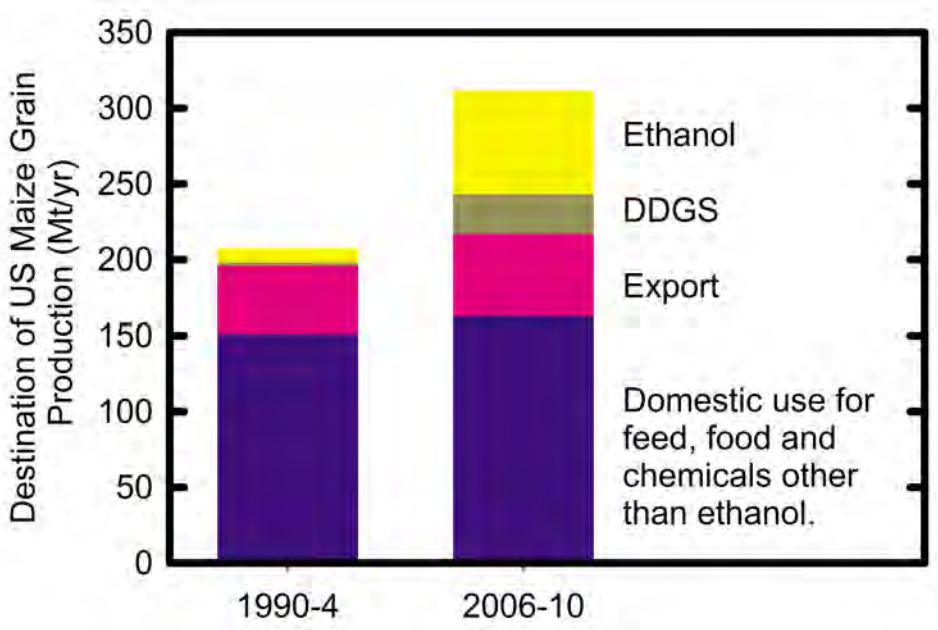


Figure 10.3. Destination of US maize grain production averaged over two 5-year periods. DDGS represents part of the grain diverted to ethanol production, but is shown to illustrate the amount returned to the feed market. Calculated from USDA-ERS (2013).

ethanol plants mothballed (EIA 2014). Indeed economic analysis has suggested that for producer countries with significant animal feeding or biofuels industries, options to protect the consumption of the most vulnerable globally from droughts and other harvest shocks are more cost-effective than emergency reserves. That is, maize ethanol can be seen as providing a reserve (Wright 2011). In the event of a shortfall, it would require some relaxation of national blending requirements for this buffer to be effective. This suggests that maize ethanol might be viewed as a partial reserve of grain, which during periods of shortage can be diverted away from ethanol production while use for ethanol production during periods of surplus would provide a floor on price that would continue to incentivize the agricultural production system to continue to grow and improve the crop (Wright 2011).

What underlies the continued increase in maize yields per unit land area, and can this be expected to continue? Maize seed supplied to farmers is almost all hybrid seed. This differs from wheat, rice and soybean, the crops which rank 2nd through 4th in the world after maize (FAOSTAT 2013). Unlike these other crops, seed of maize cannot be saved by the farmer and used the next year, as the progeny will vary widely, with the yield advantage of the original seed largely lost. Therefore new seed must be purchased annually, giving the seed supplier/developer greatly increased incentive to focus on the crop. Maize, unlike the other major seed and grain crops uses C4 photosynthesis giving

it a higher theoretical maximum efficiency of conversion of sunlight into biomass, as well as a higher efficiency of water and nitrogen use (Zhu et al. 2010; Long and Spence 2013). Maize breeders have also effectively altered plant architecture to maintain per plant productivity while increasing planting densities (Duvick 2005; Lobell et al. 2014). In the US, maize is now available with more biotechnology (GM) traits than any other crop. The proportion of the US crop with at least one *Bacillus thuringiensis* gene expressing an insecticidal protein (Bt) has risen from 2% in 1996 to 76% in 2013 while the amount carrying at least one transgenic herbicide tolerance (HT) gene has risen from 2% to 85% over the same period (USDA-ERS, 2013). This has greatly decreased losses to the European corn borer (Hutchison et al. 2010), maize rootworms, and also to weed competition compared to non-transgenic crops (Nolan and Santos 2012). The Bt insect resistance traits decrease damage to leaves, stems and roots, making the crop more drought tolerant. This is evident late in the growing season as crop moisture levels are significantly higher (Traore et al. 2000). Conventional breeding will also have increased yield over this period. So how much, if any, of the increase is due to the introduction of GM traits? A recent analysis of 164,000 trials showed that GM caused a statistically significant increase in yield over this period accounting for 29% - 33% of the total increase over the past decade (Nolan and Santos 2012). The recent release of additional Bt and HT traits suggest an accelerating rate of addition of transgenes to farmers' options. The first physiological trait, Droughtgard™, was tested by 250 growers on the Western Plains in 2012 and was reported to result in a 0.3 tha^{-1} improvement over untransformed material (Monsanto 2013). This transgene codes for a bacterial cold tolerance protein that allows continued growth in plants under mild water stress. It provides one of many potential examples of how yield tolerance to stresses may be improved. The year-on-year increases in maize yields per hectare in the USA have depended on a series of technological innovations from the Haber-Bosch process for production of nitrogen fertilizers and large-scale production of uniform hybrid seed to molecular marker assisted breeding and production of GM lines, in concert with agronomic adaptation and improvement. The completion of the maize genome, its functional annotation, the rapid growth in capacity for deep sequencing of transcriptomes, and resequencing of multiple genotypes are all factors opening the way for further technical innovation both in conventional breeding and GM traits. Inevitably, resistance in pests and weeds to GM traits will emerge. Continued value in, and acceleration of, the contribution of GM will depend on the emergence of policies that recognize the safety of these products, and decrease the current prohibitive costs and administrative hurdles involved in taking new GM products to market.

The average annual increase in maize yield in the USA between 1983 and 2013 was 0.17 t $ha^{-1}yr^{-1}$, i.e. the average slope of the line over this period, as shown in Figure10.2. From the above, we may expect that further breeding with addition of improved traits and improved agronomy will continue to increase yields at this rate for some time into the future. If we assume that the area of the USA devoted to this crop stays constant at the 2013 level of 38.6 Mha (million hectares), then total production would rise from 355 Mt in 2013 to 457 Mt by 2030. This additional 102 Mt (ca. 29%) could support a doubling of

the amount of maize used for ethanol and DDGS production, while still allowing further increases in exports and in other domestic uses. This would also mean that the US goal for 2030 of replacing 30% of the volume of transportation fuel that it used in 2007, with ethanol, could be achieved from maize grain alone without diminishing exports and supply to other domestic uses. While yield has been continually increased, water use efficiency has not. Assuming current patterns of rainfall into the future, water availability might be expected to cap further increases around the middle of this century (Ort and Long 2014). Further gains in ethanol production could be achieved by alteration of grain composition. High starch, low protein and low oil germplasm are available that could be used to develop cultivars that would yield more ethanol per metric ton of grain and also demand less nitrogen in growth (Moose et al. 2004). However, yield of DDGS and maize oil would be lower and the opportunity to sell grain into other markets may be affected. Maize offers two further renewable fuel opportunities. First, maize grain contains oil in the form of triacylglycerols (TAGs) that may be converted to biodiesel (EIA 2014). Industrial plants with wet grind facilities separate out the oil prior to digestion of the starch, while at those with dry grind facilities, the oil may be separated out by centrifugation of the thin stillage on completion of fermentation. As it is a by-product that requires little additional energy to extract, the resulting fuel qualifies as low carbon, which has incentivized retrofitting many ethanol plants for oil extraction (Cantrell and Winsness 2009; EIA 2014). Secondly, the stover, i.e. stripped cobs, stems and any remaining leaves from the maize crop may provide a ready feedstock for production of cellulosic ethanol or other fuels. The first commercial production of cellulosic ethanol from maize stover was expected to begin operation in Iowa in 2013 (Biofuels Digest 2013). By contrast to wheat and rice, the harvest index of maize has remained at about 50% since the 1950s (Lorenz et al. 2010). Therefore future increases in grain yield might also continue to be accompanied by similar increases in the availability of stover. Stover is however a valuable source of organic matter for maintaining soil structure and fertility. It was estimated that soil quality could be maintained if 50% of the stover were removed (Wilhelm et al. 2004). Since the effect on fertility will depend on the absolute amount of stover, the proportion that needs to remain could arguably become progressively less as yield rises. However, if we assume a fixed removal of 50%, then by 2030 this would amount to 228 Mt, and at an estimated 380 liters of ethanol that could be produced from the cellulose and hemicellulose in a dry metric ton of biomass, this would provide an additional 86.6 Bls of ethanol. There are two further advantages of maize in the context of cellulosic fuels. First, harvest equipment could be modified to collect stover or a portion of the stover at the time of grain harvest (Shinners et al. 2012), the single operation minimizing the additional energy required for collection. Secondly, the depth of knowledge of gene function is likely to facilitate cell wall modifications to improve saccharification faster than in any other crop. Indeed, non-GM and GM modifications have already been identified to support increased efficiency of enzymic saccharification (Park et al. 2012; Pauly et al. 2012; Torres et al. 2014).

Some 150 years of cultivation of the rich cornbelt soils is suggested to have resulted in the loss of about 50% of the carbon in the top 15 cm of soil (Nafziger and Dunker

2011). Various measures were introduced to arrest or slow this decline. These include no-till and minimal till cultivation, contour ploughing and removal of the most vulnerable lands from production as conservation reserve (USDA-NRCS 2013). Because soil C is distributed in a spatially highly heterogeneous manner and the C-content of most corn-belt soils is relatively high, detecting a statistically significant change due to management is challenging. Indeed failure to detect significant effects led to questioning of the value of no-till and minimal till cultivation for maintenance of soil C (Wander et al. 1998; Puget and Lal 2005). The development of eddy-covariance techniques, that combine 3-D air velocity with open-path infra-red gas analyzers, now allow monitoring of net carbon exchange between a crop field and the atmosphere for every second of every day. The ability to average over a large area circumvents the problems of small-scale heterogeneity in soil C content. Using this method and correcting for the carbon removed in the harvest, Bernacchi et al. (2005) showed that in side-by-side tilled and non-tilled fields of the same maize cultivar there was a net accumulation of 1.6 t C $ha^{-1}yr^{-1}$ under no-till while the tilled field showed a net loss of 0.2 t C $ha^{-1}yr^{-1}$ to the atmosphere. Assuming that the large productivity gains in maize also result in more root biomass, even with partial stover removal, carbon gain by the soil may be expected to increase substantially. Further, just as genetic traits have been exploited to develop stem biomass that is more easily digested to release sugars for fermentation, so it is feasible that the depth of knowledge of genetics in maize could allow the development of germplasm with less easily degraded biomass. By use of root specific promoters it is feasible that root biomass could be made less easily degraded to favor accumulation of C in the soil.

The long-term economic viability of using maize for ethanol is uncertain. Increasing global population and changes in diets are demanding more maize, mostly for animal feed. From these trends, Ray et al. (2013) predict that the world will require 1700 Mt yr^{-1} by 2050. Even if historical rates of maize yield improvement are maintained throughout the intervening 36 years, global supply will only rise to 1451 Mt yr^{-1} giving a major shortfall relative to demand. By contrast increased production of oil and natural gas in the USA could lead to a slower or zero rate of increase in the cost of liquid transportation fuels (McElroy and Lu 2013). This could make use of maize grain for ethanol progressively less profitable relative to sales into other markets. If however, the goal turns increasingly to decreasing the carbon footprint of transportation fuels, rather than fuel security, maize grain is less attractive than other biofuel feedstocks because of its much smaller carbon benefit relative to perennial feedstocks, including sugarcane. A recent and highly detailed well-to-wheels analysis of life cycle greenhouse gas (GHG) emissions concluded that relative to the use of petroleum, ethanol from maize grain, sugarcane, maize stover, switchgrass and Miscanthus would reduce emissions on average by 34%, 51%, 97%, 87% and 108%, respectively (Wang et al. 2012). Although maize gives the smallest advantage among these, this 2013 estimate is a significant improvement over a 2006 estimation that it was roughly equal to the use of petroleum (Farrell et al. 2006). Inevitably at the scale of maize ethanol production, learning by doing is progressively decreasing carbon losses from well-to-wheels. Further gains will come from increased productivity

per unit land area, increases in nitrogen use efficiency through both precision agriculture and improved genetics, and utilization of the oil from the grain in addition to starch for fuel. Much larger gains will be achieved if stover, or a part of it, is used for the production of cellulosic fuels. Gains could also come from using bioenergy to provide heat and power to the processing plant, in place of fossil fuels.

Of course any source of starch or sugars can be used for fermentation to ethanol and other fuels, and alcoholic beverages have been made from almost every species of grain, fruit and root crop. Excluding sugarcane ethanol, maize accounts for more than 95% of fuel ethanol production today, most within the USA (EIA 2014). Wheat is being used increasingly for fuel ethanol in the EU28, with significant new capacity in the UK (Jessen 2013). This appears to have less long-term economic viability than maize, however. While large increases in maize yield per unit land area are being achieved globally, wheat yield improvement has stagnated with no increase in yield per hectare over the past decade (Long and Ort 2010, Ray et al. 2012). Even if it is assumed that the historical rates of improvement seen in the Green Revolution years are regained, wheat global supply will fall more than 20% short of forecast global demand by 2050. Indeed, even today, the difficulty of meeting food and feed demand for wheat has caused a doubling of price over the past 7 years and accounts for the growing price separation between maize and wheat, with the latter approaching double the cost while yielding half the ethanol per unit land area (Balat and Balat, 2009; USDA-FAS 2013). As with all crops, account must be taken of co-products, in particular the protein rich feeds provided by the DDGS. This is particularly important as yields of DDGS per hectare from these sources approach yields obtained from soybean as, currently, the most common protein source used in animal feeds. Various root crops have also been explored as sources of starch for ethanol production, in particular cassava. Substantial cassava to ethanol programs have been established, for example in China and Thailand (Dai et al. 2006; Nguyen et al. 2007). Given that cassava is also among the most important sources of calories for some of the world's poorest communities great care would need to be taken with this crop to avoid affecting food supply to some of the most vulnerable, while recognizing that this would be a highly location specific issue (Naylor et al. 2007).

10.3 Sugarcane

Sugarcane is a major crop grown in the tropical and subtropical regions of the world, producing 550Mt dry biomass in 2012,, assuming 70% moisture in reported yields (FAOSTAT 2013; De Souza et al. 2014). Sugarcane is produced for its sucrose, which may be used as a sweetener, a feedstock for various chemical syntheses or for fermentation in the production of alcoholic beverages or fuel bioethanol (Amorim et al. 2011). Bagasse, the lignocellulosic residue produced after sucrose extraction, is combusted to provide electricity that is used to power sugarcane mills and bioethanol production, with the excess being sold on the electricity grid. Brazil accounted for 39% of the world's harvest of sugarcane in 2012. Brazil's sugarcane production has increased

more than 10-fold in 50 years and doubled in the last 10 years (FAOSTAT 2013 Figure 10.4). Although most yield increase is accounted for by expansion of the planted area, yield per ha has also doubled over the last 50 years (Figure 10.4). Over a similar period unit production costs of sugarcane ethanol, in real terms, have declined 67%, most driven by technological improvements in the overall process (Chen et al. 2014).

Sugarcane has a well-established agricultural production system and processing infrastructure to make it among the most advanced feedstocks for bioenergy. More importantly, it has a positive net energy balance across a range of production systems and environments and releases considerably less CO_2 than petroleum when used to produce transportation fuel (Wang et al. 2012). With the emergence of second generation (2G) bioenergy platforms to convert lignocellulose to liquid fuels, the energy output from, and GHG benefit of, sugarcane could increase significantly (De Souza et al. 2013a).

Brazil is considered to have developed the world's first sustainable biofuels economy and in many respects is the biofuels industry leader (De Souza et al. 2014). This reputation is based largely on its sugarcane industry. The main reason for Brazil's success in biofuels has been synergy between the global sugar market, electricity production, governmental support, and geography (Nass et al. 2007). Brazil's resources are sufficiently abundant to support massive agriculture, including both a large biofuel industry and traditional agricultural production of food, fiber and feed while still fostering conservation of biodiversity. Biodiversity can be preserved while maintaining sugarcane production in regions where it is most abundant when appropriate strategies are employed (Buckeridge et al. 2012).

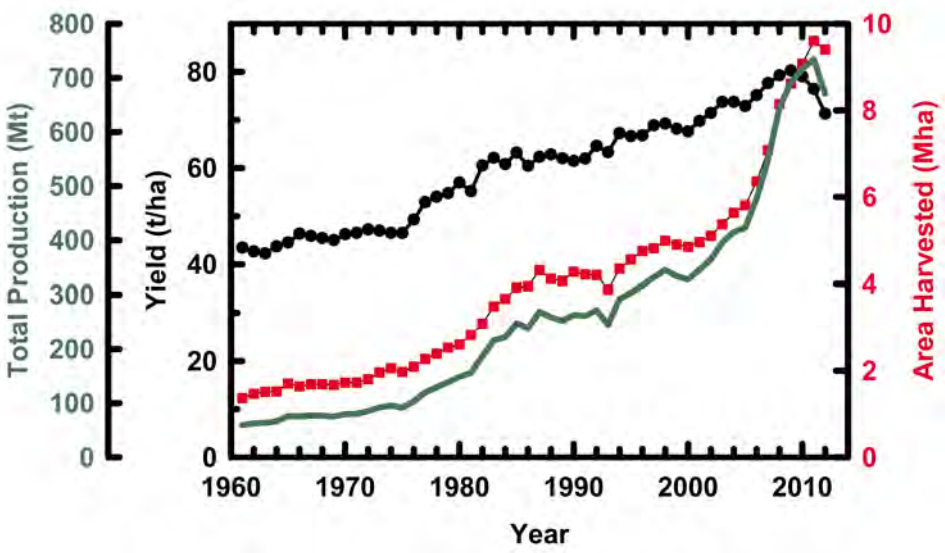


Figure 10.4. Historical progression of the sugarcane yield per hectare, total area harvested and total production in Brazil. Data source: FAOSTAT (2013).

The ability of Brazil's sugarcane industry to support demands for both sweetener and bioenergy gives flexibility in the market place and has reached the stage where, depending on the price of petroleum, approximately half of Brazil's sugarcane crop goes into sugar and half into bioethanol for bioenergy (Amorin et al. 2011; De Souza et al. 2014). When the price of petroleum is high, more of the sugarcane crop is processed to bioethanol as a substitute for petroleum, and vice-versa. This market situation can result in less sugarcane being processed to sugar with the consequence that the world price of sugar rises; the converse is also true. Thus the percentage of the sugarcane crop going to sugar or bioethanol is in constant flux. While some of Brazil's bioethanol is exported, approximately 85% remains in Brazil, 90% of which is used for transportation fuel and the remaining 10% for industrial uses (Nass et al. 2007).

Today, there is an increasing awareness that sugarcane can be used for many applications, not only as a biomass feedstock for energy production but also for bioprocessing in a biorefinery to a wide range of chemicals including a variety of polymers. Life cycle analyses indicate that sugarcane would be highly competitive with other crops as a preferred feedstock for a biomass-based industry (Tilman et al. 2006; Renouf et al. 2008).

Taking account the need to protect the Amazon, conservation of biodiversity and avoid conflict with food production, the Brazilian Government has mapped 63.5 Mha suitable for sugarcane production. This would not require the clearance of natural ecosystems, but would require significant expansion onto pasturelands, largely Cerrado, with low stocking density. This would need to be compensated by improving the remaining pasture to support an increase in the number of heads per hectare. This land area could allow the production of 800 Bl of ethanol by 2030, which in energy terms would be equivalent to 15% of total global liquid fuel use in 2009, while the bagasse could provide 30 GW of electricity (Somerville et al. 2010). This expansion of sugarcane production is likely to be incentivized by the long-term rise in petroleum prices and by climate change driving a demand for biofuels with low net GHG emissions. However, it will require development of new varieties capable of production under marginal, warmer and drier environments, as well as substantially different soils. Maintaining yield in these new areas will be important to minimize land demand. Brazil has been a leader in the development of genomic tools for both the development of molecular tools to support breeding of improved cultivars, as well as genetic engineering of sugarcane, to aid varietal improvement for this expansion (Hotta et al. 2010). A recent analysis adds further value to this expansion. Whereas the conventional practice of residue burning would have depleted carbon in these Cerrado soils, the modern practices in Brazil using mechanical harvesting are predicted to result in soil carbon at or above those in native Cerrado (Brandani et al. 2014). Another important limiting factor to sugarcane expansion could be global climate change. Although sugarcane is expected to respond positively to the increase in atmospheric CO_2 (De Souza et al. 2008), the uncertainty of precipitation forecasts made from climatic models could inhibit some expansion into new areas.

Approximately one-third of the total energy in the above-ground biomass of today's sugarcane cultivars is captured in the sucrose fraction present in the stalk while another third is present in the bagasse and the last third is in field trash which with mechanical harvesting of unburnt cane is left in the field (Table 10.1; Buckeridge et al. 2012; Leal et al. 2013). While this trash can form a mulch and recycle nutrients - it may also inhibit early season growth in the cooler part of the growing region and can harbor diseases. Much recent research has investigated how much trash should be removed, and by what means. Leaving stem tops on the field, returns most of the nutrients to the soil, while removing lower leaves as trash provides a large harvest of additional biomass (Cantarella et al. 2013; Cardoso et al. 2013; Fortes et al. 2013; Franco et al. 2013). The calculated average energy content of the total above-ground biomass of current Brazil sugarcane is 7,400 MJ t^{-1} of cane, Therefore, an average crop of around 38 t ha^{-1} yr^{-1} could deliver >600 GJ ha^{-1} yr^{-1} (Table 10.1; Leal et al. 2013).

If increasing energy output of sugarcane is the primary goal, one needs to increase the crop's lignocellulosic fraction and more fully utilize its higher energy density compared to its sugar fraction. Using conventional breeding to increase the energy content of new sugarcane varieties has been projected to potentially increase Brazil's sugarcane bioenergy yield to 1228 GJ ha^{-1} yr^{-1} over the next 20 years (Landell et al. 2010; Table 10.2). Current advances in bolting on 2nd generation technology to Brazil's existing bioethanol plants may enable this goal even sooner. Realizing this potential will also require more investment in understanding interactive effects of genotype and environment on production and quality (Sabatier et al. 2014).

Table 10.2. Projected yield and sustainability components for energycane improvement. From Landell et al. (2010).

Energycane component	Year		
	2010	2020	2030
Culm (fw t ha^{-1})	81	111	130
Trash (dw t ha^{-1})	14	19	24
Sugar (%)	15	13	12
Fiber (%)	12	18	23
Total Energy (GJ ha^{-1})	628	940	1228
Output/input energy	8	12	14
Environmental impact	High	Med.	Low

Is there opportunity to replicate Brazil's production of sugarcane elsewhere? While the area of sugarcane and its productivity have risen sharply in Brazil, this has not been seen elsewhere. Most notably the Caribbean produced more sugarcane than Brazil in 1971; 82 Mt on 1.8 Mha, compared to 24 Mt on 0.7 Mha today. Most of the land abandoned from sugarcane has dropped out of agricultural use (FAOSTAT 2013).

Bringing this land back into production could allow significant bioethanol without any impact on food production. Many other areas of the globe would be suited to replicate Brazil's success in developing an environmentally and economically sustainable sugarcane bioethanol industry. The key will be identifying abandoned or under-utilized land resources where this model could be replicated without damaging local food supply or other ecosystem services.

10.4 Perennial Grasses

Perennial grasses, including sugarcane, offer many advantages over the use of annual food crops for bioenergy, including liquid fuels. Their perennial nature avoids the need for annual cultivation and their rhizome and root systems bind the soil and add carbon to the soil, as shown by the fact that soils under perennial grasslands contain more carbon than those under forests (Guo and Gifford 2002). Perenniality also allows them to cover the ground for a longer period than annual crops, allowing greater capture of the available solar radiation. Many perennial grasses use C4 photosynthesis, which in a given environment provides a higher potential efficiency of light, water and nitrogen in carbon capture (Long and Spence 2013). Perennial C4 grasses include the most productive plant species yet known - *Echinochloa polystachya*, which on the Amazon floodplain was shown to yield 100 t $ha^{-1}yr^{-1}$ (Piedade et al. 1991). Within the wet tropics and subtropics, sugarcane is already a major bioenergy feedstock and Napier grass (*Pennisetum purpureum*) is a highly productive grass used for forage, currently being actively evaluated for bioenergy (e.g. Rengsiriku et al. 2011). Forage stands in El Salvador have been shown to yield 84 t $ha^{-1}yr^{-1}$ (Beadle and Long 1985). However, because these crops grow year-round, they must be harvested green, and so as in annual crops, the harvest will include their nutrients, in contrast to autumn and winter harvested crops of perennial temperate grasses such as switchgrass and Miscanthus. These tropical crops will therefore require large fertilizer inputs to maintain their productivity. Their large and perennial root systems though make them considerably more efficient in nutrient capture than annual crops, and by binding the soil they are suitable for areas that might be eroded in annual cultivation. In regions that may be too cold for effective production of any current C4 grass cultivar, the C3 perennial reed canary grass can produce quite high yields for use in various bioenergy projects (Table 10.1; Kandel et al. 2013).

In areas of the globe where production is seasonally limited by cold or drought, perennial grasses that dieback during this period provide a second advantage. As winter or the dry-season approach, these plants mobilize their nutrients from the senescing annual leaves and stems and transfer them to their perennial root and rhizome system (Heaton et al. 2009; De Souza et al. 2013b). If the dry dead shoots are harvested as a bioenergy feedstock the bulk of the nutrient reserves of the plant remain in the perennial underground organs and soil, making these potential feedstocks particularly sustainable. Plants using this strategy in temperate and cold climates that are being

considered as bioenergy sources or utilized commercially on a small scale include: Miscanthus (*Miscanthus x giganteus*), Switchgrass (*Panicum virgatum*), Cord-grasses (*Spartina pectinata* and *S. cynosuroides*), Giant Reed (*Arundo donax*) and Reed Canary Grass (*Phalaris arundinacea*). The first three of these are C4, and include some of the most cold-tolerant C4 plants known and the second two are C3 (Long and Spence, 2013). To date, there is very limited commercial experience with these crops, however experimental trials and limited commercial production suggest considerable promise.

Of these, there has probably been more experience with switchgrass than any other, and to the extent that there are well established breeding programs. These have resulted in increased yield potential and regionally adapted cultivars (Casler et al. 2004; Parrish and Fike, 2005; Schmer et al. 2008). *Miscanthus x giganteus* is a sterile hybrid, and most trials and commercial deployment appear to be with a single clone, termed the "Illinois" clone in the USA (USDA-NRCS 2011). Despite this name, the clone probably originated from a single plant collected in Honshu, Japan and transferred initially to Denmark, from where it was distributed to various botanical gardens in Europe and the USA (Hodkinson and Renvoize 2001). Until recently, most experience of this clone was within the EU, where it proved more productive than most potential bioenergy crops from southern England and Denmark southward (Jones and Walsh 2001). Early trials in SE England showed a peak biomass of 30 t ha^{-1} and a harvestable biomass of 20 t ha^{-1}, with a substantial addition of root and rhizome mass below ground (Beale and Long 1995). Grown over fifteen years in Rothamsted in SE England and 20 years in Foulum in Denmark the crop showed no significant response to addition of N fertilizer, confirming the anticipated sustainability of its growth habit coupled with C4 photosynthesis (Christian et al. 2008; Larsen et al. 2014). The first replicated trials of this clone in the USA, conducted in Illinois, showed even higher yields averaging over 38 t $ha^{-1}yr^{-1}$ 3-5 years after planting and although the shoots contained 400 kg[N] ha^{-1} during active growth, 90% of this had been translocated or leached from the biomass at the time of harvest (Heaton et al. 2008; 2009; Dohleman et al. 2012). However, after 8-10 years yields declined to an apparent plateau level of 22 t $ha^{-1}yr^{-1}$ (Arundale et al. 2013a). This pattern of a peak around year 5 after planting followed by a ca. 40% decline to a plateau level has also been observed in long-term trials in the EU (Larsen et al. 2014). This decline is observed even when the effects of inter-annual variation in weather are removed. The basis of this decline, which parallels ratoon decline in its close relative sugarcane, is unclear but can only be partially overcome with fertilization (Arundale et al. 2013b). Occasional disking to break-up the rhizome mat and overcome soil compaction has been shown to reverse this decline (Jorgensen, pers. comm.). Even at the lower yield of 22 t $ha^{-1}yr^{-1}$ and assuming that 380 l of ethanol may be produced from 1 t of dry biomass, the Renewable Fuel Standard mandate of the USA of 60 Bl by 2022 could be met on 6.8 Mha. This represents, just under 0.7% of the total land surface area of the 48 contiguous States. Particularly important in these long-term studies was the finding that yields were similar on land classified as having poor capability for crop production, as well as on good sites (Arundale et al. 2013a,b). This is important evidence supporting the contention that such perennial energy crops could

minimize or avoid competition for land with food production (Valentine et al. 2012). Miguez et al. (2009, 2012) developed a mechanistic model of Miscanthus production from the BioCro platform, which was successfully validated against extensive EU trials. BioCro predicted yields achieved in Illinois very effectively. It predicted that high rain-fed yields (>24 t ha^{-1}) could be achieved over large areas of the eastern USA that are currently not used for crop production (Figure 10.5).

In Illinois a similar pattern of long-term yield decline was observed in switchgrass, but this could be fully restored by adding N fertilizer. A meta-analysis (Heaton et al. 2004) and a modeling analysis (Miguez et al. 2012) using yields of regionally adapted switchgrasses suggest that *M. x giganteus* would substantially out-yield this crop at most locations (Figure 10.5). Throughout side-by-side trials at seven sites on contrasting soils across Illinois, *M. x giganteus* proved at least twice as productive as the locally adapted switchgrass cultivar "Cave-in-Rock" (Heaton et al. 2008; Arundale et al. 2013a). Maize achieves some of its highest yields globally in central Illinois, yet, in side-by-side trials, *M. x giganteus* produced 60% more biomass, without addition of N-fertilizer. This increase is due to the fact that *M. x giganteus* produces functional leaves earlier in the year and maintains them later into the year, allowing it to capture 60% more solar energy which it converts into biomass at the same efficiency rate as maize (Dohleman and Long 2009). This results from an unusual capacity among C4 species, not shared by maize or sugarcane, to form an efficient photosynthetic apparatus and maintain it at chilling temperatures, i.e. temperatures above freezing but below 15 °C (Long and Spence 2013; Spence et al. 2014). A disadvantage of *M. x giganteus* is that as a sterile hybrid there is no seed, and fields must be planted with

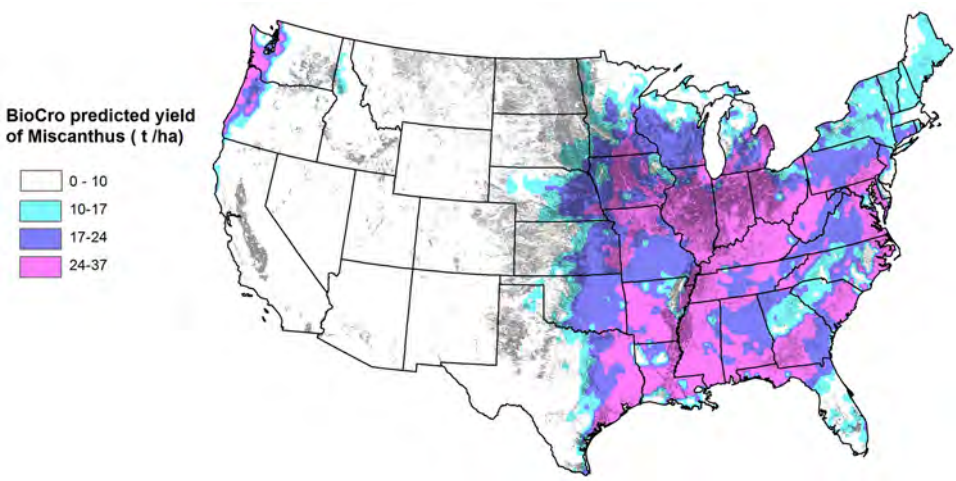


Figure 10.5. Annual average non-irrigated dry biomass yields predicted from gridded soil and daily weather data over from 1978-2010 for mature stands (fourth year) of *Miscanthus* × *giganteus* "Illinois" clone. Grey spots indicate fields currently used for production of other crops. Adapted from Miguez et al. (2012) and USDA-NASS (2013).

rhizomes or stem sections. However, this is not an insurmountable barrier given that the world's 26 Mha of sugarcane are planted in a similar way. Many years of experience in gardens and long-term trials in Europe, and now Illinois, have shown no evidence of this hybrid becoming invasive, which is not perhaps surprising for a sterile and self-incompatible plant with rhizomes that spread very little. In this respect its sterility is an advantage over fertile forms of Miscanthus and many other perennial grasses. However, one highly productive clone is clearly sub-optimal for all environments, and although no epidemics have been observed it is clearly a vulnerability that will increase as plantings increase. If it is to emerge as a major crop, creating more sterile clones from crosses of the parent species to increase the genetic and adaptive diversity of *M. x giganteus* will be critical. This will be aided by the rapid emergence of genomic tools for the parent species, and improved understanding of genomic variation across their native ranges in E. Asia (Gifford et al. 2014; Clark et al. 2014).

Cord grasses, *Spartina cynosuroides* and *S. pectinata* are C4 rhizomatous perennial grasses that are native to the N. American prairie, and like *M. x giganteus* can show a strong chilling tolerance of their photosynthetic apparatus (Long and Spence 2013). These species have proved productive in trials in the EU (Potter et al. 1995), the Dakotas and Illinois (Lee et al. 2011). Commercial seed of one cultivar is available and new productive cultivars are being identified (Voigt et al. 2013). One genotype originating from Illinois has proved particularly productive with yields similar to those of *M. x giganteus* (Voigt et al. 2013). These cord-grasses have two attributes that would allow them to use land unsuited to switchgrasses and *M. x giganteus.* They can withstand and grow under long periods of flooding or even permanent waterlogging. As a result of salt glands in their leaves they can also survive and grow well on saline soils. This would allow re-use of land that has been lost from agricultural use by salination (Boe et al. 2009).

Two C3 perennial grasses are also being trialled and used as bionenergy sources. Reed canary grass is productive in climates too cold for the effective cultivation of *M. x giganteus* and switchgrass (Lewandowski et al. 2003; Sahramaa et al. 2003; Casler et al. 2009; Table 10.1). It is not competitive with these species in warmer climates. However, a second C3 perennial grass, giant reed (*Arundo donax*) is native to the Mediterranean and given adequate water and nitrogen can be very productive in the warm temperate zone, apparently producing up to 74 t $ha^{-1}yr^{-1}$ (Borin et al. 2013). Experience with this species as a bioenergy crop is limited. It has proved invasive in California, where it was introduced, due to its fertile wind-blown seed (Goolsby and Moran 2009). Its high productivity may result in part from an unusually high stomatal conductance, which allows a high concentration of CO_2 within the leaf, which will decrease photorespiration, but at the expense of increased water loss in transpiration. Indeed, the crop has been shown to use 9 mm of water per day (Watts and Moore 2011). Over a 9-month growing season this would amount to some 2500 mm! This physiological attribute while supporting high productivity will also cause a poor water use efficiency and so water demand per unit biomass will be very much higher than in the other species.

10.5 Agave

Agave species are characterized in part by their use of Crassulacean Acid Metabolism (CAM). This photosynthetic pathway results in the highest known water use efficiency, i.e. amount of carbon gained per unit of water lost to the atmosphere. In hot semi-arid and arid environments such as the desert southwest of the USA, productivity is by definition limited by water. Production in these areas will therefore be largely determined by precipitation and water use efficiency, rather than radiation use efficiency. A key factor here is photosynthetic pathway. Biochemical differences between the C3, C4, and CAM photosynthetic pathways affect affinity for CO_2 and timing of CO_2 assimilation, resulting in intrinsically different water use efficiencies (WUE). To a first approximation C3 plants which include all trees, small grains, and oil crops are the least water use efficient. They have an intrinsic WUE, which is about 60% of that of C4 plants. Since, as in C4 plants, CAM plants assimilate CO_2 via PEP carboxylase localized in the mesophyll cytosol, a similar WUE might be expected (Borland et al. 2009). However, obligate CAM plants open their stomata almost exclusively at night, and as a result realize a higher WUE; why?

The air within a leaf is saturated with water vapor. The saturated water vapor pressure (e_s) is determined by temperature, rising exponentially with temperature. The vapor pressure deficit (VPD) is the difference between e_s and the water vapor pressure of the ambient air (e_a). While e_a will vary little between night and day, e_s will be much lower at night, because leaf temperature is lower. This diurnal variation is most pronounced in hot deserts where daytime maxima can be 10 - 30°C higher than nighttime minima. Nocturnal gas exchange, typical of CAM plants therefore occurs when VPD is much lower and allows a higher WUE than in C4 photosynthesis.

Using average monthly weather data for Oct. 2012-Oct. 2013 in the Sonoran Desert region (Maricopa, Arizona, USA) VPD during day and night was calculated (Davis et al. 2014). Averaged over these twelve months, daytime temperature was 27 °C and VPD 3.0 kPa, compared to nighttime values of 17°C and 1.3 kPa, with a total precipitation of 201mm. Assuming a loss of one third of precipitation to run-off, deep drainage and soil surface evaporation, the remaining precipitation could support the production of 2.0 t ha^{-1} for C3 crops and 3.6 t ha^{-1} for C4. If we assume the same WUE for CAM, as C4, but apply the night-time VPD, since stomatal opening here is nocturnal, then the same low level of precipitation would support 8.9 t ha^{-1}, almost 2.5x the productivity that C4 photosynthesis could support (Davis et al. 2014). Rigorous agronomic trials to establish that such yields can be obtained on arid lands in the absence of irrigation are lacking. However, a replicated trial of *Agave americana* was established in 2012 to test this prediction (Figure 10.6).

Agave species are also characterized by a thick wax covering the leaves and retractile roots. In a severe drought the roots retract leaving an air gap between the root and soil surface while the leaf stomata remain shut. This locks in the plant's moisture allowing

Figure 10.6. First field trial of *Agave americana* in Maricopa, Arizona, USA.

survival over months of drought. Although potential yields are likely less than those for sugarcane, Miscanthus and switchgrass, *Agave* spp. can be cultivated on land where these crops could not grow. With arid lands covering 30% of the Earth's land surface, there is much apparent potential.

There are two commercial industries that have historically exploited *Agave* spp.: the tequila and fiber production. The high concentration of soluble carbohydrates in the plant tissue is ideal for fermentation to alcohol. The rigid leaves that yield high-quality natural fibers are high in cellulose, and some species have much lower lignin content than many of the widely studied lignocellulosic feedstock crops. Recent changes in the fiber industry have resulted in widespread abandonment of *Agave* plantations that might be brought back into production and repurposed for biofuel. In sum, the physiology, tissue composition, and land availability is a unique combination of traits favorable for bioenergy production (Davis et al. 2011b).

Agave species are sugar-rich but are not typically food crops, although historically some foods and beverages have been sourced from these plants in Mexico. Between 55 and 90% of the mass of a mature agave stem can be soluble carbohydrates, primarily hexose with an energy yield, before conversion to fuel, of 79 to 220 GJ ha^{-1}. The total mass of sugar in commercially produced *Agave* spp. is between 5 and 14 t

ha^{-1}. Including the hexose that would result from cellulose degradation, a sugar yield of 11 to 23 t ha^{-1} is possible. This equates to ethanol yields ranging from 360 l t^{-1} (8 GJ t^{-1}) to 600 l t^{-1} (14 GJ t^{-1}). Estimates from life-cycle assessments indicate that the energy output in biofuel from *Agave* feedstock would be 4.6 to 6.1 times greater than the energy required to produce the fuel (Yan et al. 2011).

Although there are over 200 species of *Agave*, there have been no field trials conducted for most. Some of these species that have been untested in plantation production have traits that would potentially lead to improved yields across a broader range of environmental conditions than those achieved with the commercially grown varieties. For example, *A. americana* has not been grown commercially in the past, but has cold-tolerance lacking from the species used for tequila and fiber production. Cold-tolerance is a necessary trait in the southwestern U.S. where there are large areas of marginal semi-arid agricultural land that could serve the growing biofuel demand in the country without competition with food crops. As noted above, the first field trial of *A. americana* in the U.S. was initiated in 2012 (Figure 10.6). Other species are undergoing field trials in Mexico and Australia. Cold tolerance is less of an issue for these countries and a recent analysis suggests that using *A. fourcroydes* on 0.7% of Australia's land surface could provide 28.9 bl yr^{-1} or 0.62 EJ of ethanol on land where there would be no conflict with either food crop production or biodiversity (Owen and Griffiths 2013). Australia consumed 40 bl or 1.67 EJ of crude oil in 2013 (EIA 2014). Taking account of the lower energy content of a liter of ethanol, *Agave* from this analysis could replace over 37% of the country's current oil use.

10.6 Oil Crops

Oil crops serve as feedstocks for the production of biodiesel fuels. In terms of cost and energy efficiency, the conversion of oil crops to biodiesel is far more efficient than the conversion of starch or lignocellulosic crops to bioethanol. The triacylglycerol storage oils (TAGs) of these plants are mainly based on easily extractable C16 and C18 chain length hydrocarbons that are chemically similar to diesel hydrocarbons. Vegetable oils can be used in raw form as part of a diesel blend in some engines but this can reduce engine lifetime and almost all commercial biodiesel is produced today by transesterifying TAGs to their methyl ester derivatives, termed fatty acid methyl esters or FAME. Depending on the acyl chain length and degree of unsaturation, different crop oils have different freezing points, which allow them to be blended together to produce various types of biodiesel fuel. For example, higher melting point blends are more suitable for vehicle fuel use in winter conditions while more unsaturated lower melting point blends perform better under warmer conditions. These oils can also be catalytically hydrogenated to produce high performance blends that meet specifications for aviation fuel and advanced diesel engines. Several international airlines and the US Navy have made successful test flights with these fuels (Serrano-Ruiz 2012).

In 2013, biodiesel accounted for about 31% global biofuel when its estimated global production was 24.7 Mt or 1.0 EJ (Biofuels Digest 2013a; BP 2013). This is a 12-fold

increase in the decade since 2003 (Licht 2012). Three oil crops supply the vast majority of biodiesel, soybean (7 Mt), oil palm (6.3 Mt) and rapeseed/canola (6.0 Mt). Most soybean biodiesel is both produced and consumed in the major centers of soybean cultivation: Brazil, USA and Argentina. Although oil yields per unit land area are low relative to other sources, it should be appreciated that in the case of soybean the oil is a by-product, the crop is grown largely as a protein source for animal feeds. In contrast, the European Union uses both domestically produced canola biodiesel and imported palm biodiesel, mainly from Indonesia. Malaysia is increasing biodiesel production but almost all of it will be used domestically to meet the mandatory 7% blend in all vehicle diesel fuel that is being rolled out by the government (Reuters 2013). Global biodiesel production is expected to expand in the short-to-medium term, mainly driven by demand-promoting policies, to reach 37Mt or 1.55 EJ by 2022 (OECD-FAO 2013). This amount would require 15% of world vegetable oil production to be diverted to biodiesel. Over the next decade, the European Union is expected to be by far the largest producer and user of biodiesel while other significant producers/users include Argentina, USA, Brazil and Indonesia.

Although current biodiesel crops are potentially more efficient in terms of conversion of the harvested product relative to bioethanol crops, biodiesel can only supply a small fraction of current global requirements for liquid fuels because of low absolute yields - with the exception of oil palm (Table 10.3). Even if all vegetable oil production was used for biodiesel, it would only provide 5% of current liquid fuel use while this would create a huge shortage of food calories because vegetable oils are currently the second most important source of edible calories for human populations across the world. A major problem with the current temperate oilseed crops, such as soybean and canola is their relatively low productivity in terms of oil yield. For example, Table 10.3 shows the large areas of land that would be required simply to grow sufficient oil crops in the USA to replace its 2008 usage of aviation fuel. This table also includes Camelina (*Camelina sativa*), a relative of Arabidopsis, and canola that has been proposed as a new biodiesel crop (Groeneveld and Klein 2014). However, its yields are very low and even a 2-3

Table 10.3. Yield of oil for different crops and the land area that would be needed to provide the 62 Billion liter of Jet fuel used in the USA in 2008.

Crop	Liters ha^{-1}	Area of land required (Mha)
Camelina	438	136
Soybean	857	73
Canola	1,358	45
Oil Palm	5,724	10.6
Hypothetical "Oil Cane"	13,740	4.4

Average US yields (USDA-NASS 2013), except oil palm (FAOSTAT 2013), are combined with the assumption that oil is 36% of Camelina and Canola seed, and 23% of Soybean seed, and that the energy content of sugarcane recovered as sucrose could in the future be recovered as oil in the hypothetical "Oil cane"

fold increase in the future would only place it on par with canola. Further, even the untransformed crop fails the Australian Weed Risk Assessment (WRA) that is being widely used to evaluate invasive species risk for new crops globally (Davis et al. 2011a).

In contrast, oil palm is potentially a much better prospect with respect to yield of biodiesel per hectare of land. In 2012 the estimated global production of total palm oil was almost 65 Mt, of which 58 Mt was mesocarp oil and 6.8 Mt was kernel oil (USDA 2012). Typical average yields of palm oil on a global basis are in the region of 4 t ha^{-1}. This figure far outstrips the yield of the major temperate annual oilseed crops where yields range from 0.3 to 1.2 t ha^{-1}. This high yield means that the current global output of 65 Mt palm oil requires cultivation of only 15 Mha, which contrasts dramatically with the 194 Mha needed to produce just 87 Mt oil from the temperate annual oilseed crops (Table 10.3). Therefore, in terms of total oil yield (kernel + mesocarp oil) per hectare, oil palm is already more than 6.5-fold more efficient than the average combined yields of the temperate oilseed crops. Palm oil is limited to tropical wetland regions and its expansion onto natural tropical peatland forests in SE Asia, has rightly attracted much criticism (Danielsen et al. 2009). However, this has distracted attention from the possibility of expanding production elsewhere onto abandoned and degraded lands or to displace plantations of other trees that are no longer economically viable. For example, there is increasing interest and opportunity for the establishment of new oil palm plantations in non-forested areas in West/Central Africa and Central/South America (Murphy 2014).

A second tree or bush, Jatropha or Physic nut (*Jatropha curcas*) has been promoted as a productive tropical oil seed that can be grown on marginal land (Openshaw 2000). However, there is little peer reviewed literature to support these claims. While 10 t ha^{-1} has been reported on good soils, more typical yields are around 2 t ha^{-1}, and even with its high oil content, this would still be a very small amount of oil per hectare. There are further practical problems. Fruits on the plant mature at very different times and the mixture of unripe, ripe, and overripe fruits borne at the same time precludes mechanized harvesting. The oil of most cultivars is highly carcinogenic, raising serious handling issues. The crop also has a harvest index of just 10% and oil production decreases on acid soils, eliminating the crop from much marginal land (Kant and Wu 2011). However, it should not be overlooked that established crops may have had many parallel problems in their early domestication. With modern breeding techniques it should not be ruled out that these problems could be addressed (SGBIOFUELS 2013).

All vegetative tissues of plants are continually producing and metabolizing TAGs. This has encouraged much bioengineering effort to up-regulate biosynthesis and down-regulate catabolism to force vegetative tissue to accumulate TAGs as an oil source. In several recent studies a combination of the ectopic overexpression of oil-regulating genes such as WRI1 and DGAT1 with the suppression of TAG breakdown by lipases, has enabled leaf tissues to accumulate TAGs (Fan et al. 2013; Kelly et al. 2013). If this TAG is enclosed in a proteinaceous coat of modified oleosins, the oil can be accumulated in a stable manner without potentially poisoning key metabolic processes such as photosynthesis (Winichayakul et al. 2013). Already, Arabidopsis leaves have been engineered to

accumulate as much as 8% of dry weight as oil while roots can accumulate up to 17% oil. These breakthroughs could open the way to engineering highly productive plants, such as sugarcane, to form and accumulate TAG in its mature stems. This might be achieved by coupling the changes found effective in Arabidopsis to late stem promoters. If the energy currently accumulated in sugar, could be accumulated as TAG, then based on current yields, over 13,000 liters of oil could be obtained per hectare (Table 10.3).

10.7 Forests and Short Rotation Coppice (SRC)

While it is anticipated in earlier sections of this paper that a range of herbaceous perennials could become viable sources of biomass on land unsuited to food crops, this is an established fact for the many pulp and round wood supply operations that meet ISO 14001 sustainability standards (ISO 2014). Wood is the fifth most important product in world trade. The market in wood based products increased from $60 billion to $257 billion in the 20 years up to 2008 and is estimated to be $450 billion by 2020 (Gardiner and Moore 2013). In 2008, global wood usage amounted to around 4.6 billion cubic meters. The dominant traditional use is solid/sawn timber (for house building and furniture) and fibers (for pulp, paper products and boards). However, wood also represents a key sink for atmospheric CO_2, and is considered the most important natural, renewable source of energy, with around half of wood consumed today used for wood fuel (FAO 2010).

In 2006 global production of wood pellets was between 6 and 7 Mt worldwide (not including Asia, Latin America and Australia). In 2010 it reached 14.3 Mt or 0.26 EJ (including these countries) while consumption, predominantly for biopower, was close to 13.5 Mt, representing an increase of more than 110% in 4 years (IEA 2012b). Production capacity from pellet plants has also increased worldwide, reaching over 28 Mt yr^{-1} by 2010 (Goh et al. 2013). The European Union (EU) is the main market for wood pellets, but the gap between European production and consumption has grown to become 8 fold (IEA 2012b).

The increased use of industrial pellets has been mostly associated with co-firing and driven by policy frameworks supporting green electricity, whilst market expansion in heat has been incentivized via support for installations, as well as feed-in tariffs. It has stimulated large investments in new pellet plants and an increase in exports of pellets, particularly from Canada but also the US and the Russian Federation. In countries with well-developed forest industries, much of the wood-based energy generation takes place within sawmill and pulp sectors, often using waste-industrial by-products for fuel. Whilst pulp and paper markets have declined, global energy prices have risen, offering new opportunities for diversification as well as for reducing production costs.

The main raw material for pellets is sawdust but availability of traditional sawmill residues has decreased and difficulties in sourcing feedstock at competitive prices has

resulted in a lower utilization by many pellet mills. Large - scale pellet consumers (such as European or North American power plants) are increasingly looking for longer term supply agreements with well - defined volumes and prices that mirror their domestic feed-in tariffs. This conflicts with the volatile supply situation of the residue stream of the saw milling industry. Larger pellet manufacturers, and some energy producers, are thus moving up their supply chains to secure a more diversified and longer term feedstock base. Pellet producers have begun to source alternative woody feedstock, including wood chips from saw mills, round wood, residues, bark, used wood and wood from managed plantations (IEA 2012a, IEA 2012b).

In comparison with pellets, currently less than 10% of annual trade in woodchip is bioenergy-related. In the EU usage is exclusively driven by the industrial sector where chips are combusted in dedicated co- and mono-firing installations. Supplies are as chips, crushed (waste) wood, or roundwood which is chipped at the plant. International trade in woodchips for energy is not predicted to increase substantially. The key constraint is economic viability influenced by production and transport costs and also by feedstock prices (IEA 2012a). Use of roundwood, forest residues and salvage wood is likely to increase but can only supply a portion of requirements. There is a paucity of knowledge on risks associated with biomass extraction in this way but residue removal will need to be managed if negative impacts on soil productivity and nutrient balances are to be avoided (Davis et al. 2009; Lamers et al. 2013).

The complex chemical makeup of wood (cellulose, hemicelluloses, lignins, pectins and extractives) makes it a good potential raw material to replace petrochemical-based fuels and chemicals. The massive all-year-round supply needed for new installations of gasification and synthesis plants (Fischer-Tropsch), lignocellulosic plants and biorefineries represents a logistical challenge but potentially huge market (Heinimo and Junginger 2009). In the US, woody feedstocks currently account for approximately 30% of lignocellulosic biomass (Limayem and Ricke 2012).

Where is wood currently sourced to meet these markets and how will future demands be met? Demand for wood is currently met from around 30% of the world's natural forest area, whilst another 50% of natural forests are considered nominally protected or too remote to harvest (Fenning and Gershenzon 2002; Gardiner and Moore 2013). The maximum sustainable rate of timber extraction from natural forests is only ~2m^3 ha^{-1}yr^{-1} (Fenning and Gershenzon 2002). Dependency on natural forests will decline because of the increasing recognition of the need to protect them for their ecosystem rather than provisioning services and because only planted forests will be able to supply enough wood sustainably. Many tree species are grown in managed plantations for bioenergy. Depending upon geographic location, primary softwoods include pines, firs and spruce whilst the principle hardwoods are eucalypts, poplars and willows. Bioenergy trees are usually grown as short rotation forestry (SRF) in 7-15 year rotations, or as short rotation coppice (SRC) in 2-4 year rotations that are more akin to arable production (Figure 10.7). At 10 Mha globally, SRF Eucalyptus is the most widely grown, achieving dry wood yields of 30 t ha^{-1}yr^{-1} over a 7-year rotation. Poplar and willow are grown in more temperate

Figure 10.7. SRC willow: harvested rows can be seen alongside the remaining uncut rows of circa 7m high willow during winter harvest in a three-year coppicing cycle.

climates as SRC (both) and SRF (poplar), yielding on average 10 t $ha^{-1}yr^{-1}$ but cover much smaller areas in comparison, although as outlined below, a doubling of these yields is likely possible, with investment, over the next two decades (Karp and Shield 2008).

An advantage of bioenergy trees is that their efficient growth strategies, in which nutrients are largely recycled, and low-input cultivation, mean that plantations can be located on lower grade and more marginal land than is used for food production (Karp and Shield 2008). Moreover, crops like SRC willow provide natural filters and can be used to manage flooding, remove excess run-off of nitrogen from farmed land and for bioremediation of wastewater, sewage sludge or agricultural washings. As trees continue growing year after year they provide a “living inventory” of available biomass which can be harvested after several years and at different times, reducing storage and inventory holding costs and mitigating against the risk of annual yield fluctuations due to drought, disease and pest pressures (Hinchee et al. 2011). SRF can be used on land too sloped for food crop cultivation, in the absence of terracing, opening another land resource unsuited for food production.

A major limitation to biomass yield in forests and managed plantations is the available water content of the soil. Moreover, with high rates of biomass productivity, there is a risk that water resources may be adversely affected in areas where there is insufficient effective rainfall, thus reducing yield from water-supply catchments. Awareness of water balance-vegetation interactions at the stand scale is important to allow groundwater recharge to be estimated (Upham et al. 2011). When removing high biomass volumes from an area of land, there is also a risk of soil nutrient depletion (Upham et al. 2011). Impacts will be species-related. For example, Eucalyptus has caused particular concerns

but SRC willow stands can be used for soil remediation and is beneficial to biodiversity, hence their inclusion for greening in the CAP reform of the EU. The largest threats to trees are, however, pests and diseases, compounded with impacts of climate change. Recent outbreaks, such as ash dieback and mountain pine beetle, have had devastating impacts on tree populations. Similarly, rust (caused by *Melampsora* spp), can reduce yields of poplars and willows by 40% reduction, and even cause plantation death. Breeding, or genetically engineering in resistance, is the only sustainable way of protecting forests (see below). Once diverse genotypes are available, mixtures can be used to better manage pests and diseases, and minimize the risk of devastating epidemics.

What are the future prospects for increasing biomass supply from trees? The potential for additional woody biomass appears huge. A recent analysis of the eastern US brought together representatives of foresters, biologists, conservation groups, analyst groups and economists. They estimated that if woody feedstocks were cultivated with a combination of intensive management on abandoned lands and partial harvests of standing forest were conducted, with amounts removed depending on condition and conservation value, it was estimated that 176 Mt yr^{-1} could be produced sustainably (Davis et al. 2012). A second detailed analysis of the potential for SRC willow on marginal land in Saskatchewan, Canada, shows the possibility of producing 34 Mt yr^{-1}, while sequestering 3 Mt C yr^{-1} into the soil (Amichev et al. 2012). For increasing productivity per unit land area, the typically long generation cycles, large space requirements, and outcrossing nature of trees make them particularly difficult to breed compared with arable crops but for these very reasons molecular markers and biotechnology have even more to offer by way of accelerating selection (Hanley and Karp, 2013, Harfouche et al. 2012). Further, with very limited past efforts in breeding improvement compared to the major food crops, large returns might be expected for investment at this stage. For example, although good yields of current production willow cultivars in short-rotation coppice trials average 10 t ha^{-1} yr^{-1}, new triploid hybrids are already now achieving 17 t ha^{-1} yr^{-1} (Serapiglia et al. 2014). Using mapping populations, with either linkage or association genetics, both quantitative trait loci (QTLs) and genes have been identified that influence key traits, such as pest and disease resistance, stem morphology, drought tolerance, biomass yield, composition and wood quality. Such tools are available for Douglas fir, loblolly, Monterey pines, spruces, Eucalyptus, poplars and willows. Whole genome sequences are also either already available or in production for many of these trees. Efficient means to produce transgenic plants displaying improved modified traits have also been generated in many species. Coupled with advanced management practices, productivity gains have been evident, with a doubling of yields achieved in many species over the past 20-30 years (Karp and Shield 2008).

Faster and cheaper next generation sequencing has led to the development of new promising approaches for genetic improvement. Large numbers of individuals can now be screened at very large numbers of loci for as many phenotypes as possible in genome-wide association studies. Interesting variation present at very low frequencies can be detected using strategies such as ‘Breeding with Rare Defective Alleles’ which are independent of the gene targeted or tree species (Vanholme et al. 2013).

In genomic selection (Grattapaglia and Resende 2011), a "training population" is established and data from intensively phenotyping and genotyping this population is used to develop a model, which is then used to predict the "genomic breeding value" of progeny in future generations. Based on these prediction models, genomic selection could be used to select superior genotypes early in the breeding process and could considerably reduce the length of time required for completing a cycle of genetic improvement in trees (Grattapaglia and Resende 2011; Harfouche et al. 2012). The emergence of mechanistically rich models of plant growth has opened the door to identifying optimum trait values for maximizing production and resource use efficiency in a given environment *in silico.* This is providing a further tool for accelerating selection (Drewry et al. 2014). Genetically modified feedstocks would undoubtedly accelerate improvement, especially in pest resistance (Hjalten et al. 2012). Long experience in research trials of genetically modified trees has shown that ecological impacts are no different from those of genetic change through conventional breeding and inter-specific hybridization (Strauss et al. 2001). Indeed, pest and disease resistance could decrease need for use of chemicals, besides increasing yield and certainty of supply. It is time policy recognized this fact.

Production forests could in theory meet much of the world's need for sustainable energy (equivalent to half to 2/3's of current fossil fuel consumption at current levels of productivity). However, in spite of past increases in productivity, plantations currently only supply *circa* 12% of the total amount of wood consumed. It is still usually cheaper to harvest trees from the wild and current planting and replacement rates are far below that needed to sustain future demand (Fenning and Gershenzon 2002; see also Chapter 13, this volume). Advances in woody feedstock production can only be exploited if policies surrounding both existing forest management and new plantings are in place. These policies will need to tackle environmental concerns associated particularly with monocultures and overcome some misunderstandings and misconceptions about the use of forests and plantations (Sutton 2013). They will need to consider the use of genetically modified trees and the need to incentivize investment. Managed sustainably, forests and plantations could reduce reliance on fossil fuels, help mitigate climate change and bring many environmental benefits (Sims et al. 2006). However, over-utilization and unsustainable practices risk the loss of forest ecosystems and societies dependent upon them. Energy policies have to be based on the principle of sustainable development and should plan for economic and environmental longevity of woody feedstocks, which could follow the model developed by Davis et al. (2012).

10.8 Algae

As productive as palm oil trees may be, in one of the most highly cited reviews of microalgae as a source of biodiesel, Chisti (2007) claimed that microalgae would produce 45x more oil per unit ground area per year, i.e. 13.7 l m^{-2}. Such remarkable potential has been frequently noted (Vonshak 1990; Chisti 2007; 2013; Silva et al.

2014). Such high yields would mean that despite the much greater infrastructure costs, relative to cultivation of plants, economic viability would be strong (Chisti 2013, Wijffels and Barbosa 2010; Silva et al. 2014). Unfortunately there is a large discrepancy between such claims, based on predictions and extrapolations, as compared with actual experimental data, pilot plant experience and simple theory. While the concept of using microalgae as a biodiesel feedstock has been explored extensively over the past several decades, a scalable, commercially viable system has yet to emerge (Hu et al. 2008).

Are the claimed yields of oil thermodynamically possible? Algal, like plant biodiesel contains about 34 MJ l^{-1}. So Chisti's (2007) claim would represent 466 MJ m^{-2} of oil yield. Zhu et al. (2010) show from theory, considering all steps in the photosynthetic process and in the complete absence of respiration and photorespiration, that the maximum theoretical conversion efficiency of solar radiation into biomass energy is 6.5%. Average daily solar radiation in the desert southeast of the USA is among the highest at the ground surface in the world, at 7200 MJ m^{-2}. If all of this radiation is intercepted by the algae and converted at 6.5% efficiency every day of the year and if the alga is 70% oil, as assumed by Chisti (2007), this would yield 397 MJ of oil. So even if we assume the algal suspension absorbs 100% of the radiation, loses no energy in respiration and operates at maximum theoretical efficiency without a single interruption over 365 days, the claim still exceeds what is thermodynamically possible by almost 20%. This also ignores the fact that in practice, oil accumulation is a nutrient limitation response, which requires a period in which photosynthesis is zero or severely restricted by stress (Hu et al. 2008).

Claims made for algae are focused around their: fast growth, higher photosynthetic efficiency, ability to increase oil content to 70% of mass, ability to grow in saline or brackish water, and capacity (as in C3 crops) to fix more carbon in high CO_2, as well as ability to produce high value chemicals that could subsidize the cost of biodiesel production (Chisti 2007). Some of these individual claims are supported by experimental data obtained under laboratory and short-term small-scale field measurements. But, attention must be paid to the fact that these experiments were performed with an algal species or strain that met one of these goals, but it is almost impossible to have all of these properties in a single strain. For example, many of the algal species with higher potential photosynthetic efficiencies than C3 crops, achieve this by an internal, energy driven, CO_2 concentrating mechanism (Giordano et al. 2005). However, this precludes any further response to increased external CO_2 concentration, and would make the algae less, not more, efficient than a C3 crop in high CO_2. Some of the claims in what amount to "sales pitches" ignore problems for which there is no clear solution. For example, a plus that is often given is the ability to use saline water in deserts and semi-deserts. However, when grown in out-door open ponds, high evaporation rates will produce a brine that may cause severe environmental issues when the water is disposed. As demonstrated above, claims of high photosynthetic efficiency can overlook the theoretical maximum efficiency that cannot be exceeded in practice and ignore problems of the observed down-regulation of the photosynthetic activity (Vonshak and Guy 1992; Vonshak et al. 1994; Day et al. 2012), paralleling those of crop plants (Zhu et al. 2004; Murchie and

Niyogi 2011). More critical analyses of the true photosynthetic efficiency and limitations to algal biodiesel production are explained and justified in other reviews that are not receiving the attention they deserve when evaluating the true potential of these systems (Hu et al. 2008, Walker 2009, Tredici 2010, Lundquist et al. 2010).

Many claims that potential microalgal production systems can be a commercially viable alternative source of energy are based on assumptions that high productivity can be achieved easily in large scale production and be equivalent to that obtained under laboratory controlled conditions. High figures of productivity obtained from model predictions, short-term laboratory or small-scale short-term field studies are then used to estimate maximum potential in large-scale field production facilities (Guterman et al. 1990; Chisti 2007). Unfortunately, there is nothing to support those assumptions and extrapolations (Hu et al. 2008). While this is also an issue with agriculture, there is a great deal more experience in translation with agriculture than there is with algal culture. Yet, the complexity and engineering of large-scale algal culture is orders of magnitude greater (Lundquist et al. 2010). Claims that micro algae have a better, or more efficient, photosynthetic machinery are at the best incorrect and in many cases reflect the misuse of terminology. All algae and plants use the same Calvin-Benson pathway to assimilate CO_2. Many algae have energy driven mechanisms to concentrate CO_2 at the site of Rubisco, so minimizing losses in photorespiration, but this only makes them more efficient than C3 plants under conditions of low CO_2 and not more efficient than C4 plants. Different photosynthetic pigments allow some algae to capture some wavelengths of solar radiation with higher efficiency while the absence of heterotrophic organs will also improve net efficiency. However, none of these factors allow algae to escape the thermodynamic maximum efficiency explained above. On the negative side, the tumbling nature of algal suspensions moving through photo-reactors or raceways prevents the light acclimation possible in plant canopies, where investment into components of the photosynthetic apparatus can be optimized for the prevailing light conditions (Zhu et al. 2010). In practice, the current productivity in large-scale facilities based on photoautotrophic growth does not exceed 15 g m^{-2} d^{-1} on an annual basis, which is less than the annual average of 23 g m^{-2} d^{-1} achieved by the C4 bioenergy feedstock Napier grass under rainfed (see the section on perennial grasses). A detailed analysis, suggests 22 g m^{-2} d^{-1} as an achievable maximum in ponds (Lundquist et al. 2010), which even so is still very similar to that achieved by productive crops. Short-term higher productivities may be achieved as in crops, depending on stage in the growth cycle, the season of the year and location of the site (Beadle and Long 1985; Vonshak 1987). Even if a perfect site with ideal climatic conditions can be found; yield would be 40-50 Mt ha^{-1} yr^{-1} of dry biomass, when downtime for maintenance and replenishment of the culture is taken into account. It has to be noted that even this estimated productivity is yet to be rigorously demonstrated, since it assumes that there will be no contamination with other algae, introduction of pathogens and that lipid production can occur without the need to induce this via the currently necessary nutritional stress, which halts any further energy gain by the algae (Vonshak 1987; Hu et al. 2008; Lundquist et

al. 2010). A further claim is about the fact that algal feedstocks can be genetically engineered far more rapidly than crops. While unquestionably correct, GM algae would need to be contained since in open cultivation the alga may easily escape. However, enclosure would incur massive energy costs in maintaining temperature in raceways at viable levels, given that they may have to dissipate as much as 20 MJ m^{-2} s^{-1} of incoming solar radiation.

How do algae compare with respect to cost, technology and life cycle analysis? Today there are only four algal species that are produced in large scale in an economically viable manner. The first two are grown for the sale of their total biomass with very little further processing: Spirulina (*Arthrospira platensis*) about 15 kt yr^{-1} and Chlorella (*Chlorella vulgaris*), about 5 kt yr^{-1}. Grown mainly in open ponds with a bulk selling prices of $10– 25/kg for dry biomass of Spirulina and $20– 40/kg for Chlorella. These are sold into the health food/supplement market. Predicted production cost is about 60-80% of the wholesale price. The cost of drying is about 1.0 $/kg and might be a good indication for the production cost of algal biomass for biodiesel. The two other algal species, *Dunaliella salina* and *Haematococcus pluvialis*, are used for extraction of carotenoids (beta-carotene and astaxanthin, respectively) for the health supplement market. They are produced in much smaller amounts but sell at far higher prices. The higher price reflects the higher production cost due to the need to induce accumulation of the carotenoids. This process parallels the process that would be needed to induce lipid accumulation in algal biodiesel feedstocks (Hu et al. 2008). It is very difficult to see how significant reduction in production costs may be achieved without a major breakthrough leading to orders of magnitude improvement in the efficiency of production. Yet this will be necessary to make biodiesel or jet fuel economically viable at open market prices. The current production costs are the result of 30 years of continuous improvement in efficiency through engineering and downstream processing, via learning by doing, yet is still far from being viable for the fuel market (Lundquist et al. 2010). At present it is not clear how such gains could be achieved on less than a multi-decadal timescale. Although closed photo-bioreactors incur significant extra costs in construction and energy input, they are providing a platform for gaining better insight as to the improvements required to gain some improvement in efficiency (Stephenson et al. 2010; der Veld 2012; Woertz et al. 2014).

The claim that microalgae will solve the world' s energy problem or even contribute significantly to reducing the dependency on fossil fuels is unfortunately at this stage not foreseen as viable. The potential of microalgal biofuels will be realized only by addressing the real issues of productivity, strain selection and efficient use of resources in large-scale production facilities. A focus on high-value products, perhaps high value lubricants, may be a better platform for the evolution of more efficient systems and knowledge as to whether algal biofuel production has a viable future in the longer term (Hu et al. 2008).

One area where viability may be possible is in wastewater treatment. Although not a new idea, algal waste treatment offers a means to counteract the high costs of anaerobic

technologies, by allowing nutrient capture and bioenergy production. A recent analysis suggests that these combined benefits could lead to energy positive and economically viable photoautotrophic wastewater treatment in areas with year round high insolation (Shoener et al. 2014).

10.9 Conclusions

A range of different crops will be required to provide feedstocks for bioenergy and biofuels, as specific needs for light, temperature and water availability restrict the geographic ranges of individual feedstocks. The large volume of feedstocks required for bioenergy and biofuels to make a difference has resulted in both novel use of existing crops and the development of novel crops. Support should be given to efforts aimed at continuing to improve yields (sustainably) of both traditional and novel crops through breeding enhanced by genomics and biotechnology integrated with agronomic improvement. Expansion into land that is sub-optimal for food production should be encouraged but will require the selection of cultivars and appropriate agronomy adapted to perform well in these environments. It is also essential that adequate testing in target environments be carried out before any large-scale plantings are initiated.

Currently, the predominant feedstocks for biopower (heat and power) are woody species, including forests, managed woodlands and energy trees, although straws and other crops residues are also used. The current primary feedstocks for biofuel are food crops but use of the lignocellulosic (non-food) fraction and development of non-food crops is also underway.

At present, biomass accounts for only a small fraction of current liquid fuel use, ca. 2%, and about 8% of total global energy use - however most of this is traditional combustion of wood. Natural forests are still the major source of wood but this will decline under pressures to protect the valuable ecosystem services they contribute to and because only planted forests will be able to meet the rising demands. Biofuels have replaced a very substantial proportion of gasoline use in Brazil and in the USA. Of the four largest sources of these biofuels - soybean, rapeseed, maize and sugarcane, only the latter appears to have a secure future. Soybean and rapeseed produce far too little fuel per unit land area to remain competitive without mandates and subsidies (Table 10.1). The progressive divide between increase in demand and increase in production suggests that maize ethanol will lose long-term economic viability, unless the already high rate of yield per hectare improvement can be accelerated yet further. Emerging perennial crops and woody feedstocks that may be grown on marginal land, i.e. land unsuited to arable crop production or semi-arid land could allow large-scale replacement of fossil fuels. However, this will require the implementation of policies that favor these new land uses and policies that support the realization of the potential of producing cellulosic fuels or/and acceptance of bioengineered crops. Generally, re-establishment of biodiverse systems such as mixed grass prairie as a biomass source, are not viable because of their low yields. Both macro and micro algae have also been developed and promoted

as alternatives to crops, which have the advantage of no or minimal land requirement. However, claims that they will make major contributions have yet to be upheld and they may be better confined to use as feedstocks for high-value renewable products.

Crop feedstocks for bioenergy and biofuels are different from coal and oil as new chains require establishment and expansion time before sufficient quantities can be supplied and all crops feedstock chains involve many different players, and often different localities (see Chapter 11, this volume). Many of the concerns surrounding biofuels relate to feedstock production and the challenges of ensuring that bioenergy and biofuels produced with these feedstocks really do reduce greenhouse gases and result in environmental benefits, as noted in other Chapters of this volume. Considerable advances have been made in the improvement of crop yields and in the understanding of the key criteria that need to be met for sustainable production, which crops best meet these criteria and the further changes needed to improve sustainability further. The challenges of meeting feedstock supply through yield improvement and expansion of feedstocks in sustainable ways can be met, but only with secure and prolonged support and sensible, easily adoptable policies that recognize the environmental as well as the economic goals. However, the need to move swiftly has become urgent. These policies are needed now, so that strategies for increasing feedstock production in sustainable ways can be implemented immediately. Climate change is already impacting on crop production and human societies. A detailed technical and global analysis using IPCC methodology, showed that bioenergy crops could provide up to 22 new EJ yr^{-1} by 2025, mitigating 2070 Mt CO2 equivalent yr-1 in GHG emissions when taking account of build-out times (Sims et al. 2006). This chapter shows many further potential bioenergy options, but the question remains: Will policy-makers move quickly enough to release this potential in a timely enough manner to fight global climate change? Current policy on bioenergy and genetically modified crops is almost certainly a realization of the proverb “the perfect is the enemy of the good”. Without change, the significant opportunities for realizing bioenergy shown here will remain just opportunities.

10.10 Recommendations and Much Needed Science

- Genetic improvement of perennial energy crops through conventional and marker-assisted breeding and GM approaches to enhance yields, increase resource use efficiency and resilience to future climates;
- More extensive trials with a range of agronomies of these emerging crops to test the assumption that these will be high-yielding and sustainable on marginal land and other areas unsuited to competitive food crop production;
- Modeling approaches to identify optimal locations for energy crops using yield models and GIS-based opportunity mapping and constraint mapping;

- Development of policies that encourage sustainable energy crop production through recognition of multiple environmental benefits;
- Social research into barriers to adoption of new and emerging crops by farmers;
- Holding emerging bioenergy to higher standards than current agriculture and forestry will inhibit, not aid, emerging and more sustainable opportunities.

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