

# Future Feedstocks for Biofuel Systems

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## Introduction

Current and future feedstocks for biofuels can be divided into three basic categories: existing food and novel multi-purpose crops; dedicated energy crops; and residues and wastes from food or fibre production. The first category of feedstocks generally supplies feedstock conversion facilities using conventional technologies (e.g. fermentation or methyl-esterification). These crops are attractive for biofuel production because of the high proportions of the harvestable biomass comprising one or more of the following components: starch, sucrose, or fatty acids (oils). However, biomass also contains significant amounts of lignin, cellulose, and hemicelluloses which support plant structure and function (including the photosynthetic apparatus), as well as proteins, which can be separated and utilized (e.g. as animal feed).

Crop harvesting has been designed to collect and concentrate the 'high value' components,

leaving behind those of 'low value' (the economic feasibility of removing crop residues from the field varies with market and harvest conditions). Pre-processing (e.g. drying) and conversion further fractionates the product from low-value components. When used for biofuels, these conventional supply chains produce one or more co-products, which may be as economically important as the biofuel (Kindred et al. 2008). Currently, co-products are used as animal feed (e.g. DDG and oil seed cake), chemicals (e.g. glycerine), and heat/electricity generation (e.g. bagasse). Carbon dioxide or pure carbon may prove to be important new markets, particularly if emission trading schemes are developed using life-cycle assessment methodologies.

Using conventional food crops as feedstocks for biofuels also provides a degree of flexibility to the feedstock producer, by providing alternative markets for the crop.

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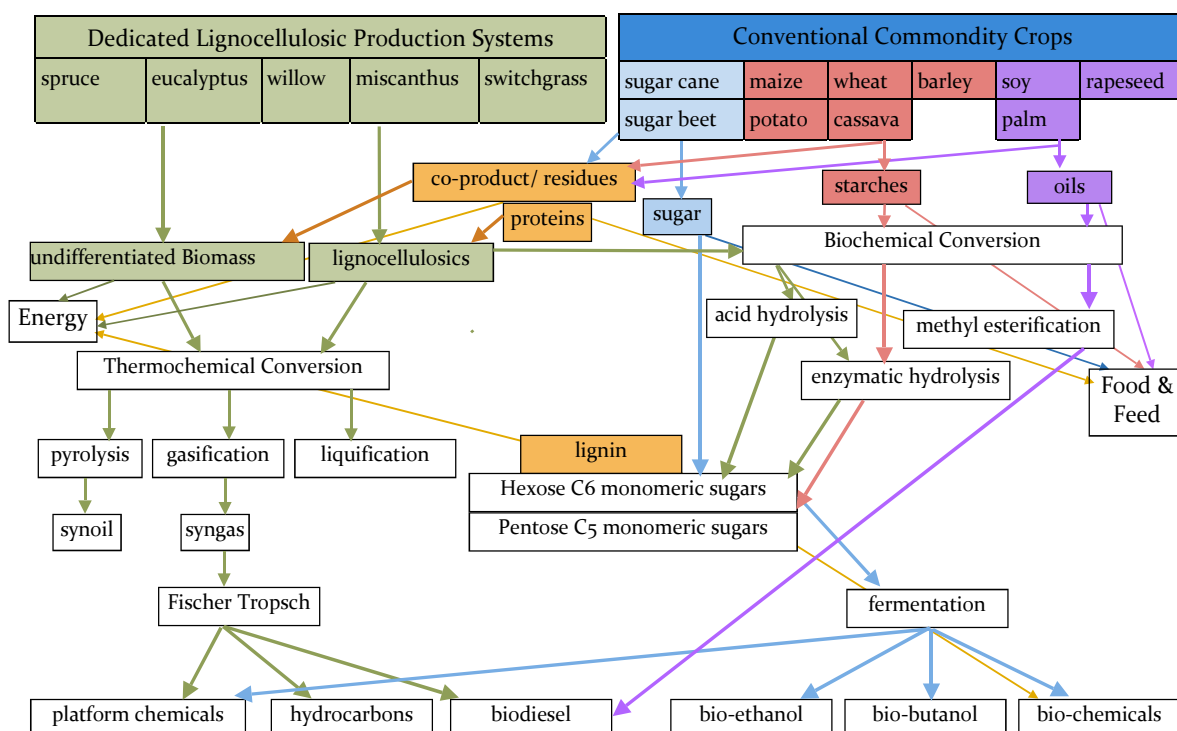
This flexibility can result in competition between the food and fuel markets, which can be severe when the signal for new demand (often policy instigated), exceeds the ability of producers to respond with increased production or when climate negatively affects yields in major supplying regions.

The second and third categories of feedstock are often referred to as 'lignocellulosic' feedstocks. The use of these is dependent on the development of novel conversion technologies; either biological or thermochemical, or a combination of both. These novel conversion processes are likely to be predominantly supplied with lignocelluloses mainly derived from trees or energy grasses, but may also be provided directly from agriculture or forestry residues or as co- or byproducts in food and biochemical

processing facilities (Ragauskas et al. 2006; Gallagher 2008).

In practice, the subdivision of feedstocks in this way is overly simplistic as the existing trend towards more flexible preprocessing and processing facilities continues, aiming to maximize the value of the incoming feedstock and targeting multiple markets simultaneously. This approach can be seen in the new generations of biofuel production facilities based on conventional feedstocks e.g. corn (maize), sugarcane, sugar beet or wheat, which co-produce a variety of high-value products. For example, British Sugar's Wisington sugar beet bioethanol refinery in the U.K. produces crystalline sugar, electricity, ethanol, CO<sub>2</sub> and heat for use in nearby greenhouses, and an osmo-protection chemical betaine. Other examples include the E3 and Range corn-based biofuel refineries in

Figure 13.1 Trends in the development of selected feedstocks for biofuels.



the US and the Tianguan Henan wheat-cassava ethanol refinery in China (Stowers 2007; Liu 2008).

This chapter explores two divergent but not necessarily competitive trends in the development of feedstocks for biofuels (Figure 13.1):

- Dedicated lignocellulosic supply chains (e.g. trees and grasses), wherein conversion systems can be thermo-chemical or biochemical. Both systems use aggressive depolymerisation technologies on the lignocellulosic feedstock, coupled to catalytic and/or biological synthesis technologies.
- Supply chains based on more compositionally diverse feedstocks (e.g. conventional commodity crops such as cereal and oilseed crops, or novel multipurpose crops), which have, historically, been developed exclusively for food or other single-purpose outcomes e.g. starch, sugar, oil or protein. However, they also co-produce cellulose, hemicellulose and lignin often in the form of residues that are generated either in-field and/or in the conversion facility. Conversion systems will tend to use milder extraction, depolymerization and decomposition technologies to obtain the high-value components (e.g. starch, sugars, oils, proteins and platform chemicals, etc.) Starch, sugars and vegetable oils may be used to make biofuels, but the large volumes of lignin and possibly cellulosic co-products or residues that may also be produced, could then be converted to biofuels (or other energy vectors) using the aggressive depolymerization systems described in the previous bullet.

These two pathways for feedstock development are likely to have very different research, development, and dissemination (RD&D) strategies and imply different demands for nutrients, water, land/soil quality, pest management and capital (social, environmental, and economic). Both outcomes blur the distinction between 'product' and 'residue' as the value, economic or otherwise, gets redistributed across a broader share of the aboveground biomass produced. Entirely new feedstocks are also emerging (e.g. algae and halophytic plants), which are likely to be grown on land where food crops are not viable, such as degraded or marginal land.

In addition, a supply chain may use genetically modified organisms (GMOs), either to supply the feedstock or in the conversion process. When using GMOs for feedstock provision, open and widespread release is implicit however, when used in the conversion facility, complete containment may be possible.

### Lignocellulosic biomass

Lignocellulose comprises almost all of the non-reproductive components of plants and forms the structural components of the plant's cell walls that make up 80% of the world's biomass. Lignocellulosic plant material is composed of carbohydrates (70 to 90% of the dry biomass), and lignin (10 to 25%). Carbohydrates are further divided into celluloses and hemicelluloses. Cellulose is a polymer that is entirely composed of hexose sugars in a form that is resistant to depolymerization (i.e. *alpha*-glucan). Hemicelluloses are polymers with variable shares of hexose (C6) and pentose (C5) sugar monomers, are less stable, and thus easier to extract.

Table 13.1 Sample compositions of a range of potential biofuel feedstocks (% dry matter). (Source: Sassner et al, 2008; US DOE, 2009 )

|                         | Cellulose | Hemicellulose | Lignin | Total Sugars |    |
|-------------------------|-----------|---------------|--------|--------------|----|
|                         |           |               |        | C6           | C5 |
| Maize (corn) grain      | 12-15     | 5-12          | 0.1    | 75           | 6  |
| Maize Stover (w/o cobs) | 35        | 22            | 23     | 42           | 26 |
| Sugar cane bagasse      | 37        | 28            | 23     | 40           | 24 |
| Softwood (Spruce)       | 40        | 31            | 28     | 59           | 8  |
| Hardwood (Eucalyptus)   | 45        | 19            | 31     | 52           | 14 |

The exact nature of the biomass composition can have important implications in feedstock processing depending on the conversion process employed. It is relatively unimportant in thermochemical conversion, because processing will decompose the biomass to CO, H<sub>2</sub> and/or CH<sub>4</sub> before being resynthesized to larger molecules (Woods and Bauen 2003). However, biomass composition is critical in biological conversion systems, particularly the breakdown of the carbohydrate fraction into its cellulose and hemicellulose fractions. The extracted hexose sugars can be fermented to ethanol using standard microbial systems. Standard yeasts cannot use pentose sugars and modified yeasts or other bacteria are required to ferment them. Alternatively, because C<sub>5</sub> fermentation can be relatively inefficient, pentoses may be separated and used for purposes other than biofuel production.

Table 13.1 highlights the heterogeneity in the composition of selected potential and actual feedstocks for biofuel production. In particular, the share of pentose sugars ranges from 6% - 26% of dry biomass, and hexose sugars from 40% - 75%. As noted above, the type of sugar polymer is a critical factor in the

potential for commercial exploitation. Grains, for example, have the highest percentage of C<sub>6</sub> sugars, but not in the form of cellulose or hemicellulose rather as starch (*alpha*-glucan). Starch can be hydrolyzed by readily available, low cost, amylases and the C<sub>6</sub> sugars can then be simply and efficiently fermented to ethanol or sold as glucose.

Substantial amounts of lignocellulosic materials are generated from all forms of terrestrial crop and forestry production. With conventional cropping, a greater amount of aboveground lignocellulosic biomass is typically produced relative to the mass of the harvested material (see harvested (i.e. product): lignocellulosic (i.e. residue) mass ratio in Table 13.2). Figure 13.8 shows potential biofuel production from lignocellulosic residues and from dedicated biomass.

### Multipurpose crops

All food and non-food crops can be converted to biofuels using either existing or advanced conversion technologies or combinations of both. This flexibility has added value to the 'bio-refinery' concept. From a biofuel

Table 13.2 Crop R (residue) and P (production) coefficients: (adapted from Rosillo-Calle et al, 2006)

| Type                        | P:R  | P GJ t <sup>-1</sup> | P comp       | R GJ t <sup>-1</sup> | R comp       |
|-----------------------------|------|----------------------|--------------|----------------------|--------------|
| Coarse grains <sup>1</sup>  | 1.3  | 14.7                 | 20% air dry  | 13.9                 | 20% air dry  |
| Oats <sup>1</sup>           | 1.3  | 14.7                 | 20% air dry  | 13.9                 | 20% air dry  |
| Maize <sup>1</sup>          | 1.4  | 14.7                 | 20% air dry  | 13.0                 | 20% air dry  |
| sorghum                     | 1.4  | 14.7                 | 20% air dry  | 13.0                 | 20% air dry  |
| wheat                       | 1.3  | 14.7                 | 20% air dry  | 13.9                 | 20% air dry  |
| barley                      | 2.3  | 14.7                 | 20% air dry  | 17.0                 | dry weight   |
| rice                        | 1.4  | 14.7                 | 20% air dry  | 11.7                 | 20% air dry  |
| Sugar cane                  | 1.6  | 5.3                  | 48% moisture | 7.7                  | 50% moisture |
| Pulses tot. <sup>2</sup>    | 1.9  | 14.7                 | 20% air dry  | 12.8                 | 20% air dry  |
| Dry beans                   | 1.2  | 14.7                 | 20% air dry  | 12.8                 | 20% air dry  |
| cassava <sup>3</sup>        | 0.4  | 5.6                  | harvest      | 13.1                 | 20% air dry  |
| potatoes                    | 0.4  | 3.6                  | 50% moisture | 5.5                  | 60% moisture |
| Sweet potatoes <sup>3</sup> | 0.4  | 6                    | harvest      | 5.5                  | harvest      |
| fruits                      | 2.0  | 3                    | harvest      | 13.1                 | 20% air dry  |
| vegetables                  | 0.4  | 3                    | fresh weight | 13                   | 20% air dry  |
| Fibre crops <sup>4</sup>    | 0.2  | 18                   | 20% air      | 15.9                 | 20% air dry  |
| Seed cotton                 | 2.1  | 25                   | dry weight   | 25                   | dry weight   |
| sunflower                   | 2.1  | 25                   | dry weight   | 25                   | dry weight   |
| soybeans                    | 2.1  | 15                   | 20% air dry  | 16                   | 20% air dry  |
| goundnuts                   | 2.1  | 25                   | 20% air dry  | 16                   | 20% air dry  |
| tea                         | 1.2  | 10                   | 20% air dry  | 13                   | 20% air dry  |
| Copra (coconut product)     |      | 28                   | 5% moisture  |                      |              |
| Fibre (coconut residue)     | 1.1  |                      |              | 16                   | air dry      |
| Shell (coconut residue)     | 0.86 |                      |              | 20                   | air dry      |

1) Values for coarse grains (including maize, sorghum and oats) are best assumptions based on those values for similar crops given by Ryan & Openshaw, 1991; Senelwa & Hall, 1994; Strehler & Stutzle, 1987; and Woods, 1990.

2) Values for pulses total are best assumptions based on those values for similar crops given by Ryan & Openshaw, 1991; Senelwa & Hall, 1994; and Strehler & Stutzle, 1987.

3) Values for cassava and sweet potatoes are best assumptions based on those values for similar crops given by Senelwa & Hall, 1994; and Strehler & Stutzle, 1987.

4) Values for fibre crops are best assumptions based on those values for similar crops given by Senelwa & Hall, 1994; and Strehler & Stutzle, 1987.5) The product : residue ratios for sunflower and groundnuts are best assumptions based on those values for similar crops given by Strehler & Stutzle, 1987.

production perspective, there are some advantages of using conventional food and non-food crops including:

- highly concentrated fractions of easy-to-process biomass, e.g. simple sugars, starches or oils
- conventional low risk and relatively cheap technologies
- reduced risk from commodity price volatility via multiple co-product streams and potential to flexibly target a range of markets

Table 13.3 highlights the differences in composition of some selected major carbohydrate, oil-rich and traditional fibre crops. An aspect of the oil-rich crops is that they can also have high protein content and are, therefore, often grown primarily for animal feed production (e.g. rapeseed and soybean). Oil extraction increases the protein content of the residual biomass, potentially raising its

fractions can be further processed, for example, to extract the protein from rapeseed or soy meal and then the residual carbohydrates converted to biofuels and/or electricity. The economic consequences of developing and deploying the technologies required to extract and process residues are now the subject of intense research and development efforts around the world (Ragauskas et al. 2006; Royal Society 2008).

### Demand for photosynthetically fixed carbon

The future demand for biofuels is one component of the expanding human demand for photosynthetically fixed carbon (Rojstaczer et al. 2001). Historically, humans have used biological material to provide a wide range of services such as food, energy (including light, heat, and transport), materials (for housing construction, early transport, clothing etc) and chemicals, particularly naturally occurring medicines. The industrial revolution of the 19th century and the

Table 13.3 Composition of conventional and lignocellulosic harvested biomass (% dry mass). Sources: adapted from Hoffman (2008) and Stowers (2007)

| Harvested biomass fraction  | Carbohydrates | Proteins | Lipids (oils) |
|-----------------------------|---------------|----------|---------------|
| Conventional crops          |               |          |               |
| Sugar beet                  | 94            | 0.04     | 0             |
| Wheat grain                 | 75            | 14       | 3             |
| Rape (canola) seed          | 25            | 25       | 45            |
| Maize (corn) grain          | 70-76         | 8-11     | 3-19          |
| Lignocellulosic crops       |               |          |               |
| Maize Stover (without cobs) | 68            | --       | --            |
| Softwood (Spruce)           | 67            | --       | --            |
| Hardwood (Euclayptus)       | 66            | --       | --            |

value as an animal feed. Alternatively, residual

Table 13.4 IEA Projected global demand for gasoline and diesel (2010 and 2020). EJ =  $10^{18}$  J; BL =  $10^9$  liters; Pg C =  $10^{15}$  grams carbon; = 1 Gt C ( $10^9$  metric tonnes).

|                                  | 2010        |             |            | 2020        |             |             |
|----------------------------------|-------------|-------------|------------|-------------|-------------|-------------|
|                                  | EJ          | BL          | Pg C       | EJ          | BL          | Pg C        |
| <b>Total (Gasoline + diesel)</b> | <b>75.3</b> | <b>2210</b> | <b>1.5</b> | <b>91.3</b> | <b>2680</b> | <b>1.81</b> |
| Gasoline-all regions             | 44.4        | 1350        | 0.87       | 53.6        | 1630        | 1.05        |
| Diesel-all regions               | 30.9        | 865         | 0.62       | 37.7        | 1060        | 0.76        |

technological/electronic revolution of the 20th century launched a dramatic increase in the use of fossil resources, reducing the share of traditional biomass resources within the global energy demand. In terms of mass or energy, though, the total demand for biological materials has not fallen (Rojstaczer et al. 2001; IEA 2007). Furthermore, with the advent of low-cost fossil fuels, much of the carbon supply needed to meet these demands has been transferred from living biomass to ancient, fossilized biomass resources. As fossil resources become constrained, either on the supply side due to extraction of a finite resource or on the demand side due to mitigation of climate change and/or technological innovation, demand for biological sources of carbon is unlikely to diminish. Rather, significant rates of expansion seem highly likely.

Based on IEA projections for global transport demand, the implied carbon demand would be about 1.5 giga tonnes (Gt C) in 2010 rising to about 1.8Gt C by 2020 (Table 13.4). By contrast, despite supply tripling between 2000 and 2007, the carbon contained in the 2007 global supply of biofuels was 28 Mt C, representing just under 2% of the carbon content of transport fuel demand.

Additional demand for fixed carbon is expected from other industries. The global chemical industry is reliant on naphtha, derived from oil and natural gas. As supplies become constrained, biological feedstocks provide the only viable alternative. The Porter Alliance (2008) estimates that about 1 Gt C would be required annually to meet the total current demand of the chemicals sector. Similarly, demands for biomass for electricity and heat are likely to expand, as the costs of alternative renewables are likely to be comparable more expensive (ICEPT and E4TECH 2003; Macedo 2008). The IPCC (2007) calculated that about 3.5 Gt C was required in 2004 for the global heat and electricity sectors.

Therefore, if biological feedstocks were to supply 10% of existing demand for transport, chemicals (including plastics), electricity and heat, at least 600 Mt C would be required annually. While a large share of this is likely to come from the residues or co-products of existing food and forestry industries (i.e. by more efficient use of the existing biomass flows and reduced wastage), a substantial fraction will need to come from increased yields and agricultural expansion (see chapter 4).

### Projected size of the transport market by 2020 and by fuel type

A wide array of transport fuels become possible and viable as the cost of conventional oil and gas-based fuels rise. In an assessment of renewable transport fuel options for the UK, Woods and Bauen (2003) found that from a subset of 88 different potential renewable fuel supply chains, at least seven different end-fuels could be derived either directly or indirectly from biomass including electricity, hydrogen, dimethyl ether (DME), biogas, biodiesel, Fischer-Tropsch diesel, straight vegetable oil, ethanol, and butanol. Each of these fuels requires differing degrees of alterations to the fuel supply infrastructure and underlying power-train technologies (The Royal Society 2008). Cost projections

were highly uncertain, as the different supply chains were characterized by technology sets ranging from currently commercial, through near-commercial, to laboratory-based concepts. Figure 13.2 highlights the interaction between the projected price for gasoline and diesel and projected cost ranges for bioethanol and biodiesel supply chains (current and future).

Figure 13.2 indicates that sugarcane ethanol and biodiesel produced from animal fats and used cooking oils are already directly competitive with fossil transport fuels when the price of oil rises above ~ \$50 USD per barrel. It also seems likely that, although subsidies to the corn-ethanol program in the USA were instrumental in establishing the industry, the

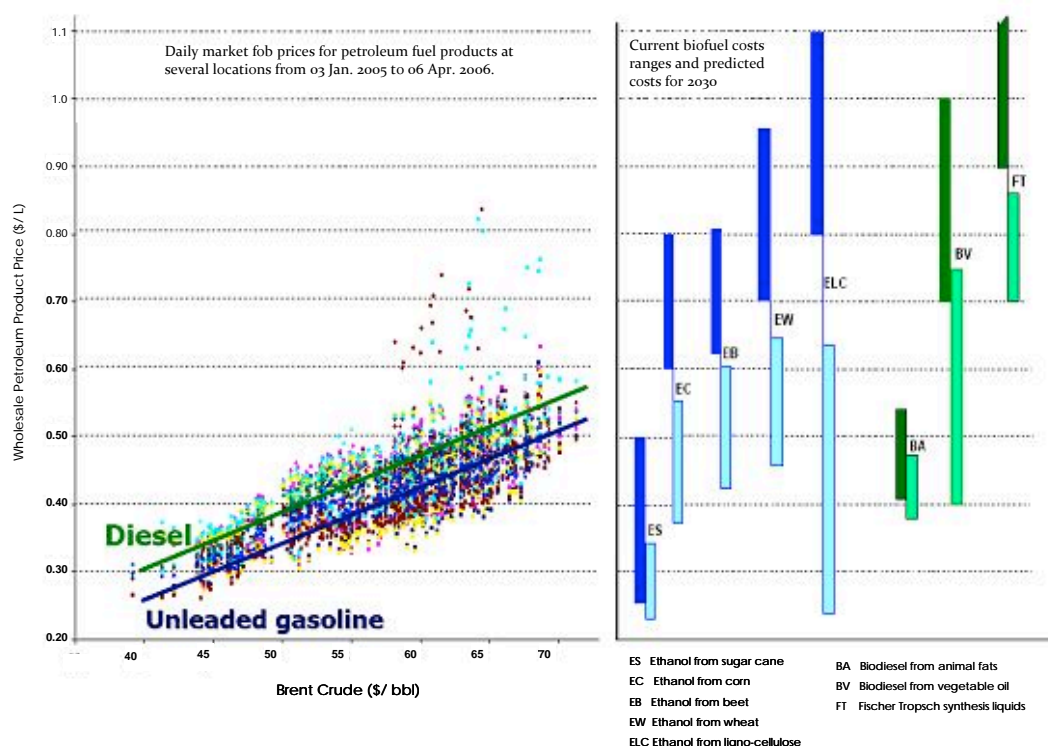


Figure 13.2 Predicted cost ranges for selected current and future biofuel supply chains versus the spread in diesel and gasoline prices between January 2005 and April 2006 (Sims, 2007)



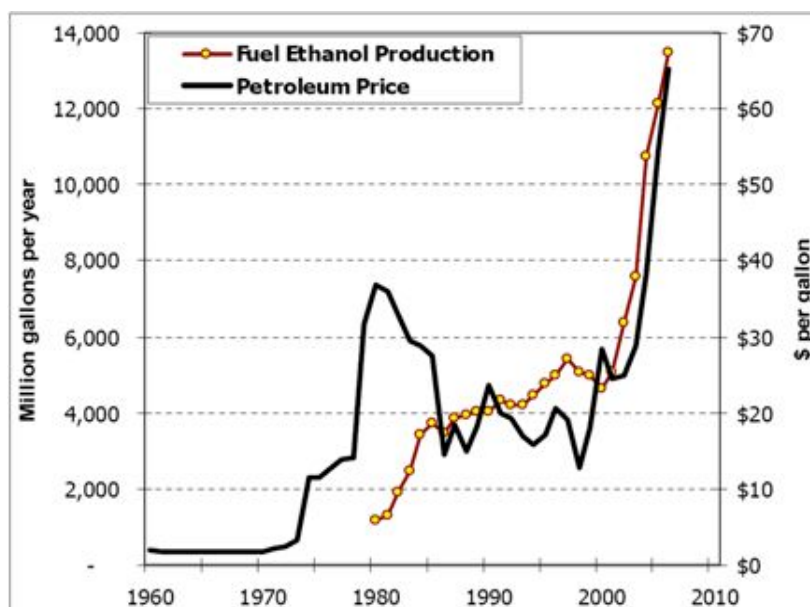


Figure 13.3 Linkage between US ethanol production and petroleum price (Kammen et al. 2007)

rapid expansion since 2000 has been mostly driven by the petroleum price, indicating a limited role of the subsidies in the recent expansion (Figure 13.3).

Substantial regional differences also exist in the relative shares of diesel and gasoline in the transport fuel mix. The IEA/WBCSD (2004), projects that 74% of North America's transport energy will be derived from gasoline with the remaining 26% being derived from diesel, while in Europe, 60% will be derived from diesel and 40% from gasoline. Given the scale of investment in the fuel supply and power-train manufacturing infrastructure and the relatively long lifespans of the vehicle stock, even with very substantial policy intervention, diesel and gasoline will remain the dominant fuels over the next 20 years. This has important implications for alternative transport fuel development and explains the emphasis on ethanol in the U.S. as a gasoline substitute and on biodiesel in Europe as diesel substitute. These relationships also explain

the US focus on starch crops (i.e. maize) and the EU focus on oilseed crops (i.e. rapeseed) as commercial feedstock crops.

While improving the energy efficiency of the transport sector and pushing for modal shifts remain important objectives at the national and international level, finding viable substitutes for diesel and gasoline must also be a central component of transport policy. Biofuels are therefore likely to have an expanding role as oil supplies become constrained, but need to be considered from the linked perspectives of energy security, climate change mitigation and adaptation, and rural development.

Fuel type and fuel quality requirements of the existing and emerging engine technologies drive demand, thus these factors will be major influences in the choice of biofuel supply pathways over the coming years and decades. In turn, this may dictate the choice of conversion technologies and biomass feedstocks required.

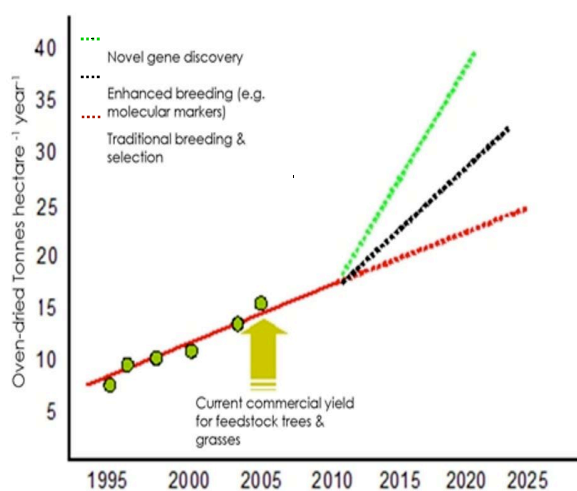


Figure 13.4 Yield improvement through breeding and potential increases through the application of biotechnology: the example of willow breeding at Rothamsted Research Station, UK.

Similarly, the two pathways for biofuel feedstock research and development outlined in the introduction, namely, dedicated lignocellulosic feedstocks and multi-product feedstocks, have major implications for the type of land/soils and the level of inputs required. There are also implications for the breeding strategies adopted, the nature of the investment and the likely scale of commercial operation (Woods 2006).

### An ideal biofuel crop?

Biomass feedstocks have inherently lower energy densities than those of the fossil alternatives and biofuel supply chain economics are sensitive to yield and quality of the crop. A selection of primary targets for crop improvement for biofuel (and bio-energy) production are outlined in Table 13.5. We discuss the potential future improvements in feedstock quantity and quality below.

*Biomass yields.* Karp and Shield (2008) offer the following three main and interlinked challenges facing yield improvement:

- How to change thermal time sensitivity to extend the growing season?
- How to increase aboveground biomass without depleting belowground biomass, so that sufficient reserves are still available for next year's growth (and thus without increasing the requirement for nutrient applications)?
  - i Maintenance or enhancement of soil organic matter contents
  - ii Maintenance or enhancement of soil C:N ratios
  - iii Potentials for soil carbon sequestration options
- How to increase aboveground biomass and not be limited by water?

Their analysis suggests that perennial energy crops (trees and grasses) have inherent advantages in terms of the ability to recycle nutrients and to more fully exploit the growing season. Crucially, they conclude that many of the traits that need manipulating to improve yields are unlikely to be amenable to simple genetic modification and will require a combination of approaches including conventional and quantitative trait loci (QTL) assisted breeding. The possible impacts of enhanced breeding through the use of molecular markers (i.e. QTL) and through novel gene discovery (i.e. GMO) are outlined in Figure 13.4. However, the direct application of novel gene discovery to yield improvement is considered controversial in the UK and yields of between 20 and 30 oven-dry tonnes per hectare are considered more likely with

Table 13.5 Some traits for sustainable yield and quality improvement (adapted from Karp &amp; Shield 2008)

| Quantity traits  | Quality traits  |
|--|---|
| <b>Maximizing radiation interception</b><br>Early bud flush/spring growth Frost (cold) tolerance<br>Fast canopy closure<br>Tolerance of high plant density<br>Resistance to lodging Low dust   | <b>Ease of harvesting/storage</b><br>Straight, upright stems<br>Resistance to lodging<br>Low moisture content<br>Disease/microbial breakdown resistance postharvest   |
| <b>Maximizing radiation use efficiency</b><br>Low-temperature-tolerant C <sub>3</sub> photosynthesis<br>Efficient C <sub>3</sub> and C <sub>4</sub> photosynthetic rates<br>Canopies with low extinction coefficients<br>Leaf traits for efficient light capture<br>High nitrogen-use efficiency<br>Drought tolerance<br>Disease resistance (including microbial breakdown postsenescence)<br>Pest resistance<br>Resistance to lodging | <b>Suitability for biological conversion technologies</b><br>Improved accessibility of carbon in the cell wall for industrial processing<br>Maximum density/high proportion of 'available' energy substrates<br><i>Desirable:</i> optimal flowering and senescence (for remobilization)<br><i>Desirable:</i> efficient nutrient recycling<br><i>Desirable:</i> low protein content? |
| <b>Maximizing water-use efficiency</b><br>Rapid attainment of maximum growth rate (drought avoidance)<br>Drought stress tolerance  | <b>Suitability for thermal conversion technologies (wastes &amp; by-products)</b><br>Maximum energy density<br>Optimal flowering and senescence (for remobilization)<br>Efficient nutrient recycling<br>Low ash and alkali metal contents   |
| <b>Environmental and financial sustainability</b><br>Optimal flowering and senescence (for remobilization)<br>Efficient nutrient recycling<br>Optimal root/shoot partitioning<br>High nitrogen-use efficiency  | <b>Health and safety</b><br>Disease/microbial breakdown resistance postharvest<br>Low dust  |

the effective application of QTL to conventional breeding.

The advantages of perennial crops are endorsed by Long (2007), which highlights a number of desirable traits similar to those in presented in Table 13.5. These traits include long canopy duration, ability to recycle nutrients to roots, low input requirements, ease of harvesting, high water use efficiency, no known pests and diseases, and cultivation with use of existing farm machinery. All of these point to focusing research and development on C<sub>4</sub> perennial rhizomatous grasses.

*C<sub>3</sub> or C<sub>4</sub> photosynthesis (radiation use efficiency; RUE)?* Typically, C<sub>4</sub> species are characterised by higher water and nitrogen

use efficiencies due to the a unique CO<sub>2</sub> concentrating mechanism which allows these plants to keep their stomata closed for longer times and to synthesize less Rubisco (Ribulose-1,5-bisphosphate carboxylase/oxygenase) per unit of carbon fixed relative to C<sub>3</sub> plants.

Published theoretical maximum photosynthetic efficiencies (i.e. the maximum amount of solar energy intercepted and captured by carbon fixation) for C<sub>3</sub> and C<sub>4</sub> plants are 5% and 6% respectively (Bolton and Hall 1991; Long 2007; Barber 2007). In practice, temperature, water, nutrients and pests and diseases can severely reduce this potential to the point where crops typically only reach ~ 0.1% to 0.8 % radiation use

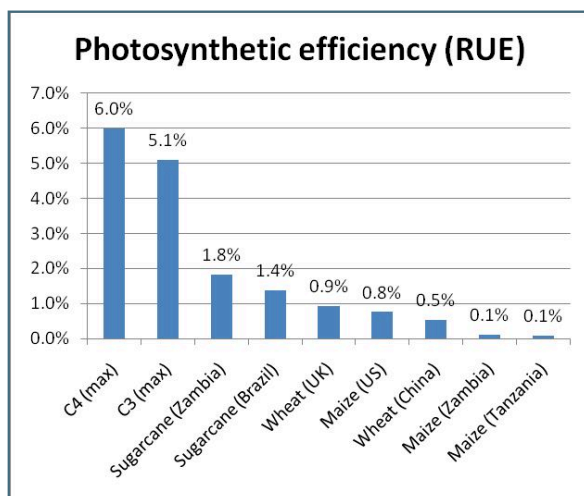


Figure 13.5 Radiation Use Efficiency (RUE) of various crops at different locations

efficiencies (RUE; MJ biomass per MJ Rg). However, high rates of RUE have been measured in natural environments. For example, *Echinochloa polystachya* achieved a RUE of 3.1% in a natural aquatic ecosystem in Manaus Brazil, and *Miscanthus x giganteus* achieved 2.0% in research trial plots in Essex, UK (Long 2007). It is interesting to note that sustained RUEs in excess of 1% have been noted in irrigated sugarcane plantations in southern Africa, as discussed below.

Such summaries disguise the very large range in RUE seen globally in managed ecosystems. It is necessary to distinguish between 'theoretical' yields that are obtainable by the plant under ideal and unlimited conditions; 'potential' yields obtainable in trial conditions; and 'actual' yields obtained in the field by farmers (Figure 13.5). In practice, a huge range of technical and non-technical issues affect farmers' and foresters' ability to achieve high yields that are both within and outside their control. Farmers and foresters attempt to mitigate these factors by both short- and long-term management strategies, but their ability to do so is constrained by knowledge, infrastructure,

investment capacity and local, national and regional policies (Hazel and Wood 2007).

Thus, yields can vary by an order of magnitude even with identical climate and soils. This inability to control the main factors related to yield can also lead to inefficient use of resources, for example, when complete crop failure occurs even after fertilizer applications have been made. This in part, explains why five times more nitrogen fertilizer was required per kg maize by Malawi's producers in 2002 compared with US maize production the same year, despite the Malawians applying 30% less nitrogen per unit area planted. On average in 2002, Malawi's farmers achieved yields of just under 1.1 t ha<sup>-1</sup> compared to the 8.1 t ha<sup>-1</sup> achieved by US farmers (FAOSTAT 2007).

According to Field et al (2008), the average annual net primary production (NPP) of croplands in any country rarely exceeds 7 tC ha<sup>-1</sup> and the global average annual NPP for native vegetation of 6.1 tC ha<sup>-1</sup> (when taken on the same land as the crops) is also generally higher than the crops that replace it. Figure 13.6 highlights the range in NPP compared to solar radiation for the same crops and locations used in Figure 13.5. As with Figure 13.5, the lack of correlation between solar radiation and yield points to varying effectiveness of management of the selected crops types in the different locations. It is also noteworthy that UK wheat, a C<sub>3</sub> temperate crop, has a higher RUE than US maize, an equivalent industrialized C<sub>4</sub> crop.

*Long canopy duration (perennials vs annuals).* Early canopy establishment increases the total amount of solar radiation that can be intercepted by the plant in a season but can also make the plant more vulnerable to frost damage in more temperate climates. However, substantial benefits in terms of dry

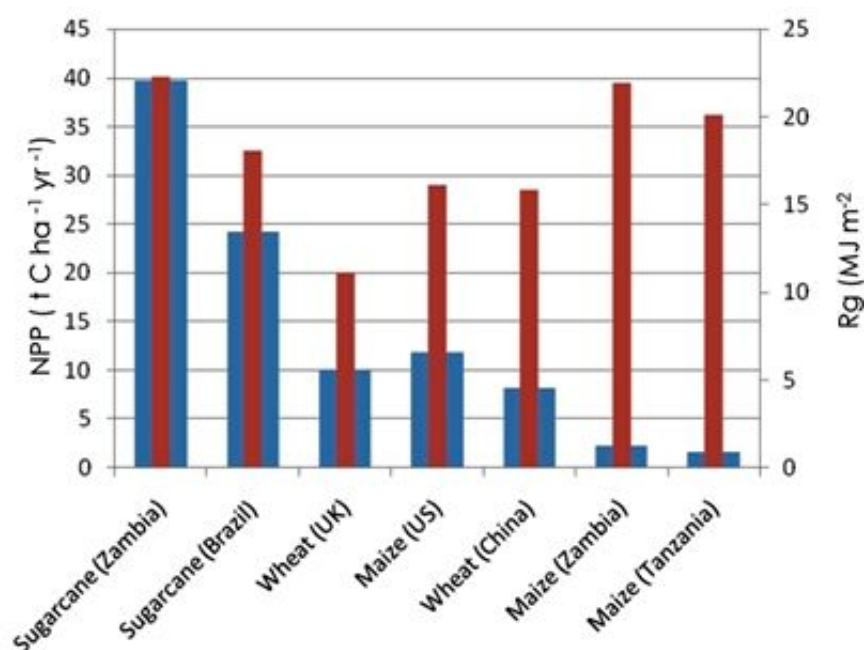


Figure 13.6 Net Primary Production (blue) versus Solar Radiation (red) for selected crops and locations

matter accumulation can result from early canopy deployment (Figure 13.7; based on Long 2007).

Advanced lignocellulosic conversion systems may allow crop breeders and biofuel producers to exploit variance in growth strategies of different plant species, by the adoption of multi-, co-, and parallel cropping strategies. These options are far more difficult to achieve where specific traits or quality parameters are needed (e.g. high sucrose content or specific carbon chain length for vegetable oils).

*Biofuel yields.* Figure 13.8 highlights the potential volumes of biofuels that could be produced from different conventional and dedicated feedstocks, using a combination of conventional and novel conversion technologies. It also compares the volumes of biofuels that could be produced from the oil, starch and sucrose fractions of conventional crops, with those that could be produced

from the cellulosic fractions of selected co-product/residue streams using hydrolysis and fermentation of the hexose and pentose sugar fractions. The output is not based on a comprehensive analysis of co-product and residues for each crop type. Where residues arise in-field and are considered suitable for recovery (e.g. straw from wheat and barley production), 50% are assumed to be recoverable (Woods & Hall 1994; Bauen et al. 2004). The choice of hydrolysis and fermentation technologies for the conversion of the cellulosic fractions to ethanol means that the lignin, and currently un-fermentable sugars, are not converted to biofuel. These are therefore available for electricity and heat production and could also form significant waste streams.

For the conventional feedstocks currently used to produce ethanol (barley, wheat, maize, sugar beet and sugarcane), productivities range from 2000 L ha<sup>-1</sup> for barley to

5500 L ha<sup>-1</sup> for sugarcane. For the oil/biodiesel crops (soybean, rapeseed and oil palm), yields range from 500 L ha<sup>-1</sup> (soybean) to 4600 L ha<sup>-1</sup> (oil palm). Substantial differences exist between crops in the amount of co-product/residues that arise at the processing/conversion plant and the share of those materials that comprise hexoses and pentoses.

The dedicated biofuel feedstocks (e.g. willow, eucalyptus and switchgrass) selected for this analysis, have a higher fraction of the total biofuel production that could be derived from C<sub>5</sub> sugars than that of the conventional crops. These crops are therefore likely more sensitive than conventional crops to the successful development of C<sub>5</sub> fermentation technologies. For example, based on published biomass sample data (Stowers 2007; Sassner et al. 2008; DOE 2009; Ray and Murphy 2009), eucalyptus has a higher fraction of accessible six-carbon (hexose) sugars than willow or switchgrass. Therefore, in the case of eucalyptus, it may be more cost-effective to use standard yeast-based fermentation for the C<sub>6</sub> sugars released and conventional technologies to burn the lignin and pentose sugars for electricity and heat production.

Figure 13.9 provides a comparison between the three feedstock types (starch, sucrose, dedicated lignocellulosic biomass and oil crops) based on the gross energy content of the biofuels produced per hectare. It also shows the potential for exploiting the residues/co-products for biofuel production. On this basis, conventional biodiesel production from Malaysian oil palm provides the greatest gross energy productivity (180 GJ ha<sup>-1</sup>); however, when residues or co-products arising at the mills are included, sugarcane achieves a gross energy yield of nearly 200 GJ ha<sup>-1</sup>. For sugarcane, and oil palm in particular,

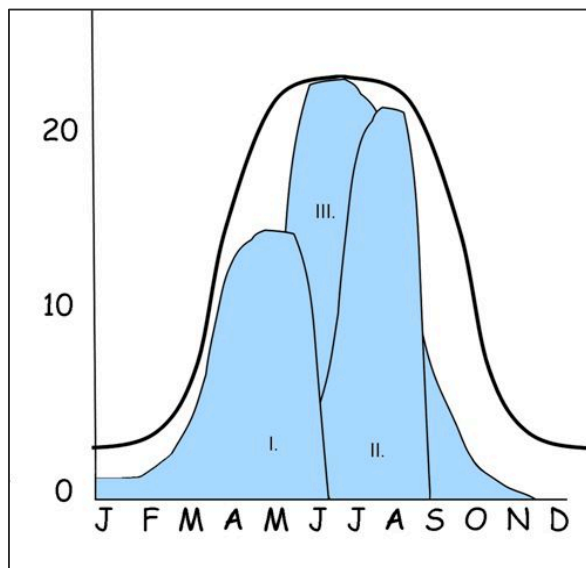


Figure 13.7 Seasonal radiation interception by I) C<sub>3</sub> (wheat), II) C<sub>4</sub> (maize), and III) C<sub>4</sub> perennial grass or C<sub>3</sub> perennial tree, crops (based on Long, 2007)

other residue and waste streams could also be used for biofuel, heat and/or electricity production including in-field residues (e.g. tops and leaves or palm fronds). It is interesting to note that the potential biofuel production from sugar beet pulp is low, although sugar beet provides the 4th highest gross energy yield per hectare of the eleven highlighted feedstocks.

This analysis does not provide an assessment of net energy returns or of the full life-cycle impacts of the different feedstock and technology supply chain options. The dedicated cellulosic crops can provide good gross energy yields with lower energy and GHG input costs compared with the other, more input intensive crops such as maize or wheat. However, the economic flexibility offered by multi-purpose, conventional crops, without substantial incentives for dedicated feedstocks, mean that conventional crops may continue to dominate the industry. Still, there are major advantages to use of dedicated cellulosic crops including more amenable

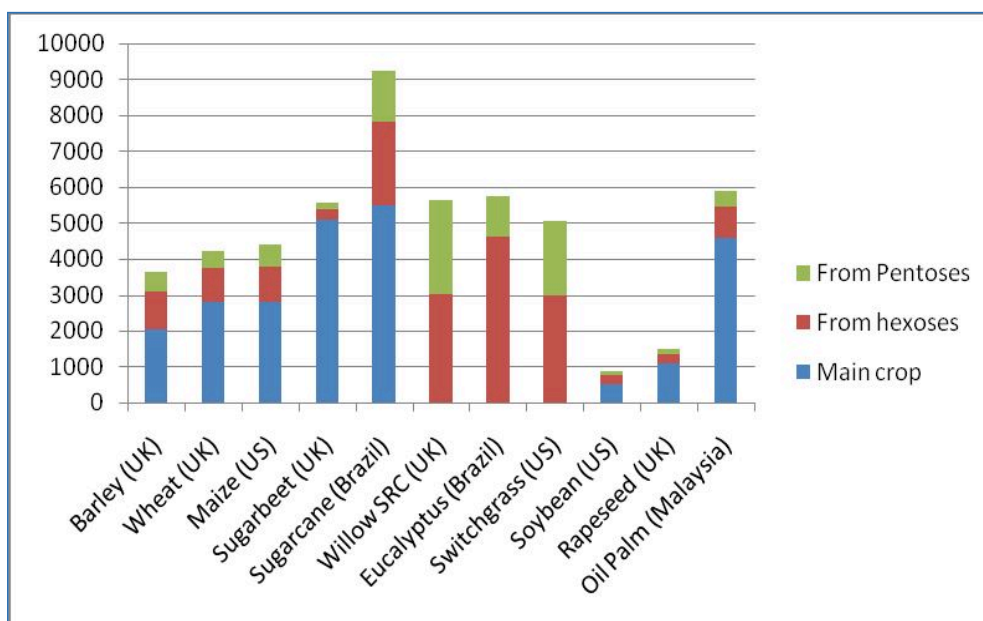


Figure 13.8 Conventional and advanced biofuel yields from a range of crops and locations (litres per hectare). Note: 'Main crop' (ethanol or biodiesel) = harvested grain (barley, wheat, maize, soybean, rapeseed/ fresh fruit bunches (oil palm)/ tubers (sugarbeet) or stem (sugarcane). 'Hexoses/pentoses' = biofuel from dedicated energy crop biomass e.g. SRC willow stems; switchgrass stem/ leaf material; or, from 'residues' wheat or rape straw, corn stover; bagasse from sugarcane, fibre and shells from oil palm

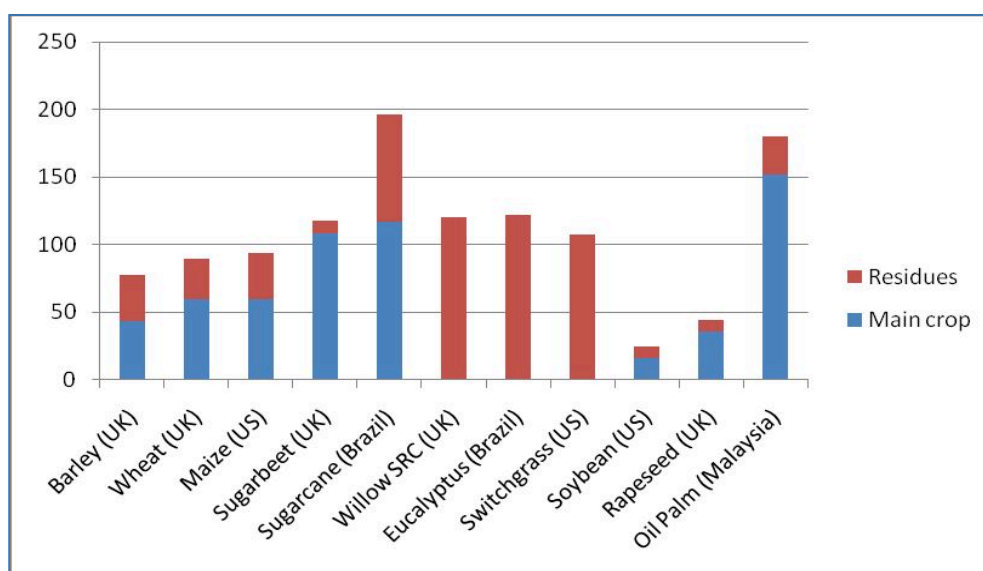


Figure 13.9 Gross biofuel energy yields ( $\text{GJ ha}^{-1}$ ) from conventional and advanced biofuel supply chains [for simplicity the dedicated biomass crops (willow, eucalyptus and switchgrass) are shown as being residue only and have no starch, oil or sucrose 'main crop' yield]

yield improvement and utilization on lower-cost land not suitable for multi-purpose crops.

### Conclusions

The potential for future feedstock crops for biofuels can be characterized by two basic emerging research, development and implementation strategies:

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

Which of these two feedstock supply strategies dominates in the provision of biofuels, as a subset of the wider demand for bioenergy by 2030, will be dictated by the technological development profile of critical technologies versus the potential for yield increase, particularly for lignocellulosic crops. Yield increases will come mainly through simple, low cost agronomic management gains in conventional cropping. Such gains, as well as capacity investment to ensure long-term viability of yield increases, are likely to be particularly important in Sub-Saharan Africa, which must also find practical ways to transition from subsistence agriculture to appropriate and equitable modern production systems.

If multi-product strategies in bio-refineries prove to be an economically effective, flexible, and robust way of improving yields, then cultivated land area may not need to be expanded. On the other hand, if advanced

lignocellulosic biofuel production technologies prove to be cost-effective, then option no. 1 will dominate and the implications for land use change, particularly in terms of carbon emissions and loss of natural habitats with high biodiversity, need to be assessed.

The economic choice to deploy advanced biofuel conversion technologies will be determined by a wide range of factors including: the value of biofuels in the transport markets (a function of fossil fuel prices); the cost of the feedstock and its ease of conversion; the capital, operational, and maintenance costs arising from the combination of the technology and feedstock choice; and the value of the co-products in alternative markets (e.g. animal feed or electricity).

While fundamental yield improvement through increased radiation interception and radiation use efficiency is a major driver in the medium to long term (10 to 30 years), in the shorter term, gains will be achieved primarily by closing the 'yield gap' in developing countries and in the former Soviet Union states. The more biomass that can be sustainably produced and turned into useful products per unit land area, the greater the likely economic return. In turn, this should lead to greater confidence in investment to infrastructure and inputs necessary to achieve longer-term yield stability. However, the ability to use increasing fractions of the total aboveground (and possibly below-ground) biomass has implications for carbon stocks, particularly soil organic matter, and therefore impacts long-term yield stability, as well as nutrient and water use efficiency and potentially biodiversity. Careful regulation and possibly novel monitoring and reward systems will be required to ensure 'good' long-term management practices are put into practice.



We foresee a major role for good agricultural practice (GAP) standards, verified by credible assurance and certification, and a number of regional and global initiatives are currently underway (e.g. the Global Roundtable for Sustainable Biofuels (RSB), the Roundtable for Sustainable Palm (RSPO), developing ISO and CEN standards). Both competitive and synergistic interactions between food and fuel are likely and policies designed to promote biofuels need to specifically enhance the synergies and avoid the competitive aspects. In addition, local and national policies to support agriculture, maintain local air quality, and, more recently, climate change mitigation are critical factors in the development of biofuel supply chains and industries. The certainty or uncertainty that policies create can have a major effect on long-term market development and on the selection of technologies that move from research through to market.

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