Moving forward with biofuels

Authors
Richard Flavell[1], Carlos Henrique de Brito Cruz[2], Martin Christie[3], Janet Allen[4], Martin Keller[5], Paul Gilna[6] and Douglas B. Kell[4]

[1] Ceres Inc., 1535 Rancho Conejo Boulevard, Thousand Oaks, California 91320, United States.

[2] São Paulo Research Foundation (FAPESP), Rua Pio XI 1500, 05468-901, São Paulo, SP, Brazil.

[3] BP Biofuels, 1 St James's Square, London SW1Y 4PD, United Kingdom.

[4] Biotechnology and Biological Sciences Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1UH, United Kingdom.

[5] Oak Ridge National Laboratory, Post Office Box 2008, Oak Ridge, Tennessee 37831-6253, United States.

[6] BioEnergy Science Center, Oak Ridge National Laboratory, Post Office Box 2008, Oak Ridge, Tennessee 37831-6342, United States.

The major source of energy for the Earth, now and in the future, is the Sun. Fossil fuels are the products of energy captured from the Sun by photosynthesis in organisms of past eras. If we are to meet the growing demands of human societies and sustain a healthy environment we must urgently maximize energy capture, using the most efficient plant systems throughout agriculture, for a huge plethora of uses including making fuels. How else are we to move to low-carbon mobility, at the same time as ensuring adequate food, feed and fibre supplies, and sufficient environmental services, and minimizing or even reversing the production of greenhouse gases, in a context in which energy use is predicted to double by 2050 (ref. 1)? Biofuels are a significant part of the answer, because they can substitute for most uses of oil and, in particular, for liquid transportation fuels. They can also serve as substitutes for oil in the petrochemical industries, for example in the production of 'green' polymers. Biomass can also be combusted to generate electricity. Larger scale biofuel production, as part of a much more efficient global agriculture, is not only vital for energy sufficiency, security and sustainability, but is also, in consequence, a major item in policy, regulatory and sustainability agendas. Biofuel production has generated much controversy and mis-understanding over land-use requirements and greenhouse gas savings. What plants to grow where and what fuel molecules to make are critically debated. Also, all biofuels are often erroneously lumped together regardless of their structure and origins. These features of, and the urgent needs for, biofuel production make this *Nature* Outlook timely and noteworthy.

Today, biofuels are a large-scale contributor to the transport fuel space whereas other renewables, such as wind and solar, make minimal contributions. The most well-known examples of biofuels are made from the soluble sugars in sugar cane (in Brazil), corn starch (in the United States), and the oils in the seeds of palm, soybean and oilseed rape. In 2010, the United States

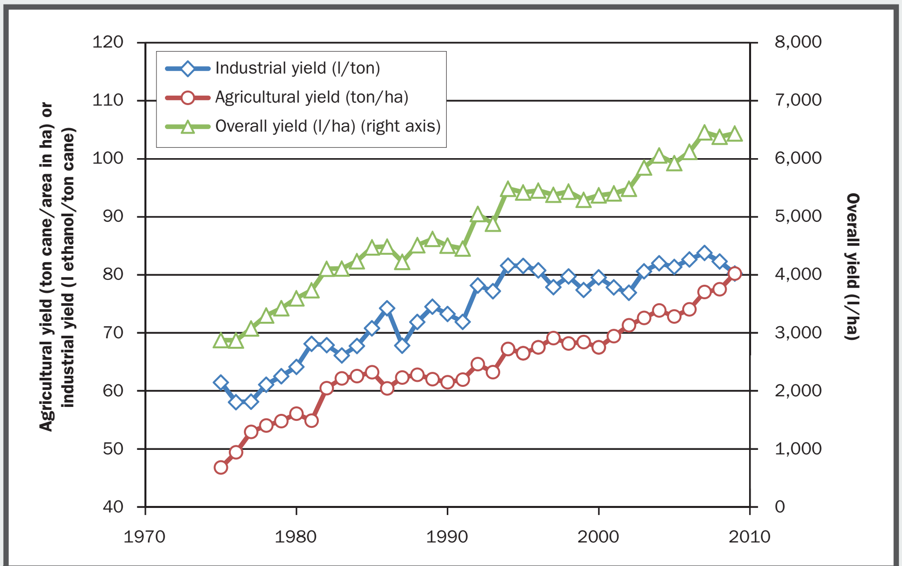


Figure 1 | Average productivity increases in sugar cane and ethanol production in Brazil. The red line shows the agricultural yield in tons of cane per hectare. The blue line shows the industrial yield in litres of ethanol per ton of cane, calculated considering the proportion of total recoverable sugar used for ethanol production. The green line shows the overall yield in litres of ethanol per hectare. Data are from ref. 18.

produced 13 billion US gallons of ethanol from corn, accounting for about 10% of the total fuel used — an 800% increase from 2000 (ref. 2). Brazil produced about 8 billion gallons from sugar cane, which is about 50% of its fuel usage[3]. These increases were achieved not just by using more land. Sugar-cane productivity increased in Brazil, for example, from 50 tons per hectare in 1975 to 80 tons per hectare in 2005 (Fig. 1). Global biodiesel production peaked at 691 million gallons in 2008, having increased more than tenfold in the European Union between 1998 and 2008. Thus, biofuels and their feedstock crops are already making a significant impact economically and agriculturally, and could contribute up to and beyond 30% of world transport needs by 2050, delivering carbon dioxide reductions from road transport of 20% or more. The importance of the sustainabilities and efficiencies of biofuel production chains has resulted in them becoming active foci of research and innovations. The broader issues surrounding the generation and use of biofuels are complex and interlinked. They include how land is used, agricultural practices, food, feed and fibre supplies, greenhouse gas emissions, carbon sequestration, climate change, management of local economies and social issues. All of these are also relevant to food production and other uses of land.

Diversity of biofuels and production processes

Which feedstocks to grow, where, how and at what scale, and which fuel molecules to make, are crucial issues that have generated much controversy and misunderstanding. There are many choices and the number will become greater as more, locally advantaged solutions are found. Similar questions are also relevant to all agricultural uses of land, including food production, as we seek to maximize energy capture through agriculture.

Biofuel production starts with the choice of plant species and varieties that will serve as feedstock. Each plant species and variety is adapted to particular environments, and grown in specific agricultural systems with widely varying economics. Sugar cane is adapted to more tropical conditions. Wheat, in contrast, does well in temperate climes. Many local criteria apply to biofuel production. The same biofuel molecule can be made from different feedstocks, by different processes with different energy and greenhouse gas balances. For example, ethanol from sugar cane has a different history from that of ethanol from wheat or corn starch. In the same way, a bio-hydrocarbon such as biodiesel can have a different history depending on whether it came from jatropha, soybean or algae.

The yields of ethanol and oils made from grain and seeds are inevitably limited, because such crops are bred to have relatively low total biomass. This is illustrated by comparing the seeds of normal grain sorghum with the total biomass of large sorghum plants bred specifically for total biomass (Fig. 2). Therefore much research is going into creating more economically attractive options for turning whole plants into biofuels, using plants of exceptionally large size, which are efficient in terms of land use. These crops include switchgrass, Napier grass (*Pennisetum purpureum*), *Miscanthus* and low-sugar forms of sugar cane (energy cane). Fast-growing trees such as varieties of coppiced willow, poplar and eucalyptus are also being specifically selected[4]. In addition 'sweet' sorghum, which is an annual plant with high concentrations of sugars in its stems, similar to the perennial vegetatively propagated sugar cane, is being introduced into Brazil to extend the operational season of sugar-cane mills. 'Waste' materials from many sources, including household, agricultural and forest 'leftovers', are also being exploited for fuel production. Methane (biogas) is produced by the anaerobic fermentation of plant biomass on ever increasing scales. Thus the potential number of sources of biofuels is large.

Figure 2 | Comparison of sorghum plants bred for grain and for high biomass. Short-seeded sorghum plants bred for grain are shown in the foreground, and non-flowering sorghum plants bred for high biomass are shown in the background. In the former, only the grain is used to make ethanol from starch, whereas in the latter the whole plant is converted into a biofuel. The high-biomass plants are routinely more than 12 feet tall.

Plant biomass that is rich in lignocelluloses (stems and leaves including wood chips) can be turned into many kinds of biofuel molecule. When ethanol is produced from cellulose, the biofuel is often called 'cellulosic ethanol' (en.wikipedia.org/wiki/Cellulosic_ethanol). Some approaches involve initially converting celluloses and hemicelluloses to sugars using complex enzyme cocktails, and then fermenting the sugars to ethanol using yeast or bacteria that are optimized for mass alcohol production. Before the enzymes can attack the lignocelluloses efficiently, some form of pre-treatment needs to be given to make the sugar residues accessible. The removal or reduction of this energetically and financially expensive step is the focus of much research. Genetic changes to the feedstock can help to reduce the pre-treatment and enzyme requirements[5].

In other frontier approaches, bacteria and yeast have been designed to complete conversion both to sugars and to alcohol (consolidated bioprocessing)[6]. Figure 3 shows *Clostridium thermocellum* bacteria attached to poplar fibres initiating such a process. Chemical processes at high temperatures can convert biomass into hydrocarbons via, for example, pyrolysis and gasification[7]. In pyrolysis, the biomass is converted into gases and pyrolysis oil, which can be further processed into fuel molecules. In gasification, gases are formed at high temperature and converted into fuel molecules via, for example, the Fischer-Tropsch process. Because internal combustion engines across the world are based on hydrocarbons, hydrocarbon 'drop-in' biofuels are appealing, as are advanced 'drop-in' molecules such as biobutanol. Yet, Brazil has shown that with comparatively minor changes to engines, ethanol as a fuel is just as viable. Algae and cyanobacteria produce biomass and oils from photosynthesis, and were probably the original source of fossil oils. Macroalgae are harvested from the oceans by several Asian countries, and processed for biofuels and chemicals. Microalgae are favoured elsewhere[8]. These have some advantages over land plants based on the combination of their oils, the ability to grow on poor quality water and the potential for cultivation in ponds on poor quality land. Strain improvements are readily possible with state-of-the art molecular genetics and synthetic biology. In addition, their biomass can be converted into biofuels, similar to higher plants. However, difficulties in culturing them at an equivalent scale to fossil fuels together with the associated costs are limiting their adoption. Nevertheless, they hold potential provided that these difficulties can be overcome. The commercialization of processes making fuels from total biomass that can compete with fossil fuels economically will radically change the landscape of biofuel production in comparison to the use of seeds, especially if co-products are routinely produced. The first 35 biorefineries are being designed and/or constructed in the United States at pilot, demonstration and commercial scales to make fuels from biomass.

Fossil oils are the source of most modern petrochemicals; hence, there are expectations that we will need a chemicals industry that uses sugars and chemicals derived from plant-based feedstocks. Such chemicals can be the by-products of biofuel industries or vice versa. For example, in Brazil in 2010, the major petrochemical company Braskem inaugurated its first plant, which is expected to produce 200,000 tons per year of 'green' polyethylene from sugar-cane ethanol. This green polyethylene is sold at a premium price over the petrochemical product for the automotive industry and other international customers. Also in Brazil, Amyris will soon start producing farnesene using microorganisms that process cane sugar. In the future, a lignin by-product from biomass-based biorefineries has the potential to provide a low-cost alternative to petroleum-based precursors in the manufacture of carbon fibre, which is a structural material with much greater specific strength and stiffness than conventional materials such as steel and aluminium, the market for which is universally projected to grow exponentially. Lignin-based carbon fibre could create significant added value for current biorefineries, in addition to reducing further the carbon footprints of future products. Thus, biorefineries with by-products that are required at large scale are likely to transform not only biofuel production but also green chemistry.

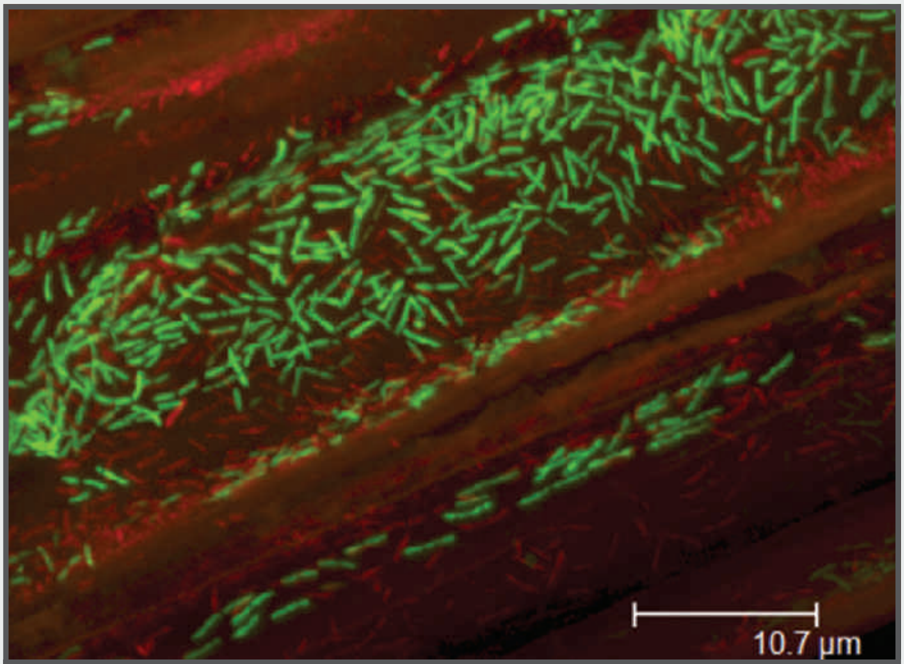


Figure 3 | *Clostridium thermocellum* bacteria (viable stained green) adhering to and digesting poplar lignocelluloses. Engineered strains of *C. thermocellum* can digest cellulose to accessible sugars and also convert the released sugars into biofuels. This integrated process is also called consolidated bioprocessing. *C. thermocellum* grown by Babu Raman and imaged by Jennifer Morrell-Falvey, Oak Ridge National Laboratory.

Box 1 | Current research and development topics

1. ***Crops, agronomy and land use (equivalent to ‘upstream’ in oil terminology):*** continuing to increase yields of feedstocks (plants, trees and algae) through genomics-driven breeding (Fig. 2), using less and cheaper land and water; boosting yields of food, feed and biofuel productivity from the same land; developing traits such as disease and drought tolerance; optimizing feedstocks for use on land that is not ideal or needed for food production; reducing energy inputs; optimizing agricultural logistics, providing mixtures of crops, including cover crops, that will allow year-round biofuel production; sustaining land fertility and managing disease by crop rotation; sequestering more soil carbon; reducing greenhouse gas emissions during crop production; integrating pasture and bioenergy crops; optimizing composition (lignin, hemicelluloses and cellulose structures for processing); optimizing co-product production; and optimizing the logistics of the harvesting, storage and transport of supply chains, at scale.
2. ***Conversion of biomass to fuels and other products (‘refining’ in oil terminology):*** increasing efficiency of conversion of lignocellulose to sugars using more effective pre-treatments; making conversion to sugars more efficient using novel enzyme cocktails; designing new conversion organisms using synthetic biology (Fig. 3); improving fermentation organisms; improving pyrolysis and gasification and other systems to create ‘drop-in’ hydrocarbon fuels; making longer-lived catalysts; reducing biorefinery capital costs; scaling up and optimizing energy efficiencies in biorefineries; producing co-products in the context of biofuel and bioenergy production; reducing inputs including water; and optimizing the supply chains at scale.
3. ***Selection and optimization of fuel molecules and other products as part of the knowledge-based bioeconomy[19] for particular commercial uses (‘downstream’ in oil and petrochemicals terminology):*** evaluating alcohols and different hydrocarbons for different modes of transport, including jet engines; evaluating co-products; optimizing distribution-systems pipelines, pumps and dealing with spills; substituting alcohols for oil in petrochemical processes.

New visions and research agendas

Given the diverse and urgent needs, researchers, governments and industries are exploring how and to what extent biofuels can be produced sustainably to contribute positively to better sources of energy at lower costs per gallon. While much information has been gathered from the large-scale experiments in the United States with corn and in Brazil with sugar cane, many innovations and/or improvements are needed at all of the steps along the existing production chains as well as in newly designed production chains and biorefineries. There is enormous scope for progress, as it is early days for many aspects of the research. With today’s genomics-assisted breeding, systems biology and synthetic biology, ideal feedstocks can be envisaged and created step-by-step. The biomass of such feedstocks will greatly exceed that of seed crops, and, unlike food crops, their nitrogen requirements are far less acute so they can grow on more marginal land. Substantial increases in photosynthetic and water-use efficiencies are both necessary and possible. Extraordinary progress is emerging from university, national institute and industrial laboratories, and there is undoubtedly much proprietary unpublished work. Some of the progress is noted in this Outlook, and some current research and development agendas for three broad areas of the value chain, for implementation in the short, medium and long terms, are shown in Box 1.

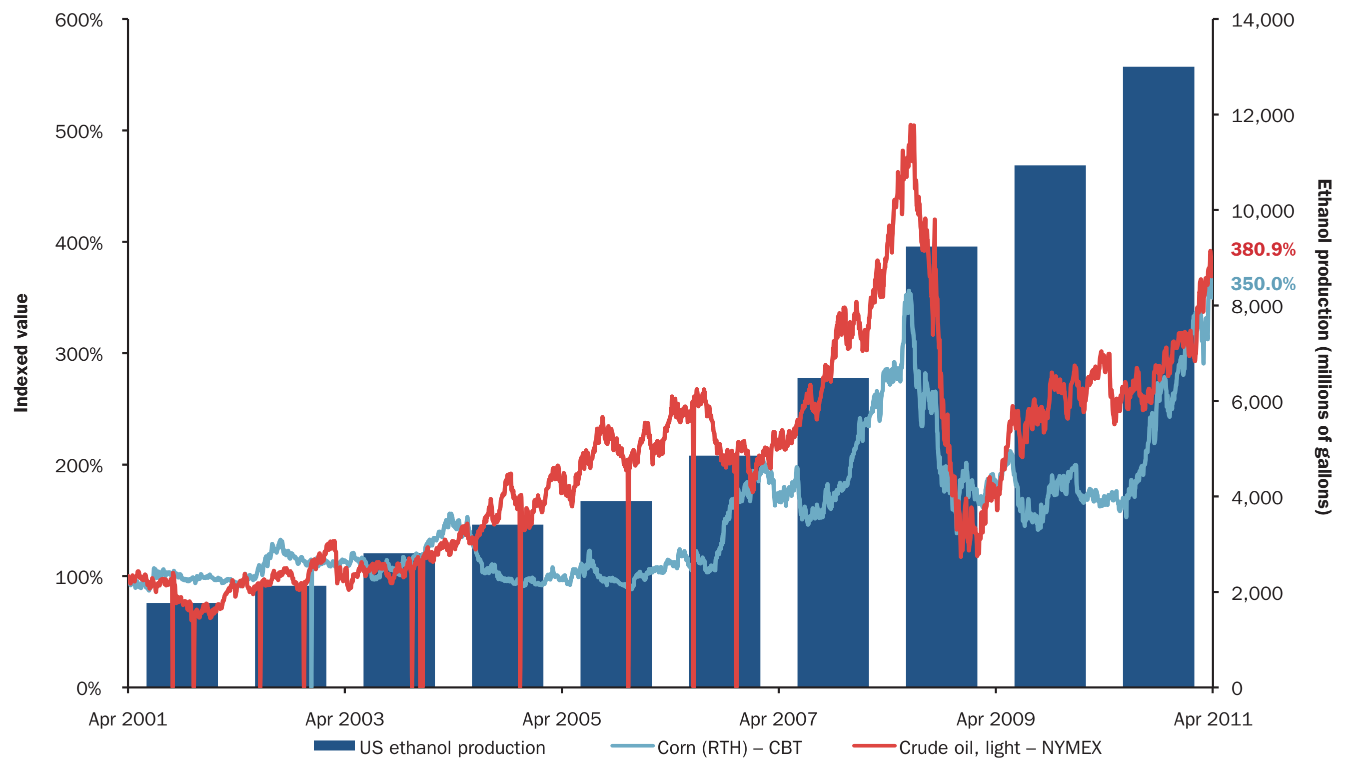
The impacts of all these research investments will be to change radically the landscape of biofuel production over time, making it much more efficient and effective, allowing biofuels to compete with fossil fuels economically and using reduced amounts of land. Over time, policy makers and citizens, commensurate with technical progress, investment profiles and policy changes, should have many more options for sources of fuels, providing that research and implementation programmes are sustained. This vision is another reason to welcome this Outlook.

Satisfying fuel, food, feed and other needs sustainably

There has been controversy surrounding biofuels because they require the use of land, and are thus perceived to be in competition with food production, forests, leisure, maintenance of biodiversity and many ecosystem services. Is this justified? A recent and comprehensive assessment from the Nuffield Council on Bioethics[9] puts this in context, and sets down six principles, the last of which is that, provided that the first five principles are met, it is in fact unethical not to develop biofuels. This is because, without an affordable alternative to fossil fuels for transport, quality of life will decline substantially over the coming decades and current strategies based on fossil fuels alone are unsustainable. Many experts have modelled the food-production potential based on current and past progress (see ref. 10 for a review). Those who recognize the potential of sustainable intensification[11], with technical and policy advances, conclude that the world could generate twice the amount of food that is grown at present on the land that is currently farmed, providing the necessary innovations in plant breeding and agronomy are made, and appropriate policies, including water management and infrastructure development, are put in place locally. Is enough land available for increased food, feed and biofuel production? One study concluded that Latin-America and Africa have at least 430 million hectares of land available, after considering that needed for food, feed, housing and forests — which contrasts with the 4.8 million hectares that Brazil has devoted currently to biofuel production (about 0.8% of its total arable land)[12]. Thus, Brazil could supply sugar-cane ethanol to displace 5% of the world usage of gasoline using an additional 21 million hectares of its available land through mild pasture intensification[13]. Also, the United States took more than 50 million acres out of agriculture between 1982 and 1999, resulting in 35 million fewer acres being in crop production. This occurred while (and, in part, because) food production efficiency increased substantially. Similarly, Europe has taken land out of production, and much additional capacity resides in Eastern Europe. Thus, there could be sufficient land for food and biofuel production in many places assuming that agricultural yields are intensified to levels that are routine today in the hands of better farmers, and that agriculturally idle lands are also used. There are predictions that top US corn yields today will become average yields in the next 20 years. If so, there will be a near doubling of corn production or — put another way — nearly one-half of the acreage could become available for other uses. Such goals are vital, and endorse the value of plant breeding and feedstock yield improvements for energy crops on marginal land. Successes will reduce land footprints for food and fuel, making so much more possible. Such assumptions are dependent on increased investments in plant breeding, and the existence of local wealth, markets and policies to drive higher production farming. Land use is local, so much local decision-making is required to achieve this, including optimizing the trade-offs between the potential economies and land requirements of larger and smaller biorefineries. As on-farm and biorefinery improvements come along, policy makers will need to ensure that the right food, feed and biofuel balances occur, so that the best standards of living are reached for all and greenhouse gas emissions are reduced.

Agriculture is unfortunately far from ideal. It has many limitations and many improvements are necessary all over the world. It is a major source of greenhouse gases, especially nitrous oxide from excessive fertilizer application and methane from ruminant animals, although biofuels can achieve net sequestration of atmospheric carbon[14]. Some of the carbon fixed in photosynthesis, at least in perennial crops, can become sequestered in soils via deep roots. Similarly, there are examples in Brazil where substituting sugar cane for degraded pastures has caused an increase in soil carbon[15]. Nevertheless, better management and fertilizer regimes for food, feed and biofuel production will need to be designed and implemented worldwide, to minimize greenhouse gas emissions while ensuring a large net carbon capture. Assessments of total energy and emission outputs coming from life-cycle analyses, adjusted to market rewards, will need to drive these regimes. We also need to understand better the direct effects of biofuels on climate[16].

It has been often stated that biofuels are responsible for driving up food prices. However, the prices of traded commodity crops are influenced by many factors, both real and speculative, and commodity crop prices usually track the price of oil, irrespective of biofuel production,



CBT, Chicago Board of Trade; NYMEX, New York Mercantile Exchange; RTH, regular trading hours.

Figure 4 | Prices of oil and corn, and production of US ethanol from corn over the past 10 years.

often making this the dominant factor (Fig. 4). It has been argued that food crops should not be used for biofuels. Actually, most crops can be used for both. Cellulosic ethanol and thermochemical conversions of biomass to biofuels will change this debate dramatically, as the parts of the crops that are not used for food or to replenish soil fertility will be available for biofuels, making major efficiency gains for both food and biofuel farming from the same land footprint. Thus, any notional separations of land for food and land for biofuels are erroneous. The challenges, as stated above, are how to develop our food and biofuel supply systems, locally and globally, at the required scale, at reduced cost[17]. Hopefully many applications of biofuel production will generate local wealth and thereby lead to poverty reductions and better nutrition than exists today.

In conclusion, there is no doubt that the world is being forced to recognize the need for transitional changes to food and energy production systems. Such changes demand that land and other resources are used more wisely and sustainably, and that greenhouse gas levels are managed more acutely. Many countries are passing legislation to achieve such ends. Transitions in farming patterns will be necessary in many places. Local economies can and will be transformed. Such visions are being matched by new ideas of how to produce biofuels at scale. These technical visions are far-reaching, in some cases involving new organisms, biochemistry, chemistry and engineering. All of the steps in the production chains are being studied with a view to making them cheaper, with smaller land and carbon footprints. Grasping these visions is important because they help policy makers and citizens to understand what is possible and probable, and in what timescales. They also define the challenges for the relevant scientific and industrial communities. We hope this *Nature* Outlook helps to raise awareness of how science and technology can provide both understanding and solutions to the problem of how best to use the land on our planet. Clearly the prize is too large and the needs are too urgent to be ignored or mismanaged. It is time to get serious about biofuels everywhere, because biofuel production can be a driver for new solutions to energy capture and agriculture, as well as the essential sustainable sources of transportation fuels and the 'green' chemical products that we all need. In future, many societies might not have access to affordable oil. However, all societies have some land and access to sunlight; the critical question is how each will use them to best advantage, for themselves and for all.

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