5. Environmental impacts of biofuels

Although biofuel production remains small in the context of total energy demand, it is significant in relation to current levels of agricultural production. The potential environmental and social implications of its continued growth must be recognized. For example, reduced greenhouse gas emissions are among the explicit goals of some policy measures to support biofuel production. Unintended negative impacts on land, water and biodiversity count among the side-effects of agricultural production in general, but they are of particular concern with respect to biofuels. The extent of such impacts depends on how biofuel feedstocks are produced and processed, the scale of production and, in particular, how they influence land-use change, intensification and international trade. This chapter reviews the environmental implications of biofuels; the social implications will be considered in the following chapter.

Will biofuels help mitigate climate change?[10]

Until recently, many policy-makers assumed that the replacement of fossil fuels with fuels generated from biomass would have significant and positive climate-change effects by generating lower levels of the greenhouse gases that contribute to global warming. Bioenergy crops can reduce or offset greenhouse gas emissions by directly removing carbon dioxide from the air as they grow and storing it in crop biomass and soil. In addition to biofuels, many of these crops generate co-products such as protein for animal feed, thus saving on energy that would have been used to make feed by other means.

Despite these potential benefits, however, scientific studies have revealed that different biofuels vary widely in their greenhouse gas balances when compared with petrol. Depending on the methods used to produce the feedstock and process the fuel, some crops can even generate more greenhouse gases than do fossil fuels. For example, nitrous oxide, a greenhouse gas with a global-warming potential around 300 times greater than that of carbon dioxide, is released from nitrogen fertilizers. Moreover, greenhouse gases are emitted at other stages in the production of bioenergy crops and biofuels: in producing the fertilizers, pesticides and fuel used in farming, during chemical processing, transport and distribution, up to final use.

Greenhouse gases can also be emitted by direct or indirect land-use changes triggered by increased biofuel production, for example when carbon stored in forests or grasslands is released from the soil during land conversion to crop production. For example, while maize produced for ethanol can generate greenhouse gas savings of about 1.8 tonnes of carbon dioxide per hectare per year, and switchgrass – a possible second-generation crop – can generate savings of 8.6 tonnes per hectare per year, the conversion of grassland to produce those crops can release 300 tonnes per hectare, and conversion of forest land can release 600–1 000 tonnes per hectare (Fargione *et al.*, 2008; The Royal Society, 2008; Searchinger, 2008).

Life-cycle analysis is the analytical tool used to calculate greenhouse gas balances. The greenhouse gas balance is the result of a comparison between all emissions of greenhouse gases throughout the production phases and use of a biofuel and all the greenhouse gases emitted in producing and using the equivalent energy amount of the respective fossil fuel. This well-established, but complex, method systematically analyses each component of the value chain to estimate greenhouse gas emissions (Figure 22).

The starting point in estimating the greenhouse gas balance is a well-defined set of boundaries for a specific biofuel system, which is compared with a suitable

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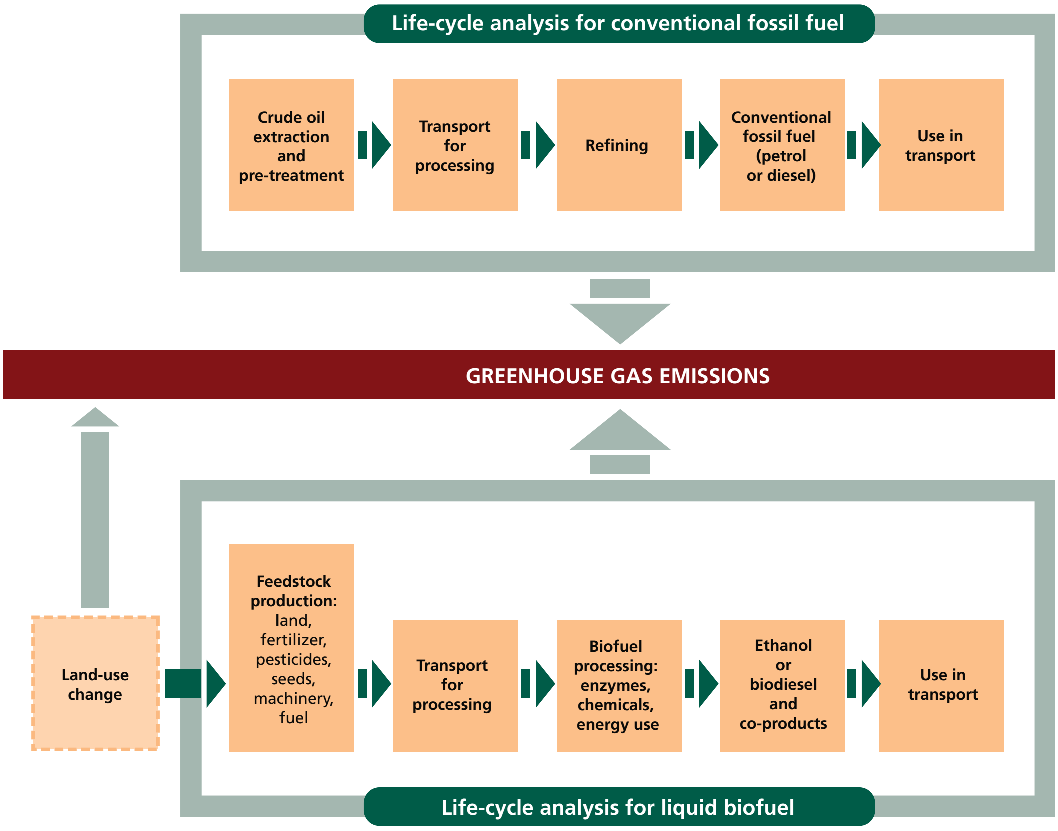
[10] The analysis in this section draws partly on FAO (2008d).

"conventional" reference system – in most cases petrol. Several biofuel feedstocks also generate co-products, such as press cake or livestock feed. These are considered "avoided" greenhouse gas emissions and are assessed by comparing them with similar stand-alone products or by allocation (e.g. by energy content or market price). Greenhouse gas balances differ widely among crops and locations, depending on feedstock production methods, conversion technologies and use. Inputs such as nitrogen fertilizer and the type of electricity generation (e.g. from coal or oil, or nuclear) used to convert feedstocks to biofuels may result in widely varying levels of greenhouse gas emissions and also differ from one region to another.

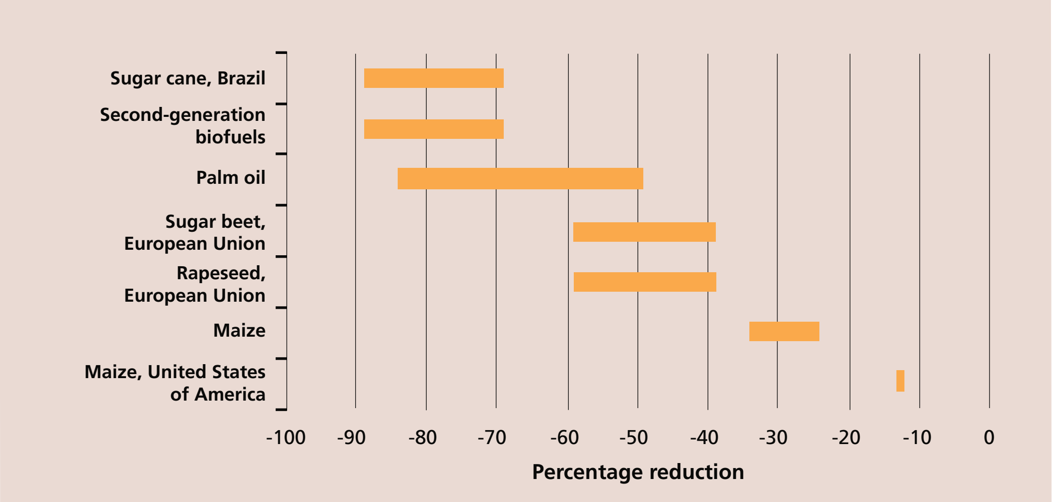
Most life-cycle analyses of biofuels, to date, have been undertaken for cereal and oilseeds in the EU and the United States of America and for sugar-cane ethanol in Brazil. A limited number of studies have considered vegetable oil; biodiesel from palm oil, cassava and jatropha; and biomethane from biogas. Given the wide range of biofuels, feedstocks and production and conversion technologies, we would expect a similarly wide range of outcomes in terms of emission reductions – which is indeed the case. Most studies have found that producing first-generation biofuels from current feedstocks results in emission reductions in the range of 20–60 percent relative to fossil fuels, provided the most efficient systems are used and carbon releases deriving from land-use change are excluded. Figure 23 shows estimated ranges of reduction in greenhouse gas emissions for a series of crops and locations, excluding the effects of land-use change. Brazil, which has long experience of producing ethanol from sugar cane, shows even greater reductions. Second-generation biofuels, although still

FIGURE 22
Life-cycle analysis for greenhouse gas balances



Source: FAO.

FIGURE 23
Reductions in greenhouse gas emissions of selected biofuels relative to fossil fuels



Note: Excludes the effects of land-use change.

Sources: IEA, 2006, and FAO, 2008d.

insignificant at the commercial level, typically offer emission reductions in the order of 70–90 percent, compared with fossil diesel and petrol, also excluding carbon releases related to land-use change.

Several recent studies have found that the most marked differences in results stem from allocation methods chosen for co-products, assumptions on nitrous oxide emissions and land-use-related carbon emission changes. At present, a number of different methods are being used to conduct life-cycle analysis and, as noted above, some of these do not consider the complex topic of land-use change. The parameters measured and the quality of the data used in the assessment need to comply with set standards. Efforts are under way within, among others, the Global Bioenergy Partnership, to develop a harmonized methodology for assessing greenhouse gas balances. There is a similar need for harmonization in assessing the broader environmental and social impacts of bioenergy crops to ensure that results are transparent and consistent across a wide range of systems.

In assessing greenhouse gas balances, the data on emissions emanating from land-use change are crucial if the resulting picture is to be complete and accurate. Such emissions will occur early in the biofuel production cycle and, if sufficiently large, may require many years before they are compensated by emissions savings obtained in subsequent stages of production and use. When land-use changes are included in the analysis, greenhouse gas emissions for some biofuel feedstocks and production systems may be even higher than those for fossil fuels. Fargione *et al.* (2008) estimated that the conversion of rainforests, peatlands, savannahs or grasslands to produce ethanol and biodiesel in Brazil, Indonesia, Malaysia or the United States of America releases at least 17 times as much carbon dioxide as those biofuels save annually by replacing fossil fuels. They find that this "carbon debt" would take 48 years to repay in the case of Conservation Reserve Program land returned to maize ethanol production in the United States of America, over 300 years to repay if Amazonian rainforest is converted for soybean biodiesel production, and over 400 years to repay if tropical peatland rainforest is converted for palm-oil biodiesel production in Indonesia or Malaysia.

Righelato and Spracklen (2007) estimated the carbon emissions avoided by various ethanol and biodiesel feedstocks grown on existing cropland (i.e. sugar cane, maize, wheat and sugar beet for ethanol, and rapeseed and woody biomass for diesel). They found that, in each case, more carbon would be sequestered over a 30-year period by converting the cropland to forest. They argue that if the objective of biofuel support policies is to mitigate global warming, then fuel efficiency and forest conservation

BOX 9
The Global Bioenergy Partnership

The Global Bioenergy Partnership (GBEP), launched at the 14th session of the United Nations Commission on Sustainable Development in May 2006, is an international initiative established to implement the commitments taken by the G8+5 countries[1] in the 2005 Gleneagles Plan of Action. It promotes global high-level policy dialogue on bioenergy; supports national and regional bioenergy policy-making and market development; favours efficient and sustainable uses of biomass; develops project activities in bioenergy; fosters bilateral and multilateral exchange of information, skills and technology; and facilitates bioenergy integration into energy markets by tackling specific barriers in the supply chain.

The Partnership is chaired by Italy, and FAO is a Partner and hosts the GBEP Secretariat. GBEP cooperates with FAO's International Bioenergy Platform, the International Biofuels Forum, the International Partnership for the Hydrogen Economy, the Mediterranean Renewable Energy Programme, the Methane to Markets Partnership, the Renewable Energy Policy Network for the 21st Century, the Renewable Energy and Energy Efficiency Partnership, the United Nations Conference on Trade and Development (UNCTAD) BioFuels Initiative and the Bioenergy Implementing Agreements and related tasks of the International Energy Agency, among others. In addition, the Partnership has formed a task force to work on harmonizing methodologies for life-cycle analysis and developing a methodological framework for this purpose. All these initiatives provide important avenues for assisting both developing and developed countries in building national regulatory frameworks for bioenergy.

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[1] The G8+5 group comprises the G8 countries (Canada, France, Germany, Italy, Japan, the Russian Federation, the United Kingdom and the United States of America), plus the five major emerging economies (Brazil, China, India, Mexico and South Africa).

and restoration would be more effective alternatives.

Among the options for reducing greenhouse gas emissions that are currently being discussed, biofuels are one important alternative – but in many cases improving energy efficiency and conservation, increasing carbon sequestration through reforestation or changes in agricultural practices, or using other forms of renewable energy can be more cost-effective. For example, in the United States of America, improving average vehicle-fuel efficiency by one mile per gallon may reduce greenhouse gas emissions as much as all current United States ethanol production from maize (Tollefson, 2008). Doornbosch and Steenblik (2007) estimated that reducing greenhouse gas emissions via biofuels costs over US$500 in terms of subsidies per tonne of carbon dioxide in the United States of America (maize-based ethanol) and the cost can be as high as US$4 520 in the EU (ethanol from sugar beet and maize) – much higher than the market price of carbon dioxide-equivalent offsets. Enkvist, Naucler and Rosander (2007) report that relatively straightforward measures to reduce energy consumption, such as better insulation of new buildings or increased efficiency of heating and air-conditioning systems, have carbon dioxide abatement costs of less than €40 per tonne.

Both the scientific and policy dimensions of sustainable bioenergy development are evolving rapidly (almost on a weekly basis). A comprehensive understanding of the relevant issues, including land-use change, and proper assessment of greenhouse gas balances are essential in order to ensure that bioenergy crops have a positive and sustainable impact on climate-protection efforts. The complexity of factors relating to land-use change has led to its omission from most bioenergy life-cycle analyses but it remains an essential piece of information that governments need to consider in formulating national bioenergy policy.

In addition to the impacts of feedstock production on greenhouse gas emissions, biofuel processing and distribution can also have other environmental impacts. As in the hydrocarbon sector, the processing of biofuel feedstocks can affect local air quality with carbon monoxide, particulates, nitrogen oxide, sulphates and volatile organic compounds released by industrial processes (Dufey, 2006). However, to the extent that biofuels can replace traditional biomass such as fuelwood and charcoal, they also hold potential for dramatic improvements in human health, particularly of women and children, through reduced respiratory diseases and deaths caused by indoor air pollution.

In some cases, national regulations require importers to certify the sustainable cultivation of agricultural land, the protection of natural habitats and a minimum level of carbon dioxide savings for biofuels. Some countries and regional organizations (e.g. the United States of America and the EU) have suggested that net greenhouse gas balances from biofuels should be in the range of 35–40 percent less than that of petrol. A careful analysis of these issues is important for all stakeholders, especially for exporters of bioenergy crops or fuels, as a basis for investment and production decisions and ensuring the marketability of their products.

Land-use change and intensification

The preceding section highlighted the influence of land-use change on the greenhouse gas balances of biofuel production. When assessing the potential emission effects of expanding biofuel production, a clear understanding is needed of the extent to which increased production will be met through improved land productivity or through expansion of cultivated area; in the latter case, the category of land is also significant. Agricultural production techniques also

BOX 10
Biofuels and the United Nations Framework Convention on Climate Change

Although no international agreements specifically address bioenergy, the United Nations Framework Convention on Climate Change (UNFCCC) guides Member States to “take climate-change considerations into account, to the extent feasible, in their relevant social, economic and environmental policies and actions, and employ appropriate methods ... with a view to minimizing adverse effects on the economy, on public health and on the quality of the environment of projects or measures undertaken by them to mitigate or adapt to climate change” (UNFCCC, 1992, Article 4). The Kyoto Protocol, which expires in 2012, provides a robust and modern framework for promoting clean technologies such as those for renewable energy.

The Clean Development Mechanism (CDM), as one of the flexibility mechanisms within the Kyoto Protocol, was designed to assist Parties not included in Annex 1 in achieving sustainable development and in contributing to the ultimate objective of the Convention, and to assist Parties included in Annex 1 in complying with their quantified emission limitation and emissions reduction commitments. Since the inception of the CDM in 2005, energy-industry projects have dominated all project types registered in the CDM, including those for bioenergy. Within the field of bioenergy, several methodologies are available for projects that use biomass for energy generation, although there are only a limited number of approved methodologies for biofuels. A biofuel methodology based on waste oil is already available and a methodology for biofuel production from cultivated biomass is under development.

Source: FAO, based on a contribution from the UNFCCC Secretariat.

contribute to determining greenhouse gas balances. Both factors will also determine other environmental impacts relating to soils, water and biodiversity.

Over the past five decades, most of the increase in global agricultural commodity production (around 80 percent) has resulted from yield increases, with the remainder accounted for by expansion of cropped area and increased frequency of cultivation (FAO, 2003; Hazell and Wood, 2008). The rate of growth in demand for biofuels over the past few years far exceeds historic rates of growth in demand for agricultural commodities and in crop yields. This suggests that land-use change – and the associated environmental impacts – may become a more important issue with respect to both first- and second-generation technologies. In the short term, this demand may be satisfied primarily by increasing the land area under biofuel crops while in the medium and long term the development of improved biofuel crop varieties, changes in agronomic practices and new technologies (such as cellulosic conversion) may begin to dominate. Significant yield gains and technological advances will be essential for the sustainable production of biofuel feedstocks in order to minimize rapid land-use change in areas already under cultivation and the conversion of land not currently in crop production, such as grassland or forest land.

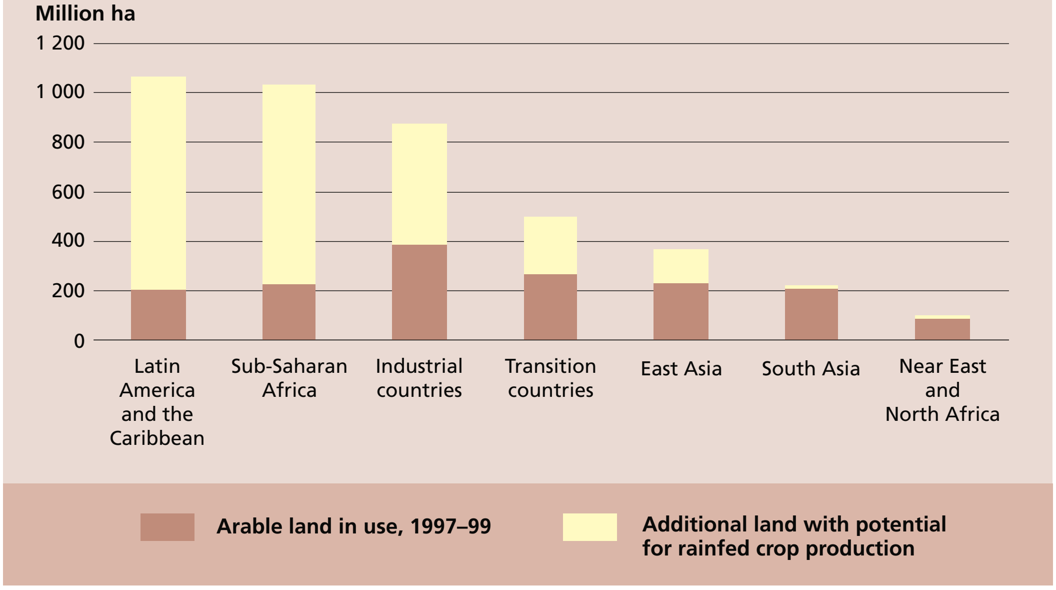
Area expansion

Of the world's 13.5 billion hectares of total land surface area, about 8.3 billion hectares are currently in grassland or forest and 1.6 billion hectares in cropland (Fischer, 2008). An additional 2 billion hectares are considered potentially suitable for rainfed crop production, as shown by Figure 24, although this figure should be treated with considerable caution. Much of the land in forest, wetland or other uses provides valuable environmental services, including carbon sequestration, water filtration and biodiversity preservation; thus, expansion of crop production in these areas could be detrimental to the environment.

After excluding forest land, protected areas and land needed to meet increased demand for food crops and livestock, estimates of the amount of land potentially available for expanded crop production lie between 250 and 800 million hectares, most of which is found in tropical Latin America or in Africa (Fischer, 2008).

Some of this land could be used directly for biofuel feedstock production, but

FIGURE 24
Potential for cropland expansion



Source: FAO, 2003.

increased biofuel production on existing cropland could also trigger expansion in the production of non-biofuel crops elsewhere. For example, increased maize production for ethanol in the central United States of America has displaced soybean on some existing cropland, which, in turn, may induce increased soybean production and conversion of grassland or forest land elsewhere. Thus, both the direct and indirect land-use changes caused by expanded biofuel production need to be considered for a full understanding of potential environmental impacts.

In 2004, an estimated 14 million hectares, worldwide, were being used to produce biofuels and their by-products, representing about 1 percent of global cropland (IEA, 2006, p. 413).[11] Sugar cane is currently cultivated on 5.6 million hectares in Brazil, and 54 percent of the crop (about 3 million hectares) is used to produce ethanol (Naylor *et al*., 2007). United States farmers harvested 30 million hectares of maize in 2004, of which 11 percent (about 3.3 million hectares) was used for ethanol (Searchinger *et al*., 2008). In 2007, area planted to maize in the United States of America increased by 19 percent (Naylor *et al*., 2007; see also Westcott, 2007, p. 8). While the United States soybean area has declined by 15 percent; Brazil's soybean area is expected to increase by 6–7 percent to 43 million hectares (FAO, 2007c).

As noted in Chapter 4, land used for the production of biofuels and their by-products is projected by the IEA to expand three- to four-fold at the global level, depending on policies pursued, over the next few decades, and even more rapidly in Europe and North America. OECD–FAO (2008) projections suggest that this land will come from a global shift towards cereals over the next decade. The additional land needed will come from non-cereal croplands in Australia, Canada and the United States of America; set-aside lands in the EU or the United States Conservation Reserve Program; and new, currently uncultivated land, especially in Latin America. Some land that may not have been cultivated profitably in the past may become profitable as commodity prices rise, and the economically feasible area would be expected to change with increased demand for biofuels and their feedstocks (Nelson and Robertson, 2008). For example, 23 million hectares were withdrawn from crop (primarily cereals) production in countries such as Kazakhstan, the Russian Federation and Ukraine following the break-up of the former Union of Soviet Socialist Republics; of these, an estimated 13 million hectares could be returned to production without major environmental cost if cereal prices and profit margins remain high and the necessary investments in handling, storage and transportation infrastructure are made (FAO, 2008e).

The sugar-cane area in Brazil is expected to almost double to 10 million hectares over the next decade; along with expansion in the Brazilian soybean area, this could displace livestock pastures and other crops, indirectly increasing pressure on uncultivated land (Naylor *et al*., 2007). China is "committed to preventing the return to row crop production" of land enrolled in its Grain-for-Green programme, but this could increase pressure on resources in other countries, such as Cambodia and the Lao People's Democratic Republic (Naylor *et al*., 2007).

The potential significance of indirect biofuel-induced land-use change is illustrated by a recent analysis by Searchinger *et al.* (2008). They project that maize area devoted to ethanol production in the United States of America could increase to 12.8 million hectares or more by 2016, depending on policy and market conditions. Associated reductions in the area devoted to soybean, wheat and other crops would raise prices and induce increased production in other countries. This could lead to an estimated 10.8 million hectares of additional land being brought into cultivation worldwide, including cropland expansions of 2.8 million hectares in Brazil (mostly in soybean) and 2.2 million hectares in China and India (mostly in maize and wheat). If projected cropland expansion follows the patterns observed in the 1990s, it would come primarily from forest land in Europe, Latin America, Southeast Asia and sub-Saharan Africa, and primarily from grasslands elsewhere. Critical to this scenario is the assumption that price increases will not accelerate yield growth, at least in the short term.

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[11] Most first-generation biofuel feedstocks (e.g. maize, sugar cane, rapeseed and palm oil) cannot be distinguished by end-use at the crop production stage, so biofuel feedstock area is inferred from biofuel production data.

Other studies also highlight the possible indirect land-use changes resulting from biofuel policies (Birur, Hertel and Tyner, 2007). Meeting current biofuel mandates and targets in the EU and the United States of America would significantly increase the share of domestic feedstock production going to biofuels while reducing commodity exports and increasing demand for imports. Effects would include an expansion in land area devoted to coarse grains in Canada and the United States of America of 11–12 percent by 2010 and in the area devoted to oilseeds in Brazil, Canada and the EU of 12–21 percent. Brazilian land prices are estimated to double as a result of increased demand for grains, oilseeds and sugar cane, suggesting that EU and United States biofuel mandates could place considerable pressure on ecosystems in other parts of the world, such as the Amazon rainforest. Banse *et al*. (2008) also foresee significant increases in agricultural land use, particularly in Africa and Latin America, arising from implementation of mandatory biofuel-blending policies in Canada, the EU, Japan, South Africa and the United States of America.

Intensification

While area expansion for biofuel feedstock production is likely to play a significant role in satisfying increased demand for biofuels over the next few years, the intensification of land use through improved technologies and management practices will have to complement this option, especially if production is to be sustained in the long term. Crop yield increases have historically been more significant in densely populated Asia than in sub-Saharan Africa and Latin America and more so for rice and wheat

FIGURE 25
Potential for yield increase for selected biofuel feedstock crops

Note: In some countries, current yields exceed potential yields as a result of irrigation, multiple cropping, input use and various applied production practices.

Source: FAO.

than for maize. Large-scale public and private investment in research on improving genetic materials, input and water use and agronomic practices have played a critical role in achieving these yield gains (Hazell and Wood, 2008; Cassman *et al.*, 2005).

Despite significant gains in crop yields at the global level and in most regions, yields have lagged in sub-Saharan Africa. Actual yields are still below their potential in most regions – as shown by Figure 25 – suggesting that considerable scope remains for increased production on existing cropland. Evenson and Gollin (2003) documented a significant lag in the adoption of modern high-yielding crop varieties, particularly in Africa. Africa has also failed to keep pace with the use of other yield-enhancing technologies such as integrated nutrient and pest management, irrigation and conservation tillage.

Just as increased demand for biofuels induces direct and indirect changes in land use, it can also be expected to trigger changes in yields, both directly in the production of biofuel feedstocks and indirectly in the production of other crops – provided that appropriate investments are made to improve infrastructure, technology and access to information, knowledge and markets. A number of analytical studies are beginning to assess the changes in land use to be expected from increased biofuel demand, but little empirical evidence is yet available on which to base predictions on how yields will be affected – either directly or indirectly – or how quickly. In one example, ethanol experts in Brazil believe that, even without genetic improvements in sugar cane, yield increases in the range of 20 percent could be achieved over the next ten years simply through improved management in the production chain (Squizato, 2008).

Some of the crops currently used as feedstocks in liquid biofuel production require high-quality agricultural land and major inputs in terms of fertilizer, pesticides and water to generate economically viable yields. The degree of competition for resources between energy crops and food and fodder production will depend, among other factors, on progress in crop yields, efficiency of livestock feeds and biofuel conversion technologies. With second-generation technologies based on lignocellulosic feedstock, this competition could be reduced by the higher yields that could be realized using these newer technologies.

How will biofuel production affect water, soils and biodiversity?

The intensification of agricultural production systems for biofuel feedstocks and the conversion of existing and new croplands will have environmental effects beyond their impacts on greenhouse gas emissions. The nature and extent of these impacts are dependent on factors such as scale of production, type of feedstock, cultivation and land-management practices, location and downstream processing routes. Evidence remains limited on the impacts specifically associated with intensified biofuel production, although most of the problems are similar to those already associated with agricultural production – water depletion and pollution, soil degradation, nutrient depletion and the loss of wild and agricultural biodiversity.

Impacts on water resources

Water, rather than land, scarcity may prove to be the key limiting factor for biofuel feedstock production in many contexts. About 70 percent of freshwater withdrawn worldwide is used for agricultural purposes (Comprehensive Assessment of Water Management in Agriculture, 2007). Water resources for agriculture are becoming increasingly scarce in many countries as a result of increased competition with domestic or industrial uses. Moreover, the expected impacts of climate change in terms of reduced rainfall and runoff in some key producer regions (including the Near East, North Africa and South Asia) will place further pressure on already scarce resources.

Biofuels currently account for about 100 km^3 (or 1 percent) of all water transpired by crops worldwide, and about 44 km^3 (or 2 percent) of all irrigation water withdrawals (de Fraiture, Giordano and Yongsong, 2007). Many of the crops currently used for biofuel production – such as sugar cane, oil palm and maize – have relatively high water requirements at commercial yield levels (see

Table 10) and are therefore best suited to high-rainfall tropical areas, unless they can be irrigated. (Rainfed production of biofuel feedstocks is significant in Brazil, where 76 percent of sugar-cane production is under rainfed conditions, and in the United States of America, where 70 percent of maize production is rainfed.) Even perennial plants such as jatropha and pongamia that can be grown in semi-arid areas on marginal or degraded lands may require some irrigation during hot and dry summers. Further, the processing of feedstocks into biofuels can use large quantities of water, mainly for washing plants and seeds and for evaporative cooling. However, it is irrigated production of these key biofuel feedstocks that will have the greatest impact on local water resource balances. Many irrigated sugar-producing regions in southern and eastern Africa and northeastern Brazil are already operating near the hydrological limits of their associated river basins. The Awash, Limpopo, Maputo, Nile and São Francisco river basins are cases in point.

While the potential for expansion of irrigated areas may appear high in some areas on the basis of water resources and land, the actual scope for increased biofuel production under irrigated conditions on existing or new irrigated lands is limited by infrastructural requirements to guarantee water deliveries and by land-tenure systems that may not conform with commercialized production systems. Equally, expansion may be constrained by higher marginal costs of water storage (the most economic sites have already been taken) and land acquisition. Figure 26 shows that the potential for growth for the Near East and North Africa region is reaching its limit. While there remains an abundance of water resources in South Asia and East and Southeast Asia, there is very little land available for extra irrigated agriculture. Most potential for expansion is limited to Latin America and sub-Saharan Africa. However, in the latter region it is expected that the current low levels of irrigation water withdrawals will increase only slowly.

Producing more biofuel crops will affect water quality as well as quantity. Converting pastures or woodlands into maize fields, for example, may exacerbate problems such as soil erosion, sedimentation and excess nutrient (nitrogen and phosphorous) runoff into surface waters, and infiltration into groundwater from increased fertilizer application. Excess nitrogen in the Mississippi river system is a major cause of the oxygen-starved "dead zone" in the Gulf of Mexico, where many forms of marine life cannot survive. Runge and Senauer (2007) argue that as maize–soybean rotations are displaced by maize cropped continuously for ethanol production in the United States of America, major increases in nitrogen fertilizer application and runoff will aggravate these problems.

Biodiesel and ethanol production results in organically contaminated wastewater that, if released untreated, could increase eutrophication of surface waterbodies. However, existing wastewater treatment technologies can deal effectively with organic pollutants and wastes. Fermentation systems can reduce the biological oxygen demand of wastewater by more than 90 percent, so that water can be reused for processing, and methane can be captured in the treatment system and used for power generation. As regards the distribution and storage phases of the cycle, because

TABLE 10

Water requirements for biofuel crops

CROP	Annual obtainable fuel yield	Energy yield	Evapotranspiration equivalent	Potential crop evapotranspiration	Rainfed crop evapotranspiration	Irrigated crop water requirement	
	(Litres/ha)	*(GJ/ha)*	*(Litres/litre fuel)*	*(mm/ha)*	*(mm/ha)*	*(mm/ha)*[1]	*(Litres/litre fuel)*
Sugar cane	6 000	120	2 000	1 400	1 000	800	1 333
Maize	3 500	70	1 357	550	400	300	857
Oil palm	5 500	193	2 364	1 500	1 300	0	0
Rapeseed	1 200	42	3 333	500	400	0	0

[1] On the assumption of 50 percent irrigation efficiency.

Source: FAO.

ethanol and biodiesel are biodegradable, the potential for negative impacts on soil and water from leakage and spills is reduced compared with that of fossil fuels.

In Brazil, where sugar cane for ethanol is grown primarily under rainfed conditions, water availability is not a constraint, but water pollution associated with the application of fertilizers and agrochemicals, soil erosion, sugar-cane washing and other steps in the ethanol production process are major concerns (Moreira, 2007). Most milling wastewater (vinasse) is used for irrigation and fertilization of the sugar-cane plantations, thus reducing both water demands and eutrophication risks.

Pesticides and other chemicals can wash into waterbodies, negatively affecting water quality. Maize, soybeans and other biofuel feedstocks differ markedly in their fertilizer and pesticide requirements. Of the principal feedstocks, maize is subject to the highest application rates of both fertilizer and pesticides per hectare. Per unit of energy gained, biofuels from soybean and other low-input, high-diversity prairie biomass are estimated to require only a fraction of the nitrogen, phosphorus and pesticides required by maize, with correspondingly lower impacts on water quality (Hill *et al*., 2006; Tilman, Hill and Lehman, 2006).

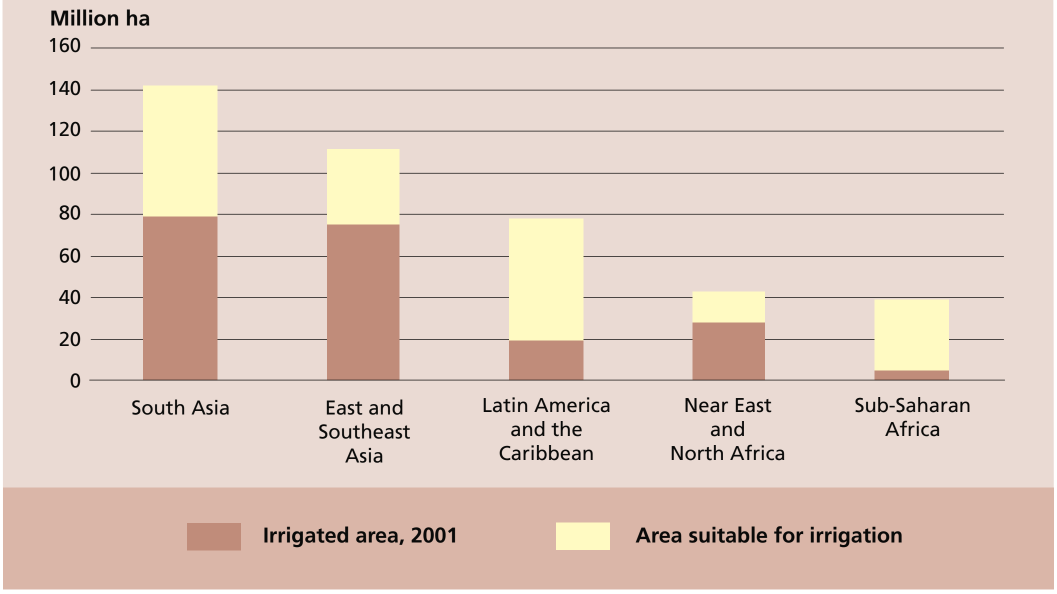
Impacts on soil resources

Both land-use change and intensification of agricultural production on existing croplands can have significant adverse impacts on soils, but these impacts – just as for any crop – depend critically on farming techniques. Inappropriate cultivation practices can reduce soil organic matter and increase soil erosion by removing permanent soil cover. The removal of plant residues can reduce soil nutrient contents and increase greenhouse gas emissions through losses of soil carbon.

On the other hand, conservation tillage, crop rotations and other improved management practices can, under the right conditions, reduce adverse impacts or even improve environmental quality in conjunction with increased biofuel feedstock production. Growing perennials such as palm, short-rotation coppice, sugar cane or switchgrass instead of annual crops can improve soil quality by increasing soil cover and organic carbon levels. In combination with no-tillage and reduced fertilizer and pesticide inputs, positive impacts on biodiversity can be obtained.

FIGURE 26

Potential for irrigated area expansion



Source: FAO.

Different feedstocks vary in terms of their soil impacts, nutrient demand and the extent of land preparation they require. The IEA (2006, p. 393) notes that the impact of sugar cane on soils is generally less than that of rapeseed, maize and other cereals. Soil quality is maintained by recycling nutrients from sugar-mill and distillery wastes, but using more bagasse as an energy input to ethanol production would reduce recycling. Extensive production systems require re-use of residues to recycle nutrients and maintain soil fertility; typically only 25–33 percent of available crop residues from grasses or maize can be harvested sustainably (Doornbosch and Steenblik, 2007, p. 15, citing Wilhelm *et al*., 2007). By creating a market for agricultural residues, increased demand for energy could, if not properly managed, divert residues to the production of biofuels, with potentially detrimental effects on soil quality, especially on soil organic matter (Fresco, 2007).

Hill *et al*. (2006) found that the production of soybean for biodiesel in the United States of America requires much less fertilizer and pesticide per unit of energy produced than does maize. But they argue that both feedstocks require higher input levels and better-quality land than would second-generation feedstocks such as switchgrass, woody plants or diverse mixtures of prairie grasses and forbs (see also Tilman, Hill and Lehman, 2006). Perennial lignocellulosic crops such as eucalyptus, poplar, willow or grasses require less-intensive management and fewer fossil-energy inputs and can also be grown on poor-quality land, while soil carbon and quality will also tend to increase over time (IEA, 2006).

Impacts on biodiversity

Biofuel production can affect wild and agricultural biodiversity in some positive ways, such as through the restoration of degraded lands, but many of its impacts will be negative, for example when natural landscapes are converted into energy-crop plantations or peat lands are drained (CBD, 2008). In general, wild biodiversity is threatened by loss of habitat when the area under crop production is expanded, whereas agricultural biodiversity is vulnerable in the case of large-scale monocropping, which is based on a narrow pool of genetic material and can also lead to reduced use of traditional varieties.

The first pathway for biodiversity loss is habitat loss following land conversion for crop production, for example from forest or grassland. As the CBD (2008) notes, many current biofuel crops are well suited for tropical areas. This increases the economic incentives in countries with biofuel production potential to convert natural ecosystems into feedstock plantations (e.g. oil palm), causing a loss of wild biodiversity in these areas. While oil palm plantations do not need much fertilizer or pesticide, even on poor soils, their expansion can lead to loss of rainforests. Although loss of natural habitats through land conversion for biofuel feedstock production has been reported in some countries (Curran *et al*., 2004; Soyka, Palmer and Engel, 2007), the data and analysis needed to assess its extent and consequences are still lacking. Nelson and Robertson (2008) examined how rising commodity prices caused by increased biofuel demand could induce land-use change and intensification in Brazil, and found that agricultural expansion driven by higher prices could endanger areas rich in bird species diversity.

The second major pathway is loss of agrobiodiversity, induced by intensification on croplands, in the form of crop genetic uniformity. Most biofuel feedstock plantations are based on a single species. There are also concerns about low levels of genetic diversity in grasses used as feedstocks, such as sugar cane (The Royal Society, 2008), which increases the susceptibility of these crops to new pests and diseases. Conversely, the reverse is true for a crop such as jatropha, which possesses an extremely high degree of genetic diversity, most of which is unimproved, resulting in a broad range of genetic characteristics that undermine its commercial value (IFAD/FAO/UNF, 2008).

With respect to second-generation feedstocks, some of the promoted species are classified as invasive species, raising new concerns over how to manage them and avoid unintended consequences. Moreover, many of the enzymes needed for their conversion are genetically modified to increase their efficiency and would need to be carefully managed within closed industrial production processes (CFC, 2007).

Positive effects on biodiversity have been noted in degraded or marginal areas where new perennial mixed species have been introduced to restore ecosystem functioning and increase biodiversity (CBD, 2008). Experimental data from test plots on degraded and abandoned soils (Tilman, Hill and Lehman, 2006) show that low-input high-diversity mixtures of native grassland perennials – which offer a range of ecosystem services, including wildlife habitat, water filtration and carbon sequestration – also produce higher net energy gains (measured as energy released on combustion), greater greenhouse gas emission reductions and less agrichemical pollution than do maize-ethanol or soybean-biodiesel and that performance increases with the number of species. The authors of this study also found that switchgrass can be highly productive on fertile soils, especially when fertilizer and pesticides are applied, but that its performance on poor soils does not match that of diverse native perennials.

Can biofuels be produced on marginal lands?

Marginal or degraded lands are often characterized by lack of water, which constrains both plant growth and nutrient availability, and by low soil fertility and high temperatures. Common problems in these areas include vegetation degradation, water and wind erosion, salinization, soil compaction and crusting, and soil-nutrient depletion. Pollution, acidification, alkalization and waterlogging may also occur in some locations.

Biofuel crops that can tolerate environmental conditions where food crops might fail may offer the opportunity to put to productive use land that presently yields few economic benefits. Crops such as cassava, castor, sweet sorghum, jatropha and pongamia are potential candidates, as are tree crops that tolerate dry conditions, such as eucalyptus. It is important to note, however, that marginal lands often provide subsistence services to the rural poor, including many agricultural activities performed by women. Whether the poor stand to benefit or suffer from the introduction of biofuel production on marginal lands depends critically on the nature and security of their rights to land.

It is not unusual to hear claims that significant tracts of marginal land exist that could be dedicated to biofuel production, thus reducing the conflict with food crops and offering a new source of income to poor farmers. Although such lands would be less productive and subject to higher risks, using them for bioenergy plantations could have secondary benefits, such as restoration of degraded vegetation, carbon sequestration and local environmental services. In most countries, however, the suitability of this land for sustainable biofuel production is poorly documented.

Growing any crop on marginal land with low levels of water and nutrient inputs will result in lower yields. Drought-tolerant jatropha and sweet sorghum are no exception. To produce commercially acceptable yield levels, plant and tree species cannot be stressed beyond certain limits; in fact, they will benefit from modest levels of additional inputs. Thus, while improved crops may offer potential over the longer term, adequate nutrients, water and management are still needed to ensure economically meaningful yields – implying that even hardy crops grown on marginal lands will still compete to some extent with food crops for resources such as nutrients and water.

Numerous studies confirm that the value of the higher economic yields from good agricultural land usually outweighs any additional costs. Thus, there is a strong likelihood that sustained demand for biofuels would intensify the pressure on the good lands where higher returns could be realized (Azar and Larson, 2000).

Ensuring environmentally sustainable biofuel production

Good practices

Good practices aim to apply available knowledge to address the sustainability dimensions of on-farm biofuel feedstock production, harvesting and processing. This aim applies to natural-resource management issues such as land, soil, water and biodiversity as well as to the life-cycle analysis used to estimate greenhouse gas

BOX 11
Jatropha – a “miracle” crop?

As an energy crop, *Jatropha curcas* (L.) (jatropha) is making a lot of headlines. The plant is drought-tolerant, grows well on marginal land, needs only moderate rainfall of between 300 and 1 000 mm per year, is easy to establish, can help reclaim eroded land and grows quickly. These characteristics appeal to many developing countries that are concerned about diminishing tree cover and soil fertility and are looking for an energy crop that minimizes competition with food crops. At the same time, this small tree produces seeds after two to five years containing 30 percent oil by kernel weight – oil that is already being used to make soap, candles and cosmetics and has similar medicinal properties to castor oil, but is also useful for cooking and electricity generation.

A native of northern Latin/Central America, there are three varieties of jatropha: Nicaraguan, Mexican (distinguished by its less- or non-toxic seed) and Cape Verde. The third of these varieties became established in Cape Verde and from there spread to parts of Africa and Asia. On Cape Verde it was grown on a large scale for export to Portugal for oil extraction and soap-making. At its peak, in 1910, jatropha exports reached over 5 600 tonnes (Heller, 1996).

The many positive attributes claimed for jatropha have translated into numerous projects for large-scale oil and/or biodiesel production as well as small-scale rural development. International and national investors are rushing to establish large areas for jatropha cultivation in Belize, Brazil, China, Egypt, Ethiopia, the Gambia, Honduras, India, Indonesia, Mozambique, Myanmar, the Philippines, Senegal and the United Republic of Tanzania. The largest-scale venture is the Indian Government’s “National Mission” to cultivate jatropha on 400 000 hectares within the period 2003–07 (Gonsalves, 2006). By 2011–12, the goal is to replace 20 percent of diesel consumption with biodiesel produced from jatropha, cultivated on around 10 million hectares of wasteland and generating year-round employment for 5 million people (Gonsalves, 2006; Francis, Edinger and Becker, 2005). The original target may well be ambitious, as Euler and Gorriz (2004) report that probably only a fraction of the initial 400 000 hectares allocated to jatropha by the Indian Government is actually under cultivation.

The plant also grows widely in Africa, often as hedges separating properties in towns and villages. In Mali, thousands of kilometres of jatropha hedges can be found; they protect gardens from livestock and can also help reduce damage and erosion from wind and water. The seed is already used for soap-making and medicinal purposes, and jatropha oil is now also being promoted by a non-

emissions and determine whether a specific biofuel is more climate-change friendly than a fossil fuel. In practical terms, soil, water and crop protection; energy and water management; nutrient and agrochemical management; biodiversity and landscape conservation; harvesting, processing and distribution all count among the areas where good practices are needed to address sustainable bioenergy development.

Conservation agriculture is one practice that sets out to achieve sustainable and profitable agriculture for farmers and rural people by employing minimum soil disturbance, permanent organic soil cover and diversified crop rotations. In the context of the current focus on carbon storage and on technologies that reduce energy intensity it seems especially appropriate. The approach also proves responsive to situations where labour is scarce and there is a need to conserve soil moisture and fertility. Interventions such as mechanical soil tillage are reduced to a minimum, and inputs such as agrochemicals and nutrients of mineral or organic origin are applied at an optimum level and in amounts that do not disrupt biological processes. Conservation agriculture has been shown to be effective across a variety of agro-ecological zones and farming systems.

governmental organization to power multifunctional platforms, a slow-speed diesel engine containing an oil expeller, a generator, a small battery charger and a grinding mill (UNDP, 2004). Pilot projects promoting jatropha oil as an energy source for small-scale rural electrification projects are under way in the United Republic of Tanzania and other African countries.

Despite considerable investment and projects being undertaken in many countries, reliable scientific data on the agronomy of jatropha are not available. Information on the relationship between yields and variables such as soil, climate, crop management and crop genetic material on which to base investment decisions is poorly documented. What evidence there is shows a wide range of yields that cannot be linked to relevant parameters such as soil fertility and water availability (Jongschaap *et al*., 2007). Experience with jatropha plantations in the 1990s, such as the "Proyecto Tempate" in Nicaragua, which ran from 1991 to 1999, ended in failure (Euler and Gorriz, 2004).

Indeed, it appears that the many positive claims for the plant are not based on mature project experiences. Jongschaap *et al*. (2007) argue that, on a modest scale, jatropha cultivation can help with soil-water conservation, soil reclamation and erosion control, and be used for living fences, firewood, green manure, lighting fuel, local soap production, insecticides and medicinal applications. However, they conclude that claims of high oil yields in combination with low nutrient requirements (soil fertility), lower water use, low labour inputs, the non-existence of competition with food production and tolerance to pests and diseases are unsupported by scientific evidence. The most critical gaps are the lack of improved varieties and available seed. Jatropha has not yet been domesticated as a crop with reliable performance.

The fear that the rush into jatropha on the basis of unrealistic expectations will not only lead to financial losses but also undermine confidence among local communities – a recurrent theme in many African countries – appears to be well founded. Sustainable jatropha plantations will mean taking the uncertainty out of production and marketing. Further research is needed on suitable germplasm and on yields under different conditions, and markets need to be established to promote sustainable development of the crop.

Good farming practices coupled with good forestry practices could greatly reduce the environmental costs associated with the possible promotion of sustainable intensification at forest margins. Approaches based on agro-silvo-pasture-livestock integration could be considered also when bioenergy crops form part of the mix.

Standards, sustainability criteria and compliance

Although the multiple and diverse environmental impacts of bioenergy development do not differ substantively from those of other forms of agriculture, the question remains of how they can best be assessed and reflected in field activities. Existing environmental impact-assessment techniques and strategic environmental assessments offer a good starting point for analysing the biophysical factors. There also exists a wealth of technical knowledge drawn from agricultural development during the past 60 years. New contributions from the bioenergy context include analytical frameworks for bioenergy and food security and for bioenergy impact analysis (FAO, forthcoming (a) and (b)); work on the aggregate environmental impacts, including soil acidification, excessive fertilizer use, biodiversity loss, air pollution and pesticide toxicity (Zah *et al*., 2007); and work on social and environmental sustainability criteria, including limits on deforestation, competition with food production, adverse impacts on biodiversity, soil erosion and nutrient leaching (Faaij, 2007).

The biofuel sector is characterized by a wide range of stakeholders with diverse interests. This, combined with the rapid evolution of the sector, has led to a proliferation of initiatives to ensure sustainable bioenergy development. Principles, criteria and requirements are under consideration among many private and public groups, along with compliance mechanisms to assess performance and guide development of the sector. The Global Bioenergy Partnership's task forces on greenhouse gas methodologies and on sustainability, and the round table on sustainable biofuels, count among these, together with many other public, private and non-profit efforts. Such diversity suggests that a process for harmonizing the various approaches may be needed, especially in the light of policy mandates and targets that serve to stimulate further biofuel production.

Most of the criteria are currently being developed in industrialized countries and are aimed at ensuring that biofuels are produced, distributed and used in an environmentally sustainable manner before they are traded in international markets. The European Commission, for example, has already proposed criteria that it considers to be compatible with WTO rules (personal communication, E. Deurwaarder, European Commission, 2008). However, to date none have yet been tested, especially in conjunction with government support schemes such as subsidies or when designated for preferential treatment under international trade agreements (Doornbosch and Steenblik, 2007; UNCTAD, 2008).

The term "standards" implies rigorous systems for measuring parameters against defined criteria, in which failure to comply would prevent a country from exporting its product. Such internationally agreed systems already exist for a range of food safety, chemical and human health topics. Is the biofuel sector sufficiently developed for the establishment of such a system and are the risks sufficiently great that its absence would pose significant, irreversible threats to human health or the environment? Should biofuels be treated more stringently than other agricultural commodities?

On the one hand, given that most environmental impacts of biofuels are indistinguishable from those of increased agricultural production in general, it could be argued that equal standards should be applied across the board. Furthermore, restricting land-use change could foreclose opportunities for developing countries to benefit from increased demand for agricultural commodities. On the other hand, there are also strong arguments that agricultural producers and policy-makers should learn from earlier mistakes and avoid the negative environmental impacts that have accompanied agricultural land conversion and intensification in the past.

Solutions to this dilemma will require careful dialogue and negotiation among countries if the combined goals of agricultural productivity growth and environmental sustainability are to be achieved. A starting point might be found by establishing best practices for sustainable production of biofuels, which can then also help transform farming practices for non-biofuel crops. In time, and accompanied by capacity-building efforts for the countries that need it, more stringent standards and certification systems could be established.

One option to explore could be payments for environmental services in combination with biofuel production. Payments for environmental services were discussed in detail in the 2007 edition of *The State of Food and Agriculture*. This mechanism would compensate farmers for providing specific environmental services using production methods that are environmentally more sustainable. Payments could be linked to compliance with standards and certification schemes agreed at the international level. Payment schemes for environmental services, although challenging and complicated to implement, could constitute a further tool to ensure that biofuels are produced in a sustainable manner.

Key messages of the chapter

- Biofuels are only one component of a range of alternatives for mitigating greenhouse gas emissions. Depending on the policy objectives, other options may prove more cost-effective, including different forms of renewable energy, increased energy efficiency and conservation, and reduced emissions from deforestation and land degradation.
- Notwithstanding that the impacts of increased biofuel production on greenhouse gas emissions, land, water and biodiversity vary widely across countries, biofuels, feedstocks and production practices, there is a strong and immediate need for harmonized approaches to life-cycle analysis, greenhouse gas balances and sustainability criteria.
- Greenhouse gas balances are not positive for all feedstocks. For climate-change purposes, investment should be directed towards crops that have the highest positive greenhouse gas balances with the lowest environmental and social costs.
- Environmental impacts can be generated at all stages of biofuel feedstock production and processing, but processes related to land-use change and intensification tend to dominate. Over the next decade, rapid policy-driven growth in demand for biofuels is likely to accelerate the conversion of non-agricultural lands to crop production. This will occur directly for biofuel feedstock production and indirectly for other crops displaced from existing cropland.
- Yield increases and careful use of inputs will be essential components in alleviating land-use pressure from both food and energy crops. Dedicated research, investment in technology and strengthened institutions and infrastructure will be required.
- Environmental impacts vary widely across feedstocks, production practices and locations, and depend critically on how land-use change is managed. Replacing annual crops with perennial feedstocks (such as oil palm, jatropha or perennial grasses) can improve soil carbon balances, but converting tropical forests for crop production of any kind can release quantities of greenhouse gases that far exceed potential annual savings from biofuels.
- Availability of water resources, limited by technical and institutional factors, will constrain the amount of biofuel feedstock production in countries that would otherwise have a comparative advantage in their production.
- Regulatory approaches to standards and certification may not be the first or best option for ensuring broad-based and equitable participation in biofuel production. Systems that incorporate best practices and capacity building may yield better short-term results and provide the flexibility needed to adapt to changing circumstances. Payments for environmental services may also represent an instrument for encouraging compliance with sustainable production methods.
- Biofuel feedstocks and other food and agricultural crops should be treated similarly. The environmental concerns over biofuel feedstock production are the same as for the impacts of increased agricultural production in general; therefore measures to ensure sustainability should be applied consistently to all crops.
- Good agricultural practices, such as conservation agriculture, can reduce the carbon footprint and the adverse environmental impacts of biofuel production – just as they can for extensive agricultural production in general. Perennial feedstock crops, such as grasses or trees, can diversify production systems and help improve marginal or degraded land.
- Domestic government policy must become better informed of the international consequences of biofuel development. International dialogue, often through existing mechanisms, can help formulate realistic and achievable biofuel mandates and targets.