What are the Final Land Limits?

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Land requirements for food and fuel at the global scale

The reality facing the world over the coming decades is a set of competing land uses. Pressures will grow on the planet's lands to provide around 8.9 billion people by 2050 (UN 2003) with food, fuel, and fiber. Food consumption per capita will grow significantly from 2803 kcal person^{-1} d^{-1} in 1997-1999 to 3050 kcal person^{-1} d^{-1} by 2030. This change will reflect the rising consumption of developing countries (FAO 2006a). Some of this increased supply will come from improved crop yields per unit area, but the remainder will come from bringing more land into cultivation. Additional demand for land will come from the need for more biomass-based fuels, more wood products, and more carbon storage. In this chapter, we focus on several key questions related to land requirements to produce biofuels in the future. How much land might be available to grow biofuel crops in the context to competing uses? How much land would be needed to grow the biofuels crops sufficient to produce significant quantities of energy? Where is this land? What criteria should we use for selecting this land?

Land use for food production is clearly a global priority. At the beginning of this century about 37% of the total land area of 13,418 Mha was in agriculture; 11% (~ 1,500 Mha) in crops and 26% (~ 3,400 Mha) in grasslands (Table 16.1). Meat consumption is increasing rapidly worldwide. The poultry population numbers around 11 billion individuals, which is fifteen times more than the population in 1900. The pig population has increased by a factor nine between 1900 and 1990, to reach about 856 million. The cattle population has been multiplied by four over the same period. Animal production in Asia has been multiplied by eight between 1975

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and 2000. This trend, which is likely to amplify over the decades to come, greatly increases demand for fodder crops. At the present time, the feed of these domestic animals is increasingly derived from cultivated cereals rather than from the grazing of pastures.

Dealing first with food, the demand to double food production by 2030 can be partially accommodated by greater productivity that, for staple crops, has been increasing at around 1.5% during recent decades. Even at that high rate of increase, however, production would be increased by just 40% requiring substantial expansion of arable land to meet the production goal. The area required can be conservatively estimated at 500 Mha, provided that the the greater productivity can be achieved on new croplands. Despite claims to the contrary, the amount of suitable land remaining for crops is very limited in most developing countries - where most of the growing food demand is expected-and, what surplus cultivatable land there is, is often under rainforest or in marginal areas (Young 1999, Döös, 2002).

Land used to produce the feedstocks for the current generation of biofuels (e.g. ethanol from maize and sugarcane) is included in the crop sector and is small; under 2% of the crop area or about 27 Mha (Chapter 6, Ravindrananth et al. 2009). In the coming decades, the demand for biomass energy will increase dramatically if it becomes an important part (10% or more) of a global energy strategy to avoid greenhouse gas emissions from fossil fuels. The amount of land needed to produce large amounts of energy is uncertain, but it may be as large as the amount of land currently in crops. Next, we briefly explore biofuel energy demand over the coming decades and how it will alter the magnitude and pattern of global land use.

Table 16.1 Global land-use areas in year 2000. Grassland includes sown pasture and rangeland (FAO, 2006b)

Land Use Catagory	*Area (Mha)*	*Extent (%)*
Forest	3989	30
Grassland*	3442	26
Agricultural crops	1534	11
Urban areas	40	0
Other land	4414	31
Total	**13418**	**100**

Land requirements for biofuels at the global scale

At the end of the 20th century, the world's commercial energy consumption was about 400 exajoules (EJ) per year, with fossil fuels contributing about 85% and all others (nuclear, biofuels, hydro, wind, solar) contributing only 15%. Typical projections of the world economy imply energy demands in 2050 of 550-1000 EJ per year, depending on resource availability and the price, scope, and effect of climate change and air quality policies on energy demand (Clarke et al. 2007). To limit greenhouse gas (GHG) emissions, we will need a variety of low-carbon energy sources operating at very large scales; for example, sources supplying 55-100 EJ y^{-1} would meet only about 10% of the estimated demand. Biofuels are being promoted as an important part of the global energy mix in the coming decades to meet

Table 16.2 Projections of increase in arable land (Mha) under different scenarios of energy production.

Source	Target	Energy Production (EJ/y)	Increase in Arable Land (Mha)
Leemans et al.(1996)	10% by 2030	181	381 – 478
Gurgel et al. (2007)	550 vppm CO_2 by 2100	128 – 141	1300
Ravindranath et al. (this volume)	2030		142 – 461
Field et al. (2008)	Use abandoned agricultural land	32 to 41	475 to 580

the climate change challenge (Pacala and Socolow 2004; Farrell et al. 2006).

Several analyses of land requirements for producing a large amount of biofuel over the coming decades have been made. These analyses have taken different approaches, made different assumption about crops used and conversion efficiencies from biomass to fuel, and use a range of scenarios about population growth. Despite the variations in approaches, the studies come to a few common conclusions:

- A large amount of land will be needed to produce biofuels by the middle of the 21st century if an aggressive biofuels plan is adopted globally
- Tropical regions of the world would be important sites for growing biofuels feedstock
- Pasturelands (broadly defined) would be a major source of lands used for biofuels

Given the uncertainty in those assumptions, and the factors actually included in the analyses, the estimates of land required to meet specified biofuel targets are extremely variable, ranging from 142 to 1300 Mha (Table 16.2).

Leemans and colleagues (1996) carried out one of the early analyses of the land-use implications of an aggressive modern biofuels program using an integrated assessment model, IMAGE2, with variations on an IPCC low-emissions scenario (Low CO_2 Emissions Energy Supply Systems (LESS BI). The projection for land demand for 2050 ranged between 381 and 478 Mha, with tropical regions accounting for a high percentage of the production.

In chapter 6, Ravindranath and colleagues projected dramatic growth in the area of land devoted to biofuels to meet 10% of the global liquid fuel needs. Between 2004 and 2007 they report almost a doubling from

box 16.1

Case Study - Brazil

Land use changes. From 1960 to 2007, the area planted with sugarcane in Brazil increased from ~1.4 Mha to 7 Mha (Martinelli and Filoso, 2008). Some 65% of new planting of sugar cane in Southeast Brazil has been on land that was previously pasture; the rest was previously used for other crops. In 2008, the planted area was 9 Mha, representing an increase of 27%. The productivity of sugarcane also increased dramatically from 45 (1960) to 81 Mg ha^{-1} (2008) (CONAB, 2008). Ethanol production consumes 57% of sugarcane yield (CONAB, 2008).

The agro-ecological zoning for sugarcane was prepared by the Brazilian federal government (Embrapa) using climate, soil, and topography data (slope up to 12º to allow the mechanized harvesting) and considering conservation units. Brazilian regulation strongly restricts sugarcane expansion in the Amazon and in the Pantanal.Thus, future expansion of sugarcane and crops for biofuels are expected to focus on the Cerrado region comprising the federal states of São Paulo, Mato Grosso, Tocantins, Maranhão, Piauí, Bahia, Minas Gerais, Goiás, and Mato Grosso do Sul.

The Cerrado, the principal savanna region south of the equator, represents about 9 % of the total area of tropical savannas in the world and one of the world's biodiversity hotspots (Myers et al, 2000). It occurs entirely within Brazil, mostly in the central region of the country, covering approximately 2 million km^2 (23% of the country). Planted pastures (mainly *Brachiaria* spp.) are the most extensive land use in the Cerradowith an area of approximately 50 Mha (Sano *et al.* 2000). In 2006, approximately 14 Mha of Center-West were cropped with soybean, maize, cotton, common bean and rice (www.conab.gov.br).

Soybean production catalyzed the agricultural expansion in the Cerrado during the last two decades. This crop occupies more than 6 Mha in the plateau regions of the Central Brazil.

Water demand by sugarcane is related to the cultivation, but also to the processing phase when 2-5m^3 water per ton of sugarcane is necessary. Climate variability may imply in the use of irrigation in some areas. Additionally, climate models indicated more extreme years predicted for some Cerrado sub-regions (Bombardi et al. 2008). Sugarcane cultivation can represent an additional pressure to water resources conservation in these particular areas.

Greenhouse Gas Emissions. In well-managed pastures on clayey soils in the Cerrado region, productivity and long term soil C stocks can surpass levels for native vegetation (100 Mg C ha^{-1} for 100 cm soil depth) (Corazza *et al.* 1999, Bustamante et al. 2006). On the other hand, poor management practices, especially overgrazing, lead to pasture degradation after a few years. Degraded pastures in the tropical region of Brazil occupy 25 million ha (Oliveira *et al.* 2004). Soil C accumulation under pastures over previous native stocks only occurs with nutrient inputs through fertilization and legumes (Silva et al. 2004). It can assume that as much as 1.5 Mg C ha^{-1} yr^{-1} can be stored in soil with the restoration of degraded pastures into productive pastures (Bustamante et al. 2006). In the case of conversion to croplands, model simulations indicated a yearly C input of about 8.5 Mg C ha^{-1} yr^{-1} was necessary to maintain the initial soil C levels under the native savanna. The C input under the soybean-fallow system (assessed to be about 4.2 Mg C ha^{-1} yr^{-1}) was insufficient to sustain these C levels. Again, gains in soil C were related to increased N inputs and reduced N losses (Bustamante et al., 2006).

Studies on sugarcane straw deposition in Northeastern (Ball-Coelho et al., 1993) and Southeastern (Cerri et al. 2004) indicated an input between 5-6 Mg C ha^{-1} yr^{-1} but soil carbon stocks are dependent on the burning regime. After 8 years of unburned sugarcane cultivation, soil C stocks were similar to the native forest (0-20 cm,~ 4 Mg C ha^{-1}) and 30% higher than in the burned area (Galdos, 2007).

The evidence suggests that conversion of degraded pasturelands to sugarcane has the potential to avoid soil degradation, and maintain or build soil carbon with appropriate tillage practices, and with mechanical harvesting that leaves large quantities of crop residue. Although these practices are not ubiquitous, the greenhouse gas savings from sugarcane have the potential to exceed the direct carbon losses of pastures converted long ago from native habitats (although the carbon and biodiversity costs of converting native Cerrado would be substantial).

Sugarcane ethanol in Brazil appears to have the potential to meet environmental and sustainability criteria but improvements remain needed and important uncertainties remain. The critical questions revolve around indirect land use. Roughly a third of sugarcane expansion displaces other crop production, which is likely to move elsewhere and the conversion of pasture also raises the risk of contributing to further forest and Cerrado conversion. Sugarcane is a small portion of agricultural land use in Brazil, and under any analysis, is a modest contributor to the country's agricultural expansion into forest, but to the extent a hectare of pasture converted to sugarcane results in a hectare of clearing of Amazon forest or Cerrado woodland, the result is likely to be an increase in greenhouse gas emissions over two to several decades. Some analysts, pointing to intensification of pasture in Sao Paulo state, have argued that this intensification is a response to sugarcane expansion and replaces livestock without land expansion (Goldemberg et al. 2008). However, and while pastureland is intensifying in this area, expansion of pastureland continues to occur elsewhere in Brazil out of rain forest, a result of many factors, including public policies, but also always influenced by supply and demand as well. Economic signals are not restricted by proximity. Because of the limited scope of sugarcane expansion in the broader landscape, it is likely that most pasture intensification, where it occurs, and most extensification as well, both result from other factors, but there is no reason to consider the contribution of sugarcane to be focused only on intensification or extensification, rather than both.

One way sugarcane might avoid indirect land use change is to confine its expansion into degraded pastures, and to put in place systems to assure that for each hectare of pasture utilized, other pastures are intensified sufficiently to replace the lost food production. That would require a level of coordination and the use of some of the revenues from biofuel production to support pasture intensification because the availability of cheap additional land for clearing is often a more attractive option than intensification for cattle ranchers.

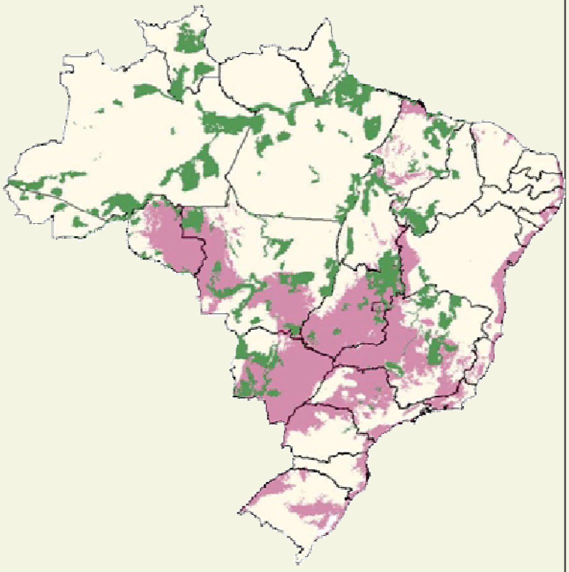

Figure 16.1 Map of the priority conservation areas of very high relevance (green) and potential area for sugarcane plantation (purple) (Machado et al. 2006)

Biodiversity. The overlap of potential areas for sugarcane expansion with priority conservation areas of extreme biological importance is 70% in the Cerrado region, 16% in the Amazon region and 40% in the Pantanal (Figure 16.2, Machado et al. 2006). Most of these priority areas for conservation are not under protection or have special programs for sustainable development. In a recent revision made by the Brazilian Ministry of Environment, areas of high biological relevance for conservation represent 19.7% of the Cerrado and Pantanal and 15.4% for the Amazon. These numbers indicates that it is possible to reconcile agricultural expansion and conservation if public policies are well coordinated. However, recent studies (www.dsr.inpe.br/canasat) in the Cerrado region showed the expansion of sugarcane over some these unprotected priority conservation areas in spite of the large area already converted in this biome that could be used for this expansion. An important aspect in the case of the Cerrado is the conservation of riparian forests that represent only 5% of the biome area but contain ca. 45% of its biodiversity (Ratter et al. 1997).

Additionally, the combined effects of climate change, loss of habitats and the small representativeness in the national system of conservation units can be catastrophic. A study of 162 tree species in the Cerrado predict that 39~48 percent of these species would be extinct, depending on the climate change scenarios (Siqueira e Peterson, 2003). It is unlikely that vegetation species in the Cerrado can suffer dispersion through the agricultural matrix to reach areas with more favourable climate.

Socio-economic factors. Biomass represents 31.6% of energy mix in Brazil – 12.5% from wood and 16% from sugarcane, being higher than the 14.7% generate by hydroelectricity. Oil represents 36.7%; coal 6.2%; natural gas 9.3% and nuclear power 1.4%. Renewable energy sources contribute with 53.6% of the energy in Brazil while in the European Community and in the US this value is 6.2% and 6.6%, respectively.

Demand for ethanol is growing fast in Brazil. In 2006, ca. 50% of new cars had flex-fuel engines that can run on any mixture of petrol and ethanol (ANFAVE, 2008). While ethanol consumption for transportation is equivalent to 2% of world consumption of gasoline – this percentage is from more than 30% in Brazil. In the case of biodiesel this percentage is 0.2%. However biodiesel production will increase by 2010 to 2.3 billion liters with the addition of 5% to diesel. Agribusiness in Brazil represents 28% of national GDP being 8% from sugarcane sector (Naves and Conejero, 2007). Investments in the sugarcane sector are US$ 2.5 billion per year (Naves and Conejero, 2007). This means that the expansion of biofuels in Brazil will not be limited by investment and technology.

In spite of the economic relevance there are serious social problems associated with labor conditions in sugarcane plantations (Goldemberg et al. 2008). In traditional areas of sugarcane cultivation in Southeast Brazil, manual harvesting is still dominant but 30% of the sugarcane planted area has now mechanized harvesting (CONAB, 2008). This will make the sugar cane industry safer but can leave a large, unskilled workforce unemployed.

about 13.8 Mha to 26.6 Mha. For reference, current crop area is about 1,600 Mha. Their projections of land demand for 2030 range from 142 to 461 Mha based on the use of either corn or sugarcane to meet ethanol demand, and either jatropha or palm oil to meet biodiesel demand.

In a recent analysis using the MIT Integrated Global Simulation Model (IGSM), Gurgel et al. (2007) explored the land-use consequences of a global-scale biofuels program driven by a climate stabilization policy with a target of 550 ppmv, and whether or not forest could be cleared. By 2050, they estimated that the land area in cellulosic biofuels would grow to between 1,400 and 1,500 Mha; an area almost equivalent to the current crop area. Land converted to biofuel feedstock production was predicted to reduce pasture and forest areas. Estimated energy production ranged between 128 and 141 EJ y^{-1}.

Field and colleagues (2008) have recently argued that a substantial amount of abandoned agricultural land that could be used for biofuel production. Their global estimate of abandoned land is between 475 and 580 Mha and they estimate that biofuels grown on this land could supply 32 and 41 EJ y^{-1}.

There are three important features of current assessments of land requirements for biofuel production. First, analyses of extra land required for biofuel production are rarely made in conjunction with that needed to feed an increasing world population. Second, no analyses include the energy cost of crop or biomass production so estimates are for gross rather than net fuel production. Given that most crops, as currently used, have energy efficiencies of 2:1 or less, the land requirements for net fuel production are around twice those otherwise estimated. Only sugarcane has a high energetic efficiency (~ 8:1) with the combustion of crop residues that, in Brazil, gains energy credits on the electricity grid and provides the large energy requirements for the distillation of ethanol. Third, the bioenergy situation will only change when, and if, the production of cellulosic ethanol becomes commercially viable. Then, crop residues, that are not a part of current analyses will be able to contribute to biofuel production and bring food crop production into the energy supply equation. This will become especially important given the large and increasing area of arable land needed for crop production to feed the increasing world population. While crop residues are required to feed livestock and protect and improve the physical and chemical conditions of soils for crop growth, some removal is possible in many areas. Stubbles are actually burnt in many agricultural systems to facilitate management. The 1 - 2 Gt that are burnt annually in the field (Smil, 1999) would be better combusted as biofuel. Crop (428 Mt) and forest residues (358 Mt) were included in the Billion Ton Vision (Perlack et al. 2005) and a separate study (Graham et al. 2007) has identified 100 Mt of corn residues that could be removed annually from land planted to corn in the USA. Residues from agriculture and the human food chain, together with those from forestry, offer the only source of bioenergy that does not require land use change additional to that required for food production itself.

Additional pressures on land use

In addition to the expansion of land dedicated to biofuel production, other forces will be shaping global land use in the future. These include urbanization, aquaculture, climate change, and land degradation.

Urbanization. It is estimated that 1 to 2 Mha of cropland are being taken out of production every year in developing countries to meet the land demand for housing, industry, infrastructure, and recreation (Döös 2002). This is likely to take place mostly on prime agricultural land located in coastal plains and in river valleys.

Aquaculture. With the oceans being increasingly depleted of their fish population, fish farms become an important provider of fish meat. Global aquaculture production more than doubled in volume and value during the 1990s. In 2001, it supplied one-third of seafood consumed worldwide (Naylor et al. 2001). Further increases in aquaculture output are planned worldwide, including in the United States and coastal countries of Asia. Fishmeal's proteins are increasingly replaced by plant-based species such as soybean, therefore creating a demand for agricultural products from this fastest-growing segment of the world food economy.

box 16.2

Case Study - United States and Europe

Land use changes. Both the United States and European Union have rapidly expanded their consumption and production of biofuels in recent years (OECD 2008b), and they have adopted or are considering laws that would mandate large increases in the future (chapter 8). In both the experience to date, and in projections, the land for expansion comes in part from the use of reserve lands and some conversion of non-croplands, but land use will mostly occur abroad as a result of reductions of food exports or increases in imports.

To date, as U.S. corn ethanol has increased to 30.3 billion liters, the corn has come from large increases in cropland devoted to corn in the U.S. (by 20% in 2007), reductions in area of some other crops (soybeans, cotton and wheat in 2007, as well as more minor crops, and the same except for soybeans in 2008), as well as large reductions in grain stocks. The United States is projected to increase production of corn ethanol up to 56.8 billion liters or more (depending on the price of oil and government policies), which will probably require the diversion of more than 40% of U.S. corn production. Whatever the level of corn ethanol predicted (which depends on various scenarios and fuel prices), virtually all economic analyses predict that these increases result in decreases in acres devoted to soybeans, and wheat and decreases in production of many livestock, which in turn result in decreases in a wide range of exports (Westcott 2007; Tyner 2008). It is important to emphasize that projections generally show U.S. production and exports growing significantly in the absence of biofuels, so these decreases are relative to otherwise predicted future levels and may not represent absolute decreases in the level of existing production and exports.

Some increases will also derive from increased crop production in the United States. In its most recent farm bill, the Congress allowed the principal cropland reserve program, the Conservation Reserve Program, to decline from the authorized 15.9 to 12.9 million hectares, in part in response to rising crop prices and there will probably also be some increase in crop areas coming from hay and pasture.

As a result, the primary effect of world land use will occur through decreased exports and resulting increased production around the world. Searchinger et al. 2008 estimated the increases in land use from a diversion of 12.8 million hectares of U.S. corn land to ethanol necessary to provide 56.8 billion liters of ethanol to occur in a fair dispersion of countries around the world, but with roughly 60% occurring in Brazil, the U.S. China and India. Different models can result in different predictions, and actual results will turn on a broad range of government policies, weather and disease patterns, biofuel policies in other countries, many other uncertain factors.

The same basic story holds in Europe, whose primary biofuels derive from rapeseed, sugar beets and some grains. As biofuel production has grown in Europe since 2000, the sources have included a large expansion of rapeseed production in Europe, increased imports of soy and vegetable oil, and decreases in oil exports. The expansion in rapeseed production came at the expense of land devoted to wheat, despite a global shortage, and some other crops, and also in use of reserve lands for biofuel production. The European Commission predicted in a number of study documents that biofuel production to meet its proposed requirement for 10% of transport fuel by *T* 2020 would result in no displacement of existing cropland from food production and would use “only” 15% of European arable land (European Commission 2007a, 2007b). But as a number of studies have analyzed, this projection ignores land use change outside the EU, assumes heavy consumption of EU reserve lands, and assumes 30% of biofuels are provided by this date from cellulosic ethanol (Dehue et al. 2008; Eickhout 2008). Dehue et al. (2008) reanalyzed the projection and found that even maintaining the same assumptions, half of all production in response to the biofuel diversion would come from outside the EU (Dehue et al. 2008). In addition, European set aside lands are already expected to decrease to 2 to 3 million hectares reflecting high world agricultural demand and the existing level of biofuels, even though it is only around one fifth of the 10% goal. A Netherlands study concluded that meeting the EU target would require a land area from 20 Mha to 30 Mha. As a whole, the use of crop-based biofuels to meet demands in the United States and Europe would appear to fail several criteria.

Greenhouse Gas Emissions. In the US, the conversion of Conservation Reserve Program lands would release substantial levels of carbon, creating a substantial carbon debt that by some calculations will take decades of corn ethanol to replace (Fargione 2008; Gibbs 2008).

Most significantly, these crops seem likely to increase greenhouse gas emissions. Several combined economic and ecological analyses find that corn-based ethanol generates sufficient emissions from land use change that it is likely to be a net source of greenhouse gas increases over decades even if those analyses are off by more than 100% (Searchinger 2008). Biodiesel, whether generated in Europe or the United States, is likely to have a worse greenhouse gas balance. For example, without counting land use change, biodiesel from rape or soybeans in Europe is estimated to generate greenhouse gas savings of 45-65 grams per mega joule (Co_2 equivalent). European biodiesel is mostly produced from European rapeseed, but chemical studies have also shown it to include significant quantities of Brazilian soybean oil and palm oil and when European rape oil is diverted to biodiesel, at least some of the replacement on world markets is likely to derive from palm oil produced in Southeast Asia, particularly because palm oil is supplying well more than half of all growth in vegetable oil demand on world markets. Depending on emissions rates used, one megajoule of palm oil grown on peatlands causes the emissions of 500 to 1,500 grams of CO_2 solely from the oxidation of the peat (Fargione 2008; De Santi et al. 2008). These figures imply that if less than 10% of biodiesel is replaced by palm oil grown on peatland, the entire greenhouse gas reductions from rapeseed are eliminated without counting any emissions from change in above ground biomass or emissions associated with the replacement of the remaining 90% of the vegetable oil.

Biodiversity. Because the primary effects of growing biofuels demand are increases in cropland abroad, there will be significant but hard to estimate impacts on biodiversity. Within the U.S. and Europe, the primary impacts derive from the conversion of some reserve lands. In the U.S., these reserve lands have played a role in maintaining populations of some grassland bird species, and they support a range of bird species in Europe as well.

Socio-economic factors. Although the economic benefits and costs of biofuels are debated (OECD 2008a), there are rural development benefits to biofuels in both regions.

Although the use of temperate food crops for biofuels is undesirable, U.S. law requires that much of future biofuels derive from cellulose, and the EU is considering amendments to its directive than may have similar requirements. Cellulosic biofuels are predicted to have better greenhouse gas balances than temperate crops because of predictions of reduced growing inputs and energy needs in refining. Perennial crops will also tend to sequester soil carbon directly. However, use of cellulosic crops has the potential to compete with food production and will trigger indirect land use change if grown in areas that now otherwise produce human needs. One desirable option would be to meet cellulosic demand by the use of residues and waste products, which by some studies can be provided in substantial amounts even while preserving long-term fertility (Perlack 2004). Care is necessary. Even without diverting crop residues, most farms are still losing soil carbon and soil erosion remains a major challenge.

Russia

Russia ranks fifth in the world by its agricultural land area. After the breakup of the Soviet Union at the end of 1991, agriculture in Russia suffered from a loss of government support and subsidies. As a result, capital investments declined and fertilizer application fell dramatically. Since the dissolution of the Soviet Union, agricultural land has been largely privatized, individual land-owners now have legal rights to most agricultural land in the country, and buying and selling land is now allowed (including to foreigners). The potential for increases in crop yields and cultivated area is large. Between 1991 and 2001, the area allocated to cereals dropped by about 25 percent. This area is now slowly being reclaimed by large corporate factory farms that replace former collective farms. The introduction of a market-oriented system has opened the door for private investments and increased efficiency. The Russian government is promoting aggressively the intensification of agriculture (e.g., through a tax on the export of fertilizers, to encourage their use domestically). Climate change scenarios predict strong gains in crop production potential for the Russian Federation (Lotze-Campen and Schellnhuber, 2005) as favorable weather conditions will become prevalent - as it was the case with the bumper harvests of 2001, 2003, and 2004.

The large oil and gas reserves in Russia are such that, presently, there are no big biofuel producers in Russia – even though new actors are entering the scene. Some have suggested that Russia, like other countries in Eastern Europe, could devote its recently abandoned agricultural land to biofuels. However, the potential for increased food production in Russia is one of the world's great potentials to meet increased food demand, and that is both the most likely and the most desirable scenario. Russia could again become a major food exporter in the next 10 to 15 years. However, to the extent land would not be brought back into crop production, these lands are likely to remain as grassland and shrublands and increasingly return to forest, causing substantial carbon gains. Using those lands for biofuels would sacrifice substantial carbon sequestration, and whether biofuels would represent any net gain is highly uncertain

to replace those uses through other lands. Although it is sometimes useful for intellectual purposes to distinguish between direct and indirect uses of land for biofuels, the distinction will often be meaningless from an economic perspective. By increasing demand for a feedstock for biofuels, people increase the total demand on the world's land resources to generate such a feedstock and economic forces will for the most part determine how that demand is fulfilled. For example, even if production of biofuels from palm oil were prohibited in peatland rainforests, producers could make biodiesel out of existing palm oil and then expand into peatlands to replace palm oil for food markets. In recent experience, diversion of rapeseed oil to biodiesel in Europe has increased the market for palm oil to replace the rapeseed oil. In general, the land use consequences of demand for a particular biofuel feedstock will depend on where it is most economical for that feedstock to be produced. To restrict these consequences, there must be an affirmative restriction on where and how a biofuel feedstock is produced to avoid direct or indirect competition with other needs.

This close relationship between direct and indirect land use is generally most commonly recognized in greenhouse gas calculations, but it applies to biodiversity and social criteria as well. For example, billions of people in developing countries obtain most of their energy supplies from firewood, sometimes gathered on sparser

Climate change. Climate change will affect the cultivation potential worldwide (Fischer et al., 2002). Based on realistic scenarios, strong gains in crop production potential would occur in North America and the Russian Federation, and significant losses are projected for Africa (particularly North and Southern Africa). Many developing countries may lose as a whole some 10 to 20% of their cereal production potential by 2080 due to climate change alone. Moreover, increasingly severe water shortages, and the incidence of crop diseases and pests may further constrain food production in the future.

Land degradation. Land degradation is taking land out of production every year or, at least, decreases the agricultural potential of agricultural land. While crop yield declines are only observed locally, the growth rates of yields have generally slowed during the last two decades. Estimates of the area affected by land degradation are still uncertain and controversial (Trimble and Crosson, 2000). Some form of severe land degradation is thought to be present on an estimated 10-20% of drylands, which cover about 41% of the land surface of the globe. Agricultural activities or agrarian land uses are the leading proximate cause of land degradation (Geist and Lambin, 2004). They include extensive grazing, nomadic pastoralism and annual cropping. Cropland expansion on areas previously used for pastoral activities leads to overstocking on the remaining, reduced rangeland, and triggers soil degradation at sites that are not suitable for permanent agriculture. Asia concentrates a lot of the land degradation due to land salinization in irrigated areas.

Suitable Lands – Lands of Low Competition

It is common to state that biofuels should focus on “marginal lands,” but the term creates some confusion. Marginal land to some means economically marginal, to others, marginal for food production. Desirable lands for biofuels might perhaps better be referred to as lands of low competition.

Lands of low competition currently produce little food and are undesirable and ill-suited for enhanced food production. They store little carbon today and stand to sequester little carbon in the future. They have a low biological diversity. Yet lands used for biofuels must also be capable of producing abundant crops, which above all implies water and nutrients. In theory, dry lands could be irrigated, but the impacts of water diversions on biodiversity and fishery resources (de Fraiture, this volume), coupled with demands for more irrigation to meet food supplies, suggests that irrigation for biofuel production should rarely be acceptable. The best candidate for biofuel production are therefore lands wet enough to support substantial production but that are not serving other valuable needs.

Most of these examples will be lands that are for some reason degraded. Some “degraded” lands simply lack chemical inputs, and are good targets for enhanced food production. But others face other obstacles: lands that have suffered great soil degradation, but that might respond to perennial grasses or trees; lands that are overrun by invasive species; or tropical grazing lands that are currently degraded and relatively unproductive. Particularly if coupled with efforts to boost the productivity of adjacent lands, such lands might be

box 16.3

Case Study - Africa

Land use changes. Africa has significant unused or underused land resources which could be used in a sustained manner to reduce food insecurity (Bekunda et al. this volume) as well as contributing to domestic, regional and international biofuel markets, but key environmental goals will need to be carefully managed.

Several scenarios could be envisioned with respect to biofuel development in Africa. A positive scenario would be sustained increases in food crop yields and improved infrastructure which significantly reduces the demand for new land for biomass production. A negative scenario might consist of export oriented; large scale biofuel production systems dominated by multi-national companies and accompanied by impacts of food security, biodiversity and carbon values.

As part of COMPETE (www.compete-bioafrica.net) Watson (2008) identified land in the arid and semi-arid regions of eight sub Saharan Africa countries (Table 3) where intensification of, or conversion to bio-energy use, will not have detrimental environmental and/ or socio-economic impacts. South Africa, Botswana, Zambia, Tanzania, Kenya, Mali, Burkina Faso and Senegal were chosen because they are working towards enabling bio-energy policies and already have several different bio-energy initiatives in place.

The potential to use both their arid and semi-arid regions for biofuel crop production, is greatest in South Africa and Kenya and least in Burkino Faso. Most of the arid regions in Botswana and Senegal also have a high potential for such use. Only about a third of Mali's arid and semi-arid regions, and two fifths of the semi-arid regions of Tanzania, Zambia and Botswana could be considered for such use. With only 6% the semi arid region of Senegal has a very poor potential for such use.

Templates of these regions within the countries were produced from WMO and UNEP (2001) and ESRI (2006) data, respectively. As a precaution against detrimental impacts on biodiversity, all categories of protected areas as per UNEP *et al.* (2006), and closed canopy forests and wetlands as per JRC's (2003) Global Land Cover database were designated as unavailable for bio-energy crop production and filtered out from the regions in the base map. The evergreen lowland category included both closed and degraded forest. It could be argued that the latter should not have been filtered out, as there is little prospect of it being rehabilitated and the rural poor would benefit more from it being converted into bioenergy crop production. In order to avoid food security concerns, the GLC database was also used to filter out areas under crops. The crops included both tree and herbaceous, and commercial and subsistence. This database was finally used to filter out areas unsuitable for bio-energy crop production. The surfaces remaining as available and/ or suitable for bio-energy crop production are: closed or sparse grassland, open grassland with sparse shrubs, open deciduous shrubland, deciduous shrubland with sparse trees, deciduous woodland, mosaic forest/

Country	*% Arid*	*% Semi-arid*
Burkina Faso	0	15
Senegal	72	6
Mali	31	29
Kenya	91	75
Tanzania	--	46
Zambia	--	42
Botswana	80	42
South Africa	94	70

Table 16.3 Percentage of the arid and semi-arid regions in eight sub-Saharan African countries available and suitable for biofuel crop production (Watson, 2008).

cropland and mosaic forest/ savanna representing an area of 184 Mha.

Biodiversity. A significant concentration of Africa's biodiversity can be found in its closed and semi-closed tropical forests. Wetlands also offer a range of ecosystem services and contain significant carbon. International financing mechanisms which provide payments for environmental services may help to retain areas of high conservation value intact.

Many would argue that the grasslands and woodlands should not be considered more amenable to conversion to biofuel crop production than forests or wetlands, just because they do not enjoy the same level of protection as forests and wetlands accorded by International Conventions. Grasslands and woodlands particularly in sub Sahara's arid and semi-arid regions generally have a very high biodiversity and play a very significant role in environmental services and rural livelihoods.

All types of biodiversity are not represented in protected areas. Ground verification is needed to check whether endemic species or valuable ecosystems are present outside the protected areas that have been filtered out in the analyses described above. If the area that is identified as available and suitable for bioenergy production lies on a corridor between protected areas or non-protected high biodiversity areas, it should be excluded.

Socio-economic factors. Infrastructure, markets, transport networks and access to inputs currently constrain more rapid agricultural gains in Africa and will also affect bio-energy production. These constraints cannot be resolved quickly but may serve as a moderating influence for rational land use and biofuel development. The human development index for Africa offers a measure of some constraints. Chronic food insecurity in many parts of Africa will constrain bio-energy development, thus meeting the food challenge should be balanced against potential export market opportunities. The lack of energy services to rural households in Africa should serve as a guide to its future bio-energy development.

Roads, railroads and rivers as per BioGeomancer Working Group (2007) and populated places as per ESRI (2006) were overlaid on the maps of the available and suitable areas for bio-energy crop production. These areas are currently being assessed to determine (a) which specific bio-energy crops they are best suited for, (b) if the land is free from legal, cultural, 1 policy, 2 environmental services and rural livelihood 3, and biodiversity 4 constraints against its utilization for bio-energy, and (c) if the water resources, potential labour markets and infrastructure can sustain conversion of this land to bio-energy production.

Once areas available and suitable for bioenergy crop production have been identified using GIS manipulation of predominately remotely sensed datasets, it is absolutely essential to check the district government records and archives and meet with the local community for ground verification. Many areas have burial sites, graves, taboo forests and trees while others have already been designated for land ownership/ tenure change under land reform programs. Moreover most traditional rural African communities are reliant on there environmental surrounds to supply services ranging from fuel wood, construction wood, thatch grass, fruit, bush meat, medicines, grazing, water etc. Even in areas where there is no evidence of habitation or use of resources, they may still be significant to rural livelihoods. An example of this is in south east Botswana where in November the larvae of the Emperor moth (*Imbrasia belina)* from *Colophospermum mopane* trees are harvested. They smoke them and then sell them as far a field as cities in neighboring countries. Per kg they sell for more than the cost of prime beef (Watson, 2002). Botswana's Central Statistics Office (2000) claims trade in mopane worms or phane as they are known locally, is second to agriculture as a source of livelihood and that the cash income it provides is particularly important to women.

African bioenergy development should promote schemes whereby small-holders' participation is considered along with larger-scale production systems. Achieving this will involve addressing land rights issues – access, use, management – which are a priority for both food and bio-energy production in Africa. Investment in agriculture, typically at a low percentage of total national investment, needs to increase significantly with a focus on transport, markets, processing inputs. Governance and institutional performance in particular with regard to private sector partnerships and participation by civil society, needs continued improvement and capacity development. National energy policy needs to reflect opportunities for renewable and biofuel development. Assessments of land potential, social and economic constraining factors and the food production system are the foundations upon which national bio-energy policies can be developed.

suitable for biofuel production. One appropriate policy would seek to map and evaluate the productivity of these areas, and thereby outline areas of appropriate use for biofuels.

Sustainability Criteria for Biofuels

Government policies have played a critical role in driving the development of biofuels through combinations of subsidies and mandates. Motives have included energy security, rural development and agricultural support. Despite this range of motivations, countries have generally expressed a desire to move forward on biofuels only to the extent they provide substantial greenhouse gas benefits, and avoid a variety of other potentially adverse environmental and social implications (see chapter 8). Although the details proposed by governments have varied, prominent environmental criteria include the safe-guarding of biodiversity, and the rights of indigenous people. In developing countries, economic development and security appear to be playing even more prominent roles, but many developing countries have also expressed their support for biofuels in environmental terms, particularly greenhouse gas reductions. A key question is which types of land can be utilized for biofuels while still meeting these criteria. As previously discussed, because of the high demand for land for other valuable purposes, including food, carbon storage and biodiversity, the areas of land left for beneficial environmental use for biofuels are necessarily restrictive.

Whatever the other limitations, of course, the fundamental constraint on biofuel production remains a biophysical constraint, i.e. the soils and rainfall must support healthy production. For example, jatropha is promoted as a feedstock that can withstand droughts, but yields are low in areas of low rainfall. For each feedstock, there are known constraints in soils, water supply, and temperature. One of the opportunities created by biofuel production is the potential expanded use of perennial crops, which build soil carbon in areas that meet temperature requirements but that face physically degraded soils of little value for food production or forest. This section discusses some criteria necessary to achieve environmental and social criteria for acceptable biofuel production.

Direct and Indirect Land Use. Biofuels represent a broad additional category of demand for land capable of high carbon productivity, adding to the traditional demands of agriculture and forestry. In light of limited land resources, any use by biofuels of lands now used for other human purposes is likely to drive people to attempt savannas, many of which are hard-pressed to meet the full demands and as a result are degrading. If those sparser savannas are converted to more intensive bioenergy production to supply the local needs, the indirect effects on land use could be positive by providing more energy per hectare and reducing the amount of land needed. But if those savannas are converted to biofuel production for export, local people will be adversely affected, and their intensified use of other areas for firewood could also have impacts on biodiversity and soil degradation. Any evaluation of whether lands are suitable areas for biofuel production must consider existing uses of that land and potential indirect effects.

Greenhouse Gas Emissions. The expectation or legal requirement that biofuels reduce greenhouse gas emissions has played a major role in government policies. A multitude of lifecycle analyses comparing various biofuels to gasoline and diesel fuel have driven this expectation. These analyses work to the extent they focus on waste products and residuals whose biomass does not require diverting the productive capacity of land from alternative uses. But otherwise, more recent work has shown these analyses to be incomplete.

Conventional lifecycle analyses of biofuels find that they reduce greenhouse gas emissions compared to gasoline or diesel, but the emissions from the production of the biofuel and its consumption in a vehicle tend to be higher for crop-based biofuels and are projected to be roughly the same for cellulosic ethanol (Searchinger et al. 2008). These analyses find that biofuels decrease emissions overall only because they assign the biofuels a credit for the carbon taken out of the atmosphere by the plants incorporated into the fuel. For most biofuels, that in effect means a land use benefit, for land is needed to grow the plants. Yet, nearly all reasonably productive lands, even if not devoted to biofuels, would still be taking up carbon from the atmosphere and incorporating it either into plants and roots for storage, as in a forest, or into useful human products, as in crops and grassland grazed by livestock. Devoting this land to biofuels sacrifices some, and often much, of these alternative carbon benefits. A proper lifecycle analysis must not only count the benefits of using land for biofuels, but must deduct the carbon benefits given up by doing so. Typical lifecycle analyses assign biofuels the gross benefit of using land, while they should only assign a net benefit or cost.

To illustrate this concretely, if biofuels are grown by plowing up forest, the clearing of the land will release large quantities of previously sequestered carbon to the atmosphere and may forego ongoing sequestration. If biofuels are grown on existing cropland, there may be no direct effect on carbon storage, or it may even be positive if perennial grasses replace crops and increase soil carbon over time. But if the food is replaced, at least some additional land will be placed into production, coming from forest and grasslands, and potentially other lands will be further intensified requiring greater use of inputs. Because the use of productive land for biofuels by definition sacrifices a great deal of food or carbon storage and sequestration potential, it has an inherently large opportunity cost, which implies that greenhouse emissions will either increase or at best only modestly decrease (Righelato 2007; Gibbs 2008; Fargione 2008; Searchinger 2008).

A net GHG benefit is most easily achieved by using waste carbon, such as municipal

box 16.4

Case Study - India

Land use changes. India has announced an ambitious target of 20% diesel substitution by biodiesel by 2017. Jatropha is being considered to meet the biodiesel demand, focusing largely on the wastelands. The land required for the 20% target substitution is estimated to be about 14 Mha. Estimates by Ravindranath et al (Chapter 6) shows that the land required for substituting 10% of projected demand for diesel and gasoline by 2030 is 7 Mha (with palm oil and sugarcane) to 21 Mha (with maize and jatropha). Area under wastelands according to the National Remote Sensing Agency is 41 Mha and in addition over 20 Mha of long-term fallow lands are available for biofuel or forestry programs. It is feasible to assume that farmers may convert currently cropped area to biofuel crops if the economics is attractive and if incentives are provided. Thus even if jatropha and maize biofuel crops are considered, the land requirement of 21 Mha for biofuel production can be met from the currently available wastelands and long-term fallow lands. These lands may require significant inputs of nutrients and soil and water conservation measures for obtaining the desired yields. The yields of major crops in India are about ½ to 2/3 of global average. Additional land may become available, if yields of main crops such as rice, wheat, sorghum and pulses are increased to the global mean level.

India has strong Forest Conservation Acts, which ban conversion of forest land for non-forest purposes. Periodic monitoring of forest area by Forest Survey of India show that forest area has stabilized since 1990 at around 64 Mha, with insignificant forest loss. Thus forest lands will not be used biofuel crops in India.

Nearly half of India's geographic area is under crops, and another 22.8% constitutes legal forest land. Other than forest and croplands, an area of 74.8 Mha is categorized mostly as wasteland, which is highly degraded, and has poor vegetation cover (MOA, 1997). Forest area in India has traditionally been defined as the land under the control of state forest departments, rather the land actually under the tree cover. Since 1987, the Forest Survey of India (FSI) is using remote sensing technology for assessing the forest cover of the country biennially. The results of the past seven FSI assessments are given in Table 16.4.

In India, area under food production has stabilized, despite the continued growth in population. Even the projections for 2020 also show the area under food production is unlikely to increase and the growing demand for food will be met from increasing cropping intensity and productivity.

Table 16.4 Forest cover estimates - 1987 to 2003 (Ravindranath et al, 2008)

Year	*Data period*	*Forest cover (Mha)*	*Percentage of geographic area*
1987	1981-83	64.08	19.49
1989	1985-87	63.88	19.43
1991	1987-89	63.94	19.45
1993	1989-91	63.94	19.45
1995	1991-93	63.89	19.43
1997	1993-95	63.34	19.27
1999	1996-98	63.72	19.39
2001	2000	75.70*	23.03
2003	2002	77.47*	23.57

or industrial wastes, or agricultural and forestry residuals, because they do not trigger land use change (Perlack 2004).

To the extent feedstock production requires the dedicated use of land, a significant net gain is likely only if the land is otherwise marginal from a carbon perspective, meaning it neither sequesters significant storage nor produces significant food, yet it has the capacity to produce biofuel feedstocks abundantly. This generally implies land wet enough to support high plant growth but degraded and unproductive for some other reason. That GHG test could also be met on dry lands with irrigation, but irrigation raises separate issues regarding competition for water (chapter 8, this volume). Another possibility is lands that currently provide bioenergy inefficiently, (e.g. areas used for firewood harvesting), to the extent they can be manipulated to provide bioenergy more efficiently.

Biodiversity. The greenhouse gas emission criteria imply that direct use of carbon-rich lands is generally inappropriate for biofuels. Unfortunately, carbon-rich lands are not the only lands that are biologically diverse. For example, two of the potential large areas for expansion in South America and Africa are savanna woodlands (Cerrado in Brazil and miombo in Southern Africa) that are of only medium levels of aboveground biomass but that have a high biodiversity value.

Habitat loss and degradation associated with land-use change or modification of the land by human activities is the leading cause of global biodiversity loss. Protecting biodiversity also requires that we consider other changes that will threaten ecosystems and therefore raise the conservation value of areas that are not now threatened. Many areas susceptible to deforestation are not protected, and many "protected" areas that could become vulnerable. Nitrogen enrichment from increasing atmospheric loadings is widely thought to be a major factor for the loss of plant species from temperate terrestrial ecosystems (Clark & Tilman 2008). Effects of N deposition in tropical systems (forests and savannas) are less studied but available data also indicate decreases in species richness (Bobbink et al., in review). The invasion of natural ecosystems by exotic plants also forms an important component of global environmental change (Vitousek et al. 1997) and pose another major threat to biodiversity (Sala et al. 2000).

The combination of increasing habitat losses and climate change is especially worrisome. Human-induced climate change can result in a great, large-scale loss of biodiversity around the world, with dramatic alterations in the distribution and extinction of species, primarily in vulnerable and fragmented ecosystems (Thomas et al. 2004). These threats warrant a prudent approach to protecting valuable habitats that may be less rare today.

Socio-economic factors. Assuring socio-economic benefits raises a host of additional land questions. While in a few regions of the "New world", vast expanses of land can be viewed as an open frontier, in most parts of the world there is a long history of land occupation. Even in regions with a low population density, such as rangelands in Africa, access to land is tightly regulated by local institutions. Whether land ownership is private or communal, land that seems to be unused is not necessarily available for development. Low productivity rangelands, for example, play a crucial role for the livelihood of pastoralists, even though they may not be permanently used. In forest regions dominated by long-fallow farming systems, large areas under a forest cover are actually used: for every hectare of cultivated land there can be as much as 5 hectares of fallow land in reserve.

The feasibility of large-scale biofuel production also depends on the presence of basic infrastructure (roads, storage, accessibility to ports for exports), the availability of a skilled labor force, the provision of services (often associated with urban centers), and a governance system that favors private investments. A lack of political stability, which is still an attribute of several Sub-Saharan African countries, is not conducive to land-based investments. The legal system of some countries prevents land acquisition by foreign enterprises. In other countries, land claims by various groups create a climate of uncertainty that is unfavorable for agricultural investments. Suitable areas for biofuel production are likely to be remote from the main energy demand centers, thus requiring long distance transportation with all its associated economic and environmental costs.

On the positive side, the development of a biofuel production sector is likely to have a multiplier effect on other sectors of the economy, provided it is linked to these sectors via the market for inputs (labor, fertilizers, machinery, etc.) and output (transportation, transformation, energy provision, services, etc.). Investment in biofuel operation will create a road network, income for rural workers, services and may lead to economies of scale benefiting other agricultural activities and the non-farm rural sector. It could thus be a catalyst for rural development.

Conclusions

The analysis of land availability for an aggressive biofuels program is summarized in the following five points:

- Supply of land is tight and a growing population will put increasing pressures on its uses.
- How much land there is available, at which yield potential, and in which locations to produce enough biofuels to provide a significant fraction of world energy is a subject of much debate.
- The real pressure points are in the tropics where new croplands could be developed, where biodiversity values are high, and where much of the population is vulnerable to multiple stresses.
- From an environmental standpoint, there are few areas where biofuels are an acceptable use of land given the alternative uses.
- At the regional and local scales there are opportunities to create acceptable uses of biofuels that have net benefits for society.

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