

# 20

## Land and Water: Linkages to Bioenergy

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## Executive Summary

Sustainably managing limited resources, such as productive land areas and available freshwater, will be one of the world's most pressing challenges in the coming years. Population increases and economic growth will significantly influence humanity's future demand for land and water for different uses. In particular, changes in food and energy use will have substantial environmental impacts. They will also influence each other in many ways. At the same time, the production of food and energy, and the water resources they require, will be affected by global climate change. Sustainability issues arising from competition and synergies between future production of bioenergy and food, and related water use, are highly important in this context.

Population growth is one of the factors contributing to increased demand for land and water. While the world's population has approximately doubled since the 1960s, global economic activity has increased approximately 40 fold. Since growth in incomes is strongly correlated with increased consumption of animal-derived food (meat, milk, eggs), the combination of population increases and economic growth will likely result in increased feed and food production. This will drive up pressures on land and water resources if not counteracted by innovations that reduce land and water use. Social inequities are increasing as well, with both very rich and very poor populations often practicing 'inefficient' methods of using land and water.

Considering the importance of these issues, in particular the need to achieve the Millennium Development Goals (MDGs) and beyond (see Chapter 2), the objective of this chapter is to assess and discuss major trade-offs related to the different uses of land and water, in particular related to future energy systems, and to discuss the corresponding sustainability issues.

With respect to land use, this chapter aims to evaluate land availability, including land for bioenergy production. It discusses competition for land from different uses (food, fuel, timber, etc.), environmental impacts, and implications for natural resources (e.g., biodiversity, atmosphere, water), as well as social factors such as food security, health, and incomes.

With respect to water use, the chapter discusses water demand for different kinds of uses, with a special emphasis on water for bioenergy crops in potential competition with water needed for food production. The multiple uses of water considered include human consumption, hydro and thermal power generation, manufacturing, agriculture, water supply security, and bioenergy. Environmental, social and strategic factors, and potential trade-offs, are examined. Competition between food and energy crops may not always be over 'the same water.' Depending on the type of feedstock, it is possible to cultivate energy crops in areas where conventional food production is not feasible due to water constraints.

This chapter confirms major studies suggesting that global land and water resources will be sufficient to adequately nourish a world population of 9–10 billion people in 2050. However, the potential to additionally produce crops for bioenergy will depend on future changes in food systems (including diets), population growth, and agricultural technologies to improve crop yields and livestock feeding efficiencies, institutional arrangements, climate conditions and area demand for biodiversity conservation. Recent studies suggest that the technical potential for bioenergy production is uncertain due to these factors, which are difficult to predict. Studies mentioned in IPCC (2011) indicate that the technical bioenergy potential may reach up to 500 EJ/yr, while others found much lower potentials. This chapter only discusses the potential of dedicated energy crops.<sup>1</sup> Considering sustainability constraints related to possible competing land demands (food, feed and fiber production, biodiversity conservation, etc.), problems posed by possible

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<sup>1</sup> Dedicated (bio)energy crops are "[f]ast growing species whose biomass yields are dedicated to the production of more immediately usable energy forms, such as liquid fuels or electricity" (Sartori et al., 2006). Dedicated energy crops refer to any crop that is grown for the primary purpose to obtain bioenergy, e.g., sugarcane, switchgrass, or *Salix*. These crops may, of course, also be grown for other purposes. See also SECO, 2008.

deforestation, and water availability, three studies analyzed in this chapter (van Vuuren et al., 2009; Erb et al., 2009; and WBGU, 2009) found global bioenergy crop potentials of 44–133 EJ/yr in 2050. Another study, Dornburg et al. (2010), concludes that for energy crops (dedicated energy crops) they are 120 EJ/yr. So the range considered in this chapter is 44–133 EJ/yr for 2050.

For a full evaluation of all other bioenergy potentials except dedicated bioenergy crops, see Chapter 7. Chapters 11 and 12 discuss technologies and utilization pathways, including biofuels and power generation from biomass.

Reaching the stated technical bioenergy potential depends on many important factors (land and water availability, feedbacks between food, livestock and energy systems, climate change, etc.). Land allocation for different purposes will have to be monitored and managed carefully through adequate policies to minimize competition between food, bioenergy and fiber markets. Adequate policies to introduce bioenergy plantations to avoid adverse social, economic and ecological effects are also needed, since best-practice examples suggest that such plantations could be sustainable if based on sound strategies. Monitoring, managing and enforcement are required to ensure sustainability of bioenergy production. Policies for sustainable land (and water) use must include agro-economic-environmental zoning and planning, in order to consider specific environmental conditions of each region, like those already existing, for example, in Brazil.

The impact of increased biofuel use on food prices has been debated widely and is also covered here. Adequate food production for the world's growing population strongly depends on future dietary choices as well as the development of agricultural technologies that increase agricultural yields and livestock feeding efficiency through enhancements in crop management and/or genetic modifications, as well as institutional changes. The impacts of biofuel production on agricultural markets and food systems will be minimized if adequate policies for biofuels are in place to ensure sustainable production, prioritize the diversification of technologies and fuels, and identify different options for the future, based on adequate environmental zoning and sustainable policies. This must occur through public intergovernmental policies that govern and regulate markets and stimulate the adoption of efficient technologies. These policies include biofuel sustainability schemes based on certification schemes. Integrated optimization of food and bioenergy production – for example, through the use of by-products and residues, or through optimization of land allocation (zoning) – can help to mitigate possible adverse effects.

Climate change can have a substantial effect on land-use systems, but its impacts are still imperfectly understood. In subtropical and tropical regions, changes in climate and rainfall may change the agricultural suitability of a region significantly. Temperature increases may lead to a shift of some crops and agricultural areas to regions with more temperate climates, or with higher levels of soil moisture and rainfall. In general, crop productivity in the tropics may decline even with a slight increase in local temperatures (1–2°C). An increase in vulnerability of food production due to climate change may also increase the risk of hunger to a large number of people in the world, mainly in poor countries, which are most vulnerable to the effects of global warming and the least prepared to deal with its impacts (IPAM, 2002).

The chapter's main conclusion on water trade-offs is that the increasing stress on freshwater resources brought about by ever-rising demand, due mainly to population growth, is of serious concern. As population increases and development requires additional allocations of groundwater and surface water for the domestic, agriculture, energy and industrial sectors, the pressure on water resources will continue to intensify, leading to further tensions and conflicts among users, and degradation and pollution of the environment. Contamination of rivers, depletion of aquifers and increased utilization for multiple purposes are challenges commonly found in regions where demand exceeds supply and where water management is poorly conducted. Indicators such as water footprints are important to understand these important issues.

Water scarcity leads to competition between different uses, with competing demands from: cities and rural areas; rich and poor people; arid lands and wetlands; public and private sectors; infrastructure and natural environments; mainstream and marginal groups; and local stakeholders and centralized authorities. Water conflicts can arise in water-stressed areas among local communities, and countries, because sharing a very limited and essential resource is extremely difficult.

The lack of adequate legal instruments exacerbates already difficult conditions. In the absence of clear and well-established rules and regulations, severe tensions tend to dominate, and political and economic power can play an excessive role, leading to inequitable allocation of water. A well-developed system of Integrated Water Resources Management, including adequate institutional set-up and a good governance system, is needed in river basins or confined regions where demand exceeds existing supply.

Climate change is expected to account for about 20% of the global increase in physical water scarcity – and countries that already suffer from water shortages will be hit the hardest. This would include African countries, where water is a limiting factor for agricultural food production and also essential for income generation.

## 20.1 Introduction

World population growth, changing diets and increasing urbanization result in a surging demand for products and services that require land and water as significant inputs. In connection with these changes, increased consumption of fibers (including wood) and bioenergy are likely to lead to a considerable growth in humanity's need for biomass from agriculture and forestry. How this will affect global land and water systems will depend on innovations in agricultural technology as well as future changes in social, economic, political and legal factors that affect land use, such as land tenure, property rights, subsidies, and markets for land and agricultural products, water access and bioenergy (Global Land Project, 2005; Turner et al., 2007).

Moreover, demand for water is likely to be driven up by changes in infrastructure (households, buildings, schools, hospitals, etc.), increased requirements for basic sanitation and drinking water, energy sector uses (e.g., for hydroelectricity or cooling water) and other factors. With increasing purchasing power, consumer preferences and behavior will affect the dynamic interplay between production, demand and consumption, and the efficiency of the whole system. Consumers continue to intervene in the impacts on the water cycle through their preferences for, and use of, various goods and services.

In order to address this complex and intertwined set of challenges, a separate chapter was proposed for a comprehensive discussion of the trade-offs and synergies involved in the use of land and water, particularly as they might affect future energy systems. In presenting this discussion, Chapter 20 addresses critical issues related to environmental and social sustainability, and their policy implications. This chapter discusses only regional and global potentials for primary bioenergy from dedicated energy crops in the year 2050, taking into account sustainability constraints and interactions with other sectors such as food supply and agriculture. Chapter 7 discusses the main concepts and potentials related to all types of primary energy resources, including all types of bioenergy (residues, animal manures, municipal solid wastes, and forestry residues) except energy crops (these potentials are taken from this chapter). Chapters 11 and 12 discuss technologies and utilization pathways, including biofuels and power generation from biomass.

The term 'bioenergy' here denotes all kinds of biomass feedstocks that can be used to produce energy carriers or heat from biomass (excluding nutritional energy for humans and livestock). This ranges from combustion of any solid biomass, including municipal and rural solid waste for heat and/or electricity production to recently introduced technologies such as production of liquid or gaseous fuels for use in vehicles from sugarcane, corn, wheat or oil crops (rape, oil palm, etc.) or other biomass. This chapter only discusses primary biomass potentials (i.e., it estimates the total amount of plant biomass (feedstock) that might become available for energy conversion processes) from energy crops; issues of total biomass energy potential (including residues and biomass from forestry) are evaluated in Chapter 7.

There are concerns related to limited availability of suitable land and/or water resources for bioenergy production. This chapter addresses this controversy and discusses recent studies estimating land areas that will be available for bioenergy as well as their productivity potential. It suggests that despite several possible constraints, significant energy crop potentials could be realized if appropriate policies are implemented (IPCC, 2000; Goldemberg et al., 2008; WBGU, 2008; Erb et al., 2009; van Vuuren et al., 2009; Haberl et al., 2010; 2011).

With respect to land, the main aim of this chapter is to discuss issues of land availability for all uses and land suitability for bioenergy production. This discussion is based on the 'food first' principle, i.e., the assumption that the provision of adequate food supplies must be guaranteed when evaluating bioenergy production options (e.g., Sims et al., 2007).

Limits to freshwater availability are also highly relevant in the context of biomass production and demand, as water is a critical input affecting the primary production of terrestrial ecosystems, including agro-ecosystems. In addition, water availability is critical for many other aspects of energy systems, including hydropower, cooling water, etc. Countries have mainly controlled water by the supply-side management approach, balancing supply and demand in an increasingly precarious way, since exploitation and water consumption indices do not take into account either ecological water demand or the spatial and temporal variability of supply and demand (EC and IPTS, undated).

The following considerations are important when discussing trade-offs and synergies related to land availability:

- The productivity of land areas depends on climate and soil conditions, nutrient inputs (e.g., fertilizers), water availability (including for irrigation when needed), and many other natural and socio-economic factors. Net primary production (NPP, i.e., biomass production per unit area and year) and the production of usable plant parts (e.g., grain in the case of cereals) depend on natural conditions and management alike. Even assuming that there is enough land available for all end uses (Berndes et al., 2003; Goldemberg, 2009), the area available for bioenergy crops, as well as for food, feed and fiber, depends on agricultural yield levels.
- Sustainability of land use in agriculture and forestry is a critical issue. While increases in yields achieved through agricultural innovation can help to save land and thereby to reduce environmental problems (Burney et al., 2010), agricultural intensification has also created a host of social and environmental problems such as nutrient leaching, soil degradation, toxic effects of pesticides, and many more (IAASTD, 2009). Therefore, it is necessary to mitigate any negative environmental effects of the agricultural intensification intended to produce yield growth. When used appropriately, land can generate more than one type of product (such as food, feed, energy, or materials) or service (including protection of the soil, wastewater treatment, recreation, or nature protection) – an observation usually denoted

as ‘multifunctionality’ or multiple use (Börjesson, 1999; Londo, 2002; Lewandowski et al., 2003; McCarney et al., 2008). Appropriate land management can reduce trade-offs or even turn them into synergies and enhance biomass production, in a win-win situation.

- Integrated optimization of biomass utilization chains – for example, the use of harvest residues or by-products of production processes, a strategy sometimes referred to as “cascade utilization of biomass” (Haberl and Geissler, 2000; WBGU, 2008) or ‘integrated food energy systems’ (IFES) (Bogdanski et al., 2010) – together with adequate policies, as discussed in this chapter, can help avoid or at least mitigate trade-offs between food and production of energy carriers. It can sometimes even create synergies (e.g., if agricultural by-products can be used for energy provision). This strategy can produce substantial amounts of biomass feedstock at low costs. Constraints to implementing “cascade” or IFES systems, and possible ways to overcome these, are discussed in Bogdanski et al. (2010).

The competition between production of food, biomass for energy, biomass for other uses and use of land for non-production functions (e.g., settlements, nature protection) can influence the amounts of different crops produced, their production costs, their prices, and their environmental impacts. How this competition plays out, however, depends on policy frameworks and the crops used. For example, production of biomass from perennial lignocellulosic crops (second-generation bioenergy crops) can involve the use of land not suitable for cultivation of food crops – for example, degraded and marginal land – and might provide the possibility of combining biomass production with food production or nature protection. On the other hand, some of these areas are currently used by herders for livestock rearing, often in subsistence systems – and this might create new, different trade-offs. Technical innovation in agriculture and biomass conversion can greatly influence trade-offs and synergies between different land uses. Socioeconomic development processes, such as transitions from subsistence to market-based production can play a similarly important role, including the benefits related to the creation of rural jobs through the production of bioenergy in developing countries. Adequate policies are required to achieve synergies where possible and to minimize potential conflicts and adverse affects.

Moreover, population density plays an important role: in regions with low population density, such as many areas in, for example, Africa and South America, bioenergy production with first-generation technologies (such as sugarcane in Brazil) may result in little, if any, competition with food and other end uses if based on well-designed policies (Goldemberg et al., 2008). In other regions conflicts may arise, also through indirect effects from increasing the total demands on land for biomass products. This could become a serious issue with bioenergy and agricultural production at much higher levels than today.

Central to the debate on water issues and water scarcity are water demands and end-use patterns. Water for meeting basic needs, drinking and general household use, though comparatively small in terms of

volume, needs to be readily available. The inexorable growth of cities, concentrating large numbers of people in small areas, exacerbates this challenge locally.

River ecosystems, and the fish and other species living in them, of course need continued running water. However, large dams used mainly for hydropower can destroy both river and terrestrial ecosystems due to impounding, flow regulation, and fragmentation of landscapes. Water is also used to produce energy in medium and small hydropower installations, and for cooling thermal power stations. Distribution of water to different sectors, including for energy purposes and for industry, is to be decided by a water management scheme.

An important use of water is for food production. As the world population continues to increase, a growing number of people will require water for cultivation of food, fiber and industrial crops, and for livestock and fish. It is estimated that crop production to feed the growing population will need to nearly double during the next 50 years. The two main factors driving food demand are population growth and dietary change, which is strongly dependent on economic growth. With rising incomes and continuing urbanization, diets move towards consumption of more animal products, fats and sugar, as well as to a greater variety of foods. Shifts in consumption are expected between different cereal crops, and away from cereals towards livestock, fish products and high-value crops that consume more water (UN-Water/FAO, 2007).

In this context, the objectives of this chapter are to assess and to discuss major trade-offs related to the different uses of land and water, in particular related to future energy systems, land availability, and land for bioenergy. It also examines competition for land from different uses (food, fuel, timber, etc.), environmental impacts, and implications for natural resources (e.g., biodiversity, atmosphere, water), as well as social factors such as food security, health, and incomes. With respect to water use, the chapter discusses water demand for different kinds of uses, with a special emphasis on the increasing need for water for bioenergy crops in competition with the increasing need for water for food production.

In relation to water use, the chapter evaluates the multiple uses of water (human consumption, hydro and thermal power generation, manufacturing, agriculture, water security, bioenergy, etc.), as well as environmental, social and strategic issues, and potential trade-offs. Competition between food and energy crops may not always be over ‘the same water.’ Depending on the type of feedstock, it is possible to cultivate energy crops in areas where conventional food production is not feasible due to water constraints, i.e., the ‘water footprints’ are of a different character (Lundqvist et al., 2008).

## 20.2 Trade-offs in Land Use

This section discusses the different uses of land and the trade-offs related to availability of suitable land areas, and derives conclusions for



adequate policies. The discussion of trade-offs starts with an evaluation of current land use, as a basis for analyzing perspectives for future land availability for bioenergy crops, which depends on future cropland areas and yields, livestock, and critical demand components such as food. Sustainability issues related to environmental, social and economic aspects are critical to this discussion.

### 20.2.1 Current Land Use and Land Availability

The global land-use dataset on a five minute grid (approximately 10x10 km at the equator) summarized in Table 20.1 has the following features:

- Reproduction of national land-use statistics (as reported by the United Nations Food and Agriculture Organization (FAO)) for cropland and forestry at the country level.
- Five land-use classes covering the Earth's total terrestrial area in the form of percent-per-grid cell layers for urban and infrastructure land, cropland, grazing land, forestry, and areas without land use (free of double-counting).
- Spatial patterns derived from thematic GIS maps based on remote sensing.
- Extensive statistical and cross-checks against other, independent datasets such as MODIS, CORINE and others (see Erb et al., 2007).
- Consistency with a geographically explicit database on net primary production (NPP) and its human use (Haberl et al., 2007) as well as with national-level biomass balances and feed balances (Krausmann et al., 2008). This consistency allows analysis of the impacts of allocating additional land for bioenergy production on all other socioeconomic biomass flows, above all feed, fiber and food supply.

Most assessments are based on a "land balance" approach: total cultivable area is identified, and then areas already being cultivated are subtracted. Young (1999) argues that this approach has several inherent shortcomings, such as: (1) overestimation of cultivable land (e.g., failure to adequately account for uncultivable land such as hills, rock, outcrops, minor water bodies, etc.); (2) underestimation of land already cultivated (up to 50% in some assessments, in particular in sub-Saharan Africa); and (3) inadequate accounting of land demand for purposes other than cultivation (e.g., grazing or settlements), conservation and ecological services, and urban development. Erb et al. (2009) suggest that it is not realistic to assume that mowing and livestock grazing are confined to "permanent pastures," as reported in FAO statistics. According to Table 20.1, about 76% of the world's land surface is used more or less intensively, with around 15 million km<sup>2</sup> being cropland.

Currently unused areas (24%) include: almost completely unproductive land (aboveground biomass productivity below 0.04 kg/m<sup>2</sup>/yr), currently

unused grasslands and scrublands (mostly remote and with low productivity), and the world's last remaining pristine forests. Except for pristine forests, currently unused lands are unlikely to be suitable for providing significant additional areas for cultivation in the future. With regard to use of forests, however, there are studies showing that converting pristine forests to bioenergy production would have long carbon payback times and would, therefore, not contribute to the mitigation of climate change over the next decades (WBGU, 2008; Searchinger et al., 2008). Negative environmental impacts from deforestation can be avoided by the introduction of adequate policies and enforcement measures, as discussed in Goldemberg et al. (2008). For production of bioenergy without deforestation, the areas available are those classified in Table 20.1 as cropland and grazing land.

In the case of cropland, it is possible to plant bioenergy crops on land currently lying fallow, or on cropland that becomes available if yield increases surpass the growth in demand for food, feed and fiber, thereby freeing up area for energy crops. Much larger land potentials can be mobilized on land classified as "grazing area" in Table 20.1. This category is a "remainder" category, i.e., it comprises all land not classified as infrastructure, cropland, forestry, or unused land. Land classified as "grazing land" in Table 20.1 includes a large variety of land, ranging from highly productive grasslands intensively used for grazing or mowing to barely productive, very extensively used land dominated by shrubs, more or less bare areas, and other vegetation. This category also includes degraded lands (except degraded cropland or forests), abandoned farmland, and other very extensively used lands.

Up to a certain point (which depends on the respective regional roughage demands of livestock), the use of the land in this category could be used to grow bioenergy crops. This would allow the production of bioenergy without deforestation and with few, if any, repercussions on the livestock sector (see Goldemberg, 2009; Goldemberg et al., 2008; Goldemberg and Guardabassi, 2009; Macedo et al., 2008; Nassar, 2009). In many cases, especially in degraded areas, use of such land for bioenergy production could have a favorable greenhouse gas (GHG) balance due to carbon sequestration in the soil, as discussed in Soares et al. (2009).

Urban areas and infrastructure are bound to grow due to population growth and increasing wealth, taking up sizeable areas of high-quality land, some of which is currently used as cropland. Expanding the amount of cropland available would almost exclusively mean bringing land into cultivation that is currently used for grazing or forestry. Expanding into land classified in Table 20.1 as "grazing land" is possible where this land is used extensively, i.e., where livestock density can be increased without causing degradation. This is possible in many regions where livestock densities are sufficiently low (see Erb et al., 2009). A comparison of the grazing land areas of quality classes 1 and 2 in Table 20.3 with livestock densities estimated by FAO (2006) suggests that much, but by far not all, of the available high-quality grazing land is used for intensive livestock rearing.

It is a difficult task to assess the area and spatial distribution of land that could be suitable as cropland but is at present not used for crops.

Table 20.1 | Global land use in 2000.

	(1) Infra-structure	(2) Cropland	(3) Used forests	(4) Grazing land total	(4.1) Grazing class 1	(4.2) Grazing class 2	(4.3) Grazing class 3	(4.4) Grazing class 4	(5) Unused land total	(5.1) Unused Forests	(5.2) Unused shrubs etc.	(5.3) Non-productive, snow	(6) Area total <sup>a</sup>
(1000 km <sup>2</sup> )													
USA	280	1782	2598	3473	853	390	524	1706	1044	383	504	157	9178
CAN	57	458	2143	1000	170	298	131	402	5673	2032	2249	1392	9331
WEU	203	1129	1475	1480	529	235	295	421	152	21	120	11	4440
EEU	60	463	370	264	158	40	54	12	1	0	1	0	1159
FSU	240	2086	7458	7053	1052	705	1578	3718	4777	1826	2671	280	21,614
NAF	20	451	245	2013	363	156	165	1328	5256	5	59	5192	7984
EAF	13	283	382	2418	978	176	323	941	158	3	28	127	3254
WCA	34	900	3382	4125	1039	1172	610	1304	2925	139	608	2178	11,367
SAF	59	431	1873	3971	832	1058	600	1482	524	5	130	389	6859
MEE	24	347	59	1721	3	1	138	1578	3018	0	16	3002	5169
CHN	95	1496	1633	3991	891	425	1669	1005	2135	1	323	1811	9351
OEA	11	167	498	1386	190	76	188	932	349	7	77	264	2411
IND	75	1698	640	653	227	101	163	163	80	1	7	73	3147
OSA	28	437	163	803	100	32	365	306	478	1	8	469	1908
JPN	38	48	245	38	25	12	0	1	25	3	22	0	394
OCN	22	531	862	3390	407	298	899	1786	3107	264	2539	305	7913
PAS	35	831	2192	1148	531	431	52	135	111	31	80	0	4317
LAC	64	1685	8733	7932	3062	1749	489	2633	1880	1446	178	256	20,295
Other	0	1	5	21	4	1	0	15	257	0	0	257	284
<b>TOTAL</b>	<b>1358</b>	<b>15,224</b>	<b>34,956</b>	<b>46,880</b>	<b>11,414</b>	<b>7356</b>	<b>8243</b>	<b>19,868</b>	<b>31,950</b>	<b>6168</b>	<b>9620</b>	<b>16,163</b>	<b>130,375</b>

<sup>a</sup> Excluding Greenland, Antarctica and inland water bodies.

Note that (1) + (2) + (3) + (4) + (5) = (6). Moreover, (4.1) + (4.2) + (4.3) + (4.4) = (4) and (5.1) + (5.2) + (5.3) = (5). Differences are due to rounding.

Source: Erb et al., 2007.

The following factors need to be taken into account when calculating area potentials for agriculture and energy crops:

- Data on settlements and related infrastructure land (and projections out to 2050) should consider rural infrastructure areas required to support cropland existing now or assumed to exist in 2050 (Table 20.2, Erb et al., 2007; Erb et al., 2009).
- Land under forestry and currently unused land (wilderness, including unused forests) are increasingly accounted separately (see, e.g., Table 20.1), which enables the exclusion of forest areas from the assessment of agriculture and bioenergy crop potentials – a plausible procedure because clearing forests for agriculture and bioenergy production results in large GHG emissions (WBGU, 2008).
- Biomass balances of feed supply and livestock production allow an evaluation of whether or not grazing land remaining after conversion to grow bioenergy crops can support the required livestock feed demand (Erb et al., 2009). An assessment of grazing land quality (Erb et al., 2007) helps to identify grazing areas suitable

for bioenergy crops (Erb et al., 2009), as well as for agricultural crops.

Table 20.2 compares current infrastructure and cropland areas with estimates of quality classes of grazing lands based on (a) the assessment of global land use in Table 20.1; (b) an assessment of cropland suitability (Ramankutty et al., 2002); and (c) assessments of cropland suitability from the Global Agro-Ecological Zoning (GAEZ) maps (FAO and IIASA, 2000). The classification of grazing land quality was based on its NPP as well as on land cover information. For example, bare areas and shrub lands were assumed to be less suitable for grazing than areas with herbaceous vegetation (Erb et al., 2007).

The GAEZ study (FAO and IIASA, 2000; Fischer et al., 2002) combined soil, terrain and climate characteristics with crop production requirements. It estimates suitability for crop production at three input levels (low, medium, and high). About 30% of the earth's land surface, except for Antarctica and Greenland (a bit more than 40 million km<sup>2</sup>), was found to be at least moderately suitable for rain-fed crop production (Bruinsma, 2009).

**Table 20.2 | Comparison of current (2000) infrastructure and cropland areas with two assessments of cropland suitability and current grazing areas.**

	Erb et al. 2007		Ramankutty et al. 2002		GAEZ: Climate, soil, terrain & slope constraints combined				GAEZ: Suitability for rainfed cultivation – maximizing technology				GAEZ: Suitability for rainfed cultivation max. tech., without forest areas				Erb et al. 2007	
	Infra-structure 2000	Plus cropland 2000	Cropland suitability >0.7	Cropland suitability >0.5	No or (very) few constraints	plus partly with constraints	plus freq. severe constraints	Very high + high	Plus good	Plus medium	plus moderate	Very high + high	Plus good	Plus medium	plus moderate	Grazing class 1	Plus grazing class 2	
USA	280	2,062	2,156	2,982	792	2,596	3,495	1,987	2,732	3,296	4,061	1,262	1,724	2,068	2,656	853	1,243	
CAN	57	514	277	539	68	356	692	156	347	695	1,039	73	159	382	607	170	468	
WEU	203	1,333	1,444	2,120	384	1,246	2,256	506	897	1,434	2,009	482	834	1,291	1,770	529	764	
EEU	60	523	537	798	132	530	933	290	556	754	938	272	516	675	809	158	198	
FSU	240	2,326	2,038	3,577	590	2,664	3,914	1,569	2,342	3,345	4,207	1,184	1,773	2,490	3,140	1,052	1,757	
NAF	20	470	438	755	60	455	820	632	838	997	1,187	628	834	992	1,181	363	519	
EAF	13	296	443	728	155	678	1,237	274	531	840	1,168	267	510	797	1,095	978	1,154	
WCA	34	935	321	1,408	76	1,601	3,050	2,981	4,175	5,175	6,313	2,034	2,966	3,752	4,568	1,039	2,211	
SAF	59	490	395	1,295	156	1,228	2,854	1,223	2,043	2,920	3,808	1,178	1,964	2,791	3,620	832	1,890	
MEE	24	371	33	84	45	155	396	8	20	58	122	8	20	58	122	3	4	
CHN	95	1,592	1,915	3,420	175	973	2,137	638	927	1,267	1,771	615	881	1,185	1,636	891	1,317	
OEA	11	178	136	266	9	129	484	169	235	308	381	131	173	223	262	190	266	
IND	75	1,773	840	1,919	351	985	1,727	1,308	1,718	2,040	2,293	1,284	1,678	1,979	2,202	227	328	
OSA	28	465	191	353	24	120	426	167	192	218	261	161	183	204	242	100	132	
JPN	38	86	234	299	40	116	223	28	58	89	136	22	41	57	77	25	36	
OCN	22	554	397	1,070	90	467	1,210	268	510	960	1,562	233	429	807	1,324	407	705	
PAS	35	866	659	1,225	106	914	2,202	445	697	1,038	1,453	385	549	734	935	531	962	
LAC	64	1,750	3,727	5,584	651	3,343	7,312	4,264	6,529	8,741	11,016	2,438	3,652	4,823	5,987	3,062	4,811	
<b>TOTAL</b>	<b>1,358</b>	<b>16,584</b>	<b>16,181</b>	<b>28,422</b>	<b>3,904</b>	<b>18,556</b>	<b>35,368</b>	<b>16,913</b>	<b>25,347</b>	<b>34,175</b>	<b>43,725</b>	<b>12,657</b>	<b>18,886</b>	<b>25,308</b>	<b>32,233</b>	<b>11,410</b>	<b>18,765</b>	

Bold numbers indicate land potentials, i.e., in regions in which more land of a certain class is available or suitable according to the respective criterion than was used for cropland and infrastructure in 2000.

"Gross availability" of land is impressive, but it is important to bear in mind that not all of that land is really available (Young, 1999). Much of this land is either already used for other purposes (e.g., infrastructure or grazing), protected for reasons of nature/biodiversity conservation, or under forests (Bruinsma, 2009). Nachtergaele and George (2009) estimate that protected areas may cover some 2 million km<sup>2</sup>, and forests some 8 million km<sup>2</sup> of that land. Further qualifications must also be made. Land suitability can only be assessed in a meaningful way for a particular crop. Land identified as potentially suitable may be prone to physical or economic constraints, such as ecological fragility, low fertility, toxic compounds in the soil, high incidence of disease, or lack of infrastructure. These factors reduce productivity and profitability (Bruinsma, 2009) and must be taken into account in the elaboration of agro-economic-environmental zoning, following the example of Brazil (see Box 20.5).

Land availability is very unevenly distributed among regions. A large percentage of the suitable land in developing countries, for any agricultural crops, including bioenergy, is located in Latin America and sub-Saharan Africa. South Asia and the Near East/North Africa have lower spare land capacity (Bruinsma, 2009).

Global infrastructure and cropland covered 16.6 million km<sup>2</sup> in 2000 – an area almost equivalent to the estimated cropland with a suitability index higher than 0.7 (Ramankutty et al., 2002). Ramankutty's cropland suitability index is calculated using climate indicators (growing degree days and water availability) and soil indicators (basically, soil pH and carbon) to estimate the probability that a grid cell possesses the physical characteristics for rain-fed cultivation.

In some regions, cropland expansion may face challenges and require costly investments, e.g., in irrigation technologies or other measures of land improvement. In other regions, considerable areas with a cropland suitability index higher than 0.7 are not yet used as cropland or infrastructure. In these regions, cropland expansion can be assumed to be less costly. Globally, only about 57% of the land with a cropland suitability index over 0.5 is already used for infrastructure and cropland. Table 20.2 shows, however, that for two regions, MEE and OSA, current infrastructure and cropland areas already exceed the land with a suitability index higher than 0.5. In these regions, quite poor land is currently used as cropland.

The GAEZ assessment of climate, soil, terrain and slope constraints suggests that the global area of land with no, very few and few constraints is smaller than the area already used for cropland plus infrastructure. However, including land classified as "partly with constraints" results in an additional area which is around the same as the area of land already used for cropland and infrastructure. Cropland expansion potentials seem to prevail in some regions, most notably in sub-Saharan Africa and Latin America and the Caribbean, where agricultural yields could also be improved significantly (Somerville et al., 2010). Moreover, changes in human diets towards less consumption of

animal products would allow a reduction in cropped areas compared to a business-as-usual scenario (Aiking et al., 2006; Erb et al., 2009; Dornburg et al., 2010).

GAEZ also provides suitability estimates for rain-fed agriculture with improved technology that differentiate between potentials on currently forested land and potentials restricted to non-forested land. Here the assessment that excludes forests is most relevant (see Table 20.2). Some analyses raise the question of how well suited land potentials labeled "suitable" in this assessment really are for large-scale, intensive cultivation – in particular in tropical regions where land degradation resulting from inappropriate agricultural practices would be a widespread problem (Stocking, 2003). However, other studies (such as Somerville et al., 2010) suggest that there may be a significant potential to improve crop yields in these regions (as also discussed in FAO (2010a) for Tanzania).

Some authors (including, e.g., Showers, 2006) consider that assessments from Ramankutty et al. (2002) and the GAEZ are based on limited sets of data that were extrapolated and applied to large areas. It is recommended that in-depth regional studies should be carried out to avoid overestimating the cropland expansion potential in regions such as sub-Saharan Africa, where transfer of European cultivation techniques has caused large-scale soil erosion, and European agricultural practices often have been unsuccessful.

Much of the cultivable land in sub-Saharan Africa and Latin America is under valuable forests or in protected areas, and these regions are also those where the largest potentials for arable land are found. Ramankutty et al. (2002) argue that tropical soils could potentially lose fertility rapidly if taken into cultivation, and are highly vulnerable to climate-change impacts. IAASTD (2009) estimates that only 7% of the cultivable areas in sub-Saharan Africa, and only 12% of those in Latin America and the Caribbean, are devoid of more or less severe soil constraints that limit sustainable and profitable production. In fact, agricultural yields mainly in Africa are very low, half of those in the United States (Somerville et al., 2010), and some studies suggest large potentials to increase these yields, and also to make more area available (UNCTAD, 2009; UNF, 2008).

A comparison of area potentials from Ramankutty et al. (2002) and GAEZ with the area listed under "grazing classes 1 and 2" (last two columns of Table 20.2) shows that regions with much land in the grazing land class 1 (best-suited grazing area) are mostly also those in which there are large potentials for cropland expansion. These results are found by both Ramankutty and the GAEZ, whereas those regions with little cropland expansion potential also have small areas of high-quality grazing land. Because the assessment of grazing land quality by Erb et al. (2007) is consistent with data on grazing intensity (Haberl et al., 2007), it can be used to calculate potentials to intensify grazing in order to make land available for the additional cultivation of crops, including bioenergy crops.

The studies mentioned in this review indicate that the availability of land for cultivation of agriculture and bioenergy crops depends mostly on the following factors:

- The most important factor is the intensity with which this land is used today for other purposes, in particular grazing. Calculating livestock feed balances based on national-level livestock data from the FAO (e.g., Wirseniens 2003a; 2003b; Haberl et al., 2007; Krausmann et al., 2008) allows us to approximate the intensity with which grazing areas are currently used for feed production (e.g., Erb et al., 2009). Together with other studies mentioned above, the analysis has shown that grazing areas are used with very different intensities across the globe, suggesting that increased feed production through improved management of grazing areas could make considerable areas available for bioenergy production.
- Other important constraints include: the need to set aside valuable areas for biodiversity/nature conservation; limited water availability; and lack of infrastructure such as roads (i.e., limited accessibility). In some regions with poor soil quality, high levels of investment might be needed to allow cultivation. More important, however, is how the availability of land will change in the future due to changes in demand for products from land, and impacts of climate change.

### 20.2.2 Competing Future Demands for Land

Basically, land is used by humans for at least three core functions (Dunlap and Catton, 2002):

- resource supply, i.e., the provision of raw materials or energy needed for production and consumption processes, including non-renewable resources such as fossil fuels, minerals and other materials extracted from geological deposits, and renewable ones such as biomass or water diverted from current biogeochemical cycles, ultimately driven by an influx of solar energy;
- waste absorption, as well as buffering and regulating capacities of ecosystems; and
- space occupied for human infrastructures, including housing, gardening and recreational areas, as well as industrial and transport facilities.

Most human uses of land are dependent upon the land's biological productivity, i.e., its NPP per unit area and year. Many land uses involve harvesting parts of the actual or accumulated NPP in the form of biomass derived through agricultural or forestry activities (Haberl et al., 2004). At the same time, human land use often alters the land's productivity (Haberl et al., 2007). In some regions, especially sub-Saharan Africa, current land-use practices result in low yields. Implementation of adequate technologies could help to raise agricultural yields considerably (Somerville et al., 2010; FAO, 2010a; Dornburg et al., 2010).

**Table 20.3** | Global average per capita supply and demand of primary biomass.

	Per capita flows of dry-matter biomass (kg/cap/yr)	Percentage of total(%)
<b>Supply</b>		
Harvest of primary crops	473	24%
Harvest of fodder crops	94	5%
Harvest by-products (residues)	485	24%
Grazed biomass (from grazing land)	634	32%
Wood harvest (excluding residues)	321	16%
Total supply	2007	100%
<b>Total Supply</b>	<b>2007</b>	<b>100%</b>
Food	248	12%
Market feed	152	8%
Seed	15	1%
Other uses	233	12%
Non-market feed, including grazing	1004	50%
Firewood	197	10%
Industrial wood	125	6%
Wastes, losses	33	2%
<b>Total Demand</b>	<b>2007</b>	<b>100%</b>

Source: Krausmann et al., 2008.

As shown in Table 20.1, biomass production through agriculture and forestry takes up by far the largest area. Many buffering and/or regulating services of ecosystems are to some extent compatible with productive functions (see discussion of "multifunctional land use" in the Introduction). Global biomass balances (Krausmann et al., 2008) show that most of the biomass is used for food and feed, fiber, and other uses, whereas the amount of biomass directly used for bioenergy production (as firewood) is relatively small.

Firewood reported in Table 20.3 amounted to about 22 EJ/yr globally in 2000. More than half of global biomass supply is used as feed for livestock (see Table 20.3).<sup>2</sup> Reuse and recycling of biomass (i.e., "cascade" or IFES utilization) already plays an important role; agricultural residues and by-products are used as feed inputs and for bioenergy production (e.g., sawdust, bark, residues from paper production, etc.). These "cascading flows" and some underreported flows (e.g., collection of firewood on non-forested land not reported in FAO data and, therefore, also missing from Table 20.3) contributed approximately half of global bioenergy production (45±10 EJ/yr) in the year 2000. Because conversion of forests to bioenergy and agricultural crop plantations would result in a large carbon debt and poor GHG emission performance (and bioenergy options in forestry are discussed in Chapter 7), we here focus on farmland, i.e., cropland and grazing areas.

<sup>2</sup> It is worth noting that, in fact, a significant part of industrial wood is used as energy (for instance, black liquor is about 50% of wood consumed in the cellulosic pulping industry).

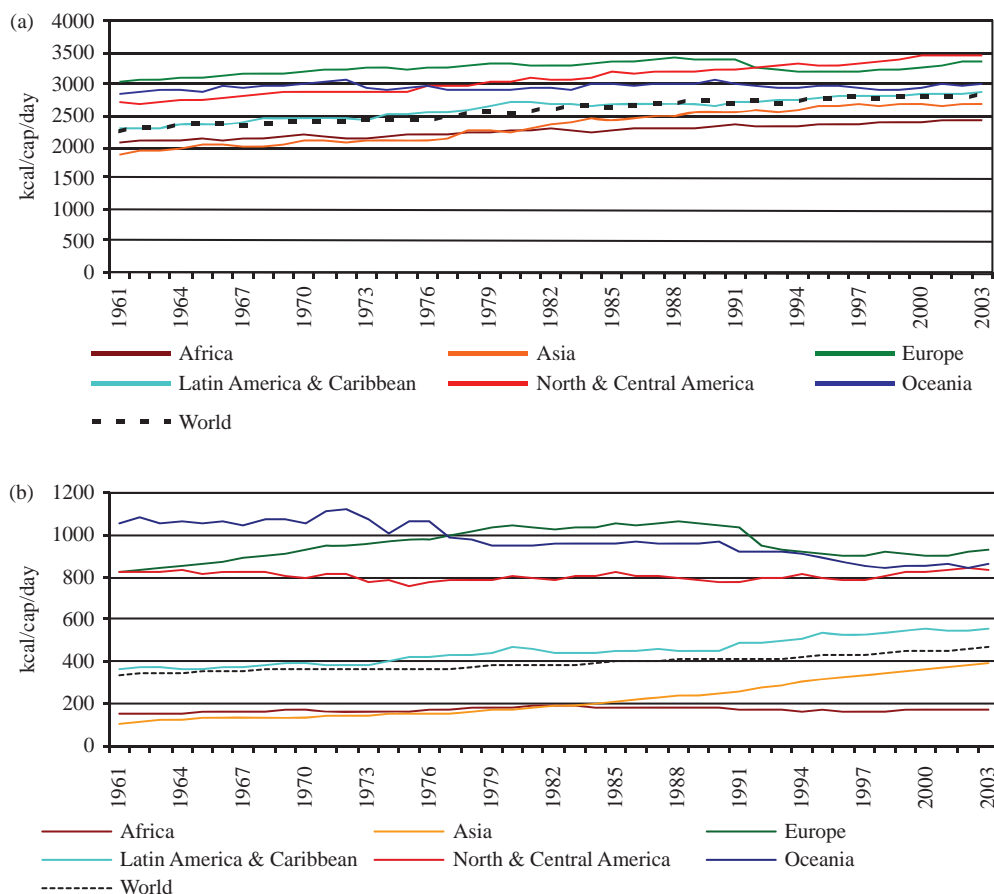


Figure 20.1 | Total food consumption (a) and consumption of animal products (b) 1961–2003. Source: based on data from FAO, 2009a.

As shown in Table 20.3, the food system accounts for a significant amount of the biomass used, as well as the area needed for producing that biomass. Three sets of factors will dominate in shaping the future trajectory of the area required globally for food production:

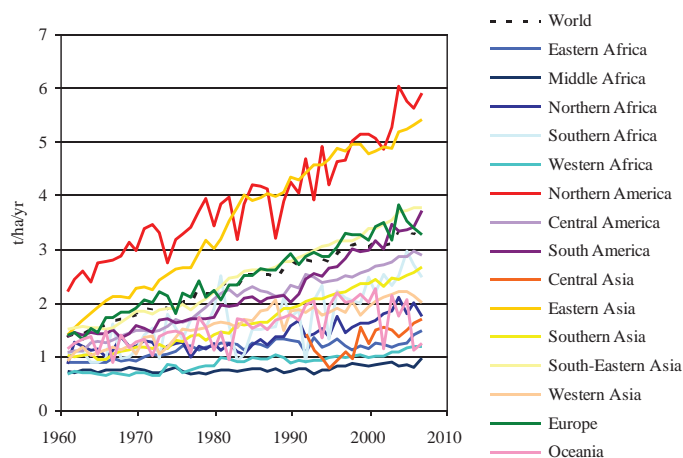
- The volume and composition of global food demand, which in turn depend on population growth and changes in diets: There is a strong correlation between income levels and the volume and composition of food consumed: food consumption rises with income. The proportions of animal products, sugars and fats rise with income, while consumption of cereals, pulses and roots drops with income (Erb et al., 2009). Figure 20.1 shows global trajectories of per capita food consumption 1961–2003.
- Yield levels on agricultural areas (cropland and grazing land): The total volume of crops, forage and by-products produced is the product of the area used times the yield per unit area and year. Yields are highly variable both between regions and across time (see Figure 20.2).
- Feeding efficiencies in the livestock sector: The relationship between feed input and product output (e.g., meat, milk, eggs) is highly variable between different livestock rearing systems. Cross-country

analyses as well as longitudinal data indicate how large these differences are (see Figure 20.3).

Figure 20.1 shows that the total amount of food calories consumed per capita and year is rising continuously in almost all regions. The only exceptions are Europe and Oceania after 1990, where food intake has more or less stabilized at a high level after 1990. The consumption of animal products seems to have stabilized in Europe, North and Central America and Oceania at between 800 and 1000 kilocalories per capita and day (kcal/cap/day); it is rising throughout the developing world, with the exception of Africa, where it has remained almost constant at a low level of 200 kcal/cap/day.

Improvements in agricultural technology have helped to increase yield levels across the globe considerably, while sometimes also resulting in undesired environmental consequences such as soil degradation, water pollution, and others (IAASTD, 2009), when increases in yields are based on intensive high-input monocultures. As Figure 20.2 shows, average global cereals yields grew from 1.35 metric tonnes per hectare and year (t/ha/yr) in 1961 to 3.54 t/ha/yr in 2008. However, yield growth has progressed at varying rates, and has led to considerably different yield levels across the globe. In the lowest-yielding region, yields have remained almost constant,





**Figure 20.2** | Cereals yields in the world. Source: based on FAO, 2009a.

below 1 t/ha/yr, whereas yields have reached more than six times that level in the highest-yielding region, North America. In some regions where yields are currently low, especially sub-Saharan Africa, implementation of adequate technologies could help to raise agricultural yields considerably (Somerville et al., 2010; FAO, 2010a; Dornburg et al., 2010).

Feeding efficiencies in the livestock sector are also highly variable across time and space (Figure 20.3). The differences are particularly strong for grazers (cattle, buffalo, sheep, goats); less so for pigs and poultry. The amount of biomass required per unit of output and, therefore, also the area needed per unit of output depend strongly on the respective livestock rearing systems.

One main reason for the large differences in feeding efficiencies is that livestock is used in a multifunctional manner in subsistence systems. Besides producing animal-based food, livestock plays a big role as a work force (draught animals), is important for the nutrient cycle (through use of dung as fertilizer), and has important social functions, e.g., in rituals, as status symbols, as buffers for times of poor food supply, etc. (Harris, 1987; Krausmann, 2004; Wildenberg, 2005).

Market-oriented systems can be relatively “inefficient” in terms of their feed balance if area is abundant and other inputs (e.g., labor) are more costly and hence more important optimization criteria (Erb et al., 2009). Considering ecological objectives, animal welfare and product quality criteria in livestock rearing may also reduce feeding efficiencies compared to intensive, indoor-housed rearing systems, although this effect should not be over-emphasized. Compared to subsistence livestock raising, and even some existing market-oriented but feed-inefficient systems, modern, optimized organic and humane livestock systems offer large gains in terms of feeding efficiency (Erb et al., 2009).

Using less land area in livestock production by increasing grazing intensities is possible. For example, in São Paulo State, Brazil (Goldemberg, 2009), cattle density heightened in the last decade, thereby increasing area for food/bioenergy crops. Soares et al. (2009) show that the overall

**Table 20.4** | Changes in cattle numbers and area dedicated to cattle in São Paulo State, 2001–2008.

	2001	2002	2003	2004	2005	2006	2007	2008
Number of cattle (million)	13.15	13.46	13.76	13.77	14.07	13.75	12.20	11.95
Pasture area (1000 km <sup>2</sup> )	102.9	101.0	101.1	101.2	100.1	97.1	91.2	76.4
Density (number/km <sup>2</sup> )	128	133	136	136	141	142	134	156

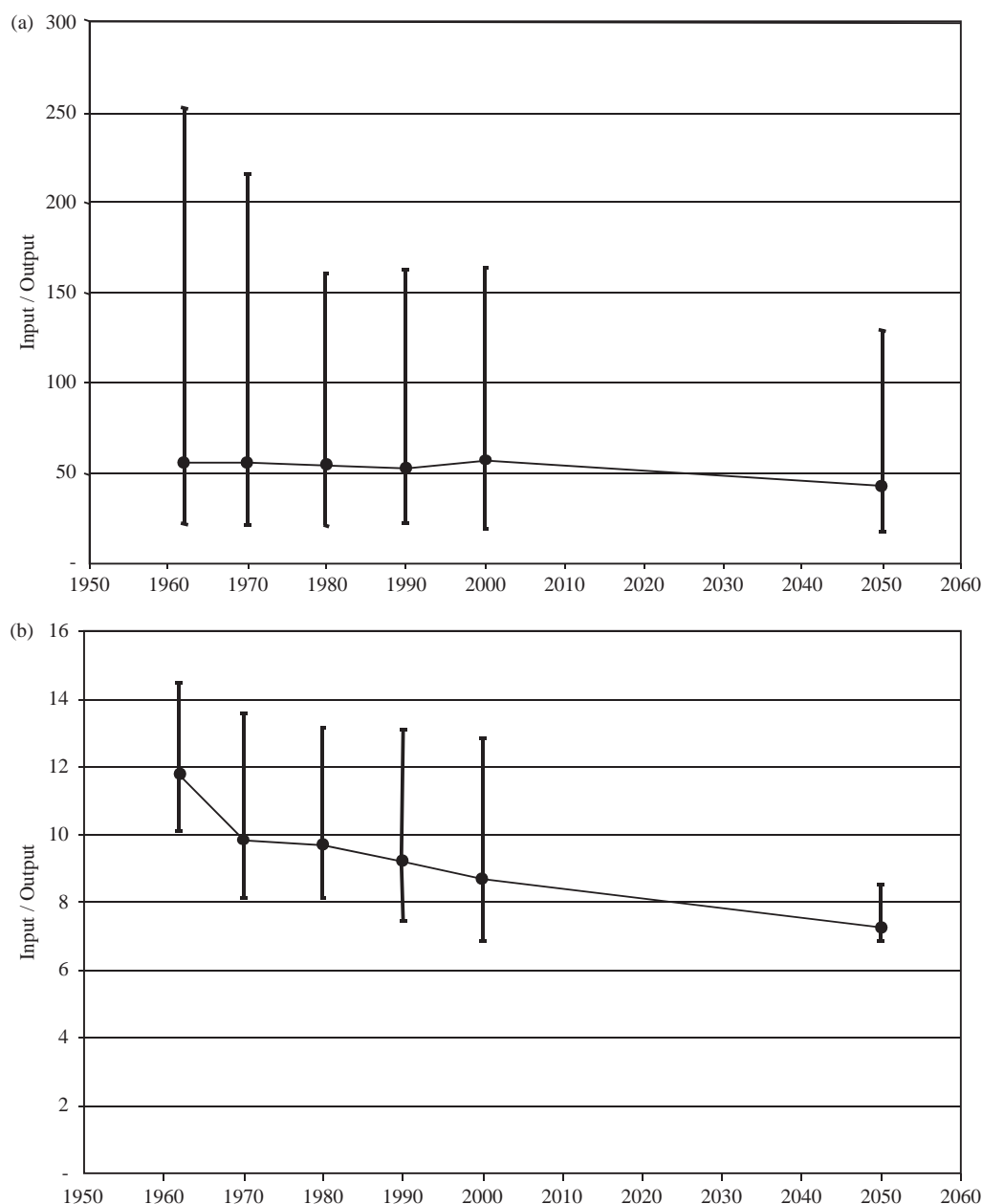
Source: Coelho et al., 2008.

balance on GHG emissions is positive, despite the increases in intensive animal husbandry and the corresponding replacement of cattle areas by sugarcane crops.

The most important uses of biomass for other uses than food, feed or bioenergy materials are pulp and paper, construction materials and chemicals, most of which come from the forestry sector, as discussed in Chapter 7. In different regions, other products – for example, cut flowers – can be important. The chemical industry could boost its use of biomass in the future, as bulk chemicals from biomass have a large potential to be substituted for fossil-fuel-based feedstocks. At present, the amounts of biomass (and related land) used for this purpose are low, and future projections still indicate a limited demand for land for that purpose. However, estimating land demands for future chemical production must also take into account the production of chemicals in bio-refineries where transport fuel and electricity can be co-generated from biomass.

Furthermore, some bio-based bulk chemicals (i.e., plastics) are often used for waste-to-energy generation in industrialized countries (see Figure 20.4).

FAO estimates that global agricultural production would have to be increased by 70% to feed the global world population expected in 2050, meeting a food supply target of 3130 kcal per capita and day (Bruinsma, 2009). This considerably exceeds global average food supply for 2000, which was 2790 kcal/cap/day (FAO, 2005), but might still leave approximately 4% of developing-country populations chronically undernourished if current patterns of inequality of food distribution persist. On the other hand, the International Food Policy Research Institute (IFPRI, 2009) indicates that daily per capita calorie availability in developing countries in 2000 was 2694 kcal, and that scenarios in these countries for 2050 could reach 2896 kcal/cap/day, if there were no climate change effects, with the largest increase (13.8%) in East Asia and the Pacific. However, there are gains for the average consumers in all countries – 3.7% in Latin America, 5.9% in sub-Saharan Africa, and 9.7% in South Asia. Taking into account climate change, calorie availability in 2050 is lower than those numbers; it actually declines relative to 2000 levels throughout the world (IFPRI, 2009).



**Figure 20.3** | Global feed efficiencies (feed input per unit of animal product output, both measured as dry-matter biomass): (a) Grazers (cattle and buffalo, sheep, goats); (b) Non-grazers (pigs, poultry), 1961–2000. Source: Haberl et al., 2011. Dots represent the weighted global average, whiskers the variability between the 11 regions covered in that study.

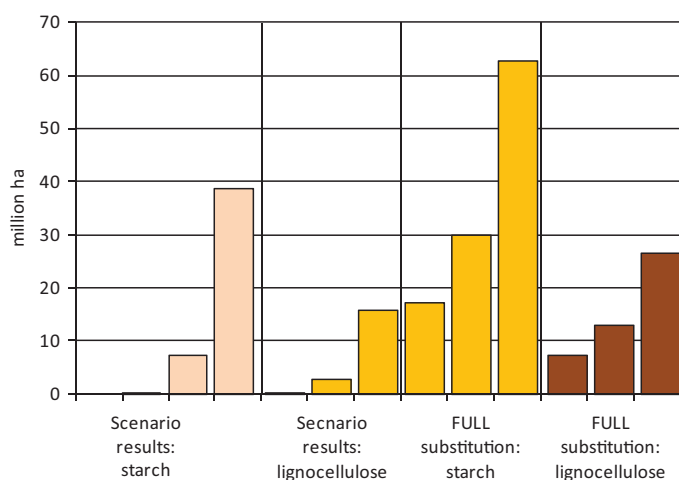
The share of animal products in people's diet would strongly affect the amount of primary biomass and area required to meet global food demand. If diets shift towards less protein from animal products, the global demand for cropland and grazing lands can be much lower than in a business-as-usual scenario (e.g., see Erb et al., 2009; Dornburg et al., 2010).

According to the "Trend" (business-as-usual) scenario of Erb et al. (2009) – based on FAO (2006) – higher yields and increased cropping intensity are expected to contribute 90% of the growth in crop

production by 2050 (80% in developing countries), with the remainder coming from land expansion. Arable land would expand by around 9% compared to 2000 in the global total. Cropland expansion would be largest in sub-Saharan Africa, Latin America and the Caribbean, and Oceania/Australia. Global cropland area would reach 16.6 million km<sup>2</sup> in 2050 in such a scenario.

In this scenario (Erb et al., 2009), growth of cropland areas in developing countries was assumed to be 12% (1.2 million km<sup>2</sup>), almost all in Africa and Latin America, which is partly offset by a decline of some





**Figure 20.4** | Total land used by 2050 for the selected organic chemicals according to the three scenarios (low, medium and high) and for full substitution of selected chemicals, i.e., 100% bio-based chemical production. Source: Dornburg et al., 2008.

0.5 million km<sup>2</sup> (8%) in developed countries. Land equipped for irrigation would increase by 0.32 million km<sup>2</sup> (11%), which is assumed to take place almost exclusively in developing countries. Water withdrawals for irrigation are forecast to increase by 11% between 2006 and 2050. It is forecast that crop yields would rise at a slower pace than in the past. Annual growth rates would halve to 0.8% per year compared to historical growth rates.

According to Cassman (1999) and Peng et al. (2000), many options to achieve yield gains have already been discovered, and further increases seem unlikely in some areas due to physiological limits. For example, these authors argue that further improvements in harvest indices that seek to increase the share of the desired product (e.g., grain) at the expense of supporting tissues such as leaves and stems (straw) seem unlikely for many cultivars because of physiological limits. Harvest indices of the most advanced rice cultivars are already around 0.50–0.55. It would seem unlikely that this can be increased substantially.

Tilman et al. (2002) argue that a continuation of past yield increases seems unlikely, because most of the best-quality farmland is already being used. According to these authors, rates of yield increases are already declining (e.g., rice in Southeast Asia), and yields have leveled off (e.g., rice in Japan, Korea, and China) as they approach limits set by soil and climate. Cassman (1999) argues that soil degradation and depletion of nutrient stocks in soils is an additional challenge. Also, a more widespread adoption of less intensive agricultural technologies (e.g., organic farming) could result in lower rates of yield growth or even declines in yields in regions where intensive conventional cultivation methods are common (Erb et al., 2009). On the other hand, Somerville et al. (2010) suggests that high investments can benefit developing countries, mainly in Africa, where countries present the lowest agricultural rates worldwide.

Improvement of management practices could help to maintain growth in yields, mostly due to improved stress tolerance, avoidance of nutrient and water shortages, improvements in pest control, etc. Some scenarios even foresee higher yield increases than the FAO (e.g., IAASTD, 2009). For example, the “Global Orchestration” scenario analyzed in the Millennium Ecosystem Assessment (2005) assumes that yields in 2050 could be, on average, 9% higher than those forecast by the FAO (2006), if world agriculture is pushed towards strong intensification.

Dornburg et al. (2010) mention other studies (Evans, 1998; Smil, 2000) suggesting that sufficient food – even for around 10 billion people – could be produced, provided that crop yields can be further improved by enhanced crop management and/or genetic modifications. It is also stressed that the large variability in regional climate and hydrology necessitates a detailed analysis of the biophysical possibilities for crop production. In any case, substantial investments will be indispensable for maintaining growth in crop yields (Khan et al., 2009), and additional ones are needed to avoid economic constraints that would prevent the realization of such technical yield potentials (Koning and van Ittersum, 2009; Somerville et al., 2010).

In many developing countries, especially in semi-arid and arid regions, yields are often far below those obtained in industrialized economies (IAASTD, 2009; IFPRI, 2009). In many regions, average increases in productivity in recent years have been only moderate, especially in Africa (FAO, 2009a; Somerville et al., 2010). Adoption, implementation and enforcement of adequate policies to foster environmentally, socially and economically sustainable yield increases could, therefore, offer large benefits (IAASTD, 2009). Recent studies call for more research efforts dedicated to “sustainable intensification,” i.e., management practices and technologies that allow further yield increases but minimize adverse environmental, social or economic effects (Godfray et al., 2010).

World food systems may be affected by changes in temperature and precipitation (mean values and variability) and the atmospheric carbon dioxide (CO<sub>2</sub>) concentration. All three factors could have substantial effects on agricultural yields. At present, however, there are substantial knowledge gaps with respect to underlying processes (e.g., downscaling of global climate scenarios to regional or local levels) and also how they will affect crop growth in the field, under real-life conditions. This depends on factors that are difficult to predict, including responses from farmers.

IFPRI (2009) analyzed climate change effects on crop production and CO<sub>2</sub> fertilization effects and predicted negative impacts, mainly in sub-Saharan Africa and South Asia. In fact, some regions were expected to be adversely affected by climate change, in particular in tropical regions (Cerri et al., 2007; IFPRI, 2009), but regional differentiation of climate change effects is important (IFPRI, 2009). Beyond 2050, climate change implications on crop yields and production were forecast to be severe on the global scale, with or without the CO<sub>2</sub> fertilization effect (IFPRI, 2009).

A recent study (Müller et al., 2010) showed that the effect of climate change on agricultural yields is highly uncertain and strongly depends on the CO<sub>2</sub> fertilization effect, which is poorly understood and could interact with management decisions of farmers. The study was based on simulations using the dynamic global vegetation model LPJmL. It considered three different emission scenarios implemented in five different Global Circulation Models. LPJmL was run with the CO<sub>2</sub> fertilization effect switched on and off, to reflect scientific uncertainty. The study found that crop yields could decrease by 13% or rise by 22% in 2050, compared to the levels forecast to prevail without climate change, depending on scenario assumptions. Using these results, Erb et al. (2009) and Haberl et al. (2011) showed that climate change impacts on agricultural crop yields would, at any given level of global food demand, result in considerable changes in the area available for the cultivation of energy crops; adverse impacts would reduce, and positive impacts would increase, the area available for bioenergy crops.

Case studies show that continuous investments in the improvement of productive technologies (i.e., Brazilian sugar cane) can mitigate or even offset adverse impacts of climate (change) on yields (von Braun, 2007). IFPRI (2009) concludes that even without climate change, greater investments in agricultural knowledge (for all different end uses) are needed to meet the demands of the future world population in 2050, mainly in developing countries, and argues that improved agricultural productivity can be an important mechanism for alleviating poverty indirectly by creating jobs and lowering food prices.

This discussion leads to the conclusion that the availability of productive areas for the cultivation of bioenergy crops in the future will strongly depend on:

- Total future food demand, which is in turn influenced by population numbers, per capita food calorie intake and the fraction of animal-based products consumed: all of this depends on future income levels and a host of other socioeconomic, political and cultural factors.
- Yield levels on farmland, in particular cropland yields: most studies agree that yield increases will be able to meet a substantial fraction of future global food demand so that the growth of cropland area required could be low, perhaps only 5–10%. But significant social, economic, environmental and technological issues related to future yield growth remain to be solved through appropriate research and technology development. Climate change could have significant impacts on yields, which could positively or negatively influence the availability of area for energy crop cultivation.
- Feeding efficiencies and many other critical issues related to the livestock sector: technological and other changes in livestock rearing are likely to contribute to increases in the output of animal-based food per unit of feed intake, but the extent of this efficiency growth, as well as its possible costs in terms of environmental impacts, product quality, and animal welfare, is at present imperfectly understood.

Comparison of livestock densities across world regions suggest that livestock densities could be increased, in some regions by large margins, thereby making substantial areas available for bioenergy crops. Appropriate management will be crucial to avoid adverse environmental and socioeconomic effects, in particular where subsistence economies might be affected.

- Area required for other purposes, including infrastructure, biodiversity conservation, and production of biogenic materials for various purposes, most notably feedstocks for the chemical industry, which seems to be of limited quantitative importance but could become more important in the future for integrated multipurpose use of biomass (“bio-refinery”).

Note that conversion of forests to bioenergy crops was excluded from that discussion due to the fact that this would entail a large carbon debt, i.e., very unfavorable GHG emissions per unit of energy produced over many years if not decades. Bioenergy potentials from forestry, residues, manures and wastes are discussed separately in Chapter 7.

### 20.2.3 Area and energy potentials from dedicated bioenergy crops in 2050

The global potential availability of biomass for energy has been assessed in various studies. Many of these studies primarily or exclusively focus on energy crops, and the potentials estimated vary significantly. Dornburg et al. (2010), Hoogwijk et al. (2003) and Berndes et al. (2003) identify methodological differences, critical parameter assumptions and varying system boundaries that are chiefly responsible for the differences in the estimated potentials. Important parameter assumptions determining the technical potential for energy crops are:

- restrictions on land available for energy crops;
- relevant factors for future development of land use, such as population growth, diets, international food trade and technology changes, in particular with regard to crop yields, and feeding efficiencies in animal husbandry;
- future productivity of energy crops;
- agricultural commodities markets; and
- sustainability restrictions on the growth of biomass.

Table 20.5 summarizes the main features of recent studies estimating the energy potentials from energy crops. The considerable differences in the estimates result from the following factors:

- all studies use aggregate modeling approaches regarding future developments of yield and land use;

- only a few studies account for possible future land-use changes and associated uncertainty by using an scenario approach analyzing different futures (Smeets et al., 2007; Hoogwijk, 2004; van Vuuren et al., 2009; WBGU, 2009; Erb et al., 2009; Dornburg et al., 2010); and
- only a few studies explicitly consider restrictions arising from environmental and social impacts of bioenergy production (e.g., land degradation, loss of biodiversity, competition with food, and water limitations) or present spatially explicit data on land-use and bioenergy potentials (WBGU, 2009; van Vuuren et al., 2009; Erb et al., 2009; Goldemberg and Guardabassi, 2009; Dornburg et al., 2010).

According to the present review, a general tendency appears to emerge that the more recent studies show lower estimated bioenergy potentials than earlier ones. The reasons for this include the following: newer studies consider environmental constraints (e.g., carbon payback time and biodiversity conservation in WBGU, 2008); constraints on the suitability of areas for bioenergy production have become more apparent (e.g., WBGU, 2008; Dornburg et al., 2010); many areas assumed to be available for bioenergy production are already used for grazing (Erb et al., 2009); and new research has demonstrated that previous studies overestimated yields of bioenergy crops, often by 100% or more (Johnston et al., 2009).

Recently, one study (Smeets et al., 2007) suggested a very high bioenergy potential from energy crops, with an upper range that even exceeds the theoretical potential for bioenergy production discussed in Chapter 7. This very high potential resulted from a large land area (36 million km<sup>2</sup>, i.e., 28% of the earth's land surface excluding Greenland and Antarctica) multiplied by a high productivity estimate (34 MJ/m<sup>2</sup>/yr). For comparison, the current global average aboveground NPP is 9.5 MJ/m<sup>2</sup>/yr.

Based on this review, four studies (Erb et al., 2009; van Vuuren et al., 2009; WBGU, 2009; Dornburg et al., 2010) were selected as the basis for this assessment. They were selected because they generally reflect essential environmental constraints such as biodiversity conservation, water scarcity, land quality/suitability, land degradation, and food supply (i.e., future cropland needs and interrelations with feed demand of livestock), although with different methods (see Table 20.5). Moreover, sufficient data allowing calculation of bioenergy potentials on the level of the 18 GEA regions were only available for three of these studies. The results derived from these three studies are then discussed in the light of a larger body of literature (including Dornburg et al., 2010).

As can be seen in the table above, the assessment of the area that would be available for dedicated energy crops varies between different studies. This survey summarized in Table 20.5 shows that yield expectations of bioenergy plantations also differ widely, approximately 1–21 kg/m<sup>2</sup>/yr. Differences in yields of bioenergy plantations largely

result from assumptions on land suitability, choice of bioenergy crop (yields of lignocellulosic crops and perennial grasses are higher than those of food crops), and management (e.g., fertilizer input) (Harberl et al., 2010).

Table 20.6 reports the energy crop areas for three studies, and Table 20.7 the bioenergy potentials found in the four recent studies selected. These potential estimates were derived as follows:

- Van Vuuren et al. (2009) used the integrated modeling framework IMAGE and the energy model TIMER (which is a part of the IMAGE framework) to calculate available area for energy crops and related bioenergy potentials in 2050. Only abandoned agricultural land (according to an approach by Hoogwijk et al. (2005)) and natural grasslands were assumed to be available for bioenergy production, thereby assuming global accessibility factors of 75% (abandoned farmland) and 50% (natural grassland). IMAGE sub-models on land use were used to simulate land required for food production, driven by demand for food and timber, and climate change. Calculations proceeded at the level of grid cells (0.5x0.5°). Water scarcity, land degradation (based on the International Soil Reference and Information Centre's (ISRIC, 1991) *Global Assessment of Human-induced Soil Degradation* – GLASOD) and biodiversity/nature reserve areas were considered in various scenario calculations ranging from "no restrictions" to "strict criteria."
- Erb et al. (2009) followed a "food-first" approach. Assumptions on future diets (four assumptions), cropland yields (three assumptions: FAO, fully organic, intermediate), cropland expansion (+9%, +19%) and livestock feeding efficiencies (conventional, humane, organic) were derived from FAO and other studies and databases. A biomass-balance model was used to identify combinations of factors ("scenarios") that were "feasible," i.e., provided sufficient food. The model closes the balance between biomass supply (harvest of primary crops and grazing) and biomass demand (food and fiber). For scenarios classified as "feasible," the area available for bioenergy crops was calculated by assuming that grazing intensity would be maximized and, if existent, all cropland area not required for food or fiber production could be used for bioenergy. The model calculates bioenergy potentials at three levels: primary bioenergy crops on cropland not needed for food supply, primary bioenergy crop potentials on grazing areas of the highest-quality class (which is assumed to be intensified to its limits), and residue potentials. As the latter are discussed separately (see Chapter 7), Table 20.7 shows only the potentials for primary bioenergy crops. This study considered growth in infrastructure areas and assumed that there would be no deforestation for bioenergy. The MIN scenario assumes the richest diet (which is only feasible with the most intensive technology and highest yield levels), whereas the MAX scenario combines the lowest food demand with the highest possible agricultural yields and livestock feed efficiencies. The "FAO world" scenario was based on FAO (2006).

Table 20.5 | Overview of recent studies on technical potentials of biomass from energy crops

Reference	Type of potential	Regions	Time frame	(Sustainability) constraints	Land use types	Land area used [mio. Km <sup>2</sup> ]	Productivity [tonnes dry matter/ha/yr]	Potential of energy crops [EJ/yr]
van Vuuren et al., 2009	Technical	Global	2050	Biodiversity, Food security, Soil degradation, Water scarcity	Abandoned agricultural land (75%) Grassland (25%)	13	Depending on land suitability and climate factors 1.0–3.2 kg dry matter/m <sup>2</sup> /yr	120–300 EJ/yr (unconstrained) 65–115 EJ/yr (constrained)
WBGU, 2008	Technical	Global	2050	Biodiversity, C balance, Deforestation, Degraded land, Food security, Water scarcity	Land suitable for bioenergy cultivation according to the crop functional types in the model, considering sustainability	2.4–5.0	7.5–12.6 t/ha/yr	34–120 EJ/yr
Campbell et al., 2008	Technical	Global	2000 (not clearly mentioned)	Agricultural lands, Ecosystems, Food security, Releasing carbon stored in forests, Water scarcity	Abandoned agricultural land (100%)	3.9–4.7	4.3 t/ha/y (AGB)	32–41 EJ/yr (AGB)
Field et al., 2008	Technical	Global	2050	Biodiversity, Food security, Ecosystems, Deforestation	Abandoned agricultural land (100%)	3.9	3.2 tC/ha/yr	27 EJ/yr (AGB)
Dornburg et al., 2010	Technical	Global	2050	Land for food excluded Various assumptions on (non-) exclusion of degraded and protected land	Not explicitly specified	Not specified	Not specified	Energy crops: 120 EJ/yr
Smeets et al., 2007	Technical	11 World regions	2050	Biodiversity, Deforestation, Food security	Surplus agricultural land (100%)	7.3–35.9	16–21 odt(oven dry tonnes)/ha/yr	215–1272 EJ/yr
Hoogwijk et al., 2005	Technical	11 World regions	2050–2100	Biodiversity, Food security	Abandoned agricultural land (100%) Remaining land not for food or material production (10–50%) Extensive grassland	Abandoned: 0.6–1.5 Rest land 0.3–1.4	Depending on land suitability and climate factors	Abandoned: 130–400 EJ/yr Rest land 235–240 EJ/yr Total: 300–650 EJ/yr
Erb et al., 2009	Technical	11 World regions	2050	Excluded: Land for food and feed, forestry and unproductive land	Cropland not needed for food and fiber supply Intensification of grazing land	2.3–9.9 depending on food and feed demand (44 scenarios)	Equal to potential (cropland) or actual (grazing land) NPP	Bioenergy crops: 28–128 EJ/yr Residues: 21–36 EJ/yr

- The German Advisory Council for Global Environmental Change (WBGU, 2009) considered two assumptions on future land requirements for food production, one in which the current cropland area was held constant, and one in which an additional demand for cropland area of 1.2 million km<sup>2</sup> was assumed. The other constraint was area requirements for nature protection (biodiversity hotspots, nature conservation areas, and wetlands) and exclusion of areas with carbon payback times exceeding 10 years. The study considered the impact of future climate change, including changes in CO<sub>2</sub> levels. Calculations were performed using the LPJmL dynamic global vegetation model that is able to simulate natural and agricultural vegetation (Bondeau et al., 2007). The MIN scenario assumes the highest area requirement for food and nature conservation, the MAX scenario the lowest. “Intermed” is the arithmetic mean of all other combinations.
- Dornburg et al. (2010) developed a sensitivity analysis, using existing modeling tools, to quantify key uncertainties regarding

biomass potentials and demand. For the sensitivity analysis, the integrated assessment model (IMAGE) was applied, using the reference scenario of the Organisation for Economic Co-operation and Development (OECD) Environmental Outlook as a baseline (OECD, 2008a). This baseline is a “medium-development” scenario in terms of changes in population, economic development, and agricultural productivity. According to the study, to assess the potential impact of water scarcity on bioenergy potentials, the maps of biomass potentials were overlaid with those of water stress as calculated by the Water Gap model. The Water Gap model uses an index in which a value of 0.2 and higher is defined as moderate water scarcity, while values above 0.4 are defined as severe water scarcity. For all the calculations, rain-fed production conditions were assumed. In order to estimate the impact of degraded land use on biomass potentials, data from the GLASOD database that classified land worldwide in terms of soil degradation was used.

**Table 20.6** | Areas assumed to be used to grow bioenergy crops in three recent bioenergy potential studies.

	vanVuuren et al.		Erb et al.			WBGU		
	No criteria	Strict criteria	MIN	MAX	FAO world	MIN	MAX	Intermed.
	(1000 km <sup>2</sup> )		(1000 km <sup>2</sup> )			(1000 km <sup>2</sup> )		
USA	242	303	0	1089	676	177	402	344
CAN	193	2	0	254	157	55	186	132
WEU	88	61	21	237	80	222	579	471
EEU	29	34	60	266	205	68	91	86
FSU	58	13	582	1167	935	168	426	360
NAF	0	0	113	282	189	59	86	73
EAF	40	9	310	740	507	88	168	131
WCA	462	99	324	858	556	142	194	176
SAF	184	1	262	652	436	271	385	333
MEE	1	139	0	13	6	11	15	13
CHN	93	148	52	602	161	210	516	413
OEA	142	170	70	156	109	18	54	40
IND	3	87	0	116	51	282	318	300
OSA	9	49	0	30	13	18	31	26
JPN	25	1	1	18	5	0	0	0
OCN	258	43	2	249	120	147	486	326
PAS	4	6	243	558	428	39	217	142
LAC	711	168	398	2622	1415	480	1062	791
<b>Total</b>	<b>2545</b>	<b>1334</b>	<b>2318</b>	<b>9912</b>	<b>6047</b>	<b>2454</b>	<b>5215</b>	<b>4156</b>

Table 20.6 shows that the area that could be available for bioenergy crops in 2050 ranges from 1.3–9.9 million km<sup>2</sup>, which is about 1–8% of the earth's total land surface excluding Antarctica and Greenland. Erb et al. (2009) found the highest land area availability of all three studies (up to 9.9 million km<sup>2</sup>), because this study did not exclude areas for nature/biodiversity conservation. The study by van Vuuren et al. (2009) found the lowest land potentials (1.3–2.5 million km<sup>2</sup>), while those of WBGU are intermediate.

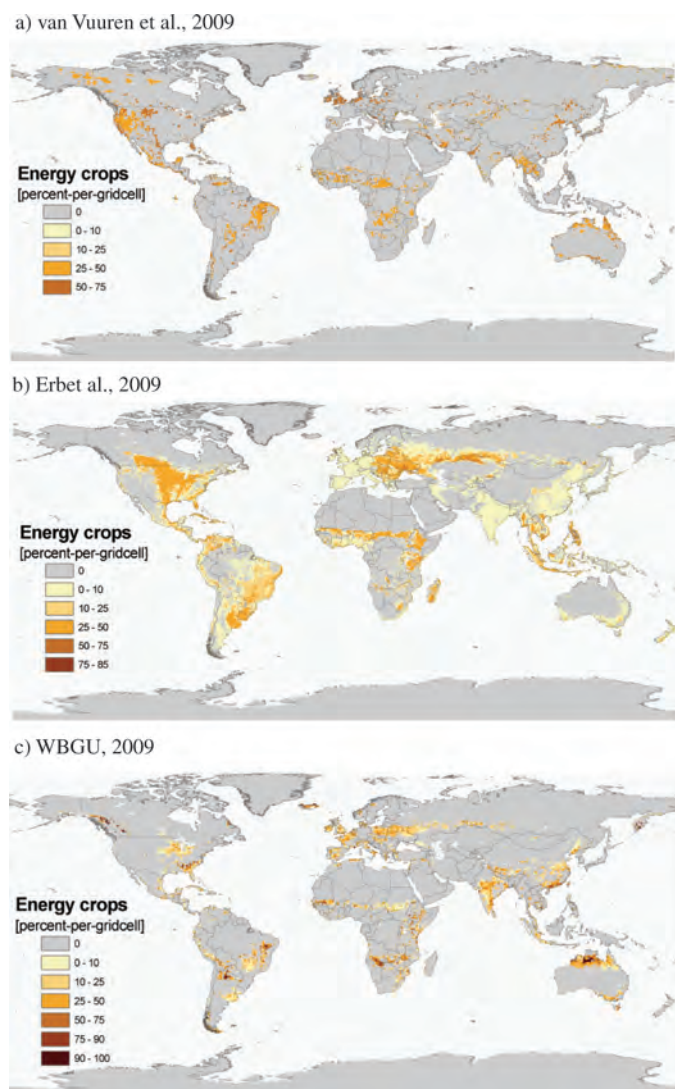
Maps of bioenergy crop areas found to be available in the first three studies are shown in Figure 20.5. These three studies agree that large areas might become available in sub-Saharan Africa and South America, and that areas in cold climates will not contribute significantly to global bioenergy production. Nevertheless, significant discrepancies with regard to extent and spatial patterns prevail in other regions of the world. For example, van Vuuren et al. (2009) and WBGU (2008) find substantial areas in Northern Australia not included in the dataset by Erb et al. (2009). In contrast to van Vuuren et al. (2009), WBGU (2008) and Erb et al. (2009) identify significant potentials in eastern China, India and Southeast Asia. In the United States and Eurasia, patterns differ due to the different assumptions of each of the studies. Erb et al. (2009) and WBGU (2008), for instance, assume that areas for energy crops might be available in the US Corn Belt, whereas van Vuuren et al. (2009) identified suitable areas in western parts of the United States. For Europe,

Erb et al. (2009) and WBGU (2008) assume substantial area potentials in Eastern Europe, whereas van Vuuren et al. (2009) identified largest potentials in Northern Germany, the United Kingdom, and Ireland. In conclusion, further work on spatial patterns of possible areas for energy crops would be helpful to identify more robust estimates of suitable areas for energy crops. A refinement of the WBGU (2008) work – which basically confirmed the results of the WBGU study – was recently published (Beringer et al., 2011).

The results displayed in Table 20.6 are in line with a recent study by the IEA (2010) which suggested that 2.5–8 million km<sup>2</sup> could be available globally for bioenergy crops if constraints such as exclusion of forested land, valuable or protected habitats, etc. are properly accounted for (see also FAO, 2008a). The figures presented in Table 20.6 are a downward revision of earlier estimates that suggested area availabilities of 12.8 million km<sup>2</sup> (IPCC, 2007) or even as much as 37 million km<sup>2</sup> (WMO, 2006). The main reason is that new studies consider constraints stemming from livestock farming, nature protection and GHG emissions (carbon pay-back time) that have previously not sufficiently been considered.

The estimates of the global technical potential of primary bioenergy production (i.e., dedicated bioenergy plants) presented in Table 20.7 were derived from data reported in the same three studies. Table 20.7 summarizes the findings of the three studies and gives ranges for the





**Figure 20.5** | Maps of the areas found to be available in the first three studies used in this assessment: (a) constrained scenario of van Vuuren et al., 2009; (b) TREND scenario based on Erb et al., 2009; and (c) scenario 2 (cropland high, conservation area low) based on WBGU, 2009.

bioenergy potential from primary bioenergy crops in 2050. These potentials were calculated as primary biomass supply potentials, i.e., more or less as the entire amount of aboveground biomass produced by bioenergy plants, multiplied by the gross calorific value of the biomass (18.5 MJ/kg in the study of Erb et al. (2009) and 19.0 MJ/kg in the study by WBGU (2008)). The comparison of these three studies leads to the following conclusions:

- A likely range of future primary bioenergy crop potentials in such studies for 2050 is 44–133 EJ/yr. Factors that would reduce the potential are high food demand (in terms of quantity and share of animal products), low agricultural yields in food production, low feeding efficiencies, large area requirements for nature conservation, and low energy crop yields. Factors that could help to increase the potential are low food demand and diets using fewer

animal products, high yields and feeding efficiencies, and low area requirements for nature conservation. Climate change could also affect this potential both directly and indirectly, i.e., by influencing yields of energy crops and by influencing yield (and, therefore, area requirements) of other crops. Moreover, these findings suggest that there may be trade-offs between different environmental considerations such as conserving ecosystems and biodiversity, reducing agricultural pressures of agriculture, animal welfare and water issues, as well as the production of renewable energy from biomass. While there has been progress in better understanding these feedbacks, some of them are at present incompletely understood.

- The studies agree that the largest bioenergy crop potentials are located in Latin America and the Caribbean (LAC) and in Western and Central Africa (WCA). Substantial potentials were also found in the United States, the Former Soviet Union (FSU), and Australia, New Zealand and other Oceania (OCN). There are, however, some differences in the regional distribution of total potentials that result from the differences in methodology. Regional patterns should, therefore, not be over-interpreted.
- Despite the differences in energy crop areas, the results are similar. Van Vuuren et al. (2009) assumed the highest yields and the lowest area availability, whereas Erb et al. (2009) found larger area availability but assumed the lowest energy crop yields. WBGU (2009) used one of the most advanced process-based plant growth models (LPJmL) that incorporated plant functional traits of woody and herbaceous (C4 grass) bioenergy plants, which suggested yield potentials between the two other studies.

Considering sustainability constraints related to possible competing land demands (food, feed and fiber production, biodiversity conservation, etc.), problems posed by possible deforestation, and water availability, the first three studies analyzed in this chapter (van Vuuren et al., 2009; Erb et al., 2009; and WBGU, 2009) found global bioenergy crop potentials of 44–133 EJ/yr in 2050. The fourth one, Dornburg et al. (2010), concluded that for bioenergy crops (dedicated energy crops) they are 120 EJ/yr. Thus the range considered in this chapter is 44–133 EJ/yr for 2050.

#### 20.2.4 Bioenergy scenarios for 2050: diets, agricultural technology and climate change

Previous sections of this chapter suggest that there are strong links between diets, agricultural technology and yield changes of food and bioenergy crops resulting from climate change. Three of the studies discussed (Erb et al., 2009; van Vuuren et al., 2009; and Dornburg et al., 2010) also analyzed possible feedbacks between diets, agricultural technology, and climate change (see Section 20.2.3. above). The model used by Erb et al. (2009) calculates primary bioenergy supply potentials

Table 20.7 | Bioenergy potentials by region from dedicated bioenergy crops from the first three studies.

[EJ/yr]	Van Vuuren et al.				Erb et al. <sup>10</sup>			WBGU <sup>10</sup>			Mean <sup>10</sup>		
	Strict criteria	Mild criteria	No criteria	Mean strict	MIN <sup>1</sup>	MAX <sup>2</sup>	FAO world <sup>3</sup>	MIN <sup>4</sup>	MAX <sup>5</sup>	Intermed <sup>6</sup>	MIN <sup>7</sup>	MAX <sup>8</sup>	Best guess <sup>9</sup>
USA	8	19	29	14	0	13	8	4	13	9	4	18	10
CAN	4	4	4	4	0	3	2	1	3	2	2	3	3
WEU	3	5	7	4	0	3	1	3	13	8	2	8	4
EEU	1	3	4	2	0	3	2	1	1	1	1	3	2
FSU	2	4	5	3	5	12	9	2	9	6	3	9	6
NAF	0	0	0	0	1	3	2	1	1	1	1	2	1
EAF	1	3	3	2	3	8	5	1	3	2	2	5	3
WCA	11	14	16	12	5	12	8	1	4	3	6	11	8
SAF	3	5	5	4	3	8	5	3	8	5	3	7	5
MEE	0	0	3	0	0	0	0	0	0	0	0	1	0
CHN	3	6	10	4	0	6	2	5	13	10	3	10	5
OEA	4	7	10	5	1	2	1	1	2	1	2	5	3
IND	0	1	3	1	0	1	0	2	4	3	1	3	1
OSA	0	1	1	1	0	0	0	0	1	1	0	1	1
JPN	0	1	3	1	0	1	0	2	4	3	1	3	1
OCN	6	9	10	7	0	3	1	2	9	5	3	7	5
PAS	0	1	1	0	3	9	7	1	11	4	1	7	4
LAC	18	30	34	24	5	40	22	10	29	17	11	34	21
<b>TOTAL</b>	<b>65</b>	<b>113</b>	<b>146</b>	<b>88</b>	<b>28</b>	<b>128</b>	<b>77</b>	<b>38</b>	<b>124</b>	<b>78</b>	<b>44</b>	<b>133</b>	<b>81</b>

<sup>1</sup> Richest diet, intensive agriculture, 20% cropland expansion

<sup>2</sup> Most modest diet, intensive agriculture

<sup>3</sup> Trend scenario, based on FAO *World Agriculture towards 2030/2050*, current diet trajectory

<sup>4</sup> Maximum constraints, no irrigation

<sup>5</sup> Minimum constraints, irrigation

<sup>6</sup> Arithmetic mean of four scenarios with intermediate constraints, with and without irrigation

<sup>7</sup> Arithmetic mean of the smallest potential of the three studies

<sup>8</sup> Arithmetic mean of the highest potential of the three studies

<sup>9</sup> Arithmetic mean of "mean strict", "FAO world", and "intermediate" potentials in the three studies

<sup>10</sup> Sums might not add due to rounding.

in 2050 depending on assumptions on diets, cropland yields, cropland expansion, and feeding efficiencies of livestock (see Figure 20.6). The model was calibrated with a comprehensive global NPP, land-use and biomass-use database (Erb et al., 2007; Haberl et al., 2007; Krausmann et al., 2008) for 2000. The FAO report *World Agriculture: towards 2030/2050* and the "best guess" UN population forecast (Bruinsma, 2003; FAO, 2006) were used as baseline ("Trend" scenario). Assumptions for changes in diets, livestock feeding efficiency, cropland yields and cropland expansion were exogenously fed into the model based on literature reviews documented in Erb et al. (2009). The impact of climate change on cropland yields was evaluated using LPJmL runs (Müller et al., 2010).

Figure 20.6 shows how changes in diets and cropland yields may affect the global bioenergy potential of energy crops in 2050.

According to Erb et al. (2009), the main assumptions underlying these calculations were:

- **Diets:** The "Trend" diet was derived for each world region by assuming that all countries in each of the 11 regions distinguished in that study would attain a level of calorie supply and animal product consumption similar to the richest country in the region. Results were similar to those derived by the FAO with a completely different methodology. The "Rich" diet assumed a global convergence to current US and European diet patterns, but did not assume that all regions would actually reach those high levels until 2050. The "Moderate" diet assumed the same per capita level of calorie supply as the "Trend" diet but a lower share of animal products. The "Frugal" diet assumed that the global per capita level of calorie supply would remain constant around the 2000 values and only

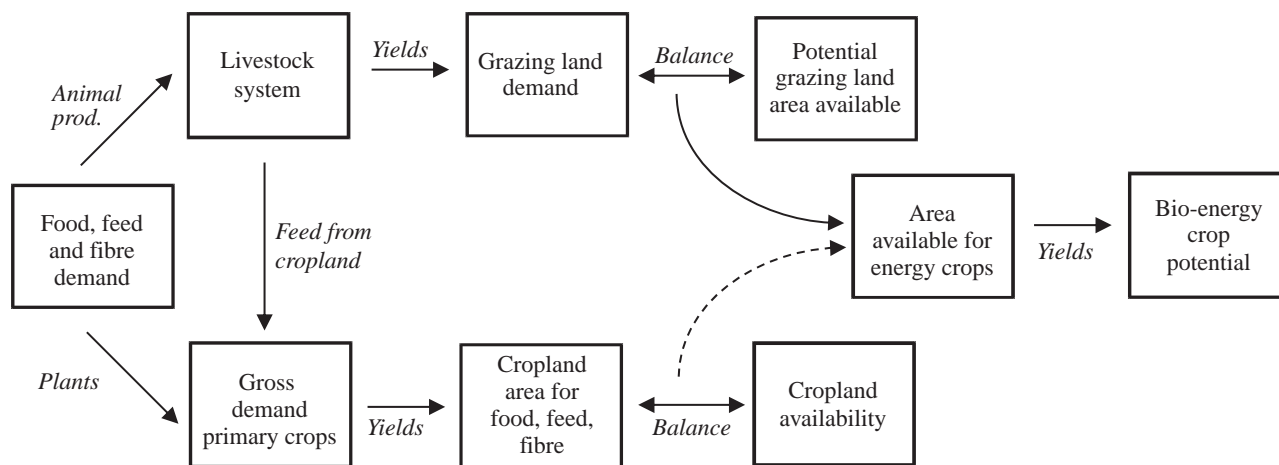


Figure 20.6 | Model structure of the land-use/biomass-balance model. Source: based on Erb et al., 2009.

20% of calories would be from animal products globally. While such a diet is nutritionally sufficient on an average basis, it would result in widespread malnutrition if current patterns of inequality of food supply persist.

- Cropland yields:** The “Trend” assumption reproduces cropland yields as forecast by the FAO (2007a). The “Organic” yields were derived by assuming that all cropland would be cultivated according to IFOAM standards of organic agriculture. While this would imply substantial yield reductions compared to intensive conventional farming practices, it would also allow significant growth of yields in regions currently dominated by traditional low-input agriculture. The “Intermediate” yields are the mean between “Organic” and “Trend” yields, reflecting a trajectory where yield growth is constrained by environmental considerations. The “High” yields assumption was not part of the original Erb et al. (2009) study. In this case, the highest yield growth trajectory (“Global Orchestration”) of the Millennium Ecosystem Assessment (2005) was adopted; yields were on average 9% higher than those forecast by the FAO (2007a).
- Feeding efficiency:** The study contrasted conventional intensive indoor-housed feeding efficiencies with feeding efficiencies achieved if animal welfare standards or the even stricter standards of organic agriculture are adopted (here only the latter are reported; the “humane” assumptions were between conventional and organic efficiencies).
- Cropland expansion:** The “Trend” assumption was taken from the FAO’s *World Agriculture: towards 2030/2050* and assumed that global cropland area would grow by 9% between 2000 and 2050 (FAO, 2006). This was contrasted with a “Massive expansion” assumption, where growth of cropland areas between 2000 and 2050 was 19% – double the growth assumed by the FAO. Note that the assumption on cropland expansion had little influence on the bioenergy crop potential, because the study calculated the additional area that could be designated to

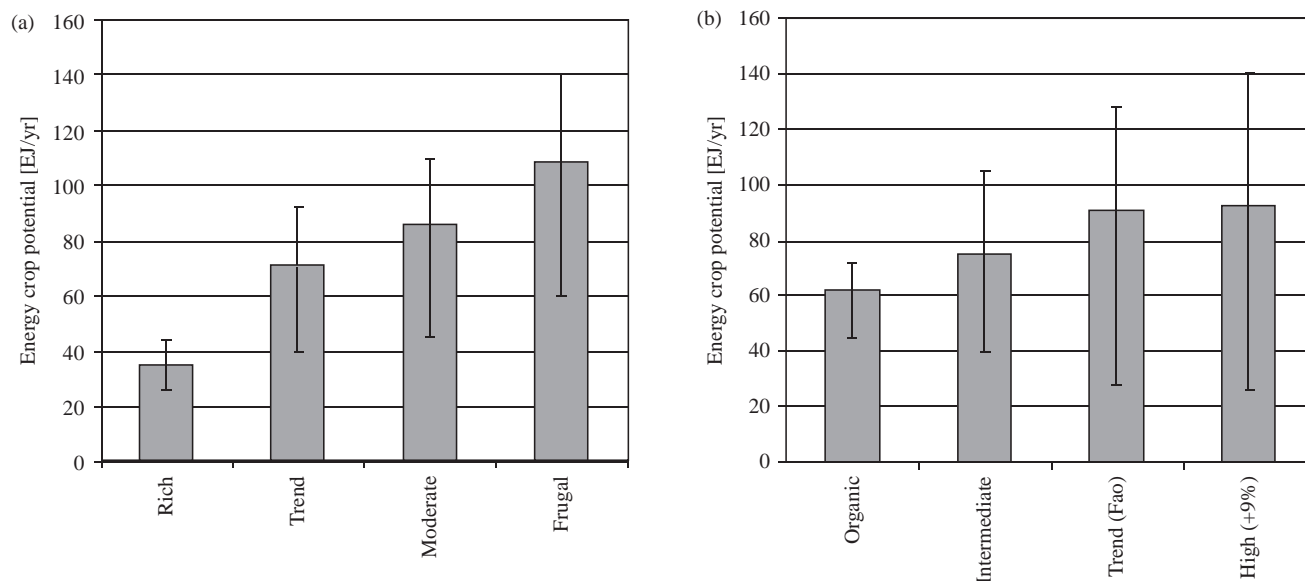
grow bioenergy crops if sufficient grazing area were available to meet the projected level of roughage demand (see Figure 20.6 above).

The results reported in Figure 20.7 show that diet has a strong effect on bioenergy crop potentials. The “Rich” diet leaves little space for bioenergy plantations, while the “Frugal” diet (which could be adopted without widespread malnutrition if food distribution were egalitarian) allows for large bioenergy crop potentials. As one moves to the poorer diets, the range between the lowest and highest potential also increases. This is because the “Frugal” diet can be easily provided if the most intensive technologies (cropland yields, feeding efficiency) are adopted. However, such a combination might seem particularly unlikely. It is interesting that in the case of the “Frugal” diet, substantial energy crop potentials exist even if “Organic” yields and feeding efficiencies are assumed.

Changes in the assumptions on food crop yields also have a substantial effect on the bioenergy crop potential, as higher yield levels obviously leave more space for bioenergy plantations, assuming all other factors remain the same.

However, note the perhaps unexpected result that the lowest bioenergy potential estimate found in any of the scenarios assumes “High” yields. The reason for this is that the “Rich” diet can only be provided if “High” or at least “Trend” yields are assumed, and this diet leaves very little space available for bioenergy plantations due to the high roughage demand, irrespective of yield levels of food crops. The Erb et al. (2009) study also analyzed the possible effect of climate change on the bioenergy potential. It found that the energy crop potential under “Trend” assumptions on all parameters would be 77 EJ/yr (see Table 20.7) if no changes in yield levels due to climate change are assumed. If the CO<sub>2</sub> fertilization were switched off in LPJmL, however, yields were lower and the energy crop potential dropped by 18% to 63 EJ/yr, while it rose to 120 EJ/yr (+56%) if the CO<sub>2</sub> fertilization effect were switched on. This





**Figure 20.7** | Dependency of the global energy crop potential in 2050 on (a) changes in diets and (b) yields of food crops. Grey bars show the mean of all “feasible” scenarios (i.e., all scenarios that would deliver enough food for the respective diets), whiskers the range between the lowest and the highest scenario. Source: Erb et al., 2009 and additional calculations – see text.

suggests that the possible effect of climate change on yields introduces considerable uncertainty in estimates of global bioenergy potentials, in particular due to the indirect effect on food crops.

Van Vuuren et al. (2009) and Dornburg et al. (2010) also analyzed feedbacks between food demand, agricultural technology, and bioenergy crop potentials. In quantitative terms, comparing their results to those of the Erb et al. (2009) study, they found higher bioenergy crop potentials, mostly due to higher yields (see above), but they found the same basic dependencies of the bioenergy potential on diets and agricultural technology. It can be concluded that future bioenergy crop potentials strongly depend on diets and agricultural technology. Beyond trade-offs between food and energy, trade-offs between environmental quality goals and bioenergy potentials are also relevant. If, however, growth in yields could be reconciled with environmental quality goals (e.g., in terms of soil degradation, water pollution, biodiversity impacts, etc.) through sustainable high-yield practices or technologies, this would result in a major breakthrough in terms of food and energy supply (IAASTD, 2009; Godfray et al., 2010).

In conclusion, it can be stressed that bioenergy potential worldwide can be significant, even considering environmental restrictions to protect fragile ecosystems. However, strong investments are needed (IFPRI, 2009), mainly in capacity-building (to allow the implementation of efficient agricultural/industrial technologies, adequate policies and enforcement related to the environmental and social factors) and also to increase agricultural yields, which is fundamental to allow the implementation of the higher bioenergy potentials.

### 20.2.5 Bioenergy and land-use change: lessons from regional case studies

The notion of land use refers to a set of human actions – for example, arrangements, activities, and inputs – aimed at using land areas for human purposes. Land use usually results in changes in land cover, ranging from subtle effects to far-reaching alterations, including change from one land-cover type, e.g., forest, to another, such as cropland or grazing land (Lambin and Geist, 2006). The term “land use” also encompasses the social and economic purposes for which land is managed (e.g., grazing, timber extraction, or conservation). Human and natural factors in terrestrial systems are strongly linked, as captured in the recently coined notion of “land systems,” conceptualized as coupled human-environment (or socio-ecological) systems in which socio-economic and natural factors are inextricably intertwined (Global Land Project, 2005; Turner et al., 2007).

Land-use change can influence surface albedo, evapotranspiration, sources and sinks of GHGs, or other properties of the climate system, and may thus have a radiative forcing effect and/or other impacts on climate, locally or globally (Baede, 2007). These environmental effects are discussed below in Section 20.4 on sustainability. At the same time, land use and land-use change are socioeconomic processes that are influenced by a host of cultural, political, legal, economic and social factors and can have substantial repercussions on humans. This subsection draws from a selection of case studies that are intended to exemplify how these drivers and feedbacks can interact in cases related to bioenergy and land-use change.

When discussing the issue of land-use change relating to agricultural and bioenergy crops, it is important to consider not only direct effects, i.e., effects caused by establishing plantations, but also indirect effects that could result from an expansion of agricultural and bioenergy crops, e.g., displacement effects between different crops. Indirect effects – indirect land-use change (ILUC) – can be more challenging than direct effects in terms of availability of evidence and the possibility of clearly establishing causal relations. For example, deforestation could result from an expansion of land under feedstock crops and the displacement of food crops from higher-value lands (Cotula et al., 2008). On the other hand, other studies (Nassar, 2009) concluded that there is no significant evidence for ILUC from bioenergy crops.

With regard to supporting rural development, new and profitable land-use systems can provide better opportunities and long-term security for farmers and employees, plus – if processing facilities are near to farms – value-addition possibilities for profits in rural areas (Cotula et al., 2008). For countries with favorable endowments of land, labor and trade conditions, biofuels and bioenergy offer an opportunity to develop new export markets and improve the trade balance (Cotula et al., 2008). However, the FAO (2008a) provides a list of 22 developing countries that are especially vulnerable to the negative effects of bioenergy production due to a combination of high levels of chronic hunger (more than 30% undernourishment) while being highly dependent on imports of petroleum products (100% in most countries) and, in many cases, on imports of major grains (rice, wheat, and maize) for domestic consumption. Countries such as Eritrea, Niger, Comoros, Botswana, Haiti, and Liberia are especially vulnerable due to a very high level of all three risk factors (FAO, 2008a).

Almost all developing countries show strong interest in implementing bioenergy production, both liquid biofuels for transportation and solid biomass/biogas for power production (GNESD, 2010). In Africa, the preliminary conclusions from the Cogen for Africa project (AFREP/ FWD, 2009), being developed under the coordination of AFREP/ FWD, funded by the Global Environmental Facility/United Nations Environment Programme (GEF/UNEP) and the African Development Bank (AfDB) and aiming to implement efficient biomass-based cogeneration technologies in sub-Saharan countries, show strong interest from these countries to increase sugarcane plantations in the region, not only to produce sugar but also ethanol from molasses (a by-product from sugar production). There is also a high interest in improving agricultural productivity in the region, showing that food production can be increased together with biofuel and bioenergy production. It is important also to notice the main objective of the project – electricity production from biomass (sugarcane bagasse) to increase energy access in the region in a sustainable way.<sup>3</sup>

Also for Latin American countries, biofuels appear an interesting option from the experience in Brazil, without competing with other end uses

(GNESD, 2010). Many studies suggest that land potentials for agricultural crops and bioenergy in Latin America are substantial. However, competing demands for land may exist, mainly for agriculture, livestock production, and forestry. The production of agricultural and bioenergy crops has recently emerged as a contentious issue in some countries, either due to the potential direct competition between bioenergy and food crops, such as the use of maize for ethanol production in Mexico, or through direct or indirect expansion of the agriculture frontier over forests, such as soybean expansion in the Amazon (mainly to produce animal feed to export) and the Chaco Region in South America. On the other hand, there are several studies (Goldemberg, Coelho and Guardabassi, 2008; Goldemberg, 2008; Goldemberg and Guardabassi, 2009) showing positive results for Brazil and also presenting the benefits for developing countries when sustainable bioenergy production occurs, such as job generation in rural areas and local investments allowing significant development in developing countries. This could continue. The current liquid biofuel production in Latin America could be doubled sustainably based on first-generation feedstocks (Arias Chalico et al., 2009). Using second-generation feedstocks could further increase the potential. Improving productivity was found to be highly important (Pistonesi et al., 2008; Dornburg et al., 2010).

Sparovek et al. (2009) collected evidence suggesting that expansion of ethanol in Brazil from 1996 to 2006 did not contribute to direct deforestation in the traditional agricultural regions where most of the expansion took place. Their results show that sugarcane expansion did result in shrinking pasture areas and cattle head counts in these areas, as well as stronger economic growth. They could not exclude the possibility that the cattle migrated elsewhere, possibly resulting in deforestation in the Amazon. However, as mentioned above, more recent experience of sugarcane expansion in the State of São Paulo occurred without such impact, and other studies (Nassar et al., 2009) concluded that there is no evidence for such ILUC in the Brazilian sugarcane sector.

In another paper, Sparovek et al. (2007) showed that, if based on sound strategic plans, sugarcane ethanol production in Brazil could be extended in a manner that adequately considers social and environmental concerns. In their view, it would be necessary to integrate sugarcane production areas with existing land-use systems. They concluded that their development model could guarantee substantial expansion of production without resulting in displacement of extensive livestock production to remote areas, i.e., into tropical rainforests. The recent agro-environmental zoning for sugarcane both in São Paulo State and in Brazil (see Box 20.5) contributed to the achievement of these goals.

In Africa, biofuel production projects in low-income countries are often motivated by the seemingly large availability of land to grow feedstock crops. Somerville et al. (2010) claims that this would be the continent with the Earth's largest under-utilized land resources suitable to grow bioenergy crops.

On the other hand, the beginning of a biofuel boom in these countries has also raised concerns about potential environmental and/or

<sup>3</sup> Coelho, S. T. Personal information by UNEP in field visits.

socioeconomic pressures. Much of Africa's land resources are characterized by soils and climate that might limit crop production, either due to low general suitability for energy crops or due to decreased potential as a result of land degradation. Bekunda et al. (2009) estimate that only 6–11% of the soils in Africa are devoid of serious constraints to effective management, with about 34% presenting medium or low potential, i.e., at least one major constraint to agriculture, and 55% altogether unsuitable for agriculture (Bekunda et al., 2009).

Food crops may be produced on lands that are less fertile but still suitable for farming, with current users having to relocate to other lands. This shift of farmers from food or cash crops to feedstocks may be voluntary in some situations, e.g., if bioenergy crop plantations offer favorable economic opportunities to farmers. For example, small-scale jatropha projects implemented in Mali have involved a shift from cotton to jatropha; this has been attributed to falling cotton prices and increases in the perceived (monetary and non-monetary) values of jatropha (Cotula et al., 2008). On the other hand, the opposite may occur. In 2011, sugarcane ethanol producers in Brazil decided to produce more sugar than ethanol, considering the high prices of sugar in the international market.<sup>4</sup>

There are concerns about indirect effects associated with large-scale cultivation of biofuel crops, which may include significant negative impacts on land access by local groups. For example, a multimillion dollar jatropha project in the Kisarawe district of Tanzania has been reported to involve the acquisition of 90 km<sup>2</sup> of land and the clearing of 11 villages, which, according to the 2002 population census, are home to 11,277 people. Approximately, US\$632,400 was set aside to compensate 2840 households (African Press Agency, 2007).

However, the FAO (2010a) Bioenergy and Food Security (BEFS)<sup>5</sup> study for Tanzania shows that such problems can be avoided when adequate planning and agro-ecological zoning are in place. The study concludes that biofuel developments could provide an important vehicle through which to revitalize agriculture by bringing a variety of investments to increase productivity. The report shows that there are areas potentially suitable for bioenergy production, excluding those that are environmentally protected or under alternative uses. The technically viable and most competitive smallholder-integrated production chains were considered. This analysis has shown that "the dividends from investing in biofuels can have positive impacts on poverty reduction and growth." This case study is the first of several focusing on African countries in the context of the BEFS project, which has the aim of strengthening developing

countries' technical understanding of how best to mitigate the impact of bioenergy development on food security.

In Asian countries such as India, some authors have argued that substantial land areas are available for biofuel production. However, several critical issues that needed to be addressed were identified, including the costs of inputs to grow the biofuels on "wastelands," the growing demand for food production, and the social implications of converting areas currently allocated to food production into bioenergy crop plantations. Bekunda et al. (2009) recently analyzed a scenario in which one quarter of the total area of "wastelands" assumed to exist in India (i.e., 104,000 km<sup>2</sup>) would be converted to jatropha plantations with an average yield of 1.5 t/ha/yr of oil. They suggest that the lands would require significant inputs of nutrients and the adoption of soil and water conservation measures to realize such yield levels.

On the other hand, a recent report from The Energy and Resources Institute (TERI, 2010) discusses the potential for bioenergy in India, mainly using agricultural wastes and dedicated energy plantations (in degraded lands and wastelands) and indicates that there are 496,000 km<sup>2</sup> of available area categorized under "wasteland," as estimated by the Department of Land Resources. Out of this total, almost 66% falls into the classification of "wasteland suitable for land conversion," with almost 40% (129,600 km<sup>2</sup>) of this land in the categories of underutilized/degraded forest land, degraded pastures and degraded land under plantation crops. The report concludes that these offer the highest potential for being converted into land for dedicated energy plantations. It also mentions that there is a large amount of available biomass in rural areas, and its usage in traditional forms causes negative social and economic impacts on rural households. In the proposed scenario, putting the available biomass to productive use would be a good strategy for the sustainable development of rural areas. Finally, the report concludes that bioenergy can contribute to rural development and poverty alleviation.

Some countries have witnessed protests against large-scale land transfers for biofuel production, indicating public concern over the implications of biofuels for land use (Cotula et al., 2008). For example, for Uganda, Cotula et al. (2008) report that there was strong public opposition to a planned allocation of national forest reserves in Bugala and Mabira to foreign plantation companies to establish oil palm and sugarcane plantations. However, conclusions from the recent Cogen for Africa project show that there is now environmental legislation in place (not only in Uganda but also in other sub-Saharan countries) to avoid such problems. Even the financial support of the AfDB is assured only when adequate Environmental Impact Assessments are developed.<sup>6</sup>

There are doubts about the concept of "idle" or "abandoned" land (Dufey et al., 2007; Cotula et al., 2008). In most situations, lands perceived to be

4 See [www.conab.gov.br](http://www.conab.gov.br).

5 The BEFS project is funded by the United Nations FAO and the Government of Germany. Under the project, the FAO has developed a quantitative and qualitative framework to analyze the interplay between bioenergy and food security. The BEFS Analytical Framework provides tools that permit policymakers to make informed decisions with respect to bioenergy.

6 Coelho, S. T. Personal information by AfDB in field visits, invited by UNEP.

"idle," "under-utilized," "marginal," or "abandoned" by governments and large private operators provide a vital basis for the livelihoods of poorer and vulnerable groups, through crop farming, herding, and gathering of wild products. Further, seemingly "abandoned" land often provides important subsistence functions in times of stress to vulnerable households. Hence, the promotion of biomass production on degraded lands must avoid competition with these other land uses. These studies also claimed that other issues may cause or increase land-use conflicts, including poor enforcement of laws on land-use planning, particularly when large profits are at stake, as in the case of the expansion of oil palm plantations on native forests or even forest reserves.

Competing demands for land in Africa are primarily for agriculture and forestry, with the production of biomass for energy an emerging issue. Recent efforts have increasingly been aimed at identifying land areas for feedstock production that reduce competition with production of food and other biomass-based products. Policy suggestions have included the planting of biofuel crops on "marginal" and "idle" lands rather than prime agricultural land. Rural development and poverty alleviation from the implementation of bioenergy programs in developing countries have also been extensively discussed.

Some calculations indicate that apparent land availability differs from region to region. This implies the need for detailed regional and national assessments of the amount of land available, the quality of land for producing biofuels, potential conflicts with (or displacement of) land for food production, and the potential to increase food insecurity (Bekunda et al., 2009). Other studies (Martínez-Alier, 2002; Vanwey, 2009) also argue that subsistence agriculture is often strongly influenced by cultural or other social values that cannot be expressed in monetary terms, and that their benefits cannot be estimated using conventional methods such as cost-benefit analysis.

The European Union (EU) biofuels directive (discussed later in this chapter) is further providing incentives for the use of "degraded" lands for feedstock production. The assumption is that biofuel production will not compete with agricultural production on prime lands. Some governments have already taken steps to identify "idle" land and to allocate it for commercial biofuel production. Some governments have claimed that significant land areas are under-utilized and available for biofuel production. For instance, the Government of Mozambique has stated that only 9% of the country's 360,000 km<sup>2</sup> of arable land is currently in use, and that there is the possibility of bringing into production an additional 412,000 km<sup>2</sup> of marginal land currently not being used (Namburete, 2006, cited in Cotula et al., 2008). In fact it has expressed a strong interest in the production of biofuels in the country in a sustainable way.<sup>7</sup>

Another recent study (Müller et al., 2007) also suggested that sub-Saharan Africa could have substantial resources in terms of suitable land and

exploitable water to expand areas for agricultural production, including bioenergy production. This conclusion is confirmed by the results of the Cogen for Africa project.

Another important issue is related to women's land rights; some studies argue that they risk being eroded by large-scale biofuel expansion, due to existing gender inequalities. In Kenya, for example, despite providing 70% of agricultural labor, women only own 1% of the land they farm (DFID, 2007). This is replicated across the developing world, with only 5% of women farmers owning their land (IUCN, 2007; Cotula et al., 2008). However, it must be noted that this is a problem for the agricultural sector as a whole and not only for biofuels.

The complexities of women's involvement are recognized in Mali, for instance, where small-scale *jatropha* cultivation to meet local energy needs has been promoted by both government authorities and development agencies. The Ministry of Mines, Energy and Water is implementing a US\$1.6 million Programme National de Valorisation Énergétique de la Plante Pourghère to promote the use of *jatropha* for rural electrification, conversion of vehicles to biofuels, and poverty reduction amongst rural women (Cotula et al., 2008).

The implementation of adequate social policies and enforcement can contribute to reducing these problems. For example, sugarcane plantations in Brazil, mainly in Ribeirão Preto, São Paulo State, allow significant improvements on gender and social issues.<sup>8</sup> Existing statistics from Uniao da Industria de Cana de Açúcar (ÚNICA, 2010) show that in this region inequalities in gender are smaller and social aspects such as strict labor legislation are very much taken into consideration.

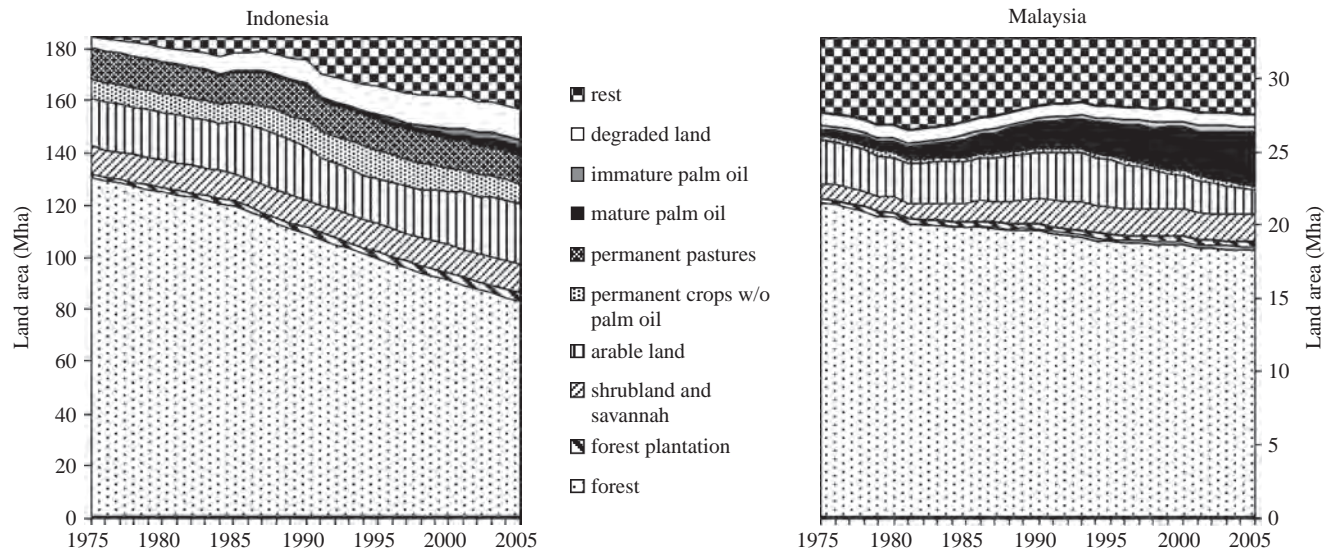
Bioenergy produced on currently grazed lands can have large-scale impacts on livestock-rearing subsistence farmers. These may be positive or negative, depending on the implementation strategy. Large-scale bioenergy plantations owned and operated by international, vertically integrated cooperatives tend not to benefit the local farming communities where the biomass is produced, as most of the revenue is generated in the production stage that involves sophisticated biochemical conversion technologies (Sagar and Kartha, 2007). On the other hand, small-scale, locally owned and operated plants, together with sustainability certification systems, might help ensure that benefits accrue to the local farming communities (Lewandowski and Faaij, 2006).

Soyka et al. (2007), focusing on Indonesia, raised the question of whether it was possible to increase tropical biofuel production without increasing tropical deforestation. However, Wicke et al. (2011) argued that palm oil crops are not the main reason for deforestation in Malaysia and Indonesia, and that there are several other factors involved, as discussed in Section 20.4. Figure 20.8 illustrates this discussion.

7 Coelho, S. T. Personal information from field visit to Mozambique invited by UNCTAD, 2010.

8 Ribeirão Preto, the most developed region in the rural areas of the country, has a local economy based almost exclusively on sugarcane crops.





**Figure 20.8** | Land-use change in Indonesia (left) and in Malaysia (right). Source: Wicke et al., 2011.

In fact, according to Wicke et al. (2011), it was found for Indonesia that “there are many, interrelated causes and underlying drivers that are responsible for this land-use change (...). Palm oil alone cannot explain the large loss in forest cover but rather a web of interrelated direct causes (including oil palm production expansion) and underlying drivers are responsible. Important direct causes were logging, palm oil expansion and other agricultural production and forest fires, while underlying drivers were found to be population growth, agriculture and forestry prices, economic growth and policy and institutional factors.”

For Malaysia, Wicke et al. (2011) show that “the most important causes of land use change vary per region: In Sabah and Sarawak the most important causes have been timber extraction and shifting cultivation, while in Peninsular Malaysia, and in recent years increasingly in Sabah, forest cover has been affected most by conversion to agriculture, mainly oil palm production.” The study also concludes that “additional forested land and peat land are not necessarily required for most projections of oil palm production expansion to be feasible. This is because yield improvements can largely reduce land requirements while also large amounts of degraded land exist in Indonesia. (...). As in Indonesia, yield improvements are also an important component of allowing potentially sustainable expansion. In Malaysia, yield improvements in the short term in both countries are mainly possible by applying fertilizer and other inputs more appropriately (and) practicing good harvesting standards (...).”

Moreover, according to the Malaysian Palm Oil Board, protected areas were defined in the country to preserve biodiversity and native forests.

Considering all these issues, Wicke et al. (2011) conclude that adequate policies and enforcement can minimize land-use conflicts due to the implementation of bioenergy crops, especially in regions where

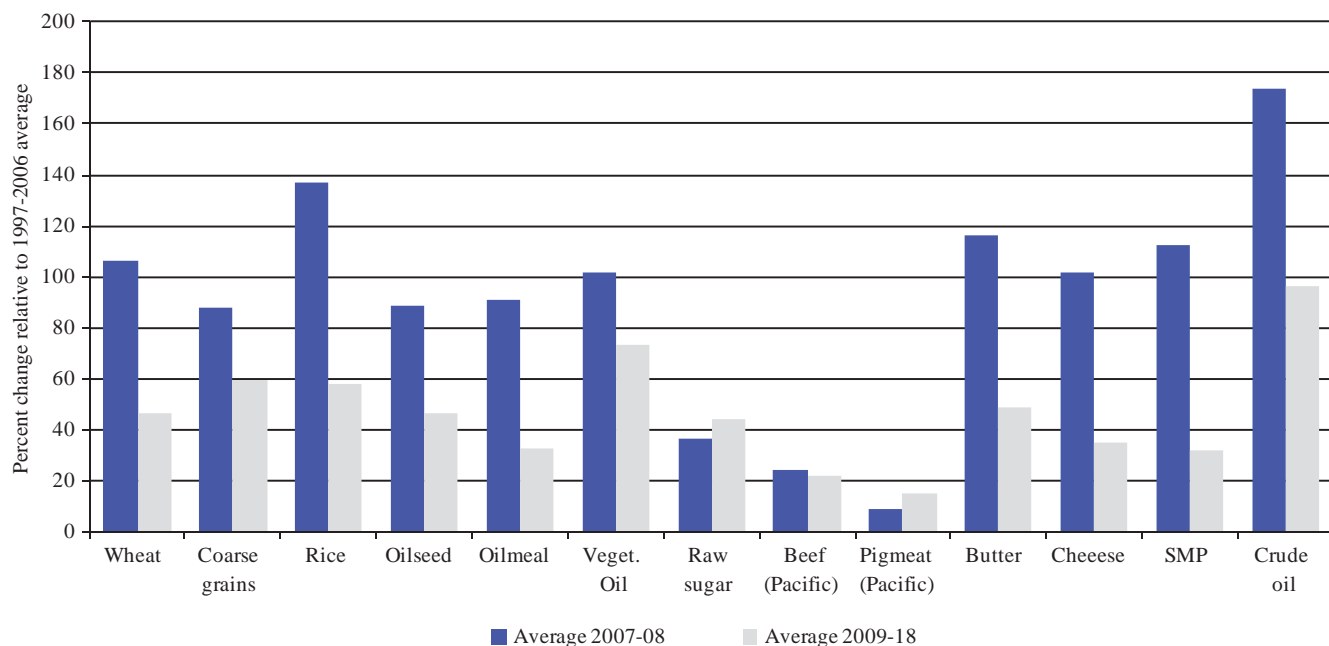
motivations of small farmers (“smallholders”) include strong components not usually considered in classical agro-economic toolboxes and dominant development models.

The FAO (2010a) also argues that “biofuel developments could play a pivotal role in promoting rural development through increased local employment and energy supply. Implementing bioenergy production can result in improvements or a worsening in the food security conditions depending on the bioenergy pathway chosen.”

In conclusion, these case studies suggest that land allocation to different uses, including agricultural and bioenergy crop production, involves sensitive socioeconomic issues related to food security, land tenure, land-use rights, subsistence versus market economy, cultural values, etc. Careful consideration of these issues, and implementation of sensible policies and legal frameworks, will, therefore, be key for the public acceptance of bioenergy crop plantation projects and will have an important impact on whether they will be perceived as beneficial development opportunities or as “land grab” (Friis and Reenberg, 2010).

## 20.2.6 Economic Effects of Land Use Competition

The discussion of fuel versus food is a long one and quite controversial. In this chapter some recent studies are presented to contribute to the discussion. A number of studies have looked at the linkages between the growth of biofuel production and the dynamics of food prices – both within the 2007–2008 time period and in the follow-up to the 2009–2010 financial market crisis and recovery period. A number of papers that emerged in the immediate wake of the 2007–2008 food price spike were strongly of the opinion that growth in biofuel production was the major contributor to food



**Figure 20.9** | Nominal commodity prices projected 15–60% higher than 1997–2006 but substantially lower than in the 2007–2008 peak. Source: OECD/FAO, 2009 (p19).

price increases (Runge and Senauer, 2007; OECD, 2008b; Mitchell, 2008; von Braun, 2007). In contrast, other authors were more cautious about the estimated impact of biofuels, and placed more weight on the macroeconomic factors such as exchange rates, grain storage policies and possible market speculation that could have played a role in the food market price dynamics during that period (Trostle, 2008; Abbot et al., 2008). Besides food price impacts, some authors also critiqued the economic efficiency of biofuel policies in terms of the distortions they place on markets, as in the case of the US corn ethanol program, where mandates, blending targets and import tariffs, combine in a way that both raises commodity prices and may even encourage the consumption of fossil fuel under certain circumstances (de Gorter and Just, 2007).

In the past, according to the FAO food price indices, nominal prices of agricultural commodities fluctuated but in a medium-term perspective were mostly stable or declining from 1990–2007 (see Figure 20.9). Deflated values suggest that food prices were fluctuating around a continuous long-term downwards trajectory in real terms in the last decades, at least until 2007.

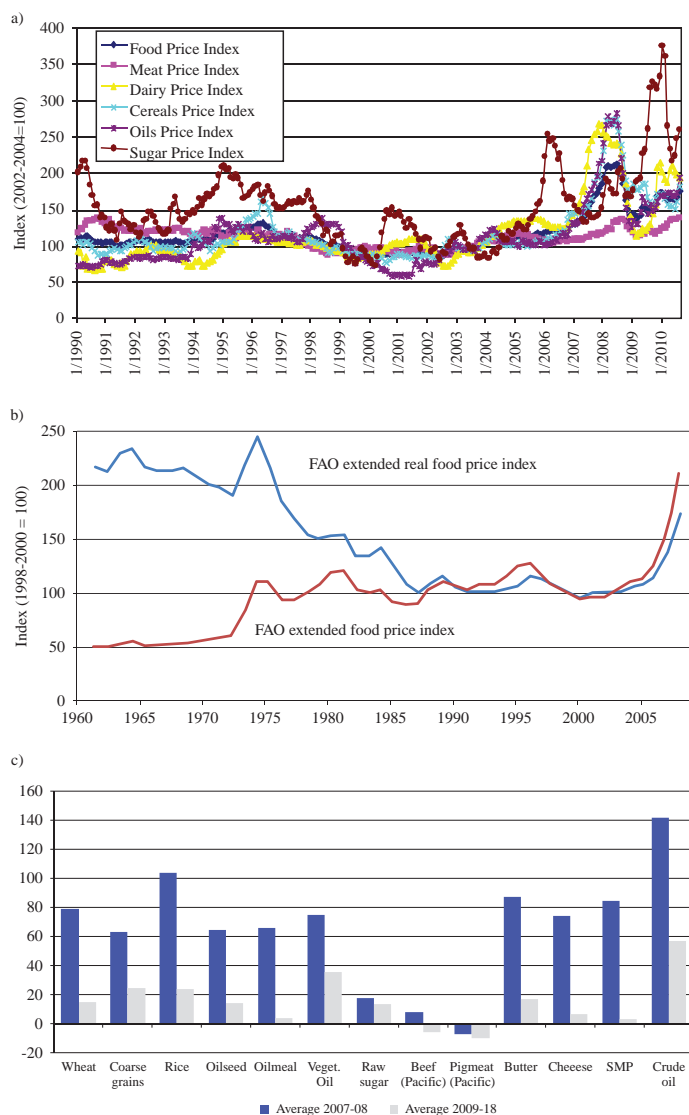
Starting in 2007, many agricultural prices increased substantially and remained high throughout most of 2008, falling sharply afterwards, most probably due to a reduction in oil prices (Faaij, 2009; Goldemberg, 2009) and reduced demand for many commodities resulting from the global financial crisis. Sugar seemed to be an exception; its price peaked in 2006 and then again in 2010 but was low during the period of high agricultural prices in 2007/2008.

These events triggered a debate on the question whether this was just another, only a bit stronger, price fluctuation that would not change the

long-term price trajectory, or whether it signaled a structural break, i.e., a long-term change in the trajectory of agricultural prices in an upward direction (FAO, 2009a; 2009b; OECD/FAO, 2009).

More recently, the OECD and FAO (OECD/FAO, 2009) showed that “despite the significant impact of the global financial crisis and economic downturn on all sectors of the economy, agriculture is expected to be relatively better off, as a result of the recent period of relatively high incomes and a relatively income-inelastic demand for food.” The report also concludes that biofuels can influence agricultural prices but in general because “energy and agricultural prices have become much more interdependent with industrialized farming (...). Crude oil prices are highly volatile (...). The crude oil price (...) assumed for the baseline is about 60% higher than the 1997–2006 average in real terms, moderately increasing to US\$70 per barrel by the end of projection period. If crude oil prices increased to the US\$90 to US\$100 per barrel level used in last year’s (report), agricultural prices would be significantly higher; with the largest impact on crops, driven mainly by reduced crop production with higher input costs, but also increased feedstock demand for biofuels.”

Figure 20.10c illustrates projections for the period 2009–2018. The study adjusted the prices for inflation, which are, in real terms, expected on average to be much below 2007–2008 average peak levels. Results show that “the crops expected to undergo the largest fall in real prices, compared to their 2007–08 average, are: rice, wheat, butter, cheese and skim milk powder. However, over the outlook period, real prices of products other than beef and pig meat are expected to be above their average 1997–2006 levels. In real terms, the average crude oil price assumption for the next decade is substantially below its 2007–08 peak, and remains well above, by around 60%, the 1997–2006 average level.”



**Figure 20.10** | (a) FAO food price index (nominal; monthly values, indexed to 2002/2004 = 100) for the period 01/1990–08/2010. Source: FAO, 2009c. (b) Nominal (yellow) and real FAO food price index 1961–2008. Source: FAO, 2009c. (c) Real crop prices to fall from peaks but to remain above 1997–2006 average. Source: OECD/FAO, 2009 (p19).

The list of potential explanations for the price rally in 2007 and 2008 is long and includes: low yields due to unfavorable weather (droughts); strong policies promoting biofuel production in the United States and Europe; high oil prices;<sup>9</sup> increasing food demand arising from strong economic growth in developing countries, in particular China and India; inflows of speculative funds; and low stocks of many agricultural commodities (OECD/FAO, 2007; 2009; FAO, 2009b; Trostle, 2008). In addition, depreciation of the value of the US dollar compared to other currencies seems to have been one of the reasons leading to the strong increases in prices. The price hikes were less dramatic when expressed in other

<sup>9</sup> The oil price affects the prices of agricultural commodities because of the energy needed in agricultural production, both directly (e.g., tractors) and indirectly (e.g., fertilizer production).

currencies. However, for the United States and all other countries whose local currencies are pegged to or weaker than the US dollar, the depreciation of the dollar did in fact increase the costs of procuring food (FAO, 2009b; OECD/FAO, 2009).

Estimates of the effects of the growing production of biofuels on food prices vary, depending on the time period considered and the food price indicator chosen. The effect of increased biofuels production on the price of commodities was much larger for those commodities that are used for both food and fuel production such as maize (for food and for corn ethanol in the United States) than the impact on food price indices that consider a broader range of commodities and processed foods.

In its *World Development Report 2008*, the World Bank (2008) argued that rapid expansion of biofuels had strongly contributed to the price hike. For example, the World Bank claimed that the massive use of maize for ethanol production in the United States had reduced maize stocks and had largely caused the surge in maize prices in 2006 and 2007. While a different report by the World Bank (Mitchell, 2008) concluded that US and European biofuel policies were responsible for most of the food price increase, a later study also published by the World Bank concluded that the effect of biofuel policies had been over-estimated in that earlier study (Baffes and Hanjotis, 2010).

The OECD (2008b) concludes that while biofuel policies did contribute to the increases in food prices in 2007 and 2008, they would result in rather limited price increases in the medium term, i.e., for the period from 2013 to 2017. For example, the OECD calculated that current EU and US policies would drive up prices of coarse grains by about 5% compared to the baseline. Vegetable oils would be more strongly affected; their prices were forecast by the OECD (2008b) to increase by 15%.

The FAO (2009b) and OECD/FAO (2009) discuss the 2007–2008 price hikes and distinguished short-term effects and long-term trends. With respect to short-term fluctuations in 2007–2008, the FAO concluded that growing consumption in India and China is unlikely to have contributed to the price hike, because, in those years, their growth rates were below that of the aggregate of all other countries and their trade patterns did not show sudden changes. (However, it was argued that changes in their consumption patterns could be relevant over the medium to long term.) This FAO study also concluded that the rapid growth in the use of maize for ethanol in the United States and oil crops for biodiesel in the EU, caused by the introduction of respective blending targets and subsidies, played a major role in influencing prices. In 2007, 12% of the global maize production and 25% of the global rapeseed production were used as feedstock for biofuels, and these shares had been growing rapidly. This coincided with bad harvests in 2005 and 2006 and hence record-low stocks.

With respect to speculation, the FAO mentioned that it was not clear whether speculation was driving prices, or whether it was attracted by prices that were increasing anyway. Speculation might have resulted in

increased volatility, according to the FAO study. In conclusion, the FAO argued that no factor in isolation could explain the price hikes, only their combination and coincidence. With respect to possible structural effects that would change price trajectories in the coming decades, the FAO concluded that biofuels, and indeed any energy technology requiring significant amounts of highly fertile lands and, therefore, competing with food production for land resources, would influence food markets.

The FAO also reckoned that biofuels are at present not competitive with fossil fuels, with the exception of ethanol from Brazilian sugarcane. Therefore, their impact on agricultural markets would remain limited to the extent to which they were subsidized, i.e., their impact on agricultural markets would remain limited except under extraordinary circumstances, such as a rapid introduction through policy interventions in response to weather or other effects. As soon as oil prices climb to a level where biofuels become economically competitive, however, agricultural and energy markets would become linked in a new way: “[a]s energy markets are huge relative to agricultural markets, demand from the biofuel sector could *in principle* absorb any additional production in crops usable as feed stocks so the energy market would effectively set a floor price for agricultural products. It would also set a ceiling on agricultural prices at the point where they have risen so much that biofuel production is no longer competitive. It would be energy demands rather than food demands that would set agricultural product prices and agricultural product prices would be tied to *energy* prices. Clearly, this would be a major departure from how agricultural product prices have been determined in the past” (FAO, 2009c).

Other authors have drawn similar conclusions. For example, Müller et al. (2007) concluded that competition for land would increase and prices of essentially all crops would rise if a growing range of crops became competitive as feedstock for biofuel production. Moreover, other agricultural products that could be used as substitutes for other, non-renewable resources would in this case become increasingly competitive, thereby giving farmers greater flexibility to switch between different crops, e.g., between food and energy crops.

On the other hand, the OECD/FAO (2009) stressed that after the (2007–2008) high-price crisis there has again been evidence of the rapid responsiveness of global agriculture. High international commodity prices have transmitted signals to farmers to allocate more resources and increase agricultural production. However, not all farmers responded similarly, as high world prices are not transmitted to local producers in many instances. A decomposition of the response of farmers by economic region reveals that output expansion in developed countries amounted to over 13%, but developing countries together could only muster a 2% increase in their cereal production. This lack of response from a large part of the world shows the need for policy reform and additional investment in productive agriculture, particularly in many developing countries. Structural problems are likely to persist, especially for the Least Developed Countries, limiting their capacity to produce. Other studies (Goldemberg, 2009; Faaij, 2009) also concluded

that the increase in food prices was mainly caused by the rising oil price and poor food distribution in developing countries.

Also, more recent FAO estimates, derived from simulations with the OECD/FAO Aglink-Cosimo model, suggest that keeping biofuel production at 2007 levels would reduce the price of maize in 2017 by 12% and that of vegetable oil by 15% compared to the respective baseline projections (FAO, 2009c).

In brief, as raised by Dornburg et al. (2010), “it is claimed that biofuels will lead to famine, deplete water resources and destroy biodiversity and soils. (...) Biofuels are often regarded as the cause of the dramatic increases in food prices that have occurred over the past few years.” In fact, “[b]iofuel developments have local, national, regional and global impacts across interlinked social, environmental and economic domains” (FAO, 2010a).

The recent increase in food prices exacerbated such criticism. However, the report from OECD/FAO (2009) mentioned above showed that agricultural markets saw a reduction in commodity prices in 2009 after their rapid rise during 2006–2008, and perspectives for future prices are not so negative. “Looking forward, real commodity prices over the 2009–2018 period are projected to remain at, or above, the 1997–2006 average. An expected economic recovery, renewed food demand growth from developing countries and the emerging biofuel markets are the key drivers underpinning agricultural commodity prices and markets over the medium term.”

As more data became available in the aftermath of the 2007–2008 food price spike, and more analysis was able to be carried out on emerging market-level price, production and consumption data, other authors began to contribute additional insight into the role that biofuels could have played in driving global and regional food prices. The analysis of Heady and Fan (2010) maintained that the influence of biofuels was still strong for markets such as maize, whereas the dynamics for other grain markets such as rice were related to trade policies and national commodity prices in individual countries. Gilbert (2010) is among those authors who argued against the premise that biofuels played a major part in the food price spikes of 2007–2008, and that speculation in agricultural commodity futures had a much stronger role. Baffes and Haniotis (2010) – following on the earlier analysis of food price impacts by Ivanic and Martin (2008) – took a more middle-of-the-road position and argue that even though the role of biofuels may not have been as strong as was suggested in the earlier literature, there does exist a strong link between energy and food prices. They, like other authors, also point to the fact that agricultural commodities are becoming a large part of financial investment portfolios, and point to trends of variability in historic prices of commodities.

Zhang et al. (2010) analyzed time-series prices on fuels and agricultural commodities, and results indicate no direct long-term price relations between fuel and agricultural commodity prices. In fact rising sugar



prices appear to be the leading cause of price inflation in other agricultural commodities; however, the study concludes that, with decentralized competitive agricultural markets, this sugar price impact is transitory.

The estimation of the impact of increased biofuel production on food prices has mostly been done with the help of country- or global-level economic multi-market equilibrium models that are either partial or fully comprehensive in terms of the economy-wide linkages that connect the supply and demand of agricultural commodities to important economic sectors. The nature of the particular model determines how closely the supply and demand dynamics of the agricultural food commodities themselves are linked to important input markets such as fertilizer, labor, and energy – especially biofuels and their interactions with crude oil prices. The particular structure and underlying assumptions of these models, by themselves, can have a considerable effect on the estimates of increased biofuel production on price impacts. A comprehensive meta-analysis of the differences in modeling the impacts of biofuels on land-use change (Edwards et al., 2010) showed evidence of systematic differences across types of modeling approaches, especially when moving from “partial-equilibrium” models that focus mostly on agricultural markets towards those “computable general-equilibrium” (CGE) models that consider the deeper complexities of linkages across many sectors of the economy.

These types of global CGE models have been used to demonstrate both the environmental as well as the price impact of increased biofuel production in more recent studies. The study carried out by al-Riffai et al. (2010) to evaluate the environmental implications of the EU Renewable Fuels Directive, for example, used a global CGE model with linkages to land availability to illustrate the implications of increased OECD biofuel production on GHG emissions.

Besides showing the relative “superiority” (in terms of environmental impacts and GHG emissions) of Brazilian sugarcane over US-based

maize ethanol, the authors also show that liberalizing world (and especially US) trade policy to reduce tariff barriers against biofuel imports has the effect of reducing grain prices for both food use and livestock feed.

A recent study by the World Bank (Timilsina et al., 2010) illustrates the effect of increased biofuel production on land use, food prices, and poverty, and argues that moving from a scenario where OECD blending mandates and biofuel production targets are announced at current levels and are further enhanced by scaling up production capacity and doubling blending targets and biofuel production results in a near doubling of modest impacts on food prices. They also show some impacts on the supply of livestock products, sugar, and grains, as a result of the expansion of biofuels production – although the overall effect on the supply of food is relatively small (on the order of 0.2% lower than the baseline case). Even though they argue that their results are similar to those of al-Riffai et al. (2010) and others, this further illustrates the influence that model structure has on the simulated impacts of increased biofuel production.

The additional flexibility that these models have built into their structure, to capture the land-use dynamics and competition between crop, livestock and forestry cover, may understate the price impacts through their tendency to freely adjust land supply in response to relative price changes across commodities. This points to trade-offs that are inherent to different modeling approaches that try to either capture the environmental impacts of biofuels or the commodity market interactions (Nassar et al., 2011).

### 20.2.7 Bioenergy and Food Security

Food security (see Box 20.1) must be addressed in line with the world’s commitment to eradicate extreme poverty and hunger as part of the Millennium Development Goals (MDGs) (UN, 2000). In fact, some food

#### Box 20.1 | Food Security

“Food security exists when all people, at all times, have physical, social and economic access to sufficient amounts of safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life. There are four dimensions to food security: availability, access, stability and utilization. Availability of adequate food supplies refers to the capacity of an agro-ecological system to meet overall demand for food (including animal products, livelihoods and how producers respond to markets). Access to food refers to the ability of households to economically access food (or livelihoods), defined in terms of enough purchasing power or access to sufficient resources (entitlements). Stability refers to the time dimension of food security. Stability of food supplies refers to those situations in which populations are vulnerable to either temporarily or permanently losing access to resources, factor inputs, social capital or livelihoods due to extreme weather events, economic or market failure, civil conflict or environmental degradation, and increasingly, conflict over natural resources. Utilization of food refers to peoples’ ability to absorb nutrients and is closely linked to health and nutrition factors, such as access to clean water, sanitation and medical services.”

Source: Faaij, 2008.

price fluctuations will always occur. Therefore, to protect poor people, and food security generally, adequate policies have to be implemented, such as adequate agro-environmental zoning together with economic and environmental legislation.

The linkages between bioenergy and food security are complex. Food availability can be threatened if land, water and other resources are diverted from food to biofuel production (Dornburg et al., 2010). Competition for resources is reduced if biofuels are produced from non-edible crops and if the biofuel crops are cultivated on land that would not be utilized for food production in the foreseeable future. Crop selection, farming practices and yield growth patterns can have significant implications for potential impacts of biofuel growth on food availability. Food access is determined by the prices of food and the income levels of the poorest segments of society depending upon food purchases to meet their dietary needs. A significant number of people produce less food than they consume and in some cases may face an immediate negative impact in response to rising commodity prices (FAO, 2008c; 2009b; 2009d; OECD/FAO, 2009).

As mentioned by Dornburg et al. (2010), biofuel production is considered by some as the reason for rises in food prices, mainly grain prices. Poorer households spend a greater percentage of their income on food, particularly on staples, than richer ones, and are thus disproportionately affected by rising food prices. However, this question is much more complex (see discussion in Section 20.2.6.)

There are also opportunities for biofuels to contribute to greater food security. Poor farmers could benefit financially from selling commodities at higher prices. At the national level, high prices offer development opportunities for countries with significant agricultural resources and

potential, such as Tanzania (Müller et al., 2007; FAO, 2010a). Greater demand for biofuels can boost incomes by revitalizing agriculture, providing new employment opportunities, and increasing access to modern energy, which can increase household welfare and contribute to rural development (FAO, 2008a; OECD/FAO, 2009).

Higher prices can also provide incentives for intensification, leading to increased food production, and improved livelihoods as long as production methods are sustainable (FAO, 2008a). Establishment of large-scale biofuel production systems could also provide benefits in the form of employment – mainly jobs in rural areas, skills development, and secondary industry (Cotula et al., 2008).

Attention must be given to developing and Least Developed Countries, since the FAO (2009d) warned that high prices for consumers do not necessarily mean high prices for poor producers in developing countries and have so far not triggered a positive supply response by smallholders there. The FAO study reported that access to means of production and assets such as land is critical for small farmers to be able to harness positive effects of price increases – if this cannot be guaranteed, large landholders are likely to benefit most from high food prices. However, the recent study from the OECD/FAO (2009) showed perspectives for agricultural commodity production increasingly shifting away from developed countries towards developing regions.

The impacts of bioenergy developments on food security depend on many factors that are country- and case-specific. Examples of these factors include the type of biomass used, the type of energy carrier produced, the type of land used for biomass production, and developments in agricultural management and in the global food markets (Box 20.2).

## Box 20.2 | Preliminary insights from FAO's Bioenergy and Food Security project<sup>10</sup>

“Bioenergy, and particularly liquid biofuels, have been promoted as a means to enhance energy independence, promote rural development and reduce greenhouse-gas emissions. In principle there are many benefits offered by bioenergy developments but these need to be balanced against the impacts on food security and the environment. While there has been a rush by many governments to develop bioenergy alternatives to fossil fuels this has often been done in the absence of a wider understanding of the full costs and benefits of bioenergy.”

Preliminary results from three countries (Peru, Tanzania, and Thailand) participating in FAO's Bioenergy and Food Security (BEFS) project suggest that bioenergy developments, if managed correctly and sustainably, can serve as an opportunity to reduce poverty and increase energy access in a number of developing countries.

The success of bioenergy developments depends most importantly on the management strategy of the investments. Biofuel developments that safeguard food security are possible, if a gradual expansion process is adopted that assesses and manages possible

<sup>10</sup> The Bioenergy and Food Security (BEFS) project has been developed by the Food and Agricultural Organization of the United Nations (FAO) with funding from the German Federal Ministry of Food, Agriculture and Consumer Protection (BMELV). It was set up to assess how bioenergy developments could be implemented without hindering food security. Available at [www.fao.org/bioenergy/](http://www.fao.org/bioenergy/).

negative impacts on the most vulnerable people and on the natural resource base. Land – especially large tracts of land – is analyzed to be allocated in line with transparent procedures, assessing land availability and considering projected food production needs, suitability for proposed feed stocks, and competing claims on the land. Particular attention must be paid to vulnerable groups that depend on the land for their livelihoods.

The BFES report for Peru (FAO, 2010b) shows that this country “has witnessed strong agricultural growth which has reduced rural poverty but at a much slower rate than urban poverty. Consequently, urban-rural inequalities have widened.”

Overall, according to the conclusions from the project, poor people in both urban and rural areas must be directly involved in the bioenergy production chain. Rural households can benefit from price increases for crops used for both food and energy. The analysis in the case of Peru for the main food staples shows that, for example, increases in the price of maize are detrimental to the urban poor but can increase the welfare of the rural poor.

The report also stresses that “bioenergy and especially biofuel developments, in principal, hold much promise for improving agricultural growth for the benefit of the poor. However, while a mandate has been already set in Peru, feedstock production for liquid biofuel can have serious consequences on food production because they compete for the same resources. Thus, an important question is whether the mandate can be met without compromising the food security status of Peru.” It concludes that the three most important policies for Peru are: to increase the knowledge base on bioenergy; to improve strategies and actions on bioenergy; and to enhance decision-making and dissemination.

Preliminary results from Tanzania indicate that countries should look beyond the most established bioenergy production chains and carefully consider feedstock and technology selection to suit the natural resource endowments, biophysical conditions, domestic capacity (including human skills), infrastructure, and economic set-up of the country. Opportunities to improve the economic viability for biofuels are closely linked to developments in the agricultural sector.

More specifically, the assessment suggests that ethanol production from cassava is a more attractive option for Tanzania than other crops, such as sugarcane. The biophysical conditions suitable for growing cassava are more widely present within the country when compared to the limited areas suitable for other crops. Additionally, cassava represents the least-cost feedstock for ethanol production in Tanzania, as it is already widely produced in all areas of Tanzania, and local farmers are familiar with the crop. Cassava ethanol production can be competitive if out-grower schemes are adopted in connection with a core plantation that can guarantee the continued optimal supplies of feedstock required by the processing plant. To ensure a viable and sustainable domestic ethanol industry based on cassava, productivity must be improved, so that the energy balance is lower; adoption of appropriate sustainable management practices, such as conservation agriculture, could considerably increase productivity. Moreover, given poor transport infrastructure and to overcome rapid post-harvest deterioration of the cassava – i.e., starch reduction – it is recommended that the cassava is sun dried into chips at the farm to extend the shelf life. The sun-dried cassava chips can then be collected in centralized sites near the area of production, and the less bulky material can be transported to an ethanol processing plant.

Analysis of the impact of rising cassava prices on the welfare of the poorest quintiles shows differences between regions and household types; while some vulnerable households may be affected negatively, there may be benefits to most people

In general, developing the biofuel industry in Tanzania will require infrastructure development, including efficient and reliable transportation networks to support the connection of the various production components along the supply chain and to facilitate processing, which requires provision of potable and industrial water (agro-processing and biofuel plants) and electrification. Biofuel processing can also be enhanced by producing value-added co-products from by-products to benefit the economies of production and to generate added-value inputs to meet local needs, i.e., biofertilizers, electricity. A sustainable biofuels industry that provides longer-term prospects for economic growth and poverty reduction can be created if the choice of technology is suited to the technical capacity available in the country.

Source: FAO, 2010a; 2010b.

Risks to food security indeed need to be considered at the local level. Large-scale allocation of land for biofuel production without adequate policies may lead to the eviction of vulnerable people, and poor people may also lose access to land, water, and other resources. In a review of large-scale land deals in sub-Saharan Africa, Cotula et al. (2009) observed that whereas there are important opportunities related to large-scale investments in land that can create employment and rural development, many countries do not have sufficient mechanisms to protect local rights and take account of local interests, livelihoods, and welfare. Insecure local land rights, inaccessible registration procedures, vaguely defined productive use requirements and insufficiently developed implementation clauses for social commitments in land contracts, as well as legislative gaps, often undermine the position of vulnerable local people. The review calls for: a careful assessment of local land uses and claims; securing land rights for rural communities; involving local people in negotiations; and proceeding with land acquisition only after their free, prior and informed consent.

On the other hand, driven by technological progress and investments in agricultural research, the rapid output growth in developing countries is particularly remarkable. Nearly 70% of incremental production came from higher yields, approximately 10% from higher cropping intensities, and only about 20% from increasing the area of land used (Müller et al., 2007).

Müller et al. (2007) also claim that, in regions where crops do not benefit from technical progress, farmers remained poor and little progress was achieved in reducing undernourishment, but in general, growth in agricultural production helped to reduce hunger and poverty. In fact, it is noted that the food production situation in developing countries has been promising; the data indicate that over the past 30 years production of food has nearly tripled. Food supply per person has increased by more than 50% in developing countries. However, this increase in gross production could result in a further increase in food consumption, but difficulties mainly related to food transportation and distribution among poor people did not allow hunger to be reduced significantly. This is mainly due to the fact that these problems do not allow poor people to have access to food, even with the increase in food production.

A recent review on integrated food-energy systems discusses possibilities for, and constraints regarding, large-scale implementation of biofuels versus food (Bogdanski et al., 2010). If policies that integrate bioenergy farming with food and feed farming are implemented, there is a potential to decrease local food shortages and increase the incomes of the world's poorest people (Müller et al., 2007; Sparovek et al., 2007).

### 20.3 Water Use

Water is a natural resource necessary for human survival and important for economic activities. It is used mainly for household purposes

(drinking water, sanitation), industrial purposes (e.g., food processing, mining), energy generation (in hydropower systems and for cooling towers in nuclear and thermoelectric power plants) and, most important, agriculture (food production, feed, bioenergy crops). The increasing stress on freshwater resources brought about by ever-rising demand, mainly resulting from population growth, is of serious concern (see Figure 20.11).

As the world population increases, and development requires increased allocations of groundwater and surface water for the domestic, agriculture, energy and industrial sectors, the pressure on water resources intensifies, leading to tensions and conflicts among users, and degradation and pollution of the environment. Contamination of rivers, depletion of aquifers and increased utilization for multiple purposes are challenges commonly found in regions where demand exceeds supply and where water management is poorly conducted. Indicators such as water footprints are important to understand these important issues.

Increased competition among different water uses due to growing demand is already happening. Water scarcity induces competition for water between users, between economic sectors, and between countries and regions sharing a common resource, as is the case for international rivers. Many different interests are at stake, and equitable solutions must be found regarding the competing demands between: cities and rural areas; rich and poor people; arid lands and wetlands; public and private sectors; infrastructure and natural environments; mainstream and marginal groups; and local stakeholders and centralized authorities.

Water conflicts can arise in water-stressed areas among local communities and between countries because sharing a very limited and essential resource is extremely difficult. The lack of adequate legal instruments exacerbates already difficult conditions. In the absence of clear and well-established rules and regulations, severe tensions tend to dominate, and power can play an excessive role, leading to an inequitable allocation of water. A greater focus is needed on the peaceful sharing and management of water at both international and local levels (UN-Water/FAO, 2007). A well-developed system of Integrated Water Resources Management, including adequate institutional set-up and a good governance system, is needed in river basins or confined regions where demand exceeds existing supply.

Climate change is expected to account for about 20% of the global increase in physical water scarcity – and countries that already suffer from water shortages will be hit the hardest (UN-Water/FAO, 2007). This would include African countries, where water is a limiting factor for agriculture food production and also essential for income generation. Examples of export cultures in water-stressed regions are flower farms in Kenya, Zambia, and Uganda, which are extremely dependent on continued access to water in critical basins and trying to limit costs by using innovative rainwater harvesting techniques (FAO, 2005; Belwal and Chala, 2008; Orr and Chapagain, 2007; Asea and Kaija, 2000).

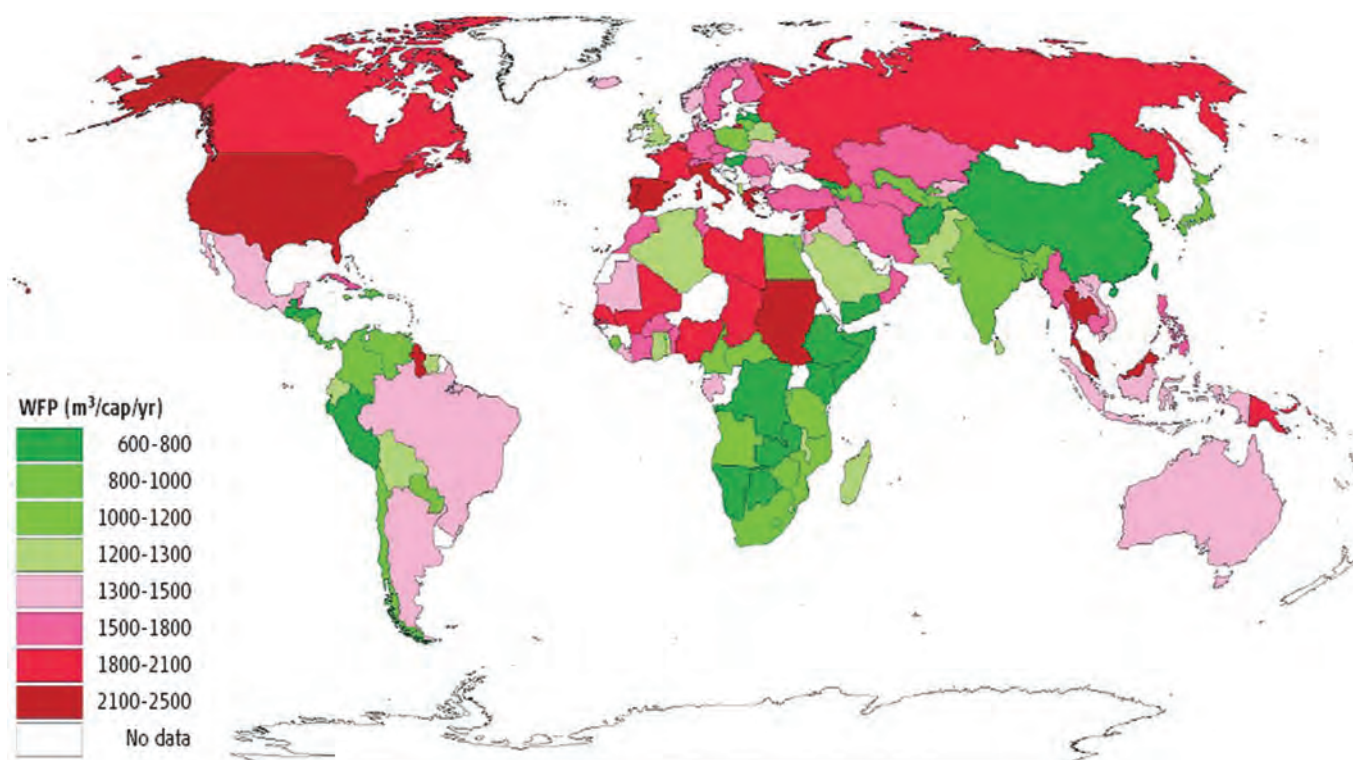


Figure 20.11 | National water footprints around the world, 2004. Source: UNESCO, 2006. Used by permission of UNESCO.

### 20.3.1 Water Withdrawal

In 2000, around 3800 km<sup>3</sup> of freshwater were withdrawn from all over the world, twice the volume withdrawn 50 years earlier (WCD, 2000). Two thirds of the freshwater on Earth is frozen in glaciers and polar ice, and most of the remaining freshwater is groundwater (WCD, 2000). If all the freshwater resources on the planet were equally shared among the world's population, there would be 5000–6000 m<sup>3</sup> of water per capita per year. However, the world's freshwater resources are distributed very unevenly, as is the world's population, and a large number of people in the low latitudes are experiencing water scarcity (see Figure 20.12).

The most dramatic water scarcity conditions are in parts of Asia and Africa. The emerging economies of India and China have regions where the climate is sub-humid or arid. Some areas depend on unsustainable pumping of groundwater aquifers and diversion of water flows for irrigation and human consumption, which can cause conflicts between communities. Unsustainable water use also occurs in developed countries, such as the mid-western parts of the United States, where the High Plains (Ogallala) aquifer has declined more than 100 feet (~30 m), and over 150 feet (~45 m) in some places. This resource underlies parts of eight states – Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. The area overlying the High Plains aquifer is one of the major agricultural regions in the world. Water-level declines began in parts of the High Plains aquifer soon after the beginning of extensive groundwater irrigation (McGuire, 2007a; 2007b).

The areas of most severe water scarcity are those where high population densities converge with low availability of freshwater. Here, people not only experience a physical water scarcity, where evapotranspiration exceeds precipitation, but also a social water scarcity, where the accessible amount of water per person has decreased below 1000 m<sup>3</sup>/person/yr. Many countries are already well below the threshold value. Jordan is an extreme case, with less than 200 m<sup>3</sup>/person/yr (FAO, 2007b).

Growing scarcity and competition for water represent major threats to future advances in poverty alleviation, especially in rural areas. In semi-arid regions, increasing numbers of the rural poor are coming to see entitlement and access to water for food production, livestock and domestic purposes as more critical than access to primary health care and education. For poor people, an economic inability to cope with increased competition for water (being unable to afford rising prices) may result in economic water scarcity. Economic scarcity is caused by a lack of investment in water, or a lack of human capacity to meet the demand for water. Much of the scarcity is due to how institutions function – for example, favoring one group over another and not hearing the voices of various groups, especially women. Symptoms of economic water scarcity include scant infrastructure development, either small- or large-scale, so that people have trouble getting enough water for agriculture or drinking. Yet, even where infrastructure exists, the distribution of water may be inequitable, reflecting social distortions among different extracts of the population. Much of sub-Saharan Africa is characterized



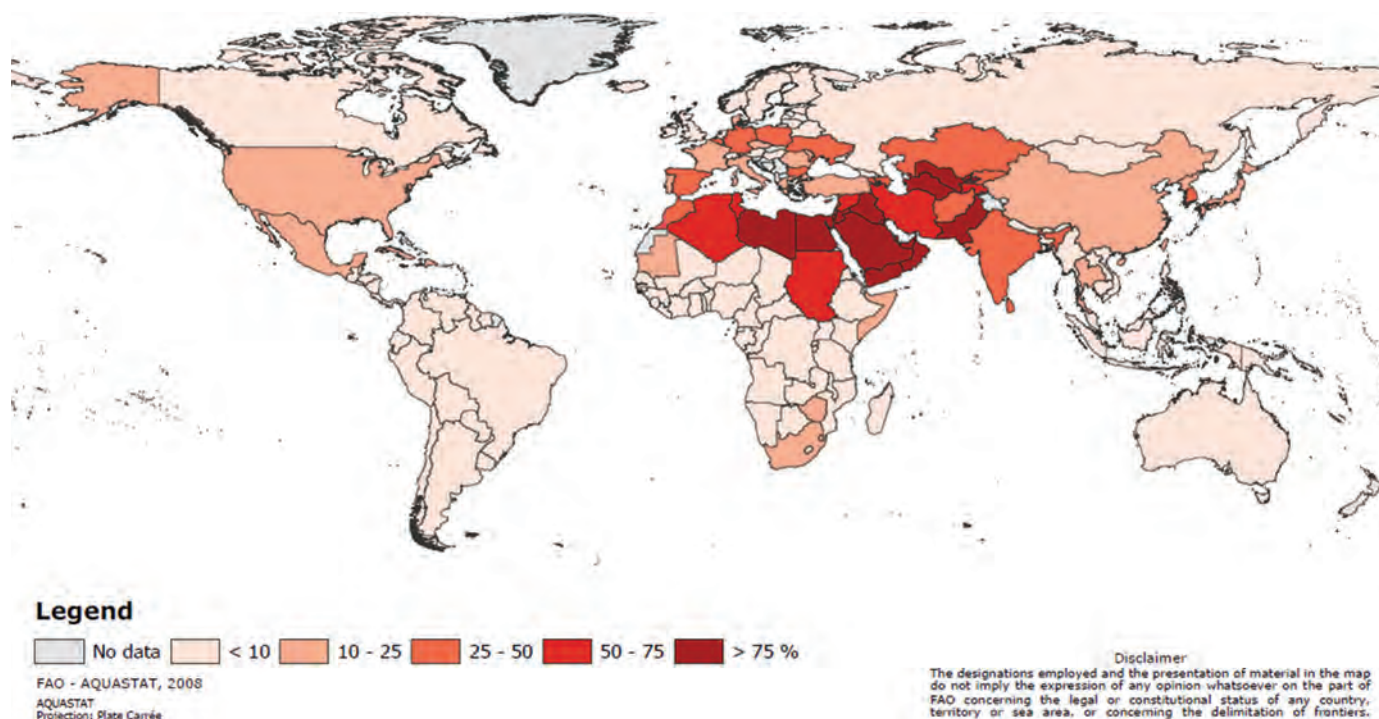


Figure 20.12 | Water resources withdrawn as a share of renewable water resources<sup>11</sup>. Source: FAO-AQUASTAT, 2008.

by economic scarcity, so further water development could do much to reduce poverty.

Physical scarcity occurs when there is not enough water to meet all demands, including environmental flows. Arid regions are most often associated with physical water scarcity, but water scarcity also appears where water is apparently abundant, when water resources are over-committed to various users due to overdevelopment of hydraulic infrastructure, most often for irrigation. In such cases, there simply is not enough water to meet both human demands and natural flow needs to supply the local environment. Symptoms of physical water scarcity are severe environmental degradation, declining groundwater, and water allocations that favor some groups over others (IWMI, 2007a).

### 20.3.2 Urbanization

In 2000, 75% of the total annual withdrawal of water (3532 km<sup>3</sup>) was used for agriculture, but this proportion could decrease to 58% in 2050

<sup>11</sup> Renewable water resources refer to the long-term average annual flow of rivers (surface water) and recharge of aquifers (groundwater) generated from precipitation; they are computed on the basis of the water cycle. Non-renewable water resources refer to groundwater bodies (deep aquifers) that have a negligible rate of recharge on the human time-scale and thus can be considered as non-renewable. While renewable water resources are expressed in flows, non-renewable water resources have to be expressed in quantity (stock) (FAO-AQUASTAT, 2008).

(IWMI, 2007a). Growing urbanization may result in tensions and conflicts for water, as large cities need to look for water supply from increasingly distant sources. One example is the city of Johannesburg, South Africa, which is largely supported by water transferred from the Orange-Senqu River basin. Farmers, who have been accustomed to liberal supplies with virtually no fees, now have to face reduced supplies and must often pay for water services (Lundqvist et al., 2007).

In some countries, governments can decide on the allocation of water from one sector to another, depending on how the water rights are defined. In other countries, where land and water rights are private, urban water service providers can buy water from the surrounding landowners, compensating them for reduced irrigation withdrawals or for giving up farming altogether. These examples are so far primarily from developed countries such as North America and Australia. Over-appropriation of ground- and surface water will continue to increase, due to increased food production and increased use of water by industry and cities, with the consequence that freshwater ecosystems will deteriorate. Cities and industries may secure their water supply at the expense of other sectors, such as agriculture and other rural uses, since water brings much higher economic returns for industrial and urban use (Lundqvist et al., 2008).

Urbanization is an important factor that influences agricultural markets. It is expected that the current rural population will remain more or less stable until 2030 and that population growth will be confined to urban

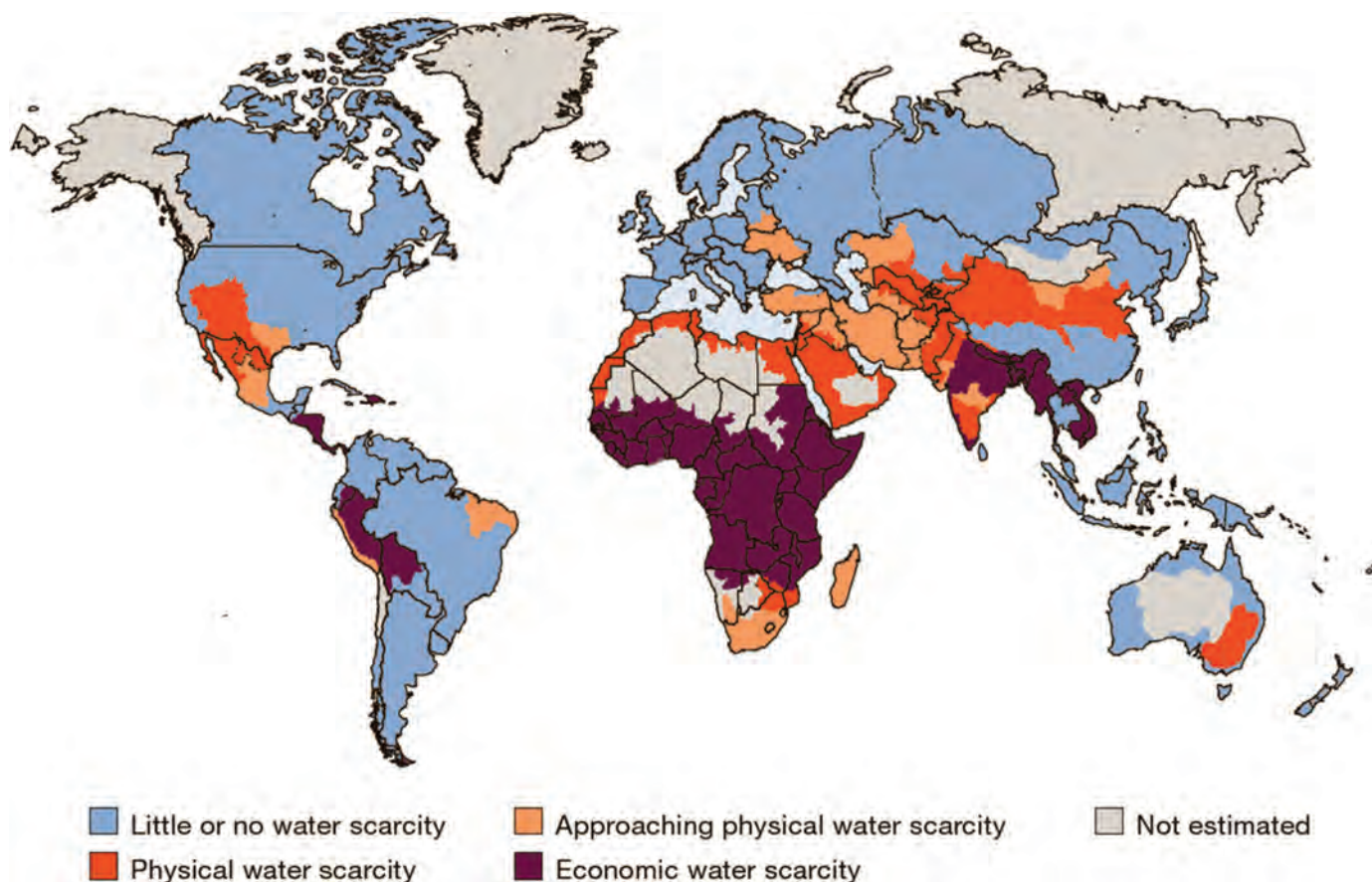


Figure 20.13 | Map of global water scarcity. Source: IWMI, 2007a.

areas. Urbanization has major impacts on markets due to high population density and infrastructure growth. Consumers become closely integrated into the international food markets, resulting in more food trade and changes in diets, with a shift from traditional vegetable foods to a greater demand for meat, which requires more water (Müller et al., 2007; Dufey et al., 2007, cited in Cotula et al., 2008).

In water-scarce regions the increasing reuse of wastewater after treatment processes such as deep-well pumping and large-scale desalination, would increase energy use in the water sector, thus generating more GHG emissions, unless “clean energy” options are used to generate the necessary energy input.

Possible conflicts between climate change adaptation and mitigation measures might arise with regard to water resources, such as biofuel crops that replace fossil fuels but require more water inputs, or water for cooling bioelectricity thermal plants. This indicates the importance of integrated land and water management strategies for river basins, to ensure the optimal allocation of scarce natural resources, including water. Also, both mitigation and adaptation have to be evaluated at the same time, with explicit trade-offs, to optimize economic investments while fostering sustainable development. Adaptation to changing

hydrological regimes and water availability will also require continuous additional energy input (Bates et al., 2008).

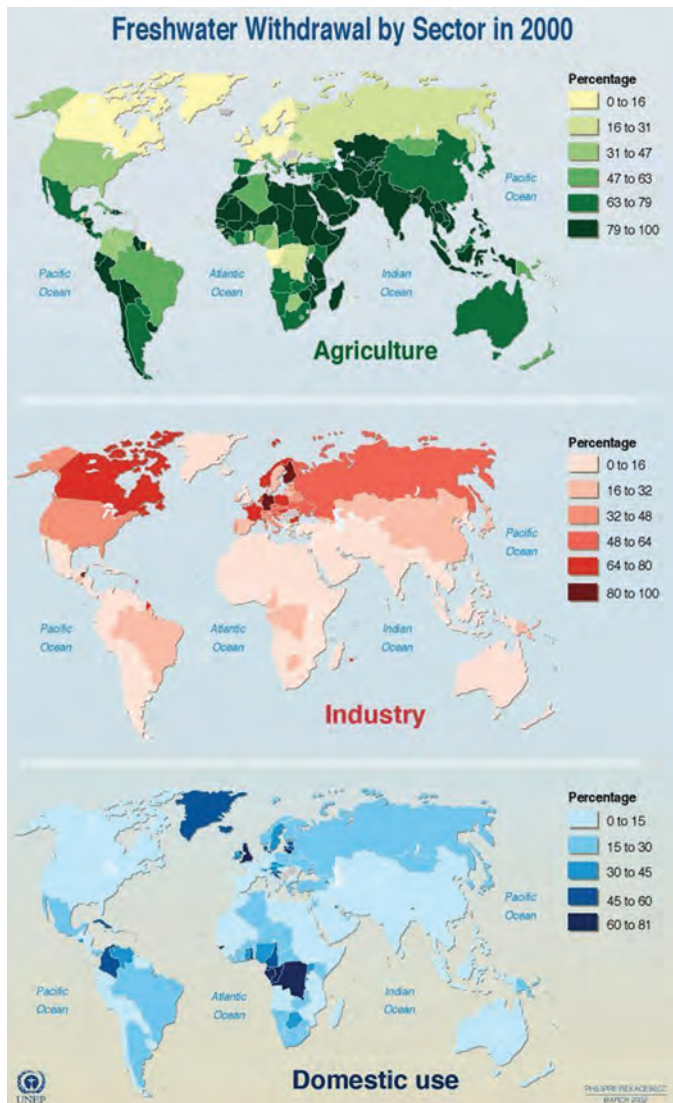
### 20.3.3 Water Use in Agriculture

Agriculture accounts for more than 70% of the world’s total water use. Its share drops in countries that import food and have a developed and diverse economy, but rises in some countries where agriculture is the primary economic activity (see Figure 20.14). Countries with water scarcity can be said to “import” virtual water when they import crops that have high water requirements.

Production of biomass for energy purposes can, in some cases, expand into areas where conventional food production is not feasible due to water constraints. This is the case with jatropha and sweet sorghum in India, where about 13 million hectares of “wasteland” are being earmarked for cultivation (FAO, 2008c).

Hydropower may offer positive environmental impacts related to water: about 75% of water reservoirs in the world were built for irrigation, flood control, and urban water supply schemes. Many could have small hydropower generation retrofits added without additional





**Figure 20.14** | Global freshwater withdrawal: agricultural, industrial and domestic use. Source: UNEP/GRID-Arendal, 2002.

environmental impacts. The many benefits of hydroelectricity, including irrigation and water supply resource creation, rapid response to grid demand fluctuations due to peaks or intermittent renewables, recreational lakes, and flood control, as well as the negative aspects, need to be evaluated for any given development. About 18% of the world's croplands now receive supplementary water through irrigation. Expanding this area (where water reserves allow), or using more effective irrigation measures, can enhance carbon storage in soils through enhanced yields and residue returns. However, some of these gains may be offset by CO<sub>2</sub> from energy used to deliver the water (Bates et al, 2008).

Irrigated agriculture provides a direct source of income generation and secure livelihoods for hundreds of millions of the rural poor in developing countries because of the food, income options and indirect benefits it generates. However, widespread irrigation practices may result in

pronounced water scarcity. The growth of modern "conventional" irrigation since 1900 has been characterized by large water projects that harnessed rivers through the construction of diversion structures and canal systems. Since 1950, the spread of such technology has accelerated through state-sponsored, large-scale irrigation schemes, including large dams for water storage and regulation (sometimes including hydropower generation). Irrigated areas increased from 40 million hectares in 1900 to 100 million hectares by 1950 and to 271 million by 1998. Water from dams supports 30–40% of this area, with the remainder supplied by direct river abstraction, groundwater and traditional water harvesting systems.

In some areas, improved conditions for increased agricultural yields and better economic growth have resulted from subsidized infrastructure (less than full cost recovery), better agricultural practices, and increased access to electricity for pumping. Irrigated agriculture has contributed to growth in agricultural production worldwide, although inefficient use of water, inadequate maintenance of physical systems, and institutional and other problems have often led to poor performance and return. Emphasis on large-scale irrigation schemes facilitated consolidation of land and brought prosperity for farmers with access to irrigation facilities and economic markets. There are major multiplier effects produced by successful large irrigation schemes. However, economic support to rain-fed agriculture has been limited, even though such systems supported more than 80% of farmers in developing countries, particularly in Africa. As a result, there has been a widening income gap between farmers in irrigated and rain-fed areas. Even within large-scale irrigation systems, there are inequities that lead to the marginalization of smallholders. The regional economic and development context for agriculture differs notably between industrial and developing countries. In the former, agriculture tends to be capital-intensive, with large, highly mechanized holdings requiring minimal labor. In contrast, agriculture in developing countries, particularly in Africa, supports hundreds of millions of smallholder cultivators who depend on the land for subsistence, livelihoods, and food security. These farmers generally do not have access to support mechanisms or economic resources to risk growing high-value crops in volatile market conditions. The low productivity of land and labor of many subsistence cultivators is also symptomatic of the absence of support and widespread neglect of their agriculture and irrigation systems. The extent of irrigated area in Africa is currently high on the political agenda for some countries. With less than one-third of the continent's potential under irrigation, opportunities exist for investing further in water for agriculture. This depends on access to land as well as water, and possibilities of compensating for the high rate of evapotranspiration (WCD, 2000).

Markets, commodity selection, ownership, land tenure, water storage for reliable supply, and international agreements on water allocations within river basins are all key factors in unlocking this potential. Many see the importance of reducing the food import bill borne by some African countries. Many also see the potential for boosting household incomes by creating labor opportunities. However, others recognize that, even in an optimistic scenario in which every hectare created two new



jobs, the significant uplifting of 60 million households would be insufficient to make major inroads into the extreme poverty that pervades the continent. A dual approach is gaining ground, one in which improvements in rain-fed food production for the very many vulnerable African farmers take place alongside the pursuit of viable irrigation opportunities (UN-Water/FAO, 2007).

Increasing water's productivity is an effective means of intensifying agricultural production and reducing environmental degradation. However, water productivity (efficiency) gains may be difficult to realize, and there are misperceptions about the actual scope for increasing physical water productivity. Much of the potential gain in physical water productivity has already been met in high-productivity regions. In addition, the amount of waste in irrigation is less than commonly perceived, especially because of reuse of water locally or downstream – farmers thirsty for water do not let it flow easily down the drain. Meanwhile, major gains and breakthroughs in agriculture that would reduce water requirements, such as those in the past from breeding and biotechnology, are much less likely to continue occurring at the same rate. Finally, a water productivity gain by one user may cause a loss or other damage to another user – an upstream gain may be offset by a loss in fisheries, or the gain may put more agrochemicals into the environment. Increasing economic water productivity would allow users to get more value per unit of water, either through switching to higher-value agricultural uses or by reducing the costs of production. Integrated approaches are important for increasing the value of water, and the number of jobs per drop (e.g., by better integrating crops and livestock in irrigated and rain-fed systems, or using irrigation water for household uses and small industries as well as agriculture). Higher physical water productivity and economic water productivity reduce poverty in two ways. First, targeted interventions enable poor people or marginal producers to gain access to water or to use water more productively for nutrition and income generation. Second, the multiplier effects on food security, employment, and incomes can benefit poor people. To reduce hunger and poverty, such programs must, however, ensure that the gains reach poor people, especially poor rural women, and are not captured by wealthier or more powerful users (IWMI, 2007a).

### 20.3.4 Water for Industry

Industry is also a water-demanding sector. Industrial use of water increases with country income, going from 10% of a country's total water use for low- and middle-income countries to 59% for high-income countries, where higher industrialization rates raise demand for water even though many processes are in themselves becoming less water-demanding. World water withdrawals for industry represent 22% of total water use. Pollution of freshwater supplies by industry is also a factor to consider in water management practices and policies. This is the case of both organic pollution (including from the food industry) and the inorganic one (e.g., chemicals, metal processing, and others). In developing countries, 70% of industrial wastes are dumped untreated into

waters, where they pollute the usable water supply. The current use of clean water for the dilution and transport of wastes is not sustainable. However, the total rate of water withdrawn (and returned) by industry worldwide is slowing, although water consumption for industry is still increasing. Aquatic ecosystems and species are deteriorating rapidly in many areas, and this is having an immediate impact on the livelihoods of some of the world's most vulnerable human communities by reducing protein sources for food, availability of clean water, and potential for income generation (UNESCO, 2003; 2009).

### 20.3.5 Energy Production, Biofuels and Water Use

Energy sources utilize water in different ways: for cooling towers in thermoelectric plants, for reservoirs in hydroelectricity production, and for irrigated biofuel crops. Despite the limited literature, an effort to assess the impacts of energy technologies on water resources from a life cycle perspective was conducted by the recent *IPCC Special Report on Renewable Energy* (Sathaye et al., 2011). Thermal power plants, hydropower and bioenergy are vulnerable to water scarcity, exhibiting risks of increased competition. Operational water consumption for different technologies in the US electricity sector is summarized in Figure 20.15.

Problems with cooling water availability (because of reduced quantity or higher water temperature) could disrupt energy supplies by adversely affecting electricity generation in thermal and nuclear power plants (Bates et al., 2008). Figures 20.16 and 20.17 compare water withdrawal across fuel cycles of electricity-generation options based on US data, except for the wind cycle, which uses information from Denmark. For thermoelectric fuel cycles, the life-cycle water withdrawal ties closely to the operational cooling type: on-site cooling water use dominates the life-cycle water withdrawal, while the dry cooling method, more expensive and energy-intensive, is an exception to the overall rule.

As conventional oil supplies become scarce and extraction costs increase, production of unconventional oil will become more economically attractive (although with higher water use and environmental costs). Mining and upgrading of oil shale and oil sands require the availability of abundant water. Technologies for recovering tar sands include open cast (surface) mining, where the deposits are shallow enough, or injection of steam into wells in situ to reduce the viscosity of the oil prior to extraction. The mining process uses about four liters of water to produce one liter of oil but produces a refinable product. Mining of oil sands leaves behind large quantities of pollutants and areas of disturbed land (Bates et al., 2008).

Most renewable energy technologies require little or no water for cooling. However, hydropower plants use water directly to generate power, diverting water from rivers through turbines, via an intake at the dam. In some cases, water is diverted outside the stream for up to several

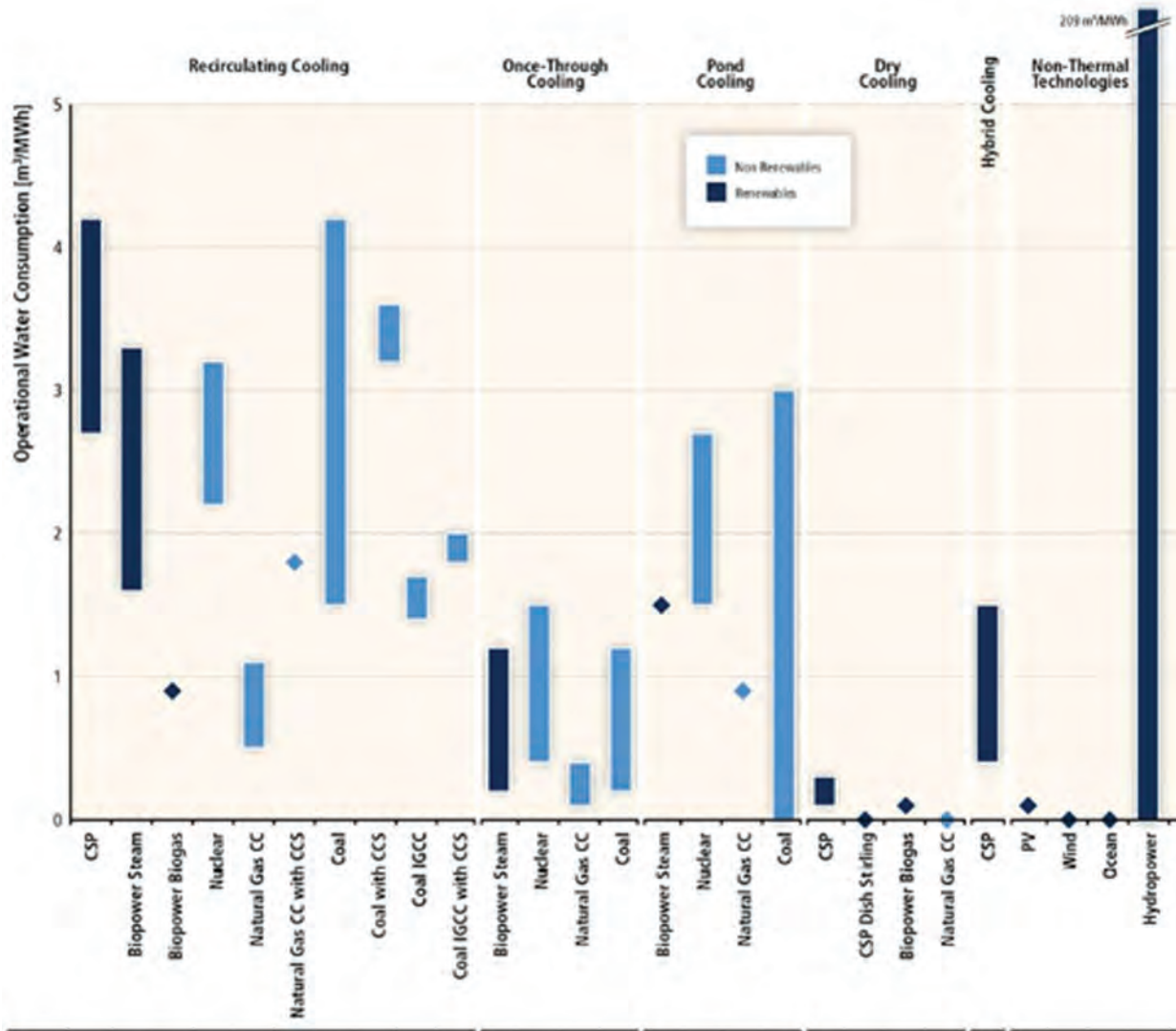


Figure 20.15 | Rates of operational water consumption by thermal and non-thermal electricity-generating technologies in the US (m³/MWh). Source: Sathaye et al., 2011.

Bars represent absolute ranges from available literature, diamonds single estimates; n represents the number of estimates reported in the sources. Upper values for hydropower result from few studies measuring gross evaporation values, and may not be representative. Notes: CSP: concentrating solar power; CCS: carbon capture and storage; IGCC: integrated gasification combined cycle; CC: combined cycle; PV: photovoltaic.

miles before being returned. Human intervention – through interbasin transfers, dams, and water withdrawals for irrigation – has fragmented 60% of the world’s rivers. Since 98% of the water used in hydropower plants is returned to its source, distinctions are made between use (when water is ultimately discharged back into the original water body, although in some cases with chemical or physical alteration) and consumption (where water is lost, typically through evaporation).

The use of water to generate power at hydropower facilities imposes unique, and by no means insignificant, ecological impacts, including:

- impacts on terrestrial ecosystems and biodiversity;
- associated GHG emissions;
- altered downstream flows affecting aquatic ecosystems and biodiversity;
- altered natural flood cycles affecting downstream floodplains;
- impacts of dams on fisheries in the upstream, reservoir and downstream areas;
- enhancement of ecosystems through reservoir creation and other means; and

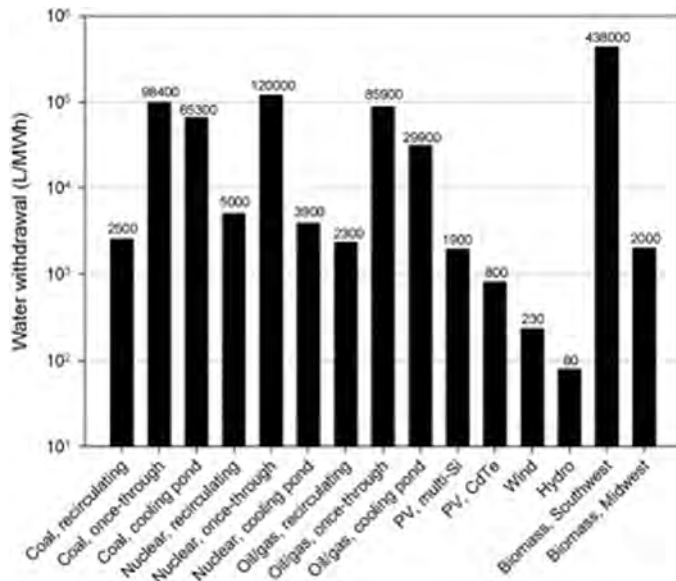


Figure 20.16 | Comparison of water withdrawal across fuel cycles, using US data, except for a Danish case for wind cycle. Source: Fthenakis and Kim, 2010.

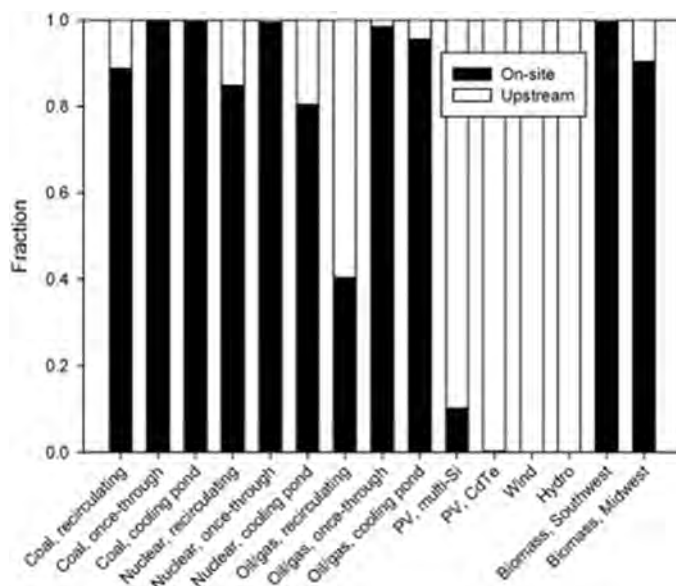


Figure 20.17 | Breakdown of water withdrawals based on the water-use stage. Source: Fthenakis and Kim, 2010.

- cumulative impacts of a series of dams on a river system (WCD, 2000).<sup>12</sup>

Solutions to these problems lie both in more environmentally friendly energy resources, and in more efficient energy end uses (Power Scorecard, 2000). Although there are large regional differences in the extent of hydropower development, hydrological changes will directly

affect the potential output of hydroelectric facilities – both those currently existing and possible future projects. A reduction in hydroelectric power is anticipated where and when river flows are expected to decline (Bates et al., 2008).

Geothermal fields of natural steam are rare; most produce a mixture of steam and hot water, requiring systems to separate out the hot water. Sustainability concerns relating to land subsidence, heat extraction rates exceeding natural replenishment, chemical pollution of waterways (e.g., with arsenic), and associated CO<sub>2</sub> emissions have resulted in some geothermal power plant permits being declined. These problems could be partly overcome by re-injection techniques and deeper drilling technology. However, expanding geothermal exploration means in the end a claim on available water resources (Bates et al., 2008).

Although bioenergy can produce climate change mitigation benefits by replacing fossil fuel use, large-scale agricultural production of biofuels could, in some cases, intensify water use, thereby reducing stream flow or groundwater reserves.

High-productivity, evergreen, deep-rooted bioenergy plantations generally have a higher water use than the land cover they replace. Some practices may also affect water quality through enhanced leaching of pesticides and nutrients. Land management practices implemented for climate change mitigation may also have different impacts on water resources.

Many of the practices advocated for soil carbon conservation – reduced tillage, more vegetative cover, greater use of perennial crops – also prevent erosion, yielding possible benefits for improved water and air quality. These practices may also have other potential adverse effects, at least in some regions or conditions. Possible effects include enhanced contamination of groundwater with nutrients or pesticides via leaching when reduced tillage practices are used. However, these possible negative effects have not been widely confirmed or quantified, and the extent to which they may offset the environmental benefits of carbon sequestration is uncertain. The group of practices known as agriculture intensification has environmental benefits that include erosion control, water conservation, improved water quality, and reduced siltation of reservoirs and waterways (Bates et al., 2008).

Total water demand for bioenergy production (prospective of about 150 EJ/year) from plantations in 2050 ranges between 4000–12,000 km<sup>3</sup>/year, depending on how much energy can be derived per unit of transpired water. Even if reduction of losses and improvements in agricultural and water productivity are accounted for, meeting the future food demand will most likely require the addition of new cropland (–20–45% of real expansion from today’s 1.5 billion ha, depending on the degree of improvements in land area productivity). The annual cropland expansion needed is estimated to be 0.48% on average between 2010–2045 (IWMI, 2007b). While the benefits of bioenergy range from

12 The European Water Framework Directive utilizes a similar classification of impacts (European Commission Environment, 2011).

reduced GHG emissions to renewability and energy independence, increased biofuel production can lead to trade-offs across other ecosystem services if not well addressed, including those derived from water. Besides decreased food supply, other trade-offs include poor water quality associated with increases in aggregate fertilizer use, nutrient runoff, and erosion (Bennett, 2008). The growing of crops for biofuel in semi-arid areas on marginal or degraded lands may require some irrigation, particularly during hot and dry seasons. Further, the processing of feedstocks into biofuels can use large quantities of water, mainly for washing plants and seeds and for cooling.

Globally, irrigation is not likely to be a major water source for biofuel production, although locally there can be water constraints in some areas where food and other non-food crops compete for the scarce available resources. In some cases, irrigated production of biofuel feedstocks has a considerable impact on local water resource balances: 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 regions on the basis of water resources and land, water quality as well as quantity may be affected. 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 use of fertilizer (FAO, 2008c).

Table 20.8 summarizes the main energy and food crops in the world today. With adequate land use management, there are enough rain-fed areas for these crops to coexist. Sugarcane ethanol is a special case, due to its significant potential to provide energy throughout large parts of the world utilizing rain-fed land (see Figure 20.18). Water use for industrial sugarcane ethanol production has improved from 5 to 1.9 m<sup>3</sup>/t of cane (1 tonne of cane crushed produces 80–100 liters of ethanol) in the period 1997–2004. Vinasse, the distillery water sludge, is used as a fertilizer, returning part of the water used back to the soil (Elia Neto, 2005).

In terms of water use, studies in other parts of the world have shown that production of energy crops for biofuel production can have substantial impacts on water demand, especially if irrigation is used for their production (Jumbe et al., 2007). The bulk of sub-Saharan Africa's agricultural production occurs under rain-fed conditions, posing substantial risks to farmers and investors because of erratic rainfall patterns and temporal and spatial variability.

Frequent short dry spells during the growing season reduce yields and, in addition, have an indirect impact, as farmers are less likely to invest in inputs and land management. Biofuel production could be affected by these existing conditions, as unreliable rainfall and highly variable yields would also pose challenges for biofuel feedstock production.

On the other hand, new market opportunities through bioenergy production may trigger additional investments in water for agriculture to

raise yields and reduce these fluctuations. The water situation in sub-Saharan Africa is also affected by the transboundary nature of most river basins, which flow through several countries. The negotiation and enforcement of water rights and international water treaties is a difficult process requiring a strong institutional infrastructure. Feedstock production requires substantial amounts of water; to produce the biomass for one liter of biofuel, crops evaporate an average 2500–3500 liters of water. Much of this water can be obtained from rainfall, where rainfall is abundant and reliable.

Compared to other regions in the world, the level of water resources development for irrigation in sub-Saharan Africa is low. Only 4% of agricultural production originates from irrigated areas, and only one-sixth of the irrigation potential in sub-Saharan Africa has been realized. In many areas of this region, water scarcity for crop production is caused by the lack of infrastructure to tap into water resources rather than an actual physical shortage (IWMI, 2007b). Development costs for irrigation are high, averaging US\$6000/ha in sub-Saharan Africa compared to US\$1500/ha in South Asia. It is unlikely that farmers and governments will be able to afford large investments in irrigation for biofuel feedstock, unless significant returns are obtained. Water use by other feedstock crops needs to be studied more systematically across the agro-climatic zones, especially when such crops are to be established in large-scale plantations (Benkunda et al., 2009).

### 20.3.6 Water Security

Although concepts of food security, energy security and access to natural resources have been widely discussed, it is only recently that the relationship between the environment and water security is becoming more widely acknowledged, mainly due to its political dimensions. It was on the agenda in the process leading up to the UN Conference on Environment and Development, held in Rio de Janeiro, Brazil, in 1992, and is reflected in the Rio Principles. Sharing water resources is an issue that particularly reflects a link between environmental degradation and resource competition resulting in conflicts. Freshwater scarcity is not just a direct cause of insecurity; it is also an indirect security threat, through its potential for causing conflicts.

A key spark for water-related tensions is a mismatch between population levels and the freshwater available for different purposes. This can produce water conflicts at a local level, such as between tribes over grazing rights or the property rights over wells, as has happened in Ethiopia. Tensions can also arise due to construction of a dam or canal which impacts water availability for riparian states, as was experienced during the 1990s by Turkey, Syria and Iraq over Turkey's Greater Anatolia Project on the Euphrates-Tigris River Basin (Coskun, 2007).

Global conflicts over water threaten geopolitical stability. An example is the Baglihar 450 MW dam, near the politically fragile Pakistan-India border along Kashmir's Chenab River. The plant will supply hydroelectric

Table 20.8 | Crops and their requirements.

Crop type	Soil requirements	Water requirements	Nutrient Requirements	Efficiency	Climate	Others
Cereals (wheat, rye, barley, oat, triticale)	less disruptive; very constant yield; straw removal affects humus balance; wheat in a wide range of soils but medium textures	wheat is the cereal with the highest water demand (450–650 mm depending on climate and length of growing period)	medium; wheat has higher fertilizer demand but good uptake	wheat on good soils and rye on poor soils for food; triticale for energy purposes	wheat: moderate climate, tropics away from the equator (winter crop)	highly developed crops; knowledge widespread among farmers
Jatropha	undemanding	both irrigated and rain-fed, wide range (200–1200 mm/yr)	adapted to low-fertility sites and alkaline soils; better yields with fertilizers	grows on marginal land, restores eroded areas, improves soil	tropical and subtropical	very resistant against pests and pathogens; toxic seeds after oil extraction
Maize	low requirements (soils well aerated and well drained); susceptible to water logging.	water demanding (500–800 mm/yr)	fertility demands for grain maize are relatively high	high water efficiency, but often irrigated (water deficits cause losses)	from temperate to tropic, mean daily temperatures above 15°C and frost-free	increased erosion risk; monoculture negative on humus balance (requires crop rotation); high pesticide use
Miscanthus (woody, perennial grass)	good water supply, not saturated brown soils with humus	crucial during main growing seasons	relatively low	high growth rates, cheap	warmer climates, fairly cold-tolerant	risk of invasive species; difficult to rehabilitate land for other uses due to deep root structure
Oil Palm	many soil types (flat, rich, deep), good drainage (tolerate floods)	demanding in excess of 2000mm, even distributed throughout the year	relatively low	highest-yielding vegetable oil crop per hectare in the world	tropical and subtropical; humid 5h/day minimum sunlight; temperature 22–32°C, basically low altitude (< 400m)	fire for land clearing, tropical forest conversion with loss of biodiversity and conflicts of land ownership with local communities, pollution by improper use of agrochemicals (little control), oil mill effluent dumping, soil erosion from land clearing
Poplar	deep, moist (highly flood tolerant)	high; irrigation might be needed	high, with good uptake	high establishing costs, not easily propagated from cuttings; short rotation crop (fast growing tree)	arctic to temperate	resistant to pests and diseases
Potato	deep, moist, well-drained and friable	500–700 mm, depending on climate; irrigation required for climatic negative balances	relatively high (under moderate demand there are late growth and soil erosion risks)	very productive	18–20°C mean; sensitive to changes; cool crop but grows well in warm conditions if water is sufficient	rotation crop (with maize, beans and alfalfa); pesticide-intensive
Rapeseed	mild, deep loamy, well-drained	600 mm/yr minimum	similar to wheat	rotation crop, poor productivity but most grown energy crop in Europe (well-known to farmers and policy supported)	very temperature-sensitive, best 15–20°C.	very intensive culture; high input of pesticides and herbicides
Rice	not demanding (permeable layer and good drainage)	very high, flooded fields	high input of fertilizers	very labor-intensive, different farming systems (rain-fed lowland, upland or dry land, irrigated, deepwater or flood-prone)	high, constant temperatures (13°C–40°C; optimum around 30°C).	high level of landscape alteration for surface infrastructure needed to move water about; anaerobic conditions in underlying soils; has unique impacts on carbon and nutrient cycling

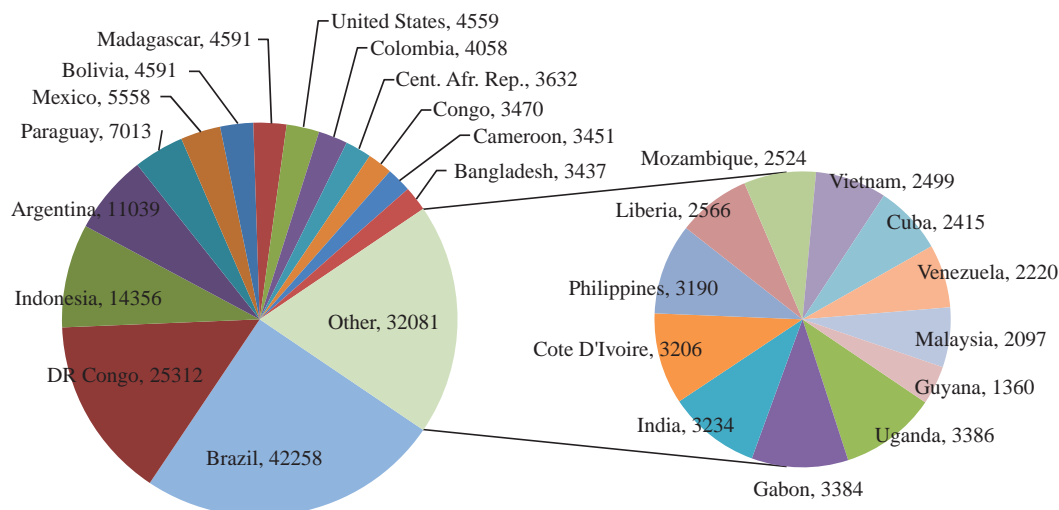


Table 20.8 | (contd.)

Crop type	Soil requirements	Water requirements	Nutrient Requirements	Efficiency	Climate	Others
Sorghum	Deep, medium-textured, well-aerated and well-drained soils; tolerant to short periods of waterlogging, moderately tolerant to soil salinity	drought-resistant; high water supply flexibility (water holding capacity of soil very important, needs progressively less water as roots reach deeper)	high in nitrogen, low in phosphorus and potassium requirements	tropical origin, adapted to southern Europe with irrigation, high yields (less than maize), machinery can be used	over 25°C; some varieties adapted to lower temperatures; needs a lot of sunlight	numerous diseases; not competitive at the beginning
Soybean	wide range of soils, optimum growth in moist alluvial with a good organic content; best on high water capacity, good structure, loose soil	relatively high (450–700 mm/ season)	atmospheric nitrogen-fixing crop		warm conditions in tropics, subtropics and temperate climates; relatively resistant to low and very high temperatures	increased risk of erosion compared to corn
Sugar beet	wide range of soils with medium- to slightly heavy- textured, well-drained preferred; tolerant to salinity	550–750 mm/growing period; tolerant to water deficits	high demand		different climates, high sugar yields with night temperatures 15–20°C and day temperatures 20–25°C during the latter part of growing period	heavy machinery and harvested mass lead to soil compaction; can provide nesting habitat and shelter in autumn; soil erosion risks; various pesticide treatments to eliminate weeds
Sugarcane	deep soils, well-aerated, groundwater table more than 1.5 to 2.0 m below the surface	1500–1800 mm/yr, high water requirement, evenly distributed through the growing season	high nitrogen and potassium needs, low phosphate requirements; at maturity nitrogen content of soil must be as low as possible for a good sugar recovery	very high efficiency in conversion of solar energy into biomass	tropical or subtropical climate; germination 32–38°C; active growth at 20°C; for ripening lower temperatures are desirable for enrichment of sucrose	pest management very important
Sunflower	wide range of soils, deep with good water holding capacity; row crop, leaves bare soil until late spring	600–1000 mm, depending on climate and length of total growing period; water-efficient crop but often irrigated as better growth	moderate demand; good fertilizer uptake	intermediate crop for maize plantations	from arid under irrigation to temperate under rain-fed conditions; susceptible to frost; needs full sun	various pesticide treatments to combat pests
Switch grass	diverse growing conditions, from prairies to arid or marsh; conserve soil and improve its quality	tolerant to floods or drought; irrigation only necessary in very hot or very dry climates; because of deep roots, groundwater abstraction is possible	little nutrient requirements	machinery can be used; high yields in marginal or erosive land	warm season plant, good resistance to dry summer months	very little pesticide use
Willow	permanent crop, good soil cover, deep rooting and leafy canopy reduces soil erosion and prevents saturation of the land during heavy rainfall; can grow on land that is too wet for other crops	substantial quantities of water (600 mm rainfall), suffers reduced growth in dry conditions or dry years	significant nutrient uptake but good uptake also	short rotation coppice; easy and relatively inexpensive to plant	can tolerate very low temperatures in winter, but frost in late spring or early autumn will damage the top shoots	level of pest and pathogen unacceptable for food crops can be accepted here; already used in commercial or near-commercial applications; can take up heavy metals (phytoremediation); weed competition is critical; riparian buffer strips; depletion of soil nutrients from frequent and repeated harvesting; rust is an important disease; very competitive, hence no or little pesticides applications necessary

Source: UNEP, 2007; UN-Energy, 2007.





**Figure 20.18** | Very suitable and suitable potential land area for sugarcane crops in major 26 countries producers, considering high-, medium- and low-input efforts, with forest area excluded, by country (units in thousand hectares). Total area in these 26 countries is 169 million hectares. Total area in all producers is 191 million hectares, equivalent to 1.46% of all land area. Source: based on data from FAO, 2009a.

power to northern India, but as the dam reaches full capacity, Pakistan is seeking compensation for what it views as a “gross violation” of an international treaty as a result of “stolen” water (Pope, 2008). Around 40% of the world’s population lives in watersheds shared between nations, with more than 260 shared river basins of social and economic importance.

Basins with potential for political stresses in the coming years include: the Ganges-Brahmaputra, Han, Incomati, Kunene, Kura-Araks, Lake Chad, La Plata, Lempa, Limpopo, Mekong, Ob (Ertis), Okavango, Orange, Salween, Senegal, Tumen, and Zambezi (Wolf et al., 2003). There are complex linkages among energy, water, agriculture, and environmental degradation issues. Also linked are water-related matters affecting humanitarianism, human health, poverty reduction, economic development, environmental protection and conservation, stability, and geopolitical security. Management of water resources can be a catalyst for cross-border cooperation or a trigger for socioeconomic instability. An instrument establishing agreements over a shared water source among different stakeholders is thus an important, anticipatory structure (Peterson and Pozner, 2008).

The FAO (2008c) outlines some conditions to ensure institutional development to promote water security, as follows:

- Set conditions for more flexible and responsive service-oriented water management.
- Develop tools for water-related conflict resolution and prevention at local and district levels.
- Develop and implement economic and financial trade instruments to remove distortions in water allocation.

- Document and quantify current patterns of water use and water entitlements.
- Develop transparent water allocation mechanisms to protect water use rights while providing greater flexibility to respond to scarcity under anticipated patterns of climate change.
- Develop innovative insurance products.

Further suggestions involve better integration of water resources management, agriculture and food security databases, with much closer monitoring of irrigated and rain-fed production and clearer distinctions between the sources of supply (rainfall, surface water, and groundwater). This effort should consider specific food staples, notably rice and wheat, as well as the productivity of water-dependent aquatic environments (FAO, 2008c).

When using a wider definition of water security, such as the one used by the United Nations Educational, Scientific and Cultural Organization (UNESCO) and several other UN agencies within UN-Water, a broader approach needs to be applied to ensure this: “Water security involves protection of vulnerable water systems, protection against water related hazards such as floods and droughts, sustainable development of water resources and safeguarding access to water functions and services.”

## 20.4 Sustainability Factors

### 20.4.1 Sustainable development: policies and measures

The concept of sustainable development – a significant one – aims to reconcile environmental, economic and social goals, which became more

important after the World Commission on Environment and Development (1987). It recognizes the multiple challenges resulting from a declining quality of the environment, increasing resource needs of mankind, and the need to reduce malnourishment, poor hygiene, insufficient water supply and other problems related to extreme poverty, without destruction of the natural resources that are the basis for life.

The influential report *Our Common Future* (the “Brundtland Report”) defined sustainable development as that which “meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987), i.e., as a universal, intra- and intergenerational human rights concept.

The 1992 United Nations Conference on Environment and Development (UNCED or Rio 92) in Rio de Janeiro, Brazil, was a major milestone in the international discussion on sustainable development. At the conference, the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity and Agenda 21 were proposed, and the two treaties were also opened for signatures. It was also decided to initiate negotiation of what became the UN Convention to Combat Desertification. The Climate Conference at Kyoto, Japan, in 1997 resulted in the Kyoto Protocol, a multilateral environmental agreement to curb GHG emissions worldwide. By 2000, the MDGs aimed at reducing global poverty and eliminating social exclusion by 2015. Two years later, energy (both energy efficiency and renewable energy) became a central point at the World Summit on Sustainable Development (WSSD or Rio+10) in Johannesburg.

A fairer and cleaner energy future includes the need to reduce negative social and environmental impacts. Sustainable energy also includes the goal to establish security of supply, which means both guaranteeing access in the short term and preserving resources for the long term. These concepts are closely related to geopolitics, trade liberalization and protectionism, land and water usage, and, not rarely, to military concerns.

Most policies that aim at a more sustainable energy supply rest upon four main pillars (although some of them may be more or less emphasized): more efficient use of energy, especially at the point of end use; increased utilization of renewable energy as a substitute for non-renewable energy resources; accelerated development and deployment of new energy technologies – particularly next-generation fossil fuel technologies that produce near-zero harmful emissions and open up opportunities for CO<sub>2</sub> sequestration; and biosequestration of carbon in terrestrial ecosystems, including soils and biota (see Box 20.4).

Achieving energy equity is another important task, providing access to modern energy to the 2 billion people that still live with only traditional solid fuels (Johansson and Turkenburg, 2004).

Sustainable development is thus a basic principle to be pursued in key policy areas directly or indirectly related to energy: technology research, development and transfer; information exchange; capacity-building;

adequate financing; ambitious environmental protection goals; removal of harmful subsidies; and shifting away from business-as-usual patterns of production and consumption.

#### 20.4.2 Sustainable Water Use

This chapter focuses on the following aspects of sustainable water use:

- environmental issues resulting from erosion; excess use of fertilizers and agrochemicals; inadequate management of water resources; inadequate wastewater treatment and disposal; and the need for increased biodiversity protection, solid and hazardous wastes management, and protection against contamination of soils;
- resource base maintenance (freshwater protection, allocation, and sustainable use);
- social concerns (including issues related to employment and access to water, particularly for women and vulnerable groups); and
- economic issues (including weighing present versus future uses).

Table 20.9 summarizes impacts from energy on water systems.

The consumptive use of water (i.e., evapotranspiration) in energy crop production changes according to different bioenergy systems. A large variation in evapotranspiration is attributed to: varying water productivity among energy crops, related to crop type, soil, and climate, and agronomic practice, including water productivity modification options such as changing sowing date and plant density, supplemental irrigation, and microclimate manipulation; variations in the share of the aboveground biomass that is usable as feedstock in electricity/fuels production; and different conversion efficiencies of technology options available for electricity/fuels production.

Irrigation is assumed to be around 15% of the energy crop’s water use calculated. If the average efficiency in irrigation water supply is 50%, then about 1175–3525 km<sup>3</sup> of additional water would have to be withdrawn in 2050. Compared to the present withdrawal for irrigation, estimated at roughly 2600 km<sup>3</sup>/yr, clearly such additional blue water demand for energy crop irrigation implies tough challenges. Rain-fed energy crop production could potentially lead to similar impacts, by redirecting runoff water to evapotranspiration and thereby affecting downstream blue water availability and quality. Establishment of bioenergy plantations can also lead to increased evapotranspiration, especially if tree crops replace shallow-rooted grasses, herbs, or food crops. It is not possible to make general statements about the impact in terms of water depletion of expanding energy crop production, since the net change of evapotranspiration is uncertain and depends on site-specific circumstances, including the current land use that it aims to replace (Box 20.3; Figure 20.19) (Lundqvist et al., 2007).

**Table 20.9** | Positive (+) and negative (-) impacts of energy on water (Lucon, 2010, own elaboration). Water indicative footprints (WF) of different energy sources (from Gerbens et al., 2008 and 2009).

Energy Source	Bioenergy	Solar	Geothermal Energy	Hydro Power	Marine Energy	Wind	Oil	Gas	Coal	Nuclear
Water usage and/or pollution	WF 24–143m <sup>3</sup> /GJ. Potentially high water demand, especially in irrigated crops. Specific water stress for cooling towers (-).	WF 0.3m <sup>3</sup> /GJ for solar thermal panels. Some toxic wastes from PV. Specific water stress for concentrated solar plant cooling towers. (-)	WF n.a. Risks of water contamination. Specific water stress for plant cooling towers.	WF 22 m <sup>3</sup> /GJ according to source, but extremely variable. High impacts in water bodies and regimes (-/+)	WF n.a.	WF ~0.0 m <sup>3</sup> /GJ.	WF 1.1 m <sup>3</sup> /GJ. Risks of severe, large scale water contamination (-)	WF 0.1 m <sup>3</sup> /GJ. Specific water stress for plant cooling towers.	WF 0.2 m <sup>3</sup> /GJ. Risks of water contamination, leaching and acid rain effects. Specific water stress for plant cooling towers. (-)	WF 0.1 m <sup>3</sup> /GJ. But potential highly toxic contamination in case of nuclear accidents, weapon proliferation tests etc. Specific water stress for plant cooling towers. (-)

Source: Gerbens-Leenes et al., 2009.

### Box 20.3 | Water Pressures and Increases in Food and Bioenergy Demand. Implications of Economic Growth and Options for Decoupling

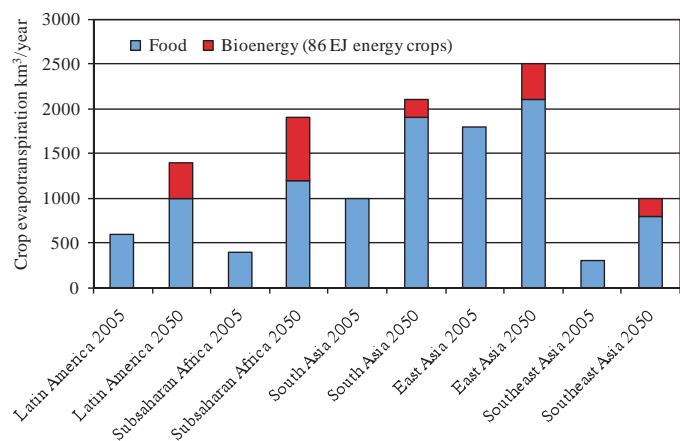
Long-term models out to 2045, as developed by Lundqvist et al. (2007), present scenarios on potential water demand, given that diets may change substantially as countries attain a higher income, and that the use of bioenergy is likely to increase. With current global levels of productivity and efficiency, the consumptive use of water to cater for growth in food demand is estimated to increase by some 50% in the period 2000–2045, from about 7000 km<sup>3</sup>/yr to about 10,600 km<sup>3</sup>/yr. Estimating the water requirements for the production of energy crops is more difficult, but crop expansion is a reasonable measure to adopt. Higher demands for food, energy and other goods and services are inevitable, but it is possible to achieve a decoupling effect, i.e., more income without a corresponding increase in the pressure on resources. While water productivity improvements on the order of 25% are considered feasible and realistic, reductions in losses and wastage in the food chain can be halved from the present 30%.

By adopting these decoupling measures, it is possible and desirable to meet expected future food requirements in 2045 with about the same water requirement as in 2005. In the search for decoupling opportunities between GDP growth and pressure on water and land resources, it is logical to pay attention to both production and consumption dynamics. Consumption is a critical driver, considering increasing purchasing power, preferences, and behavior. There are major challenges in balancing finite freshwater resources, including competition for different uses in the near future, and the need to stimulate improvements in efficiency. Improvements in yields and water productivity, as well as expanding the agricultural area, cannot by themselves solve the problem. Blue water sources (rivers, lakes, and groundwater) will not be enough to meet the increasing demands for food and biofuel. Recommended strategies include: better utilization of a larger fraction of the rainfall (i.e., a green water strategy); improved yields and water productivity, as well as expanding the agricultural area; and reduced consumption through changes in consumer preferences and behavior, and by achieving a more efficient food chain, primarily in terms of reduced losses and wastage “from field to table.” These changes will require planning and systematic implementation over decades.

Source: Lundqvist et al., 2007.

Water use for the growth of bioenergy crops may cause environmental and social problems. Global water demand has been growing by 10% per decade, adding to water stress in many regions. Agriculture accounted in 2008 for close to 70% of all freshwater use (UNEP, 2009), of which 2% was used for bioethanol production (WBGU, 2008).

Bioenergy production may need 70–400 times as much water per unit of energy as other primary energy carriers, excluding hydropower, and ranges from 24–143 m<sup>3</sup>/GJ (Gerbens-Leenes et al., 2009). The amount of water per unit of energy is highly dependent on the crops used, the efficiency of the cropping system, and the local hydrological and soil



**Figure 20.19** | Estimated water requirements for food today and hypothetical water requirements for food and bioenergy around year 2050 with lignocellulosic crops, plant breeding and improved agronomic practices, assuming in the model that lignocellulosic crops will mainly be used for with average water use efficiency of 2.5 kg biomass per m<sup>3</sup> of evapotranspiration. Source: adapted from SIWI, 2008.

conditions. Bioenergy crop plantations in marginal areas may, however, alleviate or reduce other water-related problems such as water-related erosion (Berndes, 2008).

Beyond matching supply and demand for human uses, it has become clear that management approaches need to consider also the ecological water demand and the spatial and temporal variability of supply and demand (EC and IPTS, undated).

### 20.4.3 Land-related sustainability issues

Energy provision almost always requires land area, at least for infrastructure, except perhaps for energy derived from the ocean (e.g., wave energy). Table 20.10 compiles indicative estimates of the area required for a yearly energy flow of one PJ for different primary energy sources. It shows that the land area required for fossil fuels and nuclear power is small compared to that needed for some renewable energies, particularly bioenergy and hydropower. In most cases, land is needed more or less exclusively to host the infrastructure needed; in the case of coal additional area is required for open-cast mining.

Land areas required for hydropower plants are often small, especially for run-of-river plants, but may be substantial in the case of storage power stations or in regions with flat topography. If poorly designed, hydropower plants can produce substantial negative environmental and social effects including impacts on riverine ecosystems and biodiversity, on hydrological resources, on fisheries, and on local livelihoods, particularly if dam construction requires resettlement of local populations (Goldsmith and Hildyard, 1984; Trussell et al., 1992; WCD, 2000). Plans to build large dams have, therefore, sometimes encountered strong public opposition. Hydropower plants can also have positive environmental or socioeconomic effects, including irrigation or flood control, and are

**Table 20.10** | Indicative area requirements of different primary energy sources.

	Indicative area requirement (km <sup>2</sup> /PJ/yr)	Potential sustainability issues
Bioenergy crops	50–500	Impacts on C balance, ecosystems, soils and food systems can be positive or negative, depending on management
Bioenergy residues	Almost no additional area	No or little additional area required if residues or wastes can be used; possible impacts of removal of residues on soil fertility and the soil C balance need to be considered
Solar energy	1–6	Land needed for infrastructure; excess heat can be used for grain drying
Geothermal energy	≈10	Land required for infrastructure and transmission
Hydropower	<1–100	Impacts are highly site-specific and include positive (e.g., irrigation, flood control) as well as negative aspects (e.g., biodiversity and ecosystems, resettlement during construction)
Wind power	1–32	Land for wind power plants plus transmission, affects landscapes; rotors may kill birds
Oil	<1	Land required for infrastructure and transport
Natural gas	<1	Land required for infrastructure and transport
Coal	≈1	Land required for infrastructure and transport, soil contamination
Nuclear energy	<1	Land for infrastructure and transmission; potentially much larger land areas contaminated in case of an accident

Source: calculated based on Tampier (2002), except bioenergy.

indeed sometimes constructed primarily for such purposes. These issues are discussed in detail in the World Commission on Dams (2010).

Bioenergy requires by far the largest land area per unit of energy and year; as a result, concerns about competition for land, and land-use related sustainability issues involving energy, have received most attention with regard to bioenergy. The remainder of this subsection, therefore, focuses on bioenergy. Bioenergy is produced either by planting dedicated bioenergy crops or using by-products, residues and wastes from agriculture, forestry, food processing, and other economic activities (see Chapter 7). The environmental effects of these pathways are, however, fundamentally different (Cherubini et al., 2009) and are, therefore, discussed separately.

#### 20.4.3.1 Environmental effects of bioenergy crop plantations

Creating and maintaining energy crop plantations can have positive and/or negative environmental, social and economic impacts, depending on the respective regional conditions, the specific crop or technology, and the implementation and management of bioenergy projects (Goldemberg et al., 2008; Dewulf and Langenhove, 2006). For example, growing energy crops can increase the demand for agricultural products, create income and jobs in the agricultural sector, and provide

clean, renewable energy. It can also have unintended adverse effects, however, e.g., on agricultural prices or food security, as discussed in Section 20.2.7. Proper implementation of bioenergy crop plantation projects is a key factor for their sustainability in terms of social, economic and regional development goals (see Sections 20.2.5 and 20.2.6). This section focuses on issues of ecological sustainability related to land demand of bioenergy crop plantations.

Tackling the question of how much bioenergy can be produced without harming the environment (European Environment Agency, 2006) and without creating adverse social and economic impacts (Section 20.2.6) requires a systems approach that takes into account the relevant interactions between various land uses and socioeconomic functions of biomass (food, fiber/materials, and energy). Some of these issues are particular interactions between food and bioenergy systems and the significance of constraints such as the conservation of ecologically valuable areas (e.g., biodiversity hotspots, wetlands, or forests) and areas under various kinds of nature protection.

From a systems perspective, two types of effects need to be considered:

- **Direct effects** refer to the environmental effects, positive or negative, of the energy crop plantation itself, i.e., processes happening on the area covered by the plantation. These effects are species-specific as well as site-specific and depend strongly on the former state of the area, in particular its former use by humans.
- **Indirect effects** are the effects of creating energy crop plantations on the global land system as a whole. These system-level effects, usually called ILUC effects, depend not only on the amount of bioenergy to be produced and on the area required for that, but also on the development of many other components of the global land system such as food demand, food crop yields, the livestock system, and many other factors. For example, depending on food demand and food crop yields, establishment of bioenergy plantations on land currently used for food production may imply that the food has to be produced somewhere else. If that is the case, and if there are environmental effects (e.g., increased GHG emissions) resulting from the creation of this additional food crop area, they have to be attributed to the establishment of the energy crop plantation. On the other hand, Nassar et al. (2011) concluded that there is no evidence that biofuels present ILUC effects in the case of Brazilian sugarcane ethanol.

Perennial grasses such as switchgrass, *Miscanthus* and short-rotation coppice are generally thought to be ecologically less demanding than the food crops used for first-generation biofuels – in terms of impacts on soils, soil erosion, biodiversity, nutrient leaching, pesticide application, etc. (Cherubini et al., 2009; Rogner et al., 2000). It must be noticed, however, that the example of Brazil with sugarcane-based ethanol shows that first-generation biofuels can be produced in a sustainable way when adequate policies are in place (Goldemberg et al., 2008; also see Box 20.5 on Biofuels Zoning in Brazil).

Environmental impacts associated with the creation of new plantations strongly depend on the prior state and use of the land. If cropland currently used for food or feed production is converted to bioenergy plantations using perennial grasses or short-rotation coppice, the direct environmental effects can be expected to be benign, as those energy crops generally have fewer detrimental impacts than food crops.

Globally, however, with growth of the world population and changes in diets towards more demanding, i.e., animal-based, foods, as most projections assume, the area required to grow food or feed crops will increase rather than shrink. Land-use change is, therefore, a central environmental issue associated with the expanding use of bioenergy crops (Sagar and Kartha, 2007; Firbank, 2008). Once considered a local environmental issue, land-use change has become recognized as a pervasive driver of global environmental change that affects ecosystems, biodiversity, the water balance, and the biogeochemical cycles of carbon, nitrogen, and many other substances and compounds (Foley et al., 2005; Lambin and Geist, 2006). On the other hand, other recent studies (Goldemberg, 2009; Goldemberg et al., 2008) conclude that the environmental impacts of bioenergy crops such as sugarcane in Brazil can be controlled. The FAO (2009b; 2009d) also discusses these issues in the above-mentioned study cases of Peru in Latin America and Tanzania in Africa, showing that these issues can be addressed with adequate policies. These issues have been discussed deeply in Sections 20.2.5. and 20.2.7. of this chapter.

The Millennium Ecosystem Assessment (2005) concluded that land and water use by humans has already reduced the ability of many ecosystems to build up resilience and deliver vital environmental services not related to biomass production, such as buffering capacity, water retention capacity, and self-regulation, among others. A comprehensive discussion of such effects is beyond the scope of this chapter (but see IAASTD, 2009; Lambin and Geist, 2006). Regarding water, the focus here is on two main water use impacts: effects on the GHG balance, in particular the carbon balance; and effects on biodiversity (see Subsection 20.5.3.3 below). The overall GHG balance of bioenergy includes three components: GHG emissions resulting from production of agricultural inputs (e.g., fertilizers, diesel for tractors, etc.) and from conversion processes from feedstocks to final energy (e.g., liquid fuels); GHG emissions from direct land use or land-use change effects; and GHG emissions from ILUC (UNEP, 2009).

The first component is well covered by established life-cycle-based methods. High-quality databases exist to estimate these effects, and data uncertainties are relatively small. It should be noted, however, that allocation rules (i.e., how emissions are allocated to each product if one process yields more than one output, which is common in bioenergy production process chains) are a methodological challenge here and need to be considered when interpreting results (e.g., Zah et al., 2007; WBGU 2009; UNEP, 2009; Fritsche et al., 2010; Macedo et al., 2008).

These issues are covered in Chapter 11, together with some recent estimates of GHG emissions related to land-use change or ILUC, and



will not be further discussed here. This section focuses on fundamental issues related to GHG emissions resulting from land use and land-use change. Comprehensive information on GHG emissions per unit of energy are given in Chapter 11 (see also UNEP, 2009; Fritsche et al., 2010; Macedo et al., 2008; Nassar, 2009). First, general issues related to land use (change) and the GHG balance of ecosystems are discussed, followed by the issue of direct versus indirect effects.

Land use and land-use change directly affect the exchange of GHGs between terrestrial ecosystems and the atmosphere. In order to better understand the carbon balance of processes related to land use (change), it is important to distinguish between stocks and flows. A stock is a volume of carbon present in a system at any given point in time, while a flow is the amount of carbon moved from one compartment (e.g., the soil or the phytomass of plants) to another (e.g., the atmosphere) within a defined period of time, usually one year. With reference to terrestrial ecosystems, the most important stocks are carbon in the soil and in phytomass (see Box 20.4).

For carbon, the global terrestrial gross primary productivity (GPP) is 123 GtC/yr, of which 60 GtC/yr is returned to the atmosphere through plant respiration. Of the remaining net primary productivity (NPP) of 63 GtC/yr, 53 GtC/yr is returned through heterotrophic metabolism. The remaining 10 GtC/yr is the net ecosystem productivity (NEP). A large portion of NEP is lost because of land use, biotic stresses, fires, and other disturbances. The fraction remaining after these losses, called net biome productivity (NBP), ranges between 0.3 and 5 GtC/yr (Jansson et al., 2010).

Photosynthesis removes carbon from the atmosphere, but a considerable proportion flows back into the atmosphere through respiration of plants and heterotrophic organisms (animals, microorganisms, fungi). If there is no land-use change involved, the situation is relatively simple: if photosynthesis is greater than respiration, then the system acts as a carbon sink; otherwise, it is a carbon source. As yearly flows are large, difficult to measure, and often almost balanced, most methods used to measure the net carbon balance of ecosystems over time determine the net flows into or out of the system as the difference between stocks at different points in time. Ecosystem theory generally assumes that ecosystems gradually build up carbon stocks in vegetation and soil as they mature until they reach an equilibrium (climax) point where photosynthesis equals respiration and stocks are stable (Houghton, 1995; Schimel et al., 2001).

Table 20.11 shows that almost all carbon is stored in the soil-organic carbon (SOC) component in croplands, temperate grasslands, and tundra ecosystems. Overall, stocks are highest in forests and lowest in croplands.

The data in Table 20.11 show that deforestation, as expected, results in a massive loss of carbon to the atmosphere because large stocks in the phytomass are released in a short time. Belowground processes are more complex and much slower. If the system is used as cropland, SOC

**Table 20.11** | Typical values for carbon stocks of vegetation units per unit area. Data reported for forests refer to natural or near-natural conditions except for croplands; Carbon stocks in managed forests are substantially smaller.

Vegetation unit	Phytomass (kgC/m <sup>2</sup> )	Soil organic carbon (SOC) (kgC/m <sup>2</sup> )	Total (mean) (kgC/m <sup>2</sup> )
Tropical forests	12 – 19	~12	~28
Temperate forests	5.7 – 13	~9.6	~19
Boreal forests	4.2 – 6.4	~34	~40
Tropical savannas	2.9 – 3.0	~12	~15
Tundra	0.35–0.7	~13	~14
Temperate grasslands	0.4–0.7	~24	~24
Croplands	0.2 – 0.3	~8.0	~8

Source: Watson et al., 2000; Saugier et al., 2001.

mostly declines, but in grasslands, SOC can be even larger than in forests, in particular if they are used extensively. Soil-related processes can continue over long periods of time until a new equilibrium is reached. These complexities are important here, because they are the underlying reason why it is very difficult to derive general conclusions from site-specific studies of the carbon balance of different crops. Further detailed information on this issue is shown in Box 20.4.

The carbon balance of crops, including energy crops, strongly depends on the prior state (and particular use) of the land. If, for example, land is deforested for bioenergy, then there is a large release of carbon before energy crops are produced. This “carbon debt” (Fargione et al., 2008) may be quite large, so GHG emissions of bioenergy crops from that source can exceed GHG emissions from fossil-fuel-based counterparts for years, decades, or even longer (Gibbs et al., 2008; UNEP, 2009). On the other hand, if perennial bioenergy crops are planted on degraded pasture lands, they may build up carbon stocks in the soil and act as strong carbon sinks while producing bioenergy (Goldemberg, 2009; Goldemberg et al., 2008; Goldemberg and Guardabassi, 2009; Macedo et al., 2008; Tilman et al., 2006). Moreover, the GHG balance also depends on a host of other factors, such as land-use intensity and management, crop type (perennial plants mostly build up larger carbon stocks in the soil and in phytomass than annual plants), climate, soil, landform (slope, etc.), and many more. Further information on these issues is given in Box 20.4 below.

Considering the time horizon adds further complexity. The usual assumption was that biomass production was carbon neutral except for land-use-related effects, because the CO<sub>2</sub> resulting from its oxidation had previously been absorbed by the plant through photosynthesis. This neglects the following intricacy:

If biomass is harvested and combusted, then the carbon is released immediately, often within one year. However, if biomass is not harvested and is left in the ecosystem, it may take years, decades or even centuries until the CO<sub>2</sub> returns to the atmosphere; indeed it might even be



### Box 20.4 | Carbon Sequestration in Soils

World soils constitute the third largest global carbon (C) pool, after the oceanic pool at 38,400 Pg and the geological pool at 4230 Pg. The soil C pool, estimated at 2500 Pg to a depth of 1 meter, is 3.2 times the atmospheric pool of 780 Pg, and four times the biotic pool (trees, vegetation, etc.) of 620 Pg (Batjes, 1996; Eswaran et al., 1993; Falkowski et al., 2000; Lal, 2004; Pacala and Socolow, 2004; Lal, 2010).

The loss of the soil's C pool from 1850 to 2000 is estimated at  $78 \pm 12$  Pg (Lal, 1999). Until the 1940s and 1950s, more CO<sub>2</sub>-C was emitted from terrestrial ecosystems than from fossil fuel combustion. During 2009, 8 Pg CO<sub>2</sub>-C/yr was emitted by fossil fuel combustion, and about 1.6 Pg CO<sub>2</sub>-C/yr by land-use conversion. Anthropogenic activities that lead to CO<sub>2</sub> (and CH<sub>4</sub>) emissions include deforestation, biomass burning, drainage of wetlands, soil tillage, excessive grazing, and extractive farming practices.

Soil processes that lead to gaseous emissions are: accelerated soil erosion, breakdown of structural aggregates, and decomposition/mineralization of soil organic matter. Two other soil processes that accentuate gaseous efflux from soil are: methanogenesis that leads to emission of CH<sub>4</sub> under anaerobic conditions, and nitrification/denitrification that lead to emission of N<sub>2</sub>O.

Transfer of atmospheric CO<sub>2</sub> into other pools with a relatively longer residence time is called C sequestration. Thus, C sequestration in terrestrial biosphere (i.e., soils and biota) is a natural process based on photosynthesis of atmospheric CO<sub>2</sub> followed by humification of biomass into stable humic substances and organo-mineral complexes.

Important practices of soil organic carbon (SOC) sequestration are afforestation/reforestation, wetland restoration, establishment of a Conservation Reserve Program (CRP) or land retirement, restoration of eroded/degraded soils, no-till farming, cover cropping, application of biochar, and adoption of integrated nutrient management practices. The strategy is to create a positive ecosystem C budget. The rate of soil C sequestration ranges from negative or zero under arid and hot climates to about 2 Mg/ha/yr under cool and humid climates.

The global potential of soil C sequestration is estimated at 0.4–1.2 Pg C/yr in cropland soils (Lal, 2004) or about 1 Pg C/yr by converting 1.5 billion hectares from plow till into no-till farming (Pacala and Socolow, 2004). Improved management of grasslands (range land, pasture land) has an additional potential of C sequestration of about 1 Pg C/yr. Restoration of degraded and desertified soils has an additional potential of ~1 Pg C/yr. Restoration of peatlands (wetlands) is another important strategy for C sequestration. Adoption of these practices can be promoted through payments to land managers for ecosystem services.

Modern biofuels (e.g., ethanol, methanol, methane, and triglyceride oils) are an important alternative to fossil fuels. These are also called "green gold" fuels, because their feedstocks can be grown on farmland over and over again (Vorholz, 2006). Commonly used feedstocks of ethanol include corn grains (Pimentel, 2003) and sugarcane (Goldemberg et al., 2008). However, crop residues are also being considered as a source of cellulosic ethanol (Somerville, 2006). There are serious concerns about the use of corn grains for ethanol with regard to competition for food (Mufson, 2008), energy balance, and carbon foot print (Pimentel, 2003; Oliveira et al., 2005; Lal, 2008).

While the practical issues on cellulosic ethanol production are being addressed (Ragauskas et al., 2006), the impressive progress of ethanol production from sugarcane in Brazil needs to be objectively assessed, especially with regard to soil C dynamics. The agricultural input required for sugarcane production releases 2.27 Mg CO<sub>2</sub>/ha/yr. Other sources of CO<sub>2</sub> emissions from ethanol production result from the pre-harvest burning of sugarcane and from the decomposition of vinasse. Total CO<sub>2</sub> emissions from ethanol production from sugarcane in Brazil are 3.31 Mg/ha/yr (Oliveira et al., 2005) compared with 5.03 Mg/ha/yr for corn-based ethanol in the United States (West and Marland, 2002; Shapouri et al., 2002).

The soil C budget for sugarcane production in São Paul State and elsewhere has not been widely studied. Plowing and other soil disturbances have negative impacts on the soil C pool by increasing the mineralization of soil organic matter and risks of soil erosion. However, the soil C pool can be increased by adopting reduced tillage, eliminating pre-harvest burning, and recycling wastes of the ethanol processing.

Source: Lal, 2005; 2006; 2010.

captured for geological time spans under certain circumstances (e.g., when carbon is stored belowground in wetlands under anaerobic conditions). Therefore, bioenergy production can only be considered “carbon neutral” in a strict sense if it results from additional plant growth that would not have occurred in the absence of bioenergy production and use (e.g., if the productivity of degraded land is increased over the previous state), if biomass is used that would be oxidized rapidly if left in the ecosystem, or if bioenergy use reduces biomass use in other sectors, e.g., if food or fiber consumption falls due to rising prices of agricultural products. These issues are currently being discussed intensively, and this debate might result in new accounting rules for GHG emissions of bioenergy (Bird et al., 2010; Pingoud et al., 2010; Searchinger et al., 2009; Searchinger, 2010; Goldemberg, 2009; Goldemberg and Guardabassi, 2009).

The above-discussed considerations generally apply to land use and land-use change, whether the land is used for food or energy crops or other purposes. Any production of biomass – no matter whether it is produced for food, as raw material, or for energy – requires land and may (or may not) result in land-use change. As long as changes in the production and consumption of biomass are studied in a systemic way – for example, by looking at changes in food, fiber and bioenergy demand over time – in a systems model that integrates plant production, all land-use effects of biomass conversion are direct, and no such thing as an “indirect effect” exists. The same applies for agriculture and industry, as well as final consumption.

ILUC effects need to be considered, however, when environmental effects of single resources, such as bioenergy crops, are to be evaluated without explicit consideration of the entire land system. Of course, the evaluation of ILUC effects involves uncertainties (Nassar et al., 2009; 2011) and can only yield approximate results, based on *ceteris paribus* assumptions.

In conclusion, appropriate planning and implementation of bioenergy crop plantations is of key importance. If bioenergy crop plantations can be situated on lands with low initial carbon stocks, such as degraded lands, or use perennial crops such as perennial grasses or short-rotation coppice and appropriate management technologies such as no-till agriculture, their GHG balance can be negative, or at least their GHG emissions can be low. If, on the other hand, inappropriate locations are combined with poor choices of crops and unfavorable management, GHG emissions can be very large and even exceed the fossil baseline. Therefore, adequate policies are needed to ensure that appropriate areas are used for bioenergy crops. The choice of crops should follow environmental zoning approaches, such as those currently used in Brazil (see Box 20.5 below) and in the Brazilian states of Minas Gerais and São Paulo (Joly et al., 2010).

The United Nations Department of Economic and Social Affairs (UNDESA) provides a range of recommendations that specifically address sustainability aspects of bioenergy (UNDESA, 2007). These include the use of energy crops that are suitable under local conditions

and are able to grow on marginal and arid lands with limited inputs. UNDESA also favors energy crops that have a variety of by-products that would create additional income for farmers. Energy crops that are easily propagated and allow intercropping would also be important. Bioenergy should also benefit identified marginalized groups in a community.

In conclusion, adequate policies that are appropriately enforced can allow the reduction of negative, and the promotion of positive, environmental impacts of bioenergy crops.

#### 20.4.3.2 Environmental and social effects of using by-products, residues, and wastes

Bioenergy production from agricultural by-products, residues and wastes presents advantages, as it does not: require additional land or land-use change; compete with food and fiber production; affect agricultural and food prices; or require many additional scarce inputs, such as freshwater (Berndes, 2008). Using biomass residues may help alleviate energy shortages and create employment opportunities (such as production of bioenergy crops); moreover, use of municipal solid waste (MSW) may reduce landfill requirements. However, there may also be negative environmental effects, depending on the respective biomass flow, as well as on technology and management.

The agricultural residue straw can deliver substantial amounts of energy. However, straw plays a vital role for soil fertility, soil carbon pools, and the mitigation of water and wind erosion (Lal, 2005; Lal, 2006; Wilhelm et al., 2007). WBGU (2008) assumes that about half of all crop residues could be used to produce bioenergy without compromising soil fertility. Removal of crop residues for energy purposes could also affect the GHG balance of cropping systems. There are currently studies under way evaluating how much of the residues must be left on the soil to avoid that (Hassuani et al., 2005).

The removal of biomass from forests, including forest residues, may affect forest ecosystems because the coarse woody debris is essential for biodiversity and ecosystem functioning (Harmon et al., 1986; Krajick, 2001; Shifley et al., 2006) and forest conservation objectives. The use of fuel wood and forestry residues should be jointly optimized. This can be managed through adequate capacity-building with local people, as is happening in remote villages in India (CENBIO, 2002).

Well-managed use of animal manures for biogas production can have significant positive environmental and social impacts. It reduces methane (CH<sub>4</sub>) emissions,<sup>13</sup> while returning most plant nutrients and parts of the carbon back to the soil, thereby mitigating land degradation

<sup>13</sup> Conversion of animal manures in biogas plants and subsequent application of the residues as fertilizer reduce methane (CH<sub>4</sub>) compared to the storage and direct application of manures (Bhattacharya et al., 1997; Clemens et al., 2005).

### Box 20.5 | Environmental Zoning in Brazil

Brazil began its large-scale sugarcane ethanol program, PROALCOOL, in 1975, when oil prices raised with the world oil crisis. Since then, many developments towards a sustainable production system have been achieved. These have resulted in important increases in both agricultural and industrial productivity (more than 3%/year, Goldemberg et al, 2008); as a consequence, production costs fell rapidly, making ethanol economically competitive with gasoline. At the same time, improvements in social and environmental legislation have been achieved, both at the federal and state level. Due to the expansion of sugarcane production in recent years, concerns about the direct impacts of land-use change led federal and state governments to adopt policies to determine suitable areas for this crop.

The state of Minas Gerais was the pioneer in this process and launched its economic-environmental zoning in 2007. The zoning is based on social, economic and environmental information that shows regional characteristics, potentialities, and vulnerabilities. It is an orienting tool that can support policymakers and entrepreneurs of different sectors (World Bank, 2011). In the state of São Paulo an agro-environmental zoning was based on studies related to soil and climate restrictions, topography, water availability, air quality, and existence of protected areas and biodiversity conservation areas; this assessment was the basis for a voluntary scheme with sugarcane producers, the Agroenvironmental Protocol. The text stipulates a set of measures to be followed, anticipating the legal deadlines for the elimination of sugarcane harvest burning and immediately halting burning practices in any sugarcane harvests located in expansion areas. It furthermore targets the protection and recovery of riparian forests and water springs in sugarcane farms, controls erosion and content water runoffs, implements water conservation plans, stipulates the proper management of agrochemicals, and encourages reduction in air pollution and solid wastes from industrial processes (Lucon and Goldemberg, 2010; SMA, 2011).

The federal government launched, in September 2009, the national agro-ecological zoning for sugarcane and, in 2010, for palm oil. This zoning identified the areas where sugarcane crop expansion can take place, and forbids sugarcane cultivation in 92.5% of national territory, including the Amazon Forest, Pantanal wetlands, and other native biomes. It identified 64 million hectares that comply with environmental and productivity requirements. The zoning was an intense program involving dozens of institutions and researchers of agricultural and environmental issues. In this process maps were produced showing soils, climate and rainfall, and topography. Land was classified and delimited by determining the areas of highest yield potential in detail (1:250,000), based on minimum productivity, with respect for the environmental regulations and which areas should be preserved, as well as trying to reduce competition with areas devoted to food production. According to these studies, there are in Brazil about 650,000 km<sup>2</sup> available for sugarcane and 300,000 km<sup>2</sup> for palm, without undesirable impacts (EMBRAPA, 2011a; 2011b).

and helping to maintain soil fertility (Rajabapaiah et al., 1993; Stinner et al., 2008). Moreover, energy from biogas can help to substitute for traditional biomass energy, which has tremendously negative health and environmental effects and currently contributes to millions of premature deaths due to respiratory diseases resulting from indoor pollution (Jaccard, 2005).

Using MSW for energy purposes lowers CH<sub>4</sub> emissions from waste deposits (landfills). Since waste disposal in landfills has other environmental impacts when it is not adequately controlled and enforced, such as soil and underground contamination, there can be local opposition to the construction of landfills near communities. Therefore, in some cases, incineration of MSW may provide an interesting solution for both solid waste disposal and power production.

However, effective air pollution control technology is needed to avoid large emissions of toxic pollutants such as dioxins and furans. Tight air pollution regulation that vigorously enforces the use of the most

advanced abatement technologies to reduce toxic emissions is required to minimize possible negative environmental effects from the combustion of MSW (McKay, 2002).

#### 20.4.3.3 Biodiversity

Different trade-offs on biodiversity may result from bioenergy production, depending on the adequacy of the policies in place, and their enforcement.

On a local scale, biodiversity effects depend on crops, former land uses, and management practices. Local biodiversity may benefit from biomass crops when intensive agricultural practices are replaced by low-intensity biomass production systems. In general, first-generation European agricultural crops have more negative impacts at the local level than both mixed cropping systems and bioenergy crops in developing countries (the Brazilian experience is an example of this; Goldemberg et al.,

2008), as well as second-generation perennials and woody crops (GLOBIO, 2010).<sup>14</sup>

Clearing valuable ecosystems such as native rainforests and wetlands to make an expansion of the agricultural sector possible would result in large losses of natural biodiversity. If feedstock production comes predominantly from large monoculture cultivation without appropriate environmental controls, it could reduce both the number of species and, with a growing specialization on particularly suitable varieties, even the number of varieties grown. These practices could result in a greater vulnerability of the agricultural sector to non-standard crop-growing conditions such as extreme weather patterns, pests, and diseases (Müller et al., 2007). The threat to wild biodiversity from agricultural crops and bioenergy growth is associated primarily with land-use change, as already mentioned. When areas such as natural forests are converted for feedstock production, the loss of biodiversity is significant, even if an expansion of crop land is a temporary phenomenon. A further concern is the introduction of invasive species for biofuel production. Agricultural biodiversity could be affected by large-scale monocropping practices and the introduction of genetically modified materials (FAO, 2008b).

On the other hand, the conservation and/or recuperation of native forests areas and other biomes as well as fauna corridors – such as riparian forests and the so-called environmental protection areas – are fundamental for any agricultural crop and, when introduced inside large-scale plantations, can contribute to preserving or rebuilding biodiversity (Goldemberg et al., 2008; EMBRAPA, 2008).

#### 20.4.4 Challenges

Due to the uncertainties in future oil prices and energy policies, it is still too early to understand the dimensions of the markets for biofuels sufficiently to develop a realistic scenario that quantifies the trade-offs between increased biofuel production and the provision of food (Müller et al., 2007). However, there are positive perspectives for food prices in the future, as discussed in OECD/FAO (2009).

In the long term, tropical countries will likely play an increasingly important role in feedstock production, due to favorable biophysical conditions and generally lower costs of land and labor, so long as suitable trade arrangements and stable conditions for investment prevail (Cotula et al., 2008). Considerable improvements in land and water productivity are

possible and can be significant. The example of achieving a significant increase in sugarcane productivity in Brazil shows that this is an objective that can be achieved if adequate investments are made (al-Riffai et al., 2010). In tropical farming systems, currently producing around the global average for developing countries, one can reach 2 t/ha for cereals.

In Africa, seven countries (Tanzania, Côte d'Ivoire, Burkina Faso, Ghana, Guinea, Mali, and Senegal) are participating in a UNDP Multifunctional Platform project that tackles lack of access to electricity and rural women's poverty through the provision of simple multipurpose diesel engines that are able to run on jatropha oil (Cotula et al., 2008). This project, as well as the BEFS project (FAO, 2010a; 2010b) for Peru and Tanzania (see Box 20.2), illustrates how tropical countries can implement bioenergy production if the needed overall conditions can be achieved.

As discussed in the sections above, the main challenge regarding land use is related to the increase in agricultural productivity in developing countries (mainly African countries) and the implementation of adequate policies such as agro-environmental zoning to allow the better use of land for each purpose considering the existing trade-offs. Socio-environmental assessments are fundamental for various options to meet future demands for food and biofuels.

In terms of water, challenges related to water trade-offs include the implementation of adequate strategies for water productivity improvements. This requires substantial efforts from authorities and different development agencies. A combination of incentives and sanctions are required to overcome social inertia and to demonstrate that it is a viable option. A considerable decoupling could be achieved over a period of a few decades. Technologies are generally known; the challenge is to invest in human and institutional capacity for adequate policies in all sectors, including environmental and social ones.

If improvements on the food consumption side are combined with those in water productivity on the production side, the estimated water need for food production in 2045 is estimated to be 6470 km<sup>3</sup>/yr. Estimates for water need for bioenergy in 2050 vary considerably (4000–12,000 km<sup>3</sup>/yr), but even the lower limit of such consumptive water requirements to produce biofuels is quite significant.

Increasing water productivity holds the key to future water scarcity challenges. Without further improvements in water productivity or major shifts in production patterns, or a more advanced allocation system within an Integrated Water Resources Management system, the amount of water needed for agriculture, industrial and domestic activities will increase by 60–90% by 2050, depending on population, incomes, and assumptions about water requirements for the environment. In agriculture alone, the total volume of water needed for crop production would be 11,000–13,500 km<sup>3</sup>, almost double the 7130 km<sup>3</sup> of today (FAO, 2007). Water resources will be stressed even more from increased demand for biofuel. By 2030, world energy demand will increase by

<sup>14</sup> The origins of the present GLOBIO model (GLOBIO3) go back to the GLOBIO2 model and the Natural Capital Index-IMAGE framework (NCI-IMAGE). Both approaches are universal, policy-oriented frameworks on the impact of human activities on biodiversity. To meet the challenge of evaluating the global targets on biodiversity, an international consortium, made up of the UNEP World Conservation Monitoring Centre, UNEP GRID-Arendal and the Netherlands Environmental Assessment Agency joined forces in 2003. They combined the GLOBIO2 and the NCI-IMAGE approach into a new Global Biodiversity Model: GLOBIO3. This model has been in use since 2005 (Globio, 2010).

50%, and two-thirds of this demand will come from developing countries. However, there is scope for an accelerated increase in water productivity. Water productivity in agriculture has increased steadily in recent decades, largely because of an increase in crop yields, and the potential exists for even more increases. However, the pace of such increases will vary according to the type of policies and investments put in place, with substantial variations in the impact on the environment and livelihoods of rural populations. A systematic approach to agricultural water productivity requires actions at all levels, from crops to irrigation schemes, and involving national and international economic systems, including the trade in agricultural products. It calls for an informed discussion on the scope for improved water productivity in order to ameliorate intersectoral competition for water resources and optimize social and economic outcomes (UN-Water/FAO, 2007).

“Virtual water” is the water consumed in the production process of an agricultural or industrial product (Allan, 1998). It is particularly important to water-scarce countries in their efforts to secure water for different sectors. Water for bioenergy production will become increasingly important. Taking virtual water into account in the trade balance may allow for water-scarce countries to import more water-consuming crops and produce lower water-consuming ones domestically. This may also include production of biofuels.

If improved water productivity is achieved through a more intensive application of fertilizers and other chemicals, improvements in a quantitative sense may lead to a deterioration of quality. Climate change is also a highly relevant issue but difficult to model in terms of water. Taking into account that water scarcity is already severe in many parts of the world and that growth of GDP and population and distribution are not in harmony with access to productive land and abundant water resources, the role of trade will be even more important. The virtual water perspective under those circumstances is even more important, as are the connections between production and consumption (Lundqvist et al., 2007).

With regard to hydropower, the construction of large dams often has extensive impacts on downstream areas of the river basin, including the terrestrial and aquatic ecosystems. Ecosystem restoration is a necessary measure to be addressed, and the impacts of decommissioning are complex and site-specific. The World Commission on Dams Knowledge Base demonstrates that in many cases large dams have resulted in:

- loss of forests and wildlife habitat, loss of species and degradation of upstream river basin areas due to inundation of the reservoir area, or of downstream river basin areas due to damming and subsequent loss of water for ecosystem maintenance;
- GHG emissions from reservoirs due to the anaerobic decomposition of vegetation and carbon inflows from the basin;
- loss of aquatic biodiversity, upstream and downstream fisheries and the services of downstream floodplains, wetlands and riverine, estuarine and adjacent marine ecosystems;

- creation of productive fringing wetland ecosystems with fish and waterfowl habitat opportunities in some reservoirs; and
- cumulative impacts on water quality, natural flooding, and species composition where a number of dams are sited on the same river.

The ecosystem impacts are more negative than positive and have led, in many cases, to irreversible loss of species and ecosystems. Efforts to date to mitigate the ecosystem impacts of large dams have met with limited success, owing to the lack of attention given to anticipating and avoiding impacts, the poor quality and uncertainty of predictions, the difficulty of coping with all impacts, and the only partial implementation and success of mitigation measures.

In brief, aiming to reduce the competition among the different end uses for land and water, the main challenges are related to the need for investments not only in technological aspects allowing the introduction of efficient and sustainable methods, but mainly in capacity-building in technical, economic, environmental, social, political and regulatory sectors related to this issues.

#### 20.4.5 Environmental certification

Sustainability standards are frequently proposed for the processes of environmental permitting. Based on an agreed definition of sustainable development, specific criteria and provisions are formulated, either locally (according to community priorities and expectations) or externally (based on requirements of external markets). Different organizations have developed sustainability criteria and tools, e.g., the International Labour Organization (ILO) for acceptable labor conditions, the World Wildlife Fund for ecological factors, the World Bank for financial results, and the OECD and the UN for development policymaking and information (Lewandowski and Faaij, 2006).

Applying sustainability criteria to an environmental permitting process can be done either on a case-by-case basis or following zoning plans. The example of sugarcane zoning in São Paulo, Brazil (Joly et al., 2010), is described in Box 20.5. Several GIS datasets (e.g., climate, soil potentials, water availability and vulnerability, biodiversity protection and connectivity) led to a map with different restrictions on licensing enterprises, and subsequently to federal zoning for sugarcane and oil palm plantations in Brazil.

Considering land use, and specifically the case of biofuels, several initiatives seek to establish certification and sustainability standards. Some of these initiatives overlap, and they are all broadly consistent in their principles. Different systems have been developed by the Forest Stewardship Council (FSC, 2011), the European Retailers Produce Working Group (GLOBAL GAP, 2011), and Linking Environment and Farming (LEAF, 2011). Some schemes have stronger interfaces with bioenergy: the Roundtable on Sustainable Palm Oil (RSPO, 2011), the Roundtable on Responsible Soy Association (RTRS, 2011), and the São Paulo State Green Ethanol



Program (Lucon and Goldemberg, 2010; SMA, 2011). National policies in the EU are also supporting the assessment of sustainability and certification systems for biofuels (Ecofys, 2006). An important initiative is the Roundtable on Sustainable Biofuels (EPFL, 2007), which is developing certification criteria, led by Lausanne University and supported by the Swiss government. This initiative is currently facilitating agreement on a comprehensive set of principles for sustainable biofuels, including principles on respect for land and water rights, the socioeconomic development of communities, and food security. UNEP has also an initiative aiming to support wide adoption of sustainability criteria, avoiding breaching trade rules of the World Trade Organization (UNEP, 2011).

There are different systems and methods aiming at ensuring sustainability of bioenergy, most of which fall into the following categories:

- Demand-side, voluntary, consumer-oriented, bottom-up, providing a green label for “better products,” appealing to individual perceptions, and usually covering good social practices (e.g., fair labor, small producers, from poorer regions) and organic/environmental standards (e.g., products less carbon-intensive, no deforestation in the production process, etc.).
- Demand-side, mandatory, top-down, sanitary measures and/or other requirements generally applied to imports; covering some key topics and products (e.g., absence of genetically modified organisms or proscribed substances and quality standards for a given biofuel commodity).
- Demand-side sustainability criteria, top-down general principles applied to a category of goods and services, such as biofuels, covering a broad range of topics, in many cases inspirational but also with the intention of becoming mandatory by law.
- Supply-side sustainability criteria, producer-oriented, generally voluntary schemes promoted by producer associations and/or governments, applied to main (in most cases few) topics of higher socio-environmental concern beyond law enforcement (e.g., life-cycle GHG assessments).
- Supply-side, voluntary, recognized Environmental Management Systems based on continuous improvement spirals, as in the case of the ISO 14000 series of quality standards.

An interesting example of a certification scheme already being applied is the one introduced by the Swedish company SEKAB. The company delivers about 90% of all ethanol in Sweden for E85 and ED95 (ethanol for heavy vehicles). SEKAB announced in June 2008 that it would buy certified sustainable ethanol from four Brazilian groups, in what the company said was the first deal of its kind. SEKAB said it worked with the Brazilian producers to develop sustainable and verifiable criteria for the entire life cycle of the ethanol, taking into consideration environmental, climate and social perspectives. SEKAB said the criteria are in

line with demands highlighted in the ongoing processes being led by organizations such as the UN, EU, ILO and a number of NGOs. There are requirements concerning working conditions, labor laws, and wages – and zero tolerance for child labor, non-organized working conditions (slave labor), and the destruction of rain forests. Harvesting is to be at least 30% mechanized today, increasing to 100% by 2014, and an independent international verification company will audit all production units twice a year to ensure that the established criteria are met. Criteria will gradually be developed over the coming years and synchronized with international regulations when these are in place (Lucon, 2010).

It can be observed that there has been a proliferation of certification schemes; this is a positive development, demonstrating awareness among governments, citizens, consumers and producers of the risks and challenges involved in expanding biofuel production, as mentioned by UNCTAD (2008). The inclusion of land rights criteria in some private certification schemes is also welcome. It is too early, however, to see whether they will have a real impact. The EU and government schemes, which are potentially far more influential, have not addressed land issues – in effect, giving license to European companies to ignore principles of prior informed consent in land allocation for large-scale biofuel crop cultivation (Cotula et al., 2008).

In fact, the sustainability of biofuels is a key question, and certification criteria can be used to answer it. However, as discussed in UNCTAD (2008), there are a number of issues to be considered. The same types of sustainability standards should be considered for other energy sources, and also when comparing fossil fuels with biomass energy. Sustainability standards and certification schemes, to be implemented by developing countries, mainly Least Developed Countries, need strong capacity-building measures. Also important is the question of an increase in biofuel production costs due to certification, and who could cover it. In addition, UNCTAD (2008) raised the point that certification should not be used as protectionism to farmers in industrialized countries.

Recently the United States and the EU established regulations to stimulate the use of bioenergy, in particular biofuels, and to ensure the production and use of biofuels in a sustainable manner.

The EU has two major pieces of legislation: the Renewable Energy Directive (RED) and the Fuel Quality Directive (FQD). All member states were required to implement both directives by December 2010. RED requires a minimum of 10% renewable energy fuels in transport by 2020. It also commits the EU to report by the end of 2010 on the impact of ILUC on GHG emissions from biofuels and ways to minimize that impact. FQD's target is for fuel suppliers to reduce life-cycle GHG emissions by at least 65% by weight across all transport fuels by 2020.

Minimum compliance with the EU policies includes the following: reduce GHG emissions by 50% as of 1 January 2017 and by 60% for biofuels and bioliquids produced as of 1 January 2018; biofuels may

not be made from raw material obtained from land with high biodiversity values, high carbon stock or land that was peat land in or after January 2008; and biofuel feedstock grown in the EU must meet the EU's "cross-compliance" requirement. However, it must be noted that such requirements are only for liquid biofuels and do not include solid biomass (Georgescu, 2010).

The US Renewable Fuel Standard (RFS) program came into force on March 26, 2010, as required by the Energy Independence and Security Act (EISA, 2007). The program's objective is to increase the volume of renewable fuel blended into gasoline and other transportation fuels. Renewable fuels include ethanol, biodiesel, and other motor vehicle fuels made from renewable sources. All producers of gasoline to be used in the United States are obliged to comply with the annual Renewable Volume Obligation as determined by the US Environment Protection Agency (US EPA). For 2009, the RFS was 10.21%. Renewable fuel must reduce GHG emissions by 20% in life-cycle terms when compared to average transportation fuels in 2005. Similarly, biomass-based diesel and advanced biofuels must achieve a 50% reduction, and cellulosic biofuels a 60% reduction. The US EPA considers Brazilian sugarcane ethanol adequate in terms of carbon emissions, which opens significant opportunities for other countries also producing sugarcane ethanol (US EPA, 2010).

## 20.4 Conclusions and Policy Proposals

Whether for income generation or for local energy self-sufficiency, large-scale and small-scale biofuels production can co-exist and even work together in synergy to maximize positive outcomes for rural development. Existing experiences and practices should be disseminated to document successful experiences and to analyze the conditions that make them possible, mainly the spread of costs and benefits among local land users, investors, and government. Also, it is important to consider the extent to which such experiences can be replicated elsewhere (Cotula et al., 2008).

Overall improvements in food production may be achieved by reducing the losses and waste in the food chain from production to consumption. These losses occur in harvest, transportation, transactions, storage, handling, processing, and wholesale and retail sales, not to mention changed dietary habits (more proteins, i.e., closer to the top of the food chain) and overconsumption (more food intake than necessary). As discussed earlier in this chapter, adequate funding and capacity-building are key factors to achieve such objectives.

Decoupling and mitigating water competition between food and energy crop production is also possible (see Lundqvist et al., 2007). It is not axiomatic that expanding energy crop production leads to negative consequences relative to land, water, and other resources. Properly located, designed and managed biomass plantations can provide positive benefits, such as low water consumption and adequate choice of crops

allowing production and transportation. There are options for decoupling future water needs for food and bioenergy production from increased food and bioenergy demands, through adequate planning and zoning. Effective institutions and strong capacity-building at all levels are needed for integrated land and water resources management, allowing the introduction of adequate policies to regulate the trade-offs in their use.

Land use policies should include: protecting small-scale farmers from loss of land due to pressure from large-scale producers; respect and protection of land tenure rights; use of "informed decision-making" and full participation of stakeholders when determining land-use changes; and assessing existing land-use policies in light of potential expanded bioenergy use (UNIDO, 2008).

For food, consideration should be given to annual production of main commodities, demand, prices, and trade, both for irrigated and rain-fed production. Food demand is a function of price, income, and population. There are different areas and yield functions for rain-fed and irrigated crops; crop area and yield functions include water availability as a variable.

Conflicts between food and bioenergy can be avoided through agro-economic-ecological zoning (as presented in Box 20.5), allowing adequate use of land for each purpose. The potential impact of bioenergy production on food prices is discussed in several studies and is quite controversial, but it is clear that such adverse effects can be mitigated by appropriate policies that aim at an integrated optimization of food and bioenergy production. Adequate capacity-building is needed, mainly in developing countries, to allow the implementation and enforcement of adequate policies, such as those to regulate biomass-intensive energy systems and hydropower (limitation, water availability, cooling tower, irrigation), together with agro-ecological-economical zoning to define potentials and best aptitudes for land use, as well as imposing environmental limits in harvested areas (related, for example, to conservation units, water use, monoculture, use of pesticides, burning practices).

In the case of trade-offs in water use, it is fundamental to ensure water for all, and this requires knowledge about science, ecology, and economics, as well as ethics and international cooperation. The trade-offs in water use involve large quantities and different activities, which may conflict with hydropower, thermoelectric or bioenergy production. Global freshwater distribution is unbalanced geographically, and supply is frequently affected by contamination, depletion, and increased competition for multiple purposes. The rapid increase in water demand (due to growing populations, incomes, and unsustainable consumption) must be viewed in the context of climate change, the effects of which are difficult to predict. Expanded exploitation of water resources is only a short-term option for addressing scarcity. In the long term, only ambitious policies, heavy investments in water conservation, and adequate and integrated management of multiple uses can be solutions to the long-foreseen crisis (Rogers, 2008).

Water use alternatives need to clearly consider: improvements in the efficiency and productivity of existing irrigation systems before planning and implementing new ones; adaptation and expansion of local and traditional water management solutions; more coordinated management of surface and groundwater resources; and improvement of the productivity of rain-fed agriculture.

Efforts to promote sustainable water management practices have primarily focused on the agricultural sector as the largest consumer of freshwater. Governments have several objectives in deciding the nature and extent of inputs in agriculture. These include achieving food security, generating employment, alleviating poverty, and producing export crops to earn foreign exchange. Irrigation represents one of the inputs to enhance livelihoods and achieve economic objectives in the agricultural sector with subsequent benefits for rural development. Just as strategies and approaches to rural development are context-specific, there are numerous and diverse alternatives to agricultural development and irrigation that need to be examined. The diversity relates to scale, level of technology, performance, and appropriateness to the local cultural and socioeconomic setting.

A number of policy, institutional and regulatory factors hinder the emergence and widespread use of an appropriate mix of options that would respond to different development needs, sustain a viable agricultural sector, provide irrigation, and offer livelihood opportunities to large populations. Appropriate policy options include:

- support for innovation, modernization, adaptation, maintenance, and extension of traditional irrigation and agricultural systems;
- protection or restoration of natural functioning of deltas, floodplains, and catchments in order to sustain and enhance the productivity of traditional systems in these areas;
- transferring management to decentralized bodies, local governments, and community groups for recovering tariffs and maintenance;
- agricultural support measures, mutually reinforcing and developing intersectoral linkages in the local economy to spur rural development;
- reducing transaction costs and risks for smallholder farmers in developing countries; and
- expanding access to international markets by reducing barriers and introducing supportive domestic policies (without trade distortions such as the tariff and non-tariff barriers to OECD markets).

Government policies and institutions play an important role in the promotion of particular water and agricultural/bioenergy appropriation technologies and methods. Each method has different implications for food production, food security at the local and national levels, and the distribution of costs and benefits.

The business-as-usual policy option entails continuing along the path taken so far. Each country would proceed in setting and revising policy frameworks in line with national interests, taking into account international implications of policy decisions only where these are compatible with domestic priorities (FAO, 2008b).

Certification can play an important role, mainly in the case of biofuel production, but without an internationally agreed standard, the desire expressed by many governments to start certifying sustainable biofuels may face serious obstacles, not least under international trade law considerations (FAO, 2008b).

In the short term (about 25 years), carbon sequestration in terrestrial ecosystems (notably in degraded and desertified lands through restoration and afforestation) is a prudent strategy. In the long term (over 50 years), utilizing carbon-neutral fuel sources (biofuels, solar, hydro, wind, geothermal) is the best option (Lal, 2010).

Clearer definitions of concepts of idle, under-utilized, barren, unproductive, degraded, abandoned and marginal lands (depending on the country context) are required to avoid allocation of lands on which local user groups depend for livelihoods. Similarly, productive use requirements in countries in which security of land tenure depends on active use need to be clarified so as to minimize abuse (Cotula et al., 2008).

Governments need to develop robust safeguards in procedures to allocate land to large-scale agriculture and biofuel feedstock production where they are lacking and – even more importantly – to implement these effectively. Safeguards include clear procedures and standards for local consultation and attainment of prior informed consent, mechanisms for appeal and arbitration, and periodic review. Safeguards should be applicable across agricultural and other land-use sectors, rather than only specifically to biofuels (Cotula et al., 2008).

Although bioenergy can have significant positive impacts on rural areas through the creation of jobs, the FAO (2008a) considers that an integrated approach to social protection should be adopted for rural households, combining traditional transfers (social safety nets) and policies that enable smallholders to respond quickly to the market opportunities created by higher prices.

In the very short term, however, the supply response to higher price incentives, especially by smallholders, may be limited by their lack of access to essential inputs such as seeds and fertilizers. In these cases, social protection measures, including the distribution of seeds and fertilizers, directly or through a system of vouchers and “smart subsidies,” may be an appropriate short-term response. If implemented effectively, such a program will increase the income of small producers and may reduce price increases in local markets, thereby contributing to improvements in the nutritional status of net food-buying families.

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