chapter 9

Land and Bioenergy

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Highlights

Projected land demands for bioenergy fall well within conservative estimates of current and future land availability (240 to 905 Mha). Estimates for the amount of modern bioenergy needed to meaningfully mitigate climate change range from 80 to 200 EJ in the 2050 timeframe. At the upper end of this range, we estimate that about 200 million hectares would be required. This may be compared to most estimates for the amount of land available for bioenergy, which exceed 500 million hectares. Long before the world reaches any significant fraction of 200 Mha devoted to modern bioenergy, we will have opportunity to be guided by experience rather than projection. The real danger is not that once the bioenergy genie is out of the bottle that ruinous land use change will ensue. The recent application of the brakes to bioenergy expansion worldwide provides ample evidence that the growth of bioenergy can be curtailed. Rather, the real danger is that bioenergy development will proceed so slowly that a key strategy for climate change mitigation will be taken off the table.

- Historic estimates of land demand have significantly overestimated direct and indirect land use impacts from bioenergy, particularly conventional biofuels. Timing and rates of change are however important;
- Modern bioenergy is likely to increase reforestation drivers as opposed to increase deforestation rates;
- Ignoring the importance of the integrational benefits of bioenergy with the global food production systems is dangerous and an inappropriate use of the 'precautionary principle'. Most analyses of bioenergy development are carried out independently of the development of the food production system;
- In particular, we highlight the potential and the need for increased cropping intensity (including double cropping) and for pasture intensification to simultaneously increase food and bioenergy provision whilst increasing soil fertility and improving ecosystem services. More research is urgently needed to understand the full potential for these novel approaches to land management;
- In practice, extensive interaction and integration already occurs between the food and bioenergy provisioning systems, will continue and likely expand, and presents new opportunities to optimize benefits.

Summary

In this chapter we address the questions of whether and how enough biomass could be produced to make a material contribution to global energy supply on a scale and timeline that is consistent with prominent low carbon energy scenarios. We assess whether bioenergy provision necessarily conflicts with priority ecosystem services including food security for the world's poor and vulnerable populations.

In order to evaluate the potential land demand for bioenergy, we developed a set of three illustrative scenarios using specified growth rates for each bioenergy sub-sector. In these illustrative scenarios, bioenergy (traditional and modern) increases from 62 EJ/yr in 2010 to 100, 150 and 200 EJ/yr in 2050. Traditional bioenergy grows slowly, increasing by between 0.75% and 1% per year, from 40 EJ/yr in 2010 to 50 or 60 EJ/yr in 2050, continuing as the dominant form of bioenergy until at least 2020. Across the three scenarios, total land demand is estimated to increase by between 52 and 200 Mha which can be compared with a range of potential land availability estimates from the literature of between 240 million hectares to over 1 billion hectares.

Biomass feedstocks arise from combinations of residues and wastes, energy cropping and increased efficiency in supply chains for energy, food and materials. In addition, biomass has the unique capability of providing solid, liquid and gaseous forms of modern energy carriers that can be transformed into analogues to existing fuels. Because photosynthesis fixes carbon dioxide from the atmosphere, biomass supply chains can be configured to store at least some of the fixed carbon in forms or ways that it will not be re-emitted to the atmosphere for considerable periods of time, so-called negative emissions pathways. These attributes provide opportunities for bioenergy policies to promote long-term and sustainable options for the supply of energy for the foreseeable future.

9.1 Introduction

Bioenergy[1] features strongly in most global energy provision scenarios of the Intergovernmental Panel on Climate Change (IPCC 2014), Global Energy Assessment (GEA), International Energy Agency (IEA) – as well as environmentally-motivated NGOs – e.g. World Wildlife Fund for Nature (WWF), Greenpeace. Bioenergy provides nearly 200 EJ by 2100 across all recent IPCC scenarios with somewhat higher biomass utilization in low-carbon compared to high-carbon scenarios. Most biomass is derived from terrestrial photosynthesis with its associated use of natural resources (water, soil, carbon dioxide and sunlight). Projections of land required to meet demands for food, fiber and bioenergy are uncertain, complex and controversial given the emotive issues of food security, and the provisioning of cultural, spiritual and ecosystem services that are central to the human well-being.

[1] Provision of energy for heat, mobility, light and power in all its forms

Most low-carbon energy scenarios take a "non-biomass renewables first" approach, wherein other renewables (e.g., wind, solar, etc.) are used to provide energy services for which they are suitable. But some energy services are difficult to meet with non-biomass renewables. These services include transportation over long distances (aviation, long-haul trucking, ocean transport), heat for industrial processing, and dispatchable power, heat and electricity needed to complement the variable supply characteristics of other forms of renewable energy.

As shown in Figure 9.1, scenarios developed by five organizations (IPCC, IEA, GEA, WWF and Greenpeace) average 138 EJ by 2050 with a low of 80 EJ[2] and a high of 180 EJ. These absolute amounts of biomass-derived energy correspond to a range of 14 percent to over 40 percent of primary energy supply. In some scenarios developed for these studies, biomass is the single largest primary energy source supporting humanity in 2050.

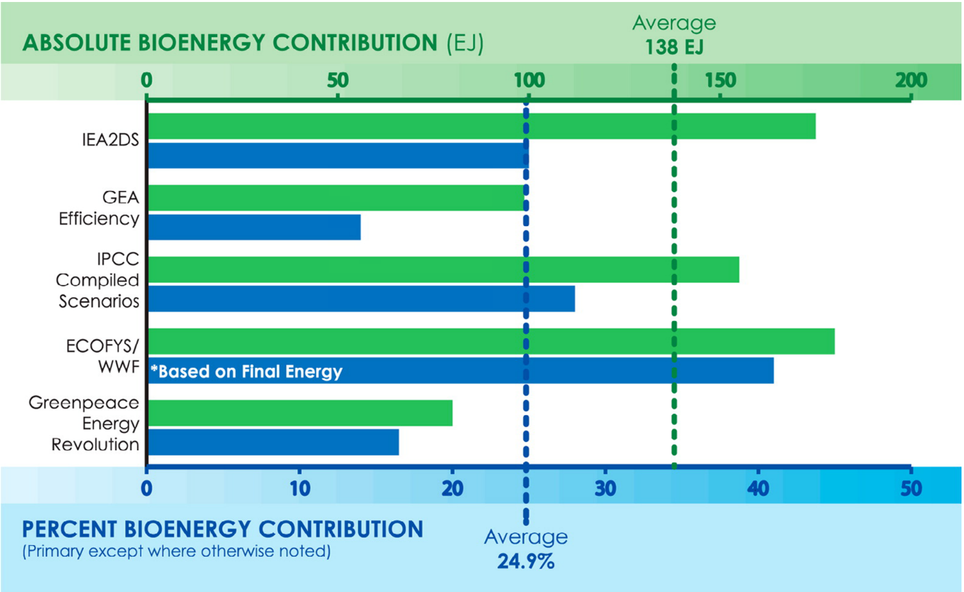

Figure 9.1. Bioenergy contribution in 2050: Comparison of five low-carbon energy scenarios (Dale et al. 2014).

Whilst most of the scenarios in these studies focus exclusively on terrestrial rather than aquatic forms of biomass provision for energy they acknowledge that aquatic systems may provide as yet unknown but potentially significant quantities of bioenergy in the future. Novel production and conversion technologies and adaptation strategies will be required over the next four decades in response to the effects of climate change on agriculture and forestry.

2 The lowest estimate reflects 70 EJ of traditional biomass use and a minimum of 10 EJ of "modern" bioenergy.

9.2 Key Findings

9.2.1 Global Land Availability and Projected Demand for Food, Fiber and Infrastructure

At the global level, the world's 13 Gha of land is categorized by the FAO into forest, pasture and crop ('arable and permanent crops') land (Table 9.1). Estimates of current and future land use and associated vegetation cover are, however, uncertain, as highlighted by Lambin and Meyfroidt (2011), and Fritz et al. (2011). The interactions among food, fiber and livestock supply systems involve multiple uses, feedbacks and rotations across categories which further complicate the assessment of current and future land demand. However, significant areas of land suitable for rainfed agriculture are currently un- or under-used offering the potential to reconcile future demands for food (including livestock), biodiversity protection, amenity and bioenergy. This potential is evaluated further in this section.

9.2.1.1 Land Demand

Most projections of global land demand reflect increasing pressures to provide services to the world's growing population. These services include provisioning services such as food, clean water, and energy, and regulating services such as biodiversity, air quality, hydrological, etc.

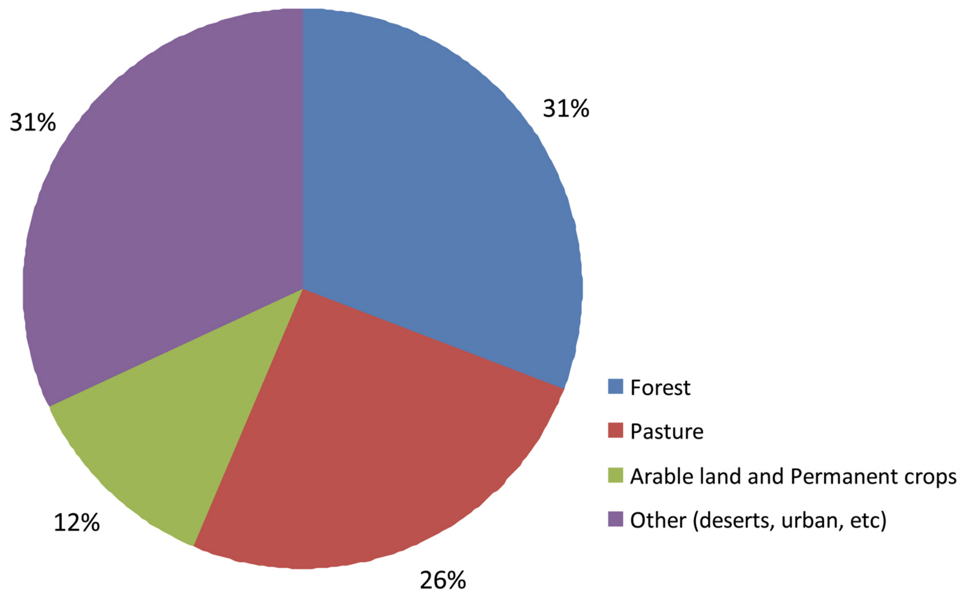

Figure 9.2. Global land use, 2010 (total land area 13.1 Gha; FAOSTAT 2014).

Land demands for food production are of central importance in estimating bioenergy potential. Land demand for fiber and construction materials is also important and forest management is expected to provide significant quantities of biomass for energy provision and other purposes. Of the world's 13 billion ha of land just over 2/3 is biologically productive and nearly 2/5 is actively managed for crops or livestock production (Table 9.1).

Global demand for food and feed is increasing by 2.4% per year (compound growth rate, FAO 2012). Over the last two decades, yields of the crops making the largest contribution to food and feed supply are increasing at slower rates than the previous two decades: 1.6% for maize, 1.0% for rice, 0.9% for wheat, and 1.3% for soy (also compound growth rates; Alexandratos and Bruinsma 2012). Over the previous century, global food prices declined by1% per year as yields outstripped global population growth and per capita demand. Based on population and dietary trends, the FAO projects a net increase in land used to grow food crops by 2050 of about 70 Mha resulting from an increase in land area under agriculture in developing countries of 130 Mha and a decrease of over

Table 9.1. Estimates of land use (Mha) in 2000 and 2010 (FAOSTAT 2014; Lambin and Meyfroidt 2011).

	Land use in 2000			Land use in 2010	Change (2010-2000)
	(Lambin and Meyfroidt 2011)		(FAOSTAT 2014; FAO 2006a)	(FAOSTAT 2014)	(FAOSTAT 2014)
	Low estimate	High estimate	Alternative estimate		
Cropland[a,c]	1510	1611	1514	1541	27
Pastures[b]	2500	3410	3420	3353	- 67
Forests	3143	3871	4085	4033	- 52
Planted forests[d]	126	215	161	274	49
Urban, built-up[d,e]	66	351	40	65	25

Notes

'Cropland' here is assumed to = FAO defined 'arable land and permanent crops' which include cultivated pastures and idle cropland

'Pastures' = FAO defined 'permanent meadows and pastures'

Total agricultural area (cropland + pastures combined) declined by 40 Mha over the past decade, primarily due to intensification in more developed nations

FAO (2006) data reflects sum of all reporting nations in the FRA 2010 (http://www.fao.org/docrep/010/ag049e/AG049E03.htm) data Tables; this estimate is not official because not all countries reported in 2000

Lambin and Meyfroidt (2011) estimate 3.3 Mha per year is converted to urban and built up areas, or about 33 Mha increase between 2000 and 2010

60 Mha in developed countries (Alexandratos and Bruinsma 2012). We use this FAO projection for the illustrative scenarios discussed below. It may be noted, however, that some projections feature little or no increase in global land planted with crops due to yield and market dynamics (Ausubel et al., 2012; Lambin, 2012), increasing production within urban areas, or sustainability-motivated dietary changes (WWF/Ecofys/OMA 2011).

9.2.1.2 Current Land Demand for Bioenergy

The IEA (2012a) estimates that c. 50 EJ of bioenergy was supplied in 2009 of which 32 EJ was in the form of traditional biomass, primarily used for household cooking. The IPCC (2011) reports traditional bioenergy in the range of 37-43 EJ for 2008. Recognizing uncertainties and under-reporting in many countries, we have estimated traditional bioenergy to be 40 EJ in 2010. Biomass production and land use in 2010 are summarized in Table 9.2. "Traditional bioenergy" represents 8% of total primary energy but occupies a negligible share of primary land use, being primarily derived from residues, wastes and harvesting from landscapes being managed for other purposes. Some forms of traditional bioenergy are inefficient and unsustainable, for example in systems providing charcoal to urban areas based on harvests that exceed regeneration rates. In fact, traditional bioenergy is now widely believed to be putting unacceptable pressures on the environment including as a driver of deforestation as discussed in Lynd et al. (in press). Despite this, there is a significant potential and need for finding alternatives where modern bioenergy solutions could make more efficient use of the biomass and reduce

Table 9.2. Bioenergy supply, feedstocks and associated land demand estimates for 2010.

	Global Production EJ	Feedstock	Land Occupied (million ha)
Global Primary Energy	520	Predominantly fossil	Not quantified
Total Bioenergy	62	All forms, traditional and modern	c. 50
Traditional Bioenergy	40	Mostly from residues, wastes and harvesting parts of live trees (pollarding)	Not quantified
Modern Bioenergy	21.5		c. 50
• Biofuels	4.2	Agricultural crops	<13
• Heating (domestic and industrial)	13.0	2/3 residues and wastes, 1/3 energy crops (lignocellulosic)	c. 30
• Electricity	4.1	50% from energy crops + 50% from residues and wastes	c. 10

Notes: derived from own calculations based on IEA (2010; 2011a+b; 2012a+b) data. Biofuels (aggregate of national production data for 2010) from F.O. Lichts Interactive Data, (2013). Traditional bioenergy data derived from IEA (2011b) and Chum et al. (2011)

the pressure on the environment (IPCC 2014; Figure 9.11). However, we have not identified reliable estimates of the land areas affected by traditional biomass harvesting. An illustrative estimate of future land demand for bioenergy is provided in Section 9.3.

In order to estimate land use for bioenergy in 2010 we assume there is no land demand associated with the use of wastes and residues and that remaining biomass demand for heat and electricity is sourced from energy crops with a global average annual yield of 10 oven dry metric tons per hectare. For domestic heating (excluding traditional bioenergy) the share of biomass derived from residues was assumed to be 2/3 with 1/3 from energy crops whilst for industrial 'power' 90% of the biomass was assumed to be derived from residues. For biofuels, land demand was estimated based on Langeveld et al. (2013) who calculated individual biofuel and associated co-product yields for each biofuel crop as used by the major biofuel producing countries (Table 9.3). Land demand for biofuels is calculated net of that land associated with co-products.

Table 9.3. Crop, biofuel and co-product yields (metric tons per hectare, as harvested or produced, variable moisture contents).

Region	Feedstock	Crop yield	Biofuel yields		Co-product	
			Langeveld et al. (2013)	This study	Langeveld et al. (2013)	This study
		(t/ha)	(l/ha)	(l/ha)	(t/ha)	(t/ha)
Brazil	Sugarcane	79.5	7200	7200	–	8.7
Brazil	Soybean	2.8	600	600	1.8	1.8
USA	Corn	9.9	3800	3800	4.2	4.2
USA	Soybean	2.8	600	850	1.8	1.8
USA	Corn stover	3.3		819		0.7
EU	Wheat	5.1	1700	1700	2.7	2.7
EU	Rapeseed	3.1	1300	1300	1.7	1.7
EU	Sugarbeet	79.1	7900	7900	4.0	4.0
Indonesia & Malaysia	Palm Oil	18.4	4200	4200	4.2	4.2
China	Corn	5.5	2200	2200	2.9	2.9
China	Wheat	4.7	1700	1700	2.5	2.5
Mozambique	Sugarcane	13.1	1100	1100	–	1.4
South Africa	Sugarcane	60.0	5000	5000	–	6.6

Source: adapted from Langeveld et al. (2013) using biofuel and co-product yields calculated from literature. For this study, US soybean biodiesel yields were revised from more recent data provided in Chapter 10, this volume

9.2.1.3 Land Availability

There is substantial controversy about the future availability of land for food or bioenergy provision (Lambin 2012) with estimates from recent studies of land available for bioenergy in 2050 ranging from less than 250 Mha to more than 1 billion ha (Table 9.4). Many of these studies use a "food and fiber first" approach wherein

Table 9.4. Estimates of land availability for bioenergy crops in recent studies (in 2050).

Reference	(Sustainability) Constraints	Land use types	Land area available (Mha)
Hoogwijk et al. (2005)	Ensuring food security; Protection of biodiversity	Abandoned agricultural land (100%)** Rest land (10 – 50%) #	Abandoned: 600-1500 Rest land: 300-1400
Smeets et al. (2007)	Ensuring food security; Protection of biodiversity; Avoiding deforestation	Surplus agricultural land (100%)	729-3 585
Campbell et al. (2008)	Ensuring food security; excluded all agricultural lands; Protection of ecosystems; Releasing carbon stored in forests	Abandoned agricultural land (100%)	385-472
Field et al. (2008)	Ensuring food security; Protection of biodiversity and ecosystems; Avoiding deforestation	Abandoned agricultural land (100%)	386
Van Vuuren et al. (2009)	Ensuring food security; Consider water scarcity; Protection of biodiversity; Avoiding soil degradation	Abandoned agricultural land (75%) Grassland (25%)	1 500
WBGU, (2009)	Ensuring food security; Protection of biodiversity; Avoiding deforestation; Consider water scarcity and avoid competition for water; Excluded all agricultural land, unmanaged land with a long carbon payback periods, degraded land, wetlands, and environmentally protected land	Remaining suitable land after excluding all agricultural land, unmanaged land, degraded land, wetlands, environmentally protected land, and land rich in biodiversity	240-500
Fischer et al. is it (2009)	Ensuring food security; Excluded forests, sloping land, and low productive land	Cropland not needed for food, feed and fiber supply	700-800

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Reference	(Sustainability) Constraints	Land use types	Land area available (Mha)
Erb et al. (2009)	Ensuring food security: land needed for food and feed was excluded; Forests and unproductive or uneconomic land were excluded	Cropland not needed for food and fiber supply	230-990
Nijsen et al. (2012)	Ensuring food security; Avoiding deforestation; Excluded forest areas, cropland, pastoral land and urban areas	Marginal and degraded lands	247
Smith et al. (2010)	Bioenergy production on 'spare land' which is cropland or grazing land not required for food production, assuming increased but still sustainable stocking densities of livestock based on Haberl et al. (2011). High bioenergy value: short-rotation coppice or energy grass directly replaces fossil fuels, energy return on investment 1 : 30 dry-matter biomass yield 10 t/ha.yr. Low bioenergy value: ethanol from maize replaces gasoline and reduces GHG by 45%, energy yield 75 GJ/ha.yr (Chum et al. 2011)	'Spare land'	390 (spare cropland) + 490 (livestock grazing area)
Wicke et al. (2011)	Protection of biodiversity; Forests, wetlands and protected areas were excluded	Salt affected lands	971
Lambin & Meyfroidt (2011)	Unused productive land		356 to 445
WWF, Ecofys, OMA (2011)	Rainfed potential (with additional exclusions including 'additional land for biodiversity protection, human development, food demand.')	Rainfed potential land	673

Modified from Batidzirai et al. (2012)

* Estimates are for 18 World regions over a timeframe 2050-2100

‡ Estimates are for 11 world regions

'Rest land' is the remaining land area (from total available land) after taking into consideration 'abandoned agricultural land' and 'low-productive land' and further subtracting/correcting for grassland areas, forest land, urban areas and bioreserves. 'Rest land' includes mainly savannah, shrubland and grassland/steppe. The overall assumption is that energy crop production should not affect food and fiber production, or biodiversity protection

** Percentage values indicate the fraction of the land category that is assumed to be put under energy crops in a respective study

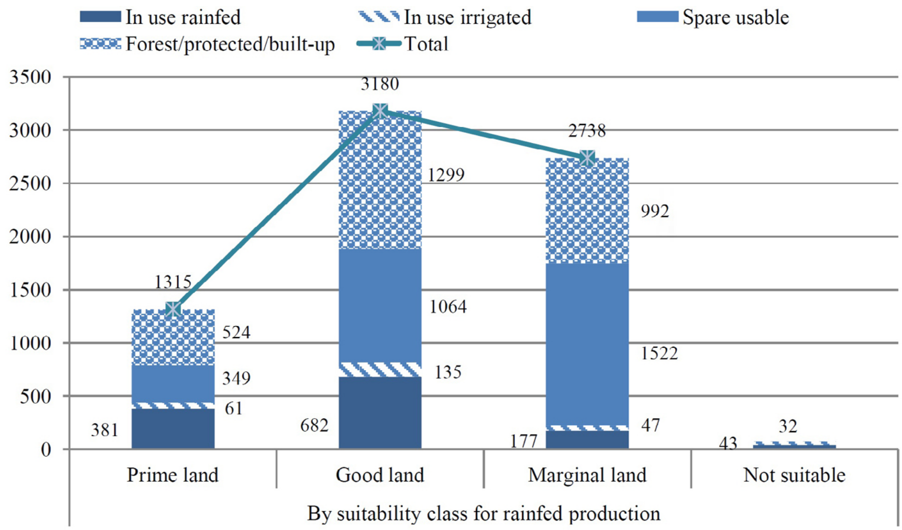

Figure 9.3. World land available (million ha) with potential for rainfed crops (Alexandratos and Bruinsma 2012).

land available for bioenergy is obtained by subtracting projected land required for food and fiber from the total land area considered suitable for bioenergy production. Additional constraints on land may then be layered on top of the land 'available for bioenergy' including infrastructure / urban and biodiversity protection as shown in Table 9.5, further decreasing land availability. This approach is considered in this section – first for land suitable for rainfed agriculture, and then for land that could potentially be used for bioenergy crops but is not suitable for rainfed agriculture.

Land Suitable for Rainfed Agriculture

The FAO (Alexandratos and Bruinsma 2012) estimates that there is about 1.4 Gha of 'prime and good' land and a further 1.5 Gha of marginal land that is 'spare and usable' (Figure 9.3). 960 Mha of this land is in developing countries with much, if not all, of this land currently under pasture / rangeland. This remaining land is unevenly distributed with 'some 85 percent of the remaining 960 million ha in developing countries in sub-Saharan Africa (450 million ha) and Latin America (360 million ha); very little or no land remaining in the other regions.' (Alexandratos and Bruinsma 2012).

Of the total 4.5 Gha classified by Fischer et al. (2011) as potential agricultural land, current row crop agriculture uses 1.3 Gha with an additional 70 to 130 Mha likely to be required to meet future food needs. As already noted, FAO (2012) estimates that the net additional land requirement is 70 Mha, with an additional 130 Mha in developing countries and a loss of 60 Mha in developed countries to infrastructure, recreation etc. Forestry, protected lands and urban demands account for a further 1.8 Gha according to Alexandratos and Bruinsma

(2012). Whilst WWF (WWF/Ecofys/OMA 2011) estimate that c. 54 Mha is needed for biodiversity protection Alexandratos and Bruinsma (2012) state that 107 Mha of the total 'potential' land is classified as 'strictly protected land' with 80 Mha of protected land in the 'very suitable' and 'suitable' classes of potential agricultural land.

Table 9.5. Current and future land use and demand (Mha; 2010 and 2050) based on FAO (Alexandratos and Bruinsma 2012).

Area (Mha)	2010		2050		
	Mha	% share global land	Mha	% share	% share potential agricultural land
Global Land (total)	13,013	100%	13,062	100%	
Agricultural land	4,894	38%	5,053	39%	
Arable land and permanent crops	1,541	12%	1,661	13%	
Arable land	1,388	11%	1,518	12%	34%
Permanent crops	153	1%	143	1%	
Permanent meadows and pastures	3,353	26%	3,391	26%	
Forest area	4033	31%	3,953	30%	
Land availability for rainfed agriculturea:					
Total (Very Suitable + Suitable)	4,495		4,495		
Of this needed for:					
Row crop production	1,260	10%	1,260		28%
Additional agricultural land by 2050 for increased food production			130b		3%
Forest, protected and urban	1,824	14%	1,824		41%
Urban and infrastructure			100		2%
Land degradation			87		2%
Forest plantation			109		2%
Of this needed for biodiversity protection			80		2%
Potentially available	1,411		905		20%

Notes

a. VS+S = very suitable and suitable for rainfed agriculture as defined under the Global Agroecological Zones (GAEZ) project. (Fisher et al. 2011)

b. Assumes all new demand for food production (130 Mha increase in land for food by 2050 as estimated by Alexandratos and Bruinsma (2012)) will come from the Very Suitable (VS) + Suitable (S) land categories

By 2050, 1.2 Gha of remaining land could be considered as available for other uses including bioenergy feedstock production (Table 9.5). This can be compared to the estimate by WWF/Ecofys/OMA (2011) of 0.7 Gha of available land using more conservative assumptions. This available land is assumed to come exclusively from pasture lands where there is enormous potential for increased efficiency and intensification of livestock production.

Land not Suitable for Rainfed Agriculture

There is also the possibility to exploit land that is not suitable for conventional rainfed agriculture. Of the 3.2 Gha of land identified by the FAO (Fischer et al. 2011) as having rainfed potential for agricultural production, 1.8 Gha are classified as moderately suitable with an ‘unused’ balance of 1.0 Gha. There are an additional 990 Mha of marginally suitable land of which 600 Mha are classified as currently unused. These lands are assessed by the FAO to be capable of providing 20 to 60% of the maximum attainable rainfed yield of ‘very suitable (prime)’ land. It may be noted, however, that this statement is in reference to food crops and may not apply to bioenergy crops.

Such degraded, marginal and abandoned agricultural land, represents a significant potential for biomass production. However the implications of lower yields and lacking or poor infrastructure on the costs of bioenergy production need to be considered.

Land categories also include saline lands and lands with vulnerable soils i.e. prone to flooding, steep slopes, and where climatic factors limit the length of growing period. Wicke et al. (2011) estimate that there are 970 Mha of salt affected land globally (Table 9.4) and WWF/Ecofys/OMA (2011) estimates that there are a further 2.5 Gha that are ‘not suited’ for rainfed agriculture but might be viable for alternative non-food cropping or soil reclamation through phytoremediation.

These emerging limitations, particularly for some novel oilseed crops e.g. Jatropha and Camelina, have led to the search for alternative crops that have the potential to be highly productive on marginal and degraded lands (see Chapter 10, this volume), including:

- CAM plants (agave),
- Drought tolerant trees, grasses and other crops (cassava, sorghum, camelina, arundo donax, etc.),
- Salt-tolerant crops.

It is therefore clear that with supportive policies and investments very considerable areas of land not suitable for food crop production could be considered for bioenergy feedstock production and which could provide significant amounts of modern bioenergy with clear links to energy access for the rural poor (Table 9.6).

Table 9.6. Estimates of global bioenergy potential on degraded or marginal lands (FAO, UNEP 2014).

Source	Lands included	Area (million ha)	Biomass yield (t/ha/year)	Bioenergy Potential (exajoules)
Van Vuuren et al, 2009	Global degraded lands not in use as forest, cropland, pastoral land or urban	n/a	2.5 - 33	31
Hoogwijk et al, 2003	Abandoned agricultural land and degraded grassland systems	430-580	1 - 10	8 - 110
Tilman et al, 2006	Agriculturally abandoned and degraded lands	500	4.74	45
Field et al, 2008	Abandoned pastoral lands and croplands not in use as urban or forest	386	3.55	27
Campbell, 2008	Abandoned pastoral lands and croplands not in use as urban or forest	385-472	4.3	32-41

9.2.2 Illustrative Example: Brazilian Land Use and Potential Availability

Brazil occupies a uniquely important place in the provision of global food and energy security with bioenergy having been central to its energy planning since the mid-1970s. It is also uniquely important in climate change mitigation and adaptation with a strong track record in using renewable energy but also in terms of managing the emissions from land use change. The carbon stocks that are embedded in the Amazonian forest and the associated biodiversity of its forests and cerados (savanna ecosystems) have focused the world's attention on the land use, energy security and deforestation policies it has developed.

Whilst deforestation continues to be a concern despite the major reductions achieved in deforestation rates over the last decade, over the last three decades Brazil has become a leading exporter of food products and the world's second largest supplier and user of bioenergy after the USA (Nepstad et al. 2014). Its agricultural sector now produces 90 million metric tons of cereals (3% of 2012 global production) including 71 million tons of corn (maize); in addition, 65 million tons of soybeans were produced making Brazil the world's second largest producer. It is also the world's largest sugarcane producer, producing 721 million tons of sugarcane in 2012 (IBGE 2012). From the sugarcane it supplied 25 billion liters of ethanol and from soy oil 2.5 billion liters of biodiesel in 2010, totaling 25% of global biofuels (0.62 EJ biofuel out of 2.5 EJ global). Significant amounts of co-generated electricity were also produced from bagasse, the by-product of sugar and ethanol production. (see Chapter 12, this volume).

Brazil is also a large livestock and meat producer, producing 24 million tons of meat in 2010 (FAOSTAT 2014; IBGE 2012). The country exports agricultural commodities, totaling more than US$ 88.6 billion in 2012 (MAPA 2012). Soybean and its derived products rank first, followed by meat products and products from the sugarcane complex.

Over the last 22 years, the total harvested area increased from 45.9 Mha in 1990 to 63 Mha in 2012. Sugarcane increased from 4.3 Mha in 1990 to 9.7 Mha in 2012. In the same period, soy's harvested area grew from 11.5 Mha to 24.9 Mha, increasing by 117% whilst productivity rose by 50%. Sugarcane's planted area increased by 130%, productivity increased by 20%. Over the last 22 years, Brazil has seen both an increase in total harvested area and in the share of land devoted to soybean, corn and sugarcane. Thus, the expansion in sugarcane and soybean production in Brazil results from a combination of cropland expansion and productivity increases.

Another factor at play in Brazil is the increase in cropping intensity. Alexandratos and Bruinsma (FAO 2012) expect 80% of the projected growth in crop production in developing countries to come from intensification, with yield increases responsible for 73% and higher cropping intensities for 6%. Langeveld et al. (2013) reported a multiple cropping index (MCI) (similar to cropping intensity) of 0.86 for Brazil in 2010 with other developing countries attaining significantly higher MCI's e.g. China 1.45 and Mozambique 1.08. This indicates a potential for increased production in Brazil resulting from increased cropping intensity. This is supported by data on corn productivities in Brazil: from 2003 to 2012, the harvested area increased due to an expansion in double cropping. In 2003, second season corn accounted for 25.3% of total corn harvest. By 2012, this had increased to 51.4% (Figure 9.4).

Projections made in 2012 by the Brazilian Ministry of Agriculture indicate that, by 2022, there will be considerable production increases across most of its main agricultural products (MAPA 2012). The study also indicates that the growth in agricultural production will be based on productivity (yield and cropping intensity) gains rather than area expansion. For example, the total grain crop production (soybean, corn, rice, beans, wheat) is expected to increase by 21.1% although with an area expansion of only 9%. The total agricultural planted area is expected to increase by 7 Mha, from 64.9 Mha in 2012 to 71.9 Mha in 2022. However, sugarcane is considered separately because the government plans to limit its expansion to 63 Mha (Somerville et al. 2010 and Chapter 10, this volume).

In São Paulo, recent sugarcane expansion has occurred over both pasture and annual crop areas (Rudorf et al. 2010). However, in the western part of the state, most expansion occurred in pasture land, because of intensification of livestock production that effectively freed-up pasture land for sugarcane plantations. Agricultural census data show that over the last 7 decades, the average number of heads per ha has steadily increased (Figure 9.6). For instance, while São Paulo, Paraná and Santa Catarina states have more than 1.5 heads per ha, Mato Grosso, Mato Grosso do Sul, Minas Gerais and Goiás, responsible for more than 45% of the nation's cattle herd, show stocking rates ranging from 0.93 to 1.15 head/ha. For Brazil as a whole, according to Martha et al. (2012) the beef yield per ha more than tripled between 1985 and 2006 with stocking density increasing from 0.71 to 1.11 head/ha over that period. Stocking density alone therefore was responsible for less than 50% of the observed

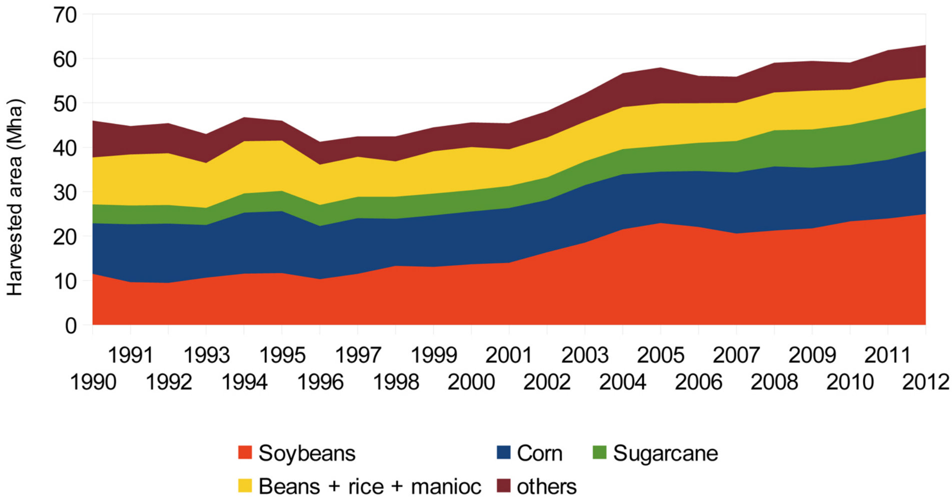

Figure 9.4. Harvested area for soybean, corn, sugarcane, beans + rice + manioc and other crops in Brazil, 1990 to 2012 (IBGE 2012).

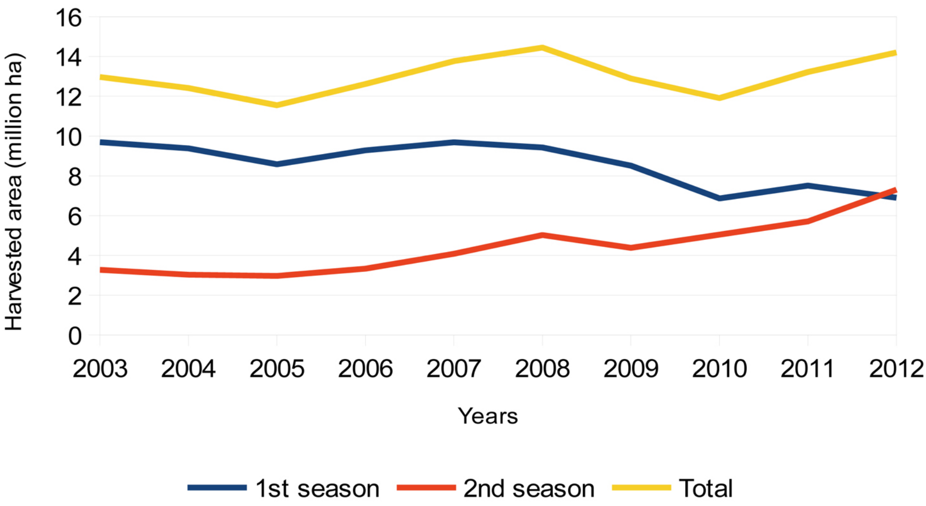

Figure 9.5. Corn harvested area, Brazil, 2003 to 2012. Total harvested area increased due to an increase in second season corn (double cropping), despite a reduction in planted area in the first season (IBGE 2012).

yield gain. At the same time improved animal production performance also helped raise the meat yield from 17.4 to 40.1 kg/head illustrating the interaction between improved pasture land and animal management practices.

FAOSTAT (2014) states that there were 196 Mha of ‘permanent meadows and pastures’ in Brazil in 2010, similar to Europe’s entire pasture area. However, the 2006 Brazilian agricultural census only identifies 102 Mha of planted pastures with 9.9 Mha declared as being degraded planted pastures (IBGE 2007). The National Confederation of Agriculture estimates that there are 140 Mha of pasture in Brazil of which 56 Mha (40%) are considered degraded (Horta Nogueira and Silva Capaz, 2013). Horta Nogueira and Silva Capaz (2013) go on to estimate that 60 to 75 Mha of degraded pasture land could be recovered and Somerville et al. (2010) discuss the potential for generating surplus land through improved pasture management in Brazil. Taking into account the Agricultural Census’ estimates, the degraded pasture area is much larger than the predicted 7 Mha increase in agricultural area estimated by the Ministry of Agriculture. It matches the potential sugarcane production area and proposed limits of its expansion to 63 Mha (Somerville et al. 2010). Thus, actions to improve pasture conditions, along with livestock production intensification, can effectively make large amounts of land available for alternative uses.

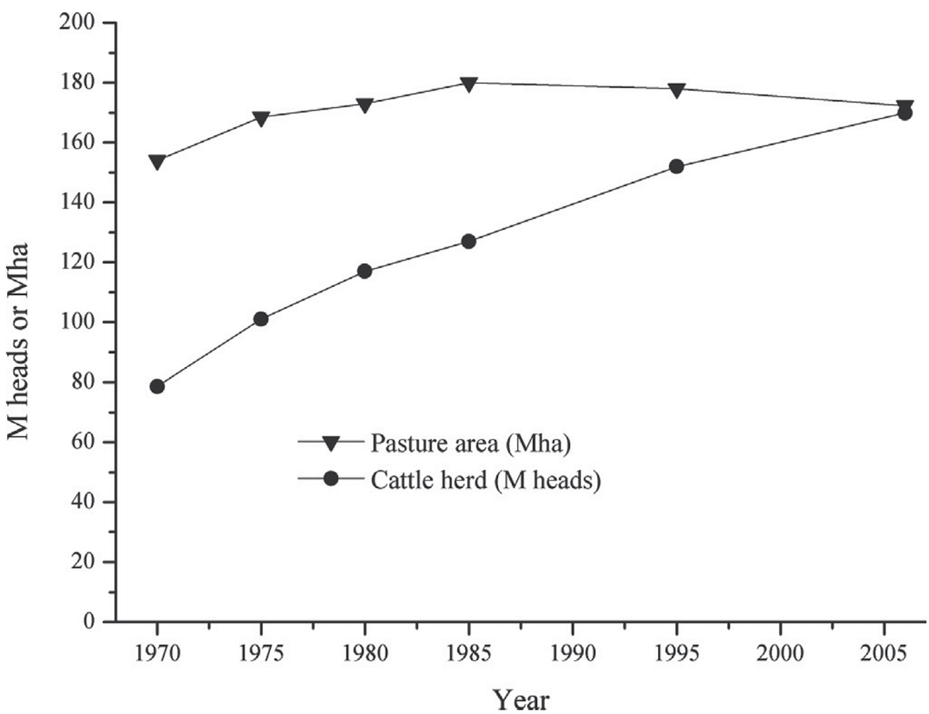

Figure 9.6. The evolution of pasture area and cattle herd in Brazil (IBGE 2007; Horta Nogueira and Silva Capaz 2013).

9.2.3 Land Use Intensities for Bioenergy Supply

Calculating future net land demand for bioenergy, as with food crops, is inherently uncertain. It requires assumptions to be made about the scale of energy demand over time for each bioenergy sub-sector (see section 9.2.4) future yield growth rates for the energy crops, location / climate, land management and inputs and conversion efficiencies. Therefore, the potential land demand for each bioenergy sub-sector needs to be assessed individually as the likely use of dedicated energy crops, by-products or co-products of conventional crops, residues and conversion efficiencies is specific to that sector and location. Direct land demand can then be calculated for each bioenergy sub-sector based on an assumed level of energy demand and an assessment of the appropriate feedstock and their average productivities and conversion efficiencies for given locations. Dynamic global average land use intensities (Mha/EJ) from 2010 to 2050 are derived for each bioenergy sub-sector (biofuels, bioelectricity and bioheat) in the following sub-sections. The use of crop and forestry residues for bioenergy is assumed to have no direct land demand.

9.2.3.1 Biofuels

For biofuels, Langeveld et al. (2013) used a novel methodology for estimating net land demand based on observational land use data from the FAO. Assessing the 34 largest biofuel producing countries[3], which accounted for over 90% of global production in 2010, they found that the increase in biofuel production (2000 to 2010) resulted in a gross land demand of 25 Mha out of a total of 471 Mha arable land. However, nearly half the gross biofuel land area was associated with commercial co-products (primarily animal feeds e.g. distillers dry (and wet) grains; soy and rape meal; Table 9.7) leaving a net direct biofuel land demand of 13.5 Mha (2.4% of arable land area). Despite this increased demand for land for biofuel feedstock production, overall there was a decline in agricultural land area of 9 Mha in the countries evaluated. Increasing cropping intensity was found to have more than compensated for the decline in agricultural land resulting in an estimated additional 42 Mha of harvested area.

Using conventional methodologies for calculating potential land demand the IEA (2011a) estimates likely land demand of 30 Mha for supplying the current (2010) biofuel demand of 1.5 EJ. This is projected to increase to 32 EJ by 2050 with an associated land demand of c. 100 Mha with land use intensity decreasing from 20 Mha / EJ to 3.2 Mha/EJ by 2050 as advanced (including cellulosic) biofuel production systems are commercialized (Table 9.8). We assume that advanced / lignocellulosic biofuels are assumed to be produced using 50% residues and wastes and 50% dedicated energy crops by 2050.

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[3] 27 EU countries plus 7 non-EU countries (Brazil, USA, Indonesia, Malaysia, China, Mozambique and South Africa.

Table 9.7. Biofuel productivity (GJ/ha) by country and feedstock (based on Langeveld et al. 2013).

Country/ Region	Feedstock	Langeveld et al.	This study
Brazil	Sugarcane	152	153
Brazil	Soybean	18	20
USA	Corn	80	81
USA	Soybean	18	28
USA	Corn stover	27	17
EU	Wheat	37	36
EU	Rapeseed	43	43
EU	Sugarbeet	168	168
Indonesia and Malaysia	Palm Oil	90	138
China	Corn	46	47
China	Wheat	36	36
Mozambique	Sugarcane	23	23
South Africa	Sugarcane	107	106

9.2.3.2 Bioelectricity

Bioelectricity provision has important development and energy access dimensions (www.se4all.org). The IEA (2012b) projects bioelectricity generation to increase from c. 0.9 EJ in 2010 (c. 250 TWh) to c. 11 EJ (3100 TWh) in 2050. Assuming a net conversion efficiency of 30% in 2010 would mean a primary bioenergy demand of 3 EJ/yr in 2010, rising to 28 EJ/yr in 2050, with an assumed increase in conversion efficiency to 40%.

In our illustrative scenario, we assume that the feedstocks for bioelectricity provision are derived from 50% dedicated energy crops with yields increasing from 10 odt/ha.yr in 2010 to 18 odt/ha.yr in 2050 (see Figure 9.7 and Chapter 10, this volume, for yield justification). The remaining 50% of the feedstock demand is assumed to be derived from residues and wastes with no associated land demand. The combination of increasing energy crop yields and the use of wastes and residues results in a declining LUI from 2.8 to 1.5 Mha/EJ in 2050 (Table.9.9).

9.2.3.3 Bio-Heat

The role of biomass in heating and cooling is expected to grow considerably in the future. However, in the IEA's World Energy Outlook and Bioenergy Technology Roadmap (2011b and 2012b) it is clear that biomass provides significant amounts of heating energy to both the domestic (predominantly traditional bioenergy in the

Table 9.8. Biofuel and land demand in 2010 and 2050 as estimated by the International Energy Agency (IEA 2011a) and this study (derived from Langeveld et al. 2013).

Year	2010	2050
Biofuel Energy Demand (EJ)		
IEA (2011a)	1.5	32
This study	4.2	40
Land demand (Mha)		
IEA (2011a)	30	100
This study	21.8	115
Land intensity (Mha/EJ) derived from:		
IEA (2011a)	20	3
Langeveld et al. (2013)	7.0	-
This study	7.0	4.7

Notes: IEA assumes a very strong growth in lignocellulosic / advanced biofuels 'The total feedstock required in 2050 to meet the ambitious goals of this roadmap is around 65 EJ of biomass. It is assumed that 50% of the feedstock for advanced biofuels and biomethane will be obtained from wastes and residues, corresponding to 1 Gt of dry biomass, or 20 EJ.'

Langeveld et al. (2013) evaluate historic net land demand for biofuel production between 2000 and 2010 allowing for co-products

This study- Land Use Intensity (LUI) for conventional biofuels assumed to decrease in-line with a projected increase in conventional food crop (cereal) productivity of c. 1% per year and an increase in advanced / lignocellulosic biofuel production growing at 10% per annum from 2015 in the '200 EJ' scenario

rural areas of developing countries but increasingly in wood chip and pellet boilers in developed countries) and industrial and buildings sectors and as high-grade heat to industry. The IEA estimated that 25% of bioenergy in 2009 was consumed in these sectors (IEA 2011b).

Table 9.9. Bioelectricity land demand and land use intensity, 2010 and 2050.

Year	2010	2050
Bioelectricity Energy Demand (EJ)a	4.1	28.9
Bioelectricity Land demand (Mha)	11.4	44.2
Land intensity (Mha/EJ)	2.8	1.5

Notes: assumes 50% of energy is derived from residues and wastes and the remaining 50% is derived from energy crops with yields starting at 10 odt/ha.yr in 2010 and growing at 1.5% per year to18 odt/ha.yr in 2050

a: in the '200 EJ' and '150 EJ' scenarios

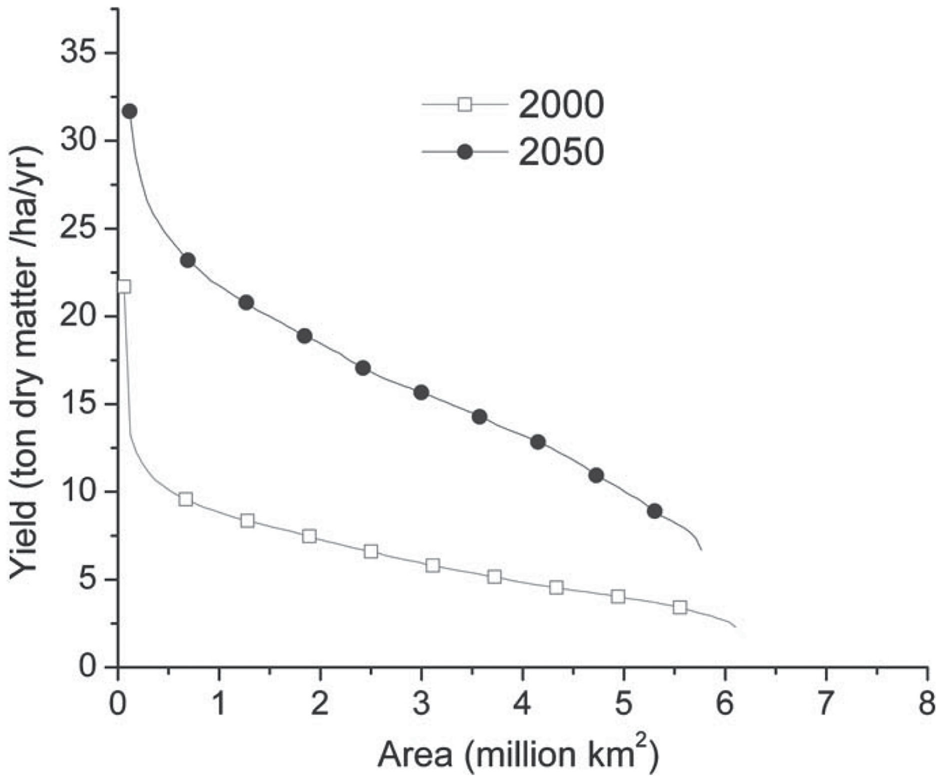

Figure 9.7. Area–yield curve for the OECD reference scenario in 2000 (lower curve) and 2050 (upper curve). van Vuuren et al. (2009).

Important links exist between energy provision for food (and fiber) production and bioenergy that are likely to grow over the coming decades. These linkages are likely to be particularly important for food supply chains which could become increasingly reliant on bioenergy provision for secure and cost-effective energy services at source.

Table 9.10. Estimated bioheat land demand and land use intensity, 2010 and 2050.

Year	2010	2050
Bioheat Energy Demand (EJ)a	13	67
Bioheat Land demand (Mha)	13	44
Land intensity (Mha/EJ)	1.0	0.8

Notes: assumes 2/3 of the energy input is derived from residues and wastes and the remaining 1/3 is derived from energy crops with yields starting at 10 odt/ha.yr in 2010 and growing at 1.5% per year to 2050

[a] 200 EJ scenario

9.2.4 Dynamics of Bioenergy Supply

Illustrative scenarios for the supply of 100, 150 and 200 EJ/yr of bioenergy by 2050 (Figure 9.8) have been developed to investigate the potential scale of land demand for bioenergy under a range of bioenergy sub-sector portfolios projected from 2010 to 2050 (Figure 9.9 and 9.10). In these scenarios, the overall land demand ranges from 50 Mha to 200 Mha with biofuels being the most land intensive sub-sector. Despite traditional biomass energy consuming between 56% and 30% of total bioenergy it has not been possible to estimate its current land requirements and there is considerable uncertainty about the future environmental impacts of its continued and expanded consumption.

Of the total estimated land demand, between 40 and 50 Mha is required to grow the feedstocks for conventional biofuels, which provide between 7% and 17% of primary energy in 2050 (Table 9.11). The land demand for conventional biofuels is thus equivalent to about two thirds of the expected increase in agricultural land demand for food production by 2050 (Alexandratos and Bruinsma 2012). The remaining 10 to 150 Mha of land demand for lignocellulosic biomass from energy crops could be met from a combination of increased agricultural land, pasture land arising from pasture intensification and perhaps dietary change. Additional feedstocks and land for bioenergy could effectively be made available from increased forestry activities where significant fractions of biomass should be harvested from existing forestry

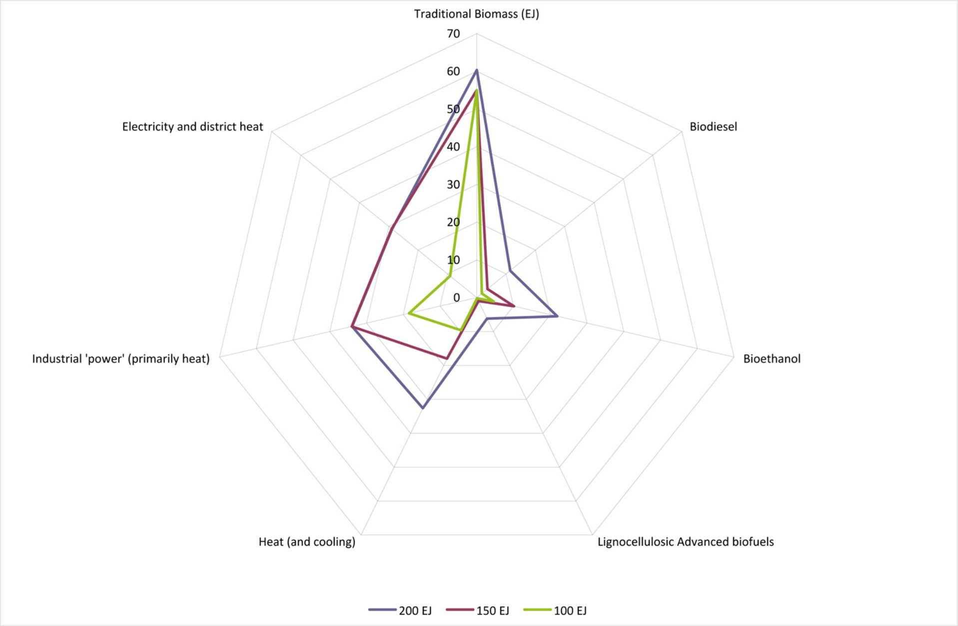

Figure 9.8. Energy provision portfolio in 2050 for each bioenergy sub-sector and bioenergy provision scenario (100, 150 and 200 EJ/yr).

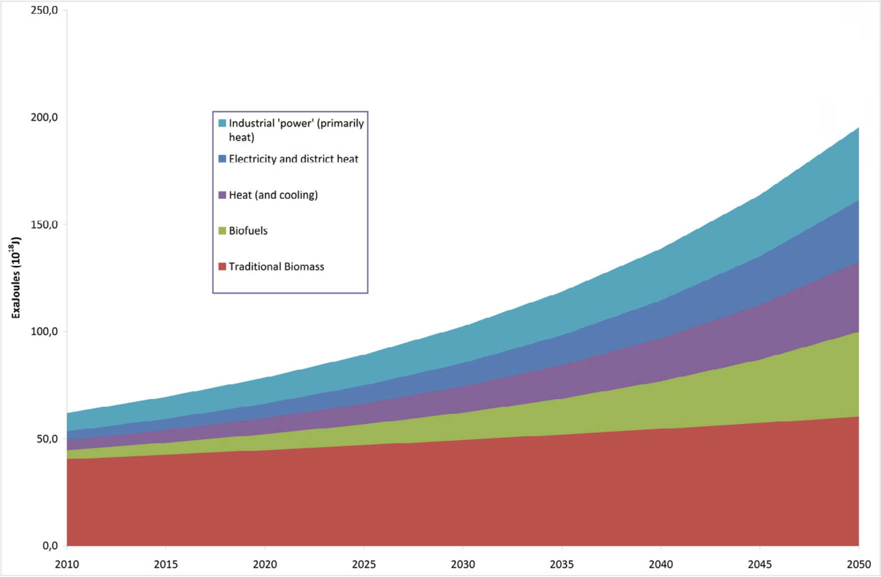

Figure 9.9. Global bioenergy (modern and traditional) demand projections under the '200 EJ/yr' scenario (2010 to 2050).

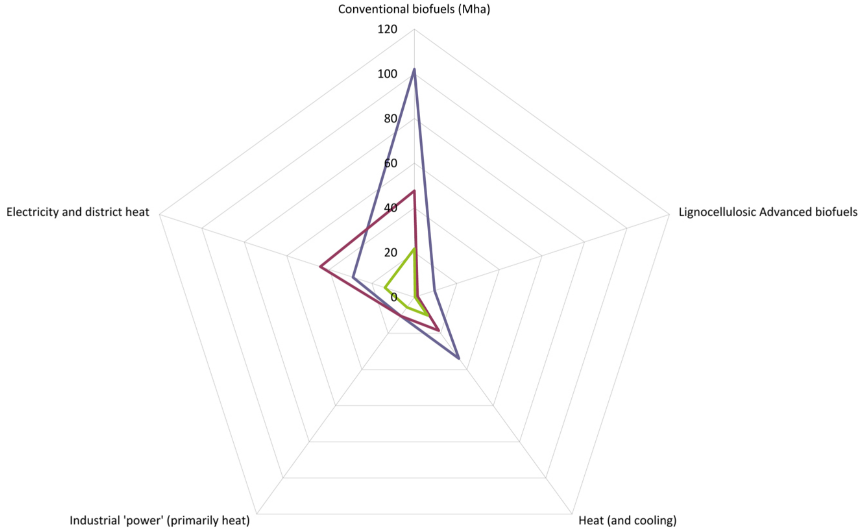

Figure 9.10. Land demand portfolio in 2050 for each bioenergy sub-sector and bioenergy provision scenario, 100, 150 and 200 EJ/yr.

plantations in order to maintain and enhance forestry yields and standing stocks (IPCC 2014).

The estimates for land demand for bioenergy are calculated using a decreasing land use intensity (land required per unit of energy produced) between 2010 and 2050 with overall bioenergy LUI falling from nearly 2 Mha/EJ to 1 Mha/EJ in 2050, primarily as a result of expected increases in yields of conventional and novel energy crops (Table 9.12; see section 9.2.3). Further reductions in land use intensity would be expected through increased cropping intensity and raised supply chain efficiencies for both modern bioenergy supply chains but perhaps more importantly for food supply chains effectively increasing the supplies of bioenergy feedstocks with no net increase in land demand or possibly even a decline as highlighted by Langeveld et al. (2013) for global biofuels, Kim and Dale (2011) and Oladosu et al. (2011) for corn ethanol in the US, and Sousa and Macedo (2010), and Seabra et al. (2011) for sugarcane ethanol in Brazil.

Table 9.11. Land demand for bioenergy and share of total, agricultural and arable land in 2010 and 2050.

	2010				2050	
	Land demand	share global land	share agricultural land	share arable land	Land demand[a]	share potential agricultural land[a]
	Mha	%	%	%	Mha	%
Biofuels (net; co-products)	14	0.1%	0.3%	1.0%	102, 48, 22	11, 5, 2
Bioelectricity	11	0.1%	0.2%	0.8%	29, 44, 14	3, 5, 2
Bioheat	28	0.2%	0.6%	2.0%	44, 29, 16	5, 3, 2
Total modern bioenergy	53	0.4%	1.1%	3.8%	200, 120, 52	22, 13, 6

Notes

a: for the 200, 150 and 100 EJ/yr scenarios

Increased land demand might be expected for bioenergy where adverse economic and climatic conditions, affect future yield potentials. However, even under such adverse conditions, bioenergy could be developed to provide secure off-take markets for damaged goods or provide some return for crops that have failed or that are contaminated e.g. with mycotoxins. During periods of excess production, bioenergy systems could be configured to provide a productive off-take again setting a price floor for biomass (agricultural and forestry) and enhancing resilience for farmers.

Table 9.12. Land use intensities (Mha/EJ) for biofuels, bio-heat and bio-electricity (2010, 2035 and 2050).

		2010	2035	2050
Basic Land demand calculation	15 odt/ha	3.70	3.70	3.70
Overall LUI		1.99	1.36	1.06
Conventional biofuels		7.01	5.5	4.7
Advanced biofuels	50% Residue share	2.78	1.91	1.53
On-site heat	66% Residue share	1.89	1.30	1.04
Electricity and district heat	50% Residue share	2.78	1.91	1.53

Notes

Conventional biofuels. LUI decreases by 1% per annum in line of forecasts for conventional crop growth

Residues are not used but land associated with co-products (e.g. animal feeds) is subtracted

Advanced biofuels: 50% is assumed to be derived from residues and wastes with no associated land demand

Heat. 66% of energy is assumed to be derived from residues and wastes with no associated land demand

Electricity. 50% is assumed to be derived from residues and wastes with no associated land demand

9.2.5 Biomass Energy Supply: The Answer Depends on How the Question Is Framed

The biomass feedstocks used for energy provision arise from resources ranging from dedicated and exclusive planting and production of crops (including conventional and novel agricultural crops and trees) through to resources currently classified as residues and wastes e.g. from food production. These waste supplies can represent biomaterials that have had multiple uses for example, having been recycled a number of times in some cases (e.g. straw used for chicken litter and then as a feedstock for electricity production). The land demand and perceived and actual environmental impacts arising from bioenergy provision will be increasingly sensitive to which category of resources are used and how quickly the demand increases relative to the scale of the resource base. Three categories of biomass supply estimates are addressed here:

- Residual biomass available from activities undertaken primarily for purposes other than bioenergy production e.g. food and fiber production.
- Dedicated energy crops: Isolated analysis of food and bioenergy production systems. The term "isolated analysis" is used herein to refer to anticipation of food production independent of the emergence of a much-expanded bioenergy industry and based largely on extrapolation of current trends.

- Integrated analysis of food and bioenergy production systems. The term “integrated analysis” is used herein to refer to anticipation of an integrated food and bioenergy system with significant weight given to sustainability objectives.

9.2.5.1 Residual Biomass Arising from Non-Bioenergy Activities

Global production of food and fiber (forestry) will increase through to 2050 and beyond as the population grows, becomes increasingly wealthy, and demands more resources. There are unlikely to be significant gains in the harvest ratio for food crops and so increasing the yields of food crops will inevitably increase the volume of residues. Equally, with forestry, increased management, particularly through thinnings will increase yields of both forestry residues and roundwood for fiber and wood-based materials.

Residues originating from forestry, agriculture and organic wastes (Table 9.13; including the organic fraction of municipal solid waste (MSW), dung, process residues etc.) are estimated at around 100 EJ/yr (Slade et al. 2014; Chum et al. 2011; WWF/Ecofys/OMA 2011; van Vuuren et al. 2009). According to Chum et al. (2011), ‘this part of the technical potential biomass supply is relatively certain,’ but competing applications and other considerations may push net availability for energy applications below the technical potential. How much below depends in significant part on development of technology, and is thus difficult to predict.

Surplus forestry other than from forestry residues, had an additional technical potential of about 60 to 100 EJ/yr (van Vuuren et al. 2009). The potential for improved management of forests has also been recognized by the IPCC (2014) (Figure 9.10) which provides a range of 25 to 75 EJ of potential arising from ‘optimal forest harvesting.’ In addition, there may be a need to remove diseased trees to manage the spread of the disease, as is the case of the pine beetle which is causing major problems in the US and Canada, providing additional forest biomass for bioenergy.

Categories of residual biomass arise from crop production, crop processing (including bioenergy), forestry, and municipal consumption. The total amount of biomass produced by these activities is considerably greater than the amount that could feasibly be used for bioenergy because the economic cost of gathering, storage, and transportation may be too high and because some residues need to be left behind to ensure sustainability in the case of agricultural and forest residues.

Accounting for the minimum bioenergy potentials for each category assessed by the IPCC (2014) there is high agreement in the literature that the combined bioenergy potential for all categories is c. 110 EJ. This can be compared with the residue demand projected in the illustrative scenario of 48 EJ.

Table 9.13. Categories of residues as used for assessing bioenergy potentials.

Agricultural residues
Residues arising in-field e.g. cereal straw, sugarcane tops and leaves
Residues arising from primary processing of food products e.g. husks, hulls, shells, bagasse, etc
Forest residues
Residues arising in-field e.g. thinnings, tops and branches (up to 40% of above-ground forest biomass)
Residues arising from primary processing at saw-mills or pulp and paper factories e.g. saw dust, chips and off-cuts, black liquor
Wastes and secondary residues
Wet wastes (livestock manure, sewage)
Dry wastes (MSW, recovered construction timber, shells and hulls e.g. from nuts and de-husking of grains)

9.2.5.2 Separate Analysis of Food and Bioenergy Production Systems

In the illustrative 200 EJ/yr scenario, nearly 90 EJ is assumed to originate from energy crops for biofuels, heat and electricity generation. Beringer et al. (2011), report a 26 to 116 EJ range for energy crops in 2050 without irrigation (and 52 to 174 EJ with irrigation). A review of the wider literature reports a much broader range in potential bioenergy supplies from energy crops. Perhaps the most severe constraint on future provision of bioenergy from energy crops arises from the perceived competition for land, particularly with food cropping. Byerlee and Deininger (2013) for example, restrict estimates of land availability for bioenergy to areas that have population densities lower than 25 people km^{-2}.

Other constraints in terms of land availability include restrictions to avoid increased deforestation pressure, loss of biodiversity and increased pressure on water resources. Overall estimates of bioenergy potentials are provided by Haberl et al. (2010), who report 160 to 270 EJ/yr in 2050 across all biomass categories. Krewitt et al. (2009), following Seidenberger et al. (2008), also estimated the technical potential to be 184 EJ/yr in 2050 using strong sustainability criteria and including 88 EJ/yr from residues. They project a ramping-up to this potential from around 100 EJ/yr in 2020 and 130 EJ/yr in 2030.

Estimates of potentially available good quality land suitable for rainfed agriculture (see Section 9.2.1.3) range from 250 to more than 900 Mha. Gross estimates of the potential for energy crops on possible surplus good quality agricultural and pasture lands range from 140 to 290 EJ/yr (surplus 'Very Suitable' and 'Suitable' land at 10 and 20 odt ha^{-1} yr^{1}). The potential contribution of water-scarce, marginal and degraded lands could amount to an additional 80 EJ/yr ('Moderately' + 'Marginally Suitable' Land; 5 odt ha^{-1} yr^{-1}).

9.2.6 Integrated Analysis of Food and Bioenergy Production Systems

The vast majority of projections for the development of the food production sector and related land demand have been conceived exclusive of the emergence of a greatly-expanded modern bioenergy industry. Thus activities related to food production have been assumed to develop without impact from, or integration with, development of the bioenergy sector, and bioenergy has been assumed to have access to land that is left over after anticipated requirements for food production, biodiversity protection and infrastructure demands are satisfied. This approach is usually justified based on the observation that food is the highest priority use for land resources managed by humanity, which is strongly endorsed here.

While food is in many situations a high or highest priority, this does not mean that separate analysis of food and bioenergy production is the best approach. Indeed, this is likely not the case. Compared to isolated analysis, integrated analysis is more realistic in that there will surely be interactions between a greatly expanded bioenergy production system and food production. Integrated analysis is also likely to be better at illuminating paths to sustainable biomass provision, whatever the end-uses.

Just as there are attractive integrated systems for the production of crops with livestock (Herrero et al. 2011; Iiayama et al. 2007; Van Kuelen and Schiere 2004), there are likely to be integrated bioenergy-crop, bioenergy-livestock, and bioenergy-crop livestock systems (Bogdanski et al. 2010; Dale et al. 2010). The presence of economically-rewarding technology for bioenergy production will create new pressures and opportunities. Negative interactions will need to be carefully managed. As developed below, there appear to be potentially favorable impacts of bioenergy on food production, which can only be identified and optimized by taking an integrated approach.

Food production agriculture faces challenges independent of bioenergy, among them maintaining and reclaiming soil fertility, preventing erosion, controlling nutrient loss to receiving waters, and enhancing wildlife habitat. There is strong evidence that growing perennial grasses on land formerly used for row crops, or in rotation with row crops, improves soil organic matter and fertility and that this occurs with harvest of bioenergy crops as well as without it (Anderson-Teixiera 2013; Jordan et al. 2007; Lal 2004). In particular, several studies have found that growing perennial grasses in lieu of row crops increases soil carbon stocks at a rate of 1 Mg C/ha.year or more (Gebhart et al. 1994; Penman et al. 2003). Similar outcomes have recently been found for sugarcane when it replaces soy or pasture in Brazil (Mello et al. 2014). Lal (2004) calculate that an increase of 1 ton C/ha in the soil carbon pool of degraded cropland soils may increase crop yield by 20 to 40 kilograms per hectare for wheat and 10 to 20 kg/ha for maize. Such integrated approaches combine adaptation and mitigation whilst simultaneously providing mechanisms to close the yield-gap in major food crops (Hall and Richards 2013; van Ittersum et al. 2013).

Perennials also radically reduce rates of erosion and nutrient runoff as compared to conventional tillage, often by over 100-fold, and are widely recognized as leading management strategies to achieve these objectives (McLaughlin 1996; Chesapeake Bay Commission 2012). Buffer strips along the edges of streams are widely used, and more widely recommended, to intercept pollutants and provide wildlife habitat (Gopalakrishnan et al. 2012; Christen and Dalgaard 2013). A comprehensive study of Midwestern US grasslands found substantial differences between biodiversity indicators for maize and perennial grasslands, whereas indicators were similar for harvested switchgrass and unmanaged prairie (Werling et al. 2014).

Along with the multiple benefits that perennials offer to food production agriculture, they could also produce bioenergy feedstocks on a scale large enough to matter in the context of energy supply at both global and local scales. If, for example, 5% of cropland were planted in perennial bioenergy crops in a combination of buffer strips and long-term rotation, this would correspond to about 60 million ha of land globally, potentially providing over a quarter of the projected land needed to produce 200 EJ of bioenergy by 2050. At a representative yield of 10 odt ha^{-1} yr^{-1}, planting 5% of the area within a feedstock catchment area with a 50 km radius would provide over 1000 oven dry tons per day to an individual processing facility. This is enough to produce about 100 Ml of ethanol per year (30 million gallons), or 4.5 TWh of electricity.

9.2.6.1 Sustainable Intensification

Intensification, increasing output per unit land, is in principle possible for production of goods from cropland, forestland, and pasture. There is broad consensus that sustainable intensification of the world's cropland is necessary in order to meet anticipated food demand (Godfray et al. 2010, Tilman et al. 2011, The Royal Society 2009, Foley et al. 2011, Clay. 2011). Mueller et al. (2012) estimate the difference between potential and actual yields for 18 row crops, with potential yields based on near maximum (e.g. 95th percentile) yields currently achieved under climatically-similar conditions. Based on this analysis, Sheehan et al. (in review) calculate intensification potentials (the potential yield divided by the actual yield) for global maize and wheat land of 1.64 and 1.71 respectively. Future yield increases for crops are widely expected to be needed to keep up with increased food demand (Alexandratos and Bruinsma 2012). Thus, whilst integrating of perennial crops into agricultural landscapes offers potential benefits, the intensification of cropland to make room for production of bioenergy feedstocks may need to be supplemented by other options for the supply of biomass for bioenergy.

Managed forests and residues from the forest products industry make a substantial contribution in many bioenergy scenarios. In the World Wildlife Fund for Nature's 100% Renewables scenario (WWF/Ecofys/OMA 2011), for example, sustainable harvesting of forests contributes 27EJ and forest residues and wood waste provide an additional 25 EJ. Sustainability criteria are applied to these estimates, although not all studies have values as high as the WWF study.

The world's roughly 3.4 billion hectares of pasture (taken here to include rangeland) represents over twice as much land as currently used to grow crops. Although pasture and rangeland is a critical source of livelihood and ecosystem services in many locations, on a global scale it plays a strikingly smaller role than cropland as a source of food. As presented in Table 9.14, grazed land provides about 3% of human dietary protein consumption and about 1% of total dietary calories.

Table 9.14. Contribution of pasture land to dietary calories and protein.

	A	B	C	D	E	F=A*C	G=A*E
Animal Product	**Production from Grazing**	**Animal Product Consumption (kcal/person/ day)**	**Percent of Total Calories**	**Animal Protein Consumption (kcal/person/ day)**	**Percent of Protein as Calories**	**Total Calories from Pasture**	
Meat	8.4%	252	8.9%	58	17.8%	0.8%	1.5%
Milk	12.0%	127	4.5%	33	10.1%	0.5%	1.2%
Eggs	0.8%	33	1.2%	11	3.4%	0.0%	0.0%
Total		412	14.6%	102	31.3%	1.3%	2.7%
Sources	1	2	2	2	2	1,2	1,2

Note: Human calories consumption: 2,831 kcal/day; Per capita protein: 325 kcal/day

Sources

1. FAO 2006b
2. FAO/FAOSTAT 2009

Data for pasture performance are in general much more limited than for row crops. While there is no global database for pasture yield, the FAO Gridded Livestock Study (Wint and Robinson 2007), provides a global inventory of pastured animals. Using stocking density to represent pasture performance, Sheehan et al. (in review) have developed the first geospatially-explicit estimate of the intensification of global pasture land. Their findings include:

- 43% of pasture land in one of the most widely used land classification schemes (Ramunkutty et al. 2008) does not have livestock on it according to the FAO Gridded Livestock Study. For multiple reasons, much of this land may not be available for bioenergy production. Still, it is notable that the area of pasture apparently not occupied by livestock is nearly equivalent to the area of global cropland.
- Significantly higher animal stocking density (head/ha), and by inference yield of animal products (kg per ha per year), could be realized on the world's pastureland (see section 9.2.1.3). In particular, increasing animal stocking densities to the 95th percentile of their climate-appropriate, currently-attainable, levels would

allow existing pastureland to support 3.8 fold more animals. Bringing the poorest-performing pastures up to 50% of their maximum attainable density would more than double the global stock of grazing animals.

- The potential for intensifying pasture is found to be much larger than that of grain crops determined using a similar approach.

The potential to achieve several-fold intensification of pasture is supported by detailed regional studies (World Bank 2012; Thornton and Herrero 2010). Brazil, the world's second largest beef producer, increased carcass weight per ha by 3.5-fold over a twenty one year period between 1985 and 2006 (Martha et al. 2012). Notably, animal performance (kg per head per year) was a larger contributor to this result than stocking density (head/ha) and thus the intensification potentials calculated by Sheehan et al. (in review) may prove to be conservative upon further study. Reflecting on the causes of intensified production of pastured livestock in Brazil, Geraldo Martha comments that "Prior to the mid-80s, land and animals in Brazil were treated as capital reserves against economic instability, since then there has been a major drive for productivity gains" (Personal communication 2014). Managing pasture land as a capital asset may well be widespread but remains to be systematically assessed. Further information on the intensification of pastureland in Brazil is included in (see Section 9.2.2 and Landers 2007).

Deeper analysis of pasture intensification is a priority. In particular, a detailed sustainability analysis of pasture intensification remains to be carried out. Pasture intensification will likely be accompanied by at least two positive impacts from a sustainability perspective: increased soil carbon storage and decreased methane per unit animal product. Pasture intensification in the presence of a robust bioenergy industry will likely be larger than without such an industry. The relatively small role of pasture in food supply combined with the extensive area it occupies and its apparently large intensification potential make it logical to consider pasture land as a major potential bioenergy feedstock provider. These observations are underscored by Table 9.15, and explain why pasture land is by far the largest land category used to grow energy crops in most scenarios.

9.2.7 Estimates of Bioenergy Potential

The literature includes many estimates for the potential magnitude of bioenergy that could be produced, as well as some excellent surveys that aggregate results from multiple studies (e.g. Slade et al, 2014; IPCC, 2014). Estimates of bioenergy potential are based on a wide range of assumptions. For example, studies differ widely with respect to:

- What categories of land are and are not considered. Few studies consider all of the categories identified in this chapter;
- The operational criteria used for whether land is designated as 'available';
- The extent to which analysis of biomass potential is evaluated using integral or separate approaches relative to food production (see Section 9.2.5.2.).

Table 9.15. Summary properties of the three major land classes that can grow terrestrial biomass.

Land Type	Area1 (109 ha)	Potential win-win integration options	Potentially competing priorities	Food Production	
				Importance	Intensification potential
Cropland	1.6	Perennials improve sustainability metrics	Food	Very large	Moderate, likely needed for food
Forestland	3.9	Selective harvest, thinning	• C storage • Habitat	Almost zero	---
Pastureland	3.4	• Sustainable intensification • Crop-livestock-bioenergy systems	Less apparent	Very small	Large, likely in excess of food needs

[1] See Table 9.1 and Lambin and Meyfroidt 2011

Given these differences, it is not surprising that estimates for bioenergy potential vary widely.

Among the two most comprehensive aggregated studies are those by the IPCC (2014) and Slade et al. (2014). The IPCC study considers the global bioenergy potential originating from industrial organic residues, forest and agricultural residues, dedicated crops and optimal forest harvesting, while also projecting reduced demand for traditional biomass for energy purposes (Figure 9.11).

The wide variation in bioenergy supply estimates, previously noted, is evident – particularly with respect to energy crops, for which estimates vary from 25 to 675 EJ. Summing the minimum value in every category gives about 110 EJ. Slade et al. (2014) aggregate results from 28 studies that provided over 120 estimates for the future contribution of biomass to global energy supply into categories of energy crops, wastes and residues, and forestry (Figure 9.12). As with the IPCC 2014 study, estimates vary widely and the highest estimates of potential are for energy crops.

9.3 Discussion and Conclusions

Based on dynamic considerations, we calculate a gross land demand for modern bioenergy of 45 Mha in 2010, and indicatively between 50 Mha and 200 Mha by 2050. Whilst highly uncertain, this scale of land use delivers about 20 EJ/yr of modern bioenergy in 2010, and between 44 and 135 EJ/yr of modern bioenergy in 2050. In all our indicative scenarios, traditional biomass remains the single largest bioenergy sub-sector, providing between 55 and 60 EJ/yr in 2050. Sensitivity analysis suggests that

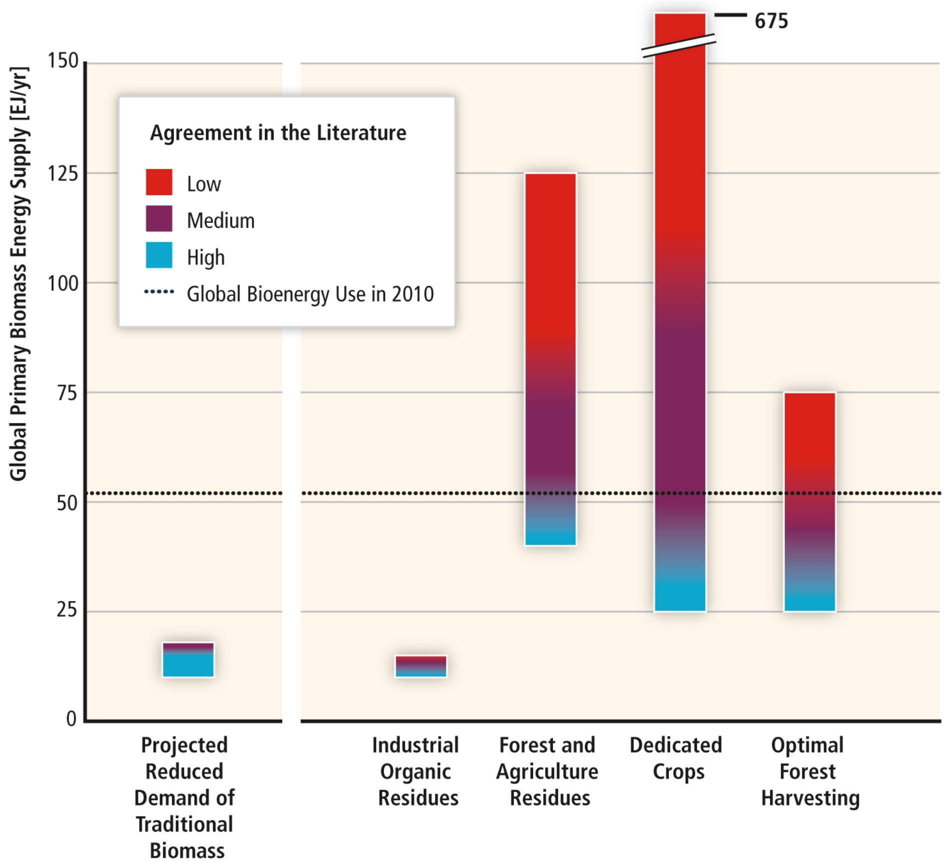

Figure 9.11. Bioenergy potentials (ranges based on expert opinion). The medium to high potential range was 100 to 300 EJ (IPCC 20 14).

independent of the specific scenario considered, e.g. with respect to the distribution of bioenergy products, approximately 0.7 EJ per Mha is a reasonable ballpark land use intensity for production of modern bioenergy at a scale in the order of 80 to 160 EJ in the 2050 timeframe. In practice the overall land demand for bioenergy is likely to be lower than these estimates as a result of integrational co-benefits with food and fiber production, but precise numbers are difficult to calculate.

Most global studies of land availability for bioenergy in 2050 exceed 500 million ha after allowing for food production, protected areas, urban expansion, and increased biodiversity protection (Table 9.1). The FAO (Alexandratos and Bruinsma 2012), for example, estimates that there is currently about 1.4 Gha of 'suitable to moderately suitable' land that is currently unused or 'spare' and that has rainfed cropping potential. Taking into account the sources reviewed and considering all categories of potentially available land, and not just land suitable for rainfed cultivation of row crops, we find this estimate to be quite reasonable.

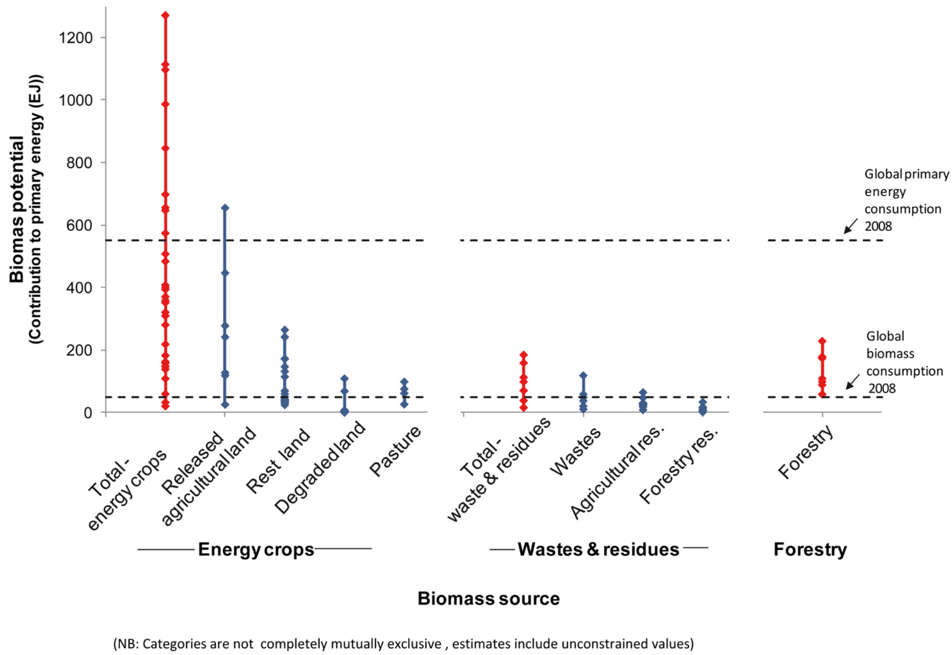

Figure 9.12. Bioenergy supply potentials based on meta-analysis of 28 global studies (Slade et al. 2014).

Our estimates for the land demand of bioenergy are lower than other estimates because of the inclusion of key factors supported by recent analysis: the ability of bioenergy to recycle biomass through the use of wastes and residues and support crop yield growth through investments in infrastructure and development capacity in agriculture and forestry. Furthermore, the potential to use alternative crops and in particular to increase the area of perennial cropping will diversify agricultural landscapes and provide novel and productive tools to manage and ameliorate the impacts of intensified food cropping.

Land potentially available for bioenergy includes:

a) Land suitable for rainfed agriculture expected not to be needed for other purposes (Section 9.2.1.3),

b) Degraded land (Section 9.2.1.3),

c) Land not suitable for rainfed agriculture but potentially suitable for energy crops (Section 9.2.1.3, not easily distinguished from degraded land),

d) Land made available by pasture intensification (discussed in Section 9.2.5.2).

Whilst not quantified here, we note that increasing cropping intensity, including double cropping (Langeveld 2013; Feyereisen et al. 2013), is already increasing biomass production on existing cropland with considerable potential for further expansion, as highlighted in section 2.6.

It is not currently possible to clearly distinguish between these categories of land, which represent a key knowledge gap (see below). If available land is estimated assuming that land in category a) includes land in categories b), c), and d), the resulting estimate will be conservative – that is lower than the actual amount of land available. If on the other hand, available land is estimated by summing categories a) through d), the estimate will be too high and will involve some double counting.

Taking the more conservative approach, Figure 9.13 compares only the land areas considered suitable for rainfed agriculture and that is potentially available for bioenergy production (905 Mha), with the 200 Mha estimated to be required for production of 135 EJ of modern bioenergy in a scenario that delivers 200 EJ/yr of bioenergy (modern + traditional) by 2050 as defined in Section 9.2.4). As presented in Section 9.2.1.3, Table 9.5, potentially available land is exclusive of anticipated demands for cropland, natural forests and forest plantations, urban land (including allowance for expansion), and increased land for biodiversity protection as recommended by the World Wildlife Fund (see Section 9.2.1.3). Most of this potentially available land is currently categorized as pasture, although not all of it has livestock on it, and is managed at very low intensity if at all.

In practice, accessing land for bioenergy production will be a function of diverse local biophysical, economic, cultural and political factors, requiring widespread public and political support to enable the needed investments in infrastructure and human capacity. The underpinning science needed to provide the evidence base to enable the public and political support is currently lacking and more work is needed to reduce uncertainties, remove data gaps and provide guidance on beneficial rather than detrimental pathways for substantive modern bioenergy provision.

As illustrated in Figure 9.13, a small (0% to 11%) portion of potentially available land considered suitable for rainfed agriculture is required for energy crops. We note that bioenergy crops currently under investigation or development are able to access wider categories of land than considered as 'very suitable' or 'suitable' for rainfed agriculture. When land categories classified as 'moderately' and 'marginally' suitable for rainfed agriculture are included, an additional 1 billion ha of land could be considered for bioenergy crops. We therefore conclude that there is vastly more land than necessary in order to produce in excess of 100 EJ of modern bioenergy, consistent with low carbon energy scenarios. Long before the world reaches any significant fraction of 100 EJ of modern bioenergy, we will have ample opportunity to be guided by experience rather than projection.

Given this novel perspective on land availability for bioenergy, we consider that the critical question is not one of managing a competition for land between energy and food, but rather whether and how bioenergy production can be gracefully incorporated into human and natural systems. The authors believe the answer to this question to be yes, but leave detailed consideration to other chapters in this volume.

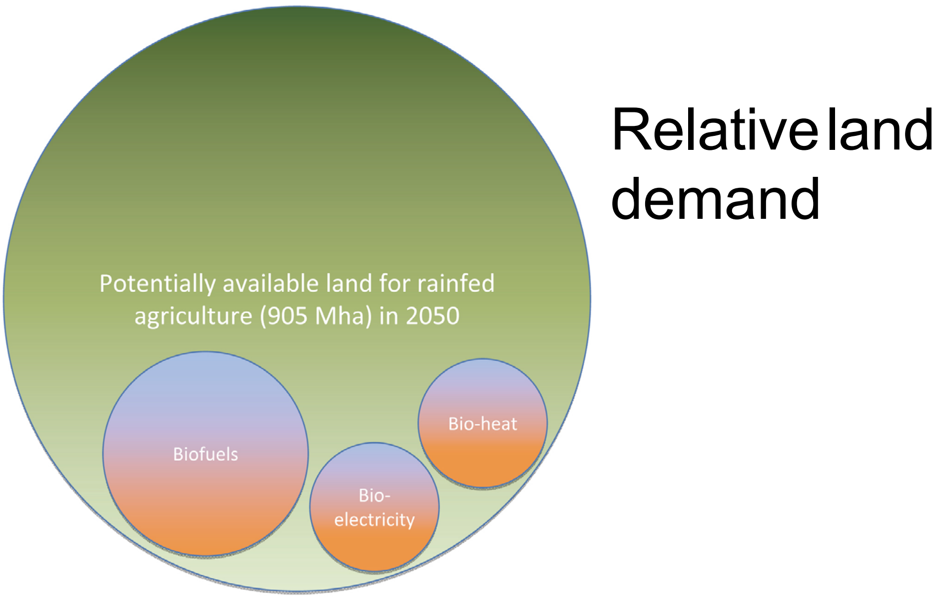

Figure 9.13. Indicative share of potentially available rainfed agricultural land (Alexandratos and Bruinsma 2012) occupied by bioenergy crops (22%) under a scenario where bioenergy (modern and traditional) delivers 200 EJ/yr in 2050.

9.4. Recommendations

The need for a significant expansion of modern bioenergy provision and better understanding of the systems that must be developed to ensure the sustainable provision of biomass to supply the new bioenergy demand urgently needs addressing. As a result of the spatially distributed nature and heterogeneous technological options of bioenergy pathways the underpinning research capabilities will also need to be distributed and broadly based with integrative global science programs, closer integration with the global food research system and the private sector. More specific recommendations include:

- Support the development of new markets for modern bioenergy systems;
- Develop better understanding of the catalytic role of bioenergy in promoting economic and agricultural development;
- Develop capacity to develop regionally-responsive, spatially explicit, new conversion processes and supply chains, and cropping systems;
- Stimulate efforts to understand, monitor and assist poor people to gain access to modern bioenergy services and technologies. The role and scale of traditional bioenergy remains heavily under-researched;

- Significant effort is needed to better understand the role of biomass in the provision of high-grade heat to industry (including agro-industry) and domestic / residential space heating;
- Better data and improved understanding of the actual land use impacts of modern and traditional bioenergy is urgently required;
- Develop integrative perspective of bioenergy with agriculture, livestock and forestry production systems;
- Support the investigation, demonstration, and synergy maximization for integrated bioenergy and food production systems.

9.5. The Much Needed Science

Substantial uncertainty remains in the understanding of land availability, the dynamics of its use (particularly temporal dynamics) and in the potential impacts of climate change on crop productivity and production. The role the very broad range of bioenergy cropping systems could play in ameliorating these impacts is not well recognized or understood and substantial interdisciplinary and international science programs are urgently required to reduce the uncertainty in land availability estimates and the potentials for integrative cropping.

- Supporting this macro-level understanding, new science is needed to understand the potential and need for:
- Increased cropping intensity, evaluating novel crop rotations including winter cover crops, pasture – arable – perennial bioenergy cropping systems. In particular, evaluating the impacts and management potentials to modify:
- Site-specific environmental (biophysical, biochemical and biological) characteristics of soils / land, including soil organic matter and soil carbon, soil and above ground biodiversity, nutrient status / retention, soil management particularly with regard to erosion, hydrology including modified soil water holding capacity; potential for bioenergy cropping to remediate degraded / damaged soils;
- Socio-economic, including; land planning, land tenure, access, long run productivity / productivities for multiple rotations / seasons.
- Potential for and practical implementation strategies that result in sustainable pasture intensification;
- Novel integrated land management options arising from a better understanding of the interlinkages between pasture intensification, food crop production and bioenergy cropping;
- The local level socio-economic drivers and policy linkages needed to provide the markets and regulatory frameworks to promote integration and sustainable intensification.

- Improved data provision across the range of bioenergy service provision including, heating and cooling, electricity, transport / mobility and their implications on the associated land demands.
- A particular focus is required on understanding the scale, and impacts (environmental, health, etc.) of traditional biomass use for energy. Current understanding and data on consumption is limited and the driving forces underpinning the demand for traditional bioenergy are dynamic e.g. rural and urban population growth in developing countries, particularly African countries.

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