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Chapter 11

Agriculture, Forestry and Other Land Use (AFOLU)

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(Sub)Section:	All			
Author(s):	CLAs:	Pete Smith, Mercedes Bustamante		
	LAs:	Helal Ahammad, Harry Clark, Hongmin Dong, Elnour A. Elsiddig, Helmut Haberl, Richard Harper, Mostafa Jafari, Omar Masera, Cheikh Mbow, Emmanuel Nzunda, Nijavalli H. Ravindranath, Charles W. Rice, Carmenza Robledo Abad, Anna Romanovskaya, Frank Sperling, Francesco Tubiello		
	CAs:	Göran Berndes, Simon Bolwig, Hannes Böttcher, Ryan Bright, Francesco Cherubini, Helena Chum, Esteve Corbera, Felix Creutzig, Andre Faaij, Garvin Heath, Mario Herrero, Jo House, Oswaldo Lucon, Daniel Pauly, Richard Plevin, Alexander Popp, Alexandre de Siqueira Pinto, Steve Rose, Saran Sohi, Anders Stromman, Sangwon Suh, Robert Zougmore		
Support:	CSA:	Heather Jacobs, Marina Molodovskaya		
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Table of changes

No	Date	Version	Place	Description	Editor
1	20.11.2012	01		First consolidated SOD; new Executive Summary, and new section 11.1, Partly revised sections 11.2 and 11.10	Pete & Mercedes
2	12.12.2012	02		As above but with all contributions received to date consolidated	Pete & Mercedes
3	17.12.2012	03		New sections 11.4, 11.4.5, 11.5, 11.7, 11.8 and 11.9 & various edits/updates	Pete & Mercedes
4	27.12.2012	04		New sections 11.2.2 (FNT), revised 11.2.1 (HC), new 11.10 and part of 11.6	Pete & Mercedes
5	04.01.2013	05		Various edits and updated section 11.5	Pete & Mercedes
6	26.01.2013	06		New sections 11.3 (parts) and 11.9	Pete & Mercedes
7	29.01.2013	07		New 11.2,11.6, 11.7, 11.6; revised 11.4	Pete & Mercedes
8	31.01.2013	08		Consolidated after edits – complete but unedited. Bioenergy annex added	Pete & Mercedes
9	01.02.13	09		Final version except references	Pete & Mercedes

Chapter 11: Agriculture, Forestry and Other Land Use (AFOLU)

Contents

Executive Summary

Agriculture, Forestry and Other Land Use (AFOLU) is unique among the sectors considered in this volume, since the mitigation potential is derived from management of land and livestock [*11.1, high agreement; robust evidence*]. The land provides livelihoods for billions of people worldwide and is a critical resource for sustainable development in many regions. The land provides a multitude of ecosystem services; greenhouse gas mitigation is just one of many services that are vital to human wellbeing [*11.1, high agreement; robust evidence*]. Mitigation options in the AFOLU sector, therefore, need to be assessed for their potential impact on all of the other services provided by land.

The AFOLU sector is responsible for about one third of anthropogenic GHG emissions [*11.2, high agreement; robust evidence*], mainly from deforestation and agricultural emissions from livestock and soil and nutrient management. Forest degradation and biomass burning (forest fires and agricultural burning) also represent relevant contributions. Leveraging the mitigation potential in the sector is extremely important in meeting emission reduction targets [*11.3, high agreement; robust evidence*]. Opportunities for mitigation include supply-side measures through reduction of emissions arising from land use change and land management, increasing carbon stocks by sequestration in soils and biomass, or the substitution of fossil fuels by biomass for energy production, and demand-side measures (i.e. by reducing losses and wastes of food, changes in diet, changes in wood consumption). Considering demand-side options, changes in diet can have a significant impact on GHG emissions from food production [*11.4, high agreement, medium evidence*]. There are considerably different challenges involved in delivering demand-side and supply-side measures, which also have very different synergies and risk-tradeoffs.

The nature of the sector means that there are, potentially, many barriers to implementation of available mitigation options. Similarly, there are important feedbacks to adaptation, conservation of natural resources, such as water and terrestrial and aquatic biodiversity. There can be competition between different land-uses due to different motivations and objectives, but also potential for synergies, e.g. integrated systems or multifunctionality at landscape scale [*11.4, high agreement; medium evidence*]. Recent frameworks, such as those for assessing environmental or ecosystem services, provide a mechanism for valuing the multiple synergies and trade-offs that may arise from mitigation actions [*high agreement, medium evidence*]. The sustainable management of agriculture, forests, and other land is essential for achieving sustainable development [*11.4, high agreement; robust evidence*].

Multi-sector, top-down estimates of costs and potentials suggest that AFOLU mitigation could be an important part of a global cost-effective abatement strategy [*11.6, high agreement, medium evidence*] under different stabilization scenarios. AFOLU forms a critical component of transformation pathways, offering a variety of mitigation options and a large, cost-competitive mitigation potential. Large scale energy generation or carbon sequestration in the AFOLU sector provide headroom for the development of mitigation technologies in the energy supply and energy end-use sectors, since the technologies described in this Chapter already exist [*11.6, high agreement, medium evidence*]. In climate management scenarios with idealized comprehensive climate policies, agriculture, forestry and bioenergy contribute substantially to mitigation of global CO2, CH4, and N2O, and to the energy system, thereby reducing policy costs [*11.9, high agreement, medium evidence*]. However, more realistic partial and delayed policies for global land mitigation are shown to have potentially significant spatial and temporal leakage and economic implications, but could still be cost-effectively deployed [*11.9, high agreement, low evidence*].

A consolidated estimate of economic potentials for GHG mitigation within the AFOLU sector as a whole is still difficult because of potential leakages derived from competing demands on land, and only some of the potentials are additive. Global estimates for economic mitigation potentials in the AFOLU sector in 2030 are 490 to 10600 Mt CO2-eq./yr at prices up to 100 US$/t CO2-eq., with ranges among agricultural sectoral studies of 260 to 4600 Mt CO2-eq./yr at prices up to 100 US$/t CO2-eq., and among forestry sectoral studies of 198 to 13000 Mt CO2-eq./yr at prices up to 100 US$/t CO2-eq. [*11.6, medium agreement, medium evidence*]. Demand-side measures have largely so far, only been assessed for their technical potential, which ranges from ~760-9300 Mt CO2-eq./yr [*11.4 and 11.6, medium agreement, low evidence*]. There are significant regional differences in terms of mitigation potential, costs and applicability, due to differing local biophysical, socioeconomic and cultural circumstances, for instance between developed and developing regions, and among developing regions [*11.6, high agreement, medium evidence*]. In developing countries, agriculture is often central to the livelihoods of many social groups and accounts for a significant share of GDP.

The size and regional distribution of future mitigation potential is difficult to estimate accurately as it depends on a number of factors that are inherently uncertain. Critical factors include population (growth), economic and technological developments, changes in behaviour over time and how these translate into fibre, fodder and food demand, and development in the agriculture and forestry sectors. Other important factors are: potential climate change impacts on carbon stocks in soils and forests, including their adaptative capability [*11.5, high agreement, medium evidence*]; considerations set by biodiversity and nature conservation requirements; and interrelations with land degradation and water scarcity [*11.8, high agreement, robust evidence*].

Land use and land use change associated with bioenergy expansion can affect GHG balances, albedo and other climate drivers in several ways, and depending on how and where implemented, can lead to either beneficial or undesirable consequences for climate change mitigation [*11.3, high agreement, robust evidence*]. Top-down estimates project between 15-225 EJ/yr bioenergy deployment potential in 2050 [*11.9, medium agreement, medium evidence*]. Sustainability and livelihood concerns might constrain beneficial deployment to lower values. With limited availability of productive land, increased competition for land may induce substantial LUC, causing high GHG emissions and/or agricultural intensification, which could result in more fertilizer use, energy use for irrigation and higher N2O emissions. However, societal preferences and technological changes also shape the LUC and intensification outcomes. AFOLU mitigation options can promote innovation, and many technological supply-side mitigation options also increase agricultural and silvicultural efficiency [*11.3, high agreement, robust evidence*].

Large-scale reliance on bioenergy and sequestration in afforestation and reforestation projects will likely increase the competition for land, water, and other resources, and conflicts may arise with important sustainability objectives such as food security, soil and water conservation, and the protection of terrestrial and aquatic biodiversity. In some cases land-based mitigation projects may provide land, water and biodiversity co-benefits. Sustainability frameworks to guide development of such mitigation projects need to consider competition for land [*low agreement, medium evidence*]. Emphasis should be given to multifunctional systems that allow the delivery of multiple services from land [*high agreement, medium evidence*].

Policies governing practices in agriculture and in forest conservation and management need to account for the needs for both mitigation and adaptation. One of the most visible current policies for the AFOLU sector is the implementation of REDD mechanisms and its variations, that can represent a very cost-effective option for mitigation [*11.10, high agreement, medium evidence*], with social and other environmental co-benefits (e.g. conservation of biodiversity and water resources).

11.1 Introduction

Land is a finite resource that provides a multitude of goods and ecosystem services, which underpin human well-being (MEA, 2005). Humans rely directly on these services, and the land provides livelihoods for billions of people worldwide. Land is a critical resource for sustainable development in many regions (section 11.9). Figure 11.1 shows the many provisioning, regulating, cultural and supporting services provided by land. In this long list of services, climate regulation (through which climate change mitigation in the AFOLU sector operates) is just one. Mitigation options in the AFOLU sector need to be assessed for their potential impact on all of the other services provided by land. AFOLU mitigation measures involve the reduction of emissions (e.g. avoiding deforestation, reducing nitrous oxide and methane emissions, reducing supply emissions; see section 11.3), increasing carbon stocks (by sequestration in soils and biomass; see section 11.3), the substitution of fossil fuels by biomass (see Annex I) and demand-side measures (e.g. by reducing losses and wastes of food, changes in diet, changes in wood consumption).

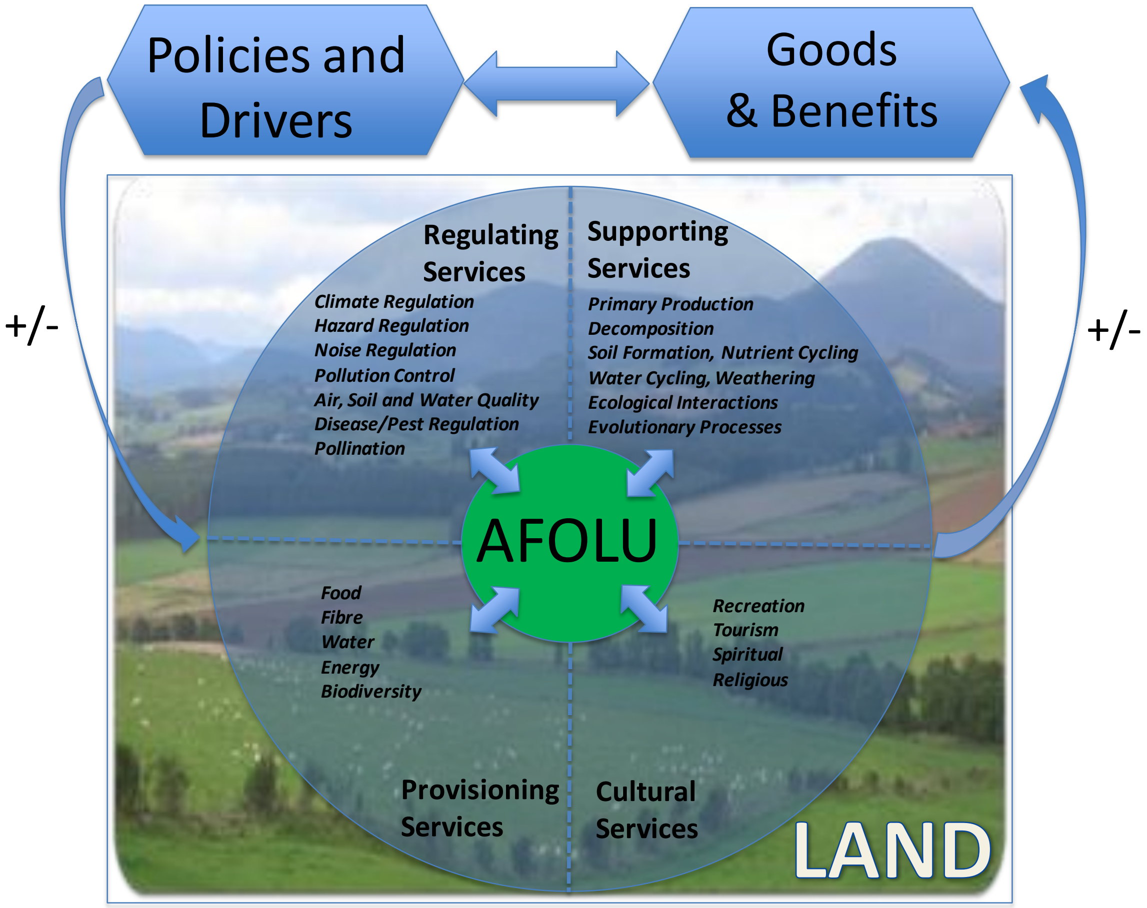

Figure 11.1. Multiple ecosystem services, goods and benefits provided by land (after (MEA, 2005); (UNEP-WCMC, 2011). Mitigation actions aim to enhance climate regulation, but this is only one of the many functions fulfilled by land.

In the IPCC SAR (IPCC, 1996) and in AR4 (IPCC, 2007), agricultural and forestry mitigation were dealt with in separate chapters. In the TAR (IPCC, 2001), there were no separate sectoral chapters on either agriculture or forestry. In AR5, for the first time, the vast majority of the terrestrial land surface, comprising agriculture, forestry and other land use (AFOLU (IPCC, 2006a), is considered together in a single chapter, though settlements are dealt with in chapter 12. This approach ensures that all land based mitigation options can be considered together; it minimises the risk of double counting or inconsistent treatment (e.g. different assumptions about available land) between different land categories, and allows the consideration of systemic feedbacks between mitigation options related to the land surface (section 11.5). Considering AFOLU in a single chapter allows phenomena that are common across land use types to be considered consistently, such as competition for land (e.g. Smith et al., 2010; Lambin and Meyfroidt, 2011) and water (e.g., Jackson et al., 2007), co-benefits (Sandor et al., 2002; Venter et al., 2009), risk-tradeoffs, uncertainty and spill-overs (section 11.7) and interactions between mitigation and adaptation (section 11.5). The complex nature of land also presents a unique range of barriers and opportunities in the AFOLU sector (section 11.8), and policies to promote mitigation in the AFOLU sector (section 11.10) need to take account of this complexity.

In this chapter, we consider the conflicting uses of land for mitigation and for providing other services (sections 11.7 and 11.8). Unlike the chapters on agriculture and forestry in AR4, impacts of sourcing bioenergy from the AFOLU sector are considered explicitly in a dedicated annex (Annex I). Also new to this assessment is the explicit consideration of food / dietary demand-side measures for GHG mitigation in the AFOLU sector (section 11.4), and the consideration of freshwater fisheries and aquaculture (=fish farming), which often compete with the agriculture and forestry sectors, mainly through their requirements for land and/or water, and indirectly, by providing fish and other products to the same markets as animal husbandry.

In this chapter we deal with AFOLU in an integrated way with respect to the underlying scenario projections of e.g. population growth, economic growth, dietary change, land use change and cost of mitigation, by assessing the scenarios also being considered by IPCC WGI and WGII. We attempt to draw evidence from both “bottom-up” studies that estimate mitigation potentials at small scales or for individual measures or technologies and then scale up, and multi-sectoral “top-down” studies that consider AFOLU as just one component of a total multi-sector system response (section 11.9).

Mitigation potentials in the agricultural sector in IPCC AR4 were estimated to be 1.5-1.6, 2.5-2.7, and 4.0-4.3 Gt CO_2-eq. yr^{-1} at 20, 50 and 100 USD / t CO_2-eq. in 2030 (Smith et al., 2007). The equivalent figures for forestry, from bottom-up estimates, were 1.4, 2.5 and 3.1 Gt CO_2-eq yr^{-1} at the same carbon prices (Nabuurs et al., 2007). (Chum, Faaij, Moreira, Berndes, Dhamija, Gabrielle, et al., 2011) estimated that bioenergy could contribute 120 to 155 EJ/yr (median values) to global primary energy supply by 2050 (50 EJ in 2008) (Annex I). In this chapter we provide updates on emissions trends and changes in drivers and pressures in the AFOLU sector (section 11.2), describe the practices available in the AFOLU sector (section 11.3), and we provide refined estimates of mitigation costs and potentials for the AFOLU sector, by synthesising studies that have become available since IPCC AR4 (section 11.6). We conclude the chapter by identifying gaps in knowledge and data (section 11.11), and the preenting an Annex on bioenergy to update the SRREN (Annex I). Frequently Asked Questions and information Boxes are threaded throughout the chapter.

11.2 New developments in emission trends and drivers

Anthropogenic sources and sinks of GHGs in the AFOLU sector include net CO_2 fluxes from management of land (croplands, forests, grasslands, wetlands), changes in land use or cover (e.g. conversion of forests and grasslands to cropland and pasture, afforestation) and non-CO_2 emissions from agriculture (e.g. CH_4 from livestock and rice cultivation, N_2O from manure storage and agricultural soils) and biomass burning. Global trends in total GHG emissions from AFOLU activities between 1971 and 2010 are shown in figure 11.2; figure 11.3 shows trends of major drivers of emissions.

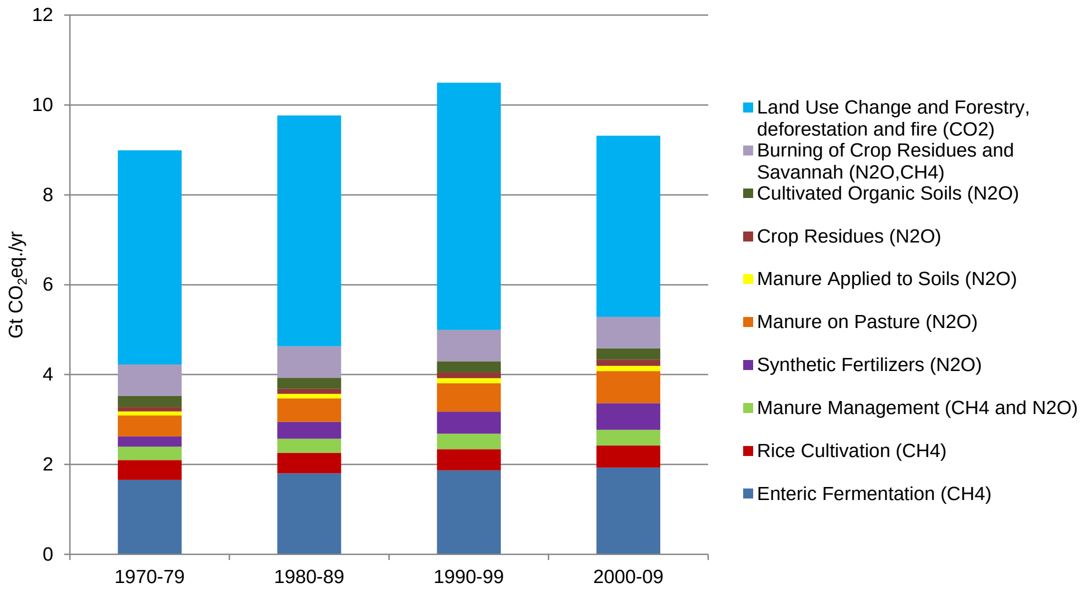

Figure 11.2. AFOLU emissions for the last four decades. Agricultural emissions shown for separate categories, crop residues, manure applied to soils, manure on pasture and synthetic fertilizers, all usually aggregated for reporting to the category "emissions from agricultural soils". FOLU emissions are those arising from land use change and forestry, including deforestation and fires. The data differ slightly from those presented in Chapter 5.7.4 (based on JRC/PBL data (2012)), since (FAO, 2012a) data were used to further disaggregate agricultural emissions by practice, and FOLU emissions use more up-to-date estimates of land use change, deforestation and fire data (same as used in WGI Chapter 6) than those used in EDGAR (Box 11.1). The EDGAR database is used in the AFOLU section of Chapter 5.7.4, as it allows cross-sectoral comparison using the same cross-sectoral database. Figure 11.4 shows the differences between available databases for agricultural emissions.

11.2.1 Supply and consumption trends in agriculture and forestry

In 2010 world agricultural land occupied 4889 Mha, an increase of 7% (311 Mha) since 1970 (FAOSTAT, 2012). From 2000, the agricultural land area has decreased by 53 Mha due to a decline of the cropland area (OECD90 countries, and countries with reforming economies, REF) and a decrease in permanent meadows and pastures (OECD90 countries and Asia). The average amount of cropland and pasture land per-capita has decreased by 42% since 1990 and, in 2010, comprised 0.2 and 0.5 ha per capita, respectively (FAOSTAT, 2012).

Changing land-use practices, technological advancement and varietal improvement have enabled world grain harvests to double from 1.2 to 2.5 billion tonnes per year between 1970 and- 2010 (FAOSTAT, 2012). During these years there has been a 233% increase in global fertilizer use (FAOSTAT, 2012), and a 70% increase in the irrigated cropland area (Foley et al., 2005). Since 1970, average world yield of cereals has increased from 1602 kg/ha to 3034 kg/ha; however, production per unit of nitrogen fertilizers consumed, has decreased globally from 37.6 in 1970 to 23.2 tons of dry matter/tonne of N in 2010, with major decreases in Asia and Latin America.

Since 1970 there has been a 1.4 fold increase in the global numbers of cattle and buffalo, sheep and goats, with increases of 1.6 and 3.7 fold for pigs and poultry, respectively (FAOSTAT, 2012). Major regional trends between 1970 and 2010 include a decrease in the total number of animals in REF and OECD90 countries (except poultry), and continuous growth in other regions, particularly in the Middle East and Africa region (MAF) and Asia.

Global daily per-capita food availability has risen from 10,008 to 11,850 kJ /capita/day between 1970 and 2010, an increase of 18.4%; growth in Africa (10,716 kJ/capita/day in 2010) has been 22%, and in

Asia, 32% (11,327 kcal/capita/day in 2010) (FAOSTAT, 2012). The percentage of animal products in per capita food consumption has increased consistently in Asia since 1970 (7% to 16%), remained constant in Africa (8%) and, since 1985, has decreased in OECD90 countries (FAOSTAT, 2012). As a result of population growth, rising per-capita energy intake and changing dietary preferences, the demand for agricultural products in the future is anticipated to increase significantly, especially in Asia, Latin America, and Africa (FAO, 2006a; Popp et al., 2010; Tilman et al., 2011; Erb, Mayer, et al., 2012; Rosegrant et al., 2001);. In comparison with 2005/2007 global meat consumption is projected to increase 68% and global milk consumption 57% by 2030, while by 2050 total food consumption will increase by 70% (FAO, 2009). Given these increases in food consumption, GHG emissions from the agricultural sector are projected to rise under a business as usual scenario (Havlik et al., 2013).

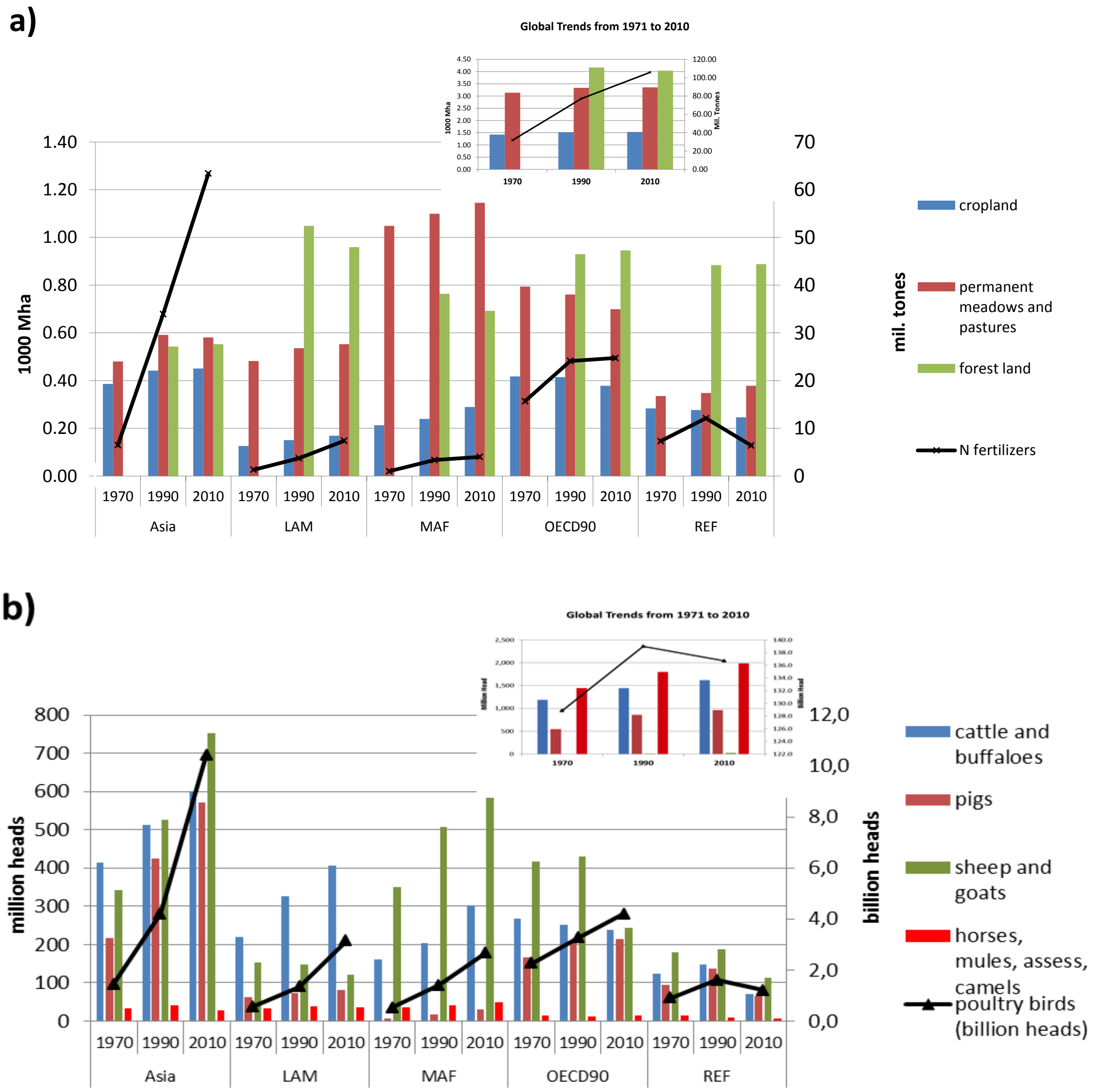

Figure 11.3. Global trends from 1971 to 2010 in (a) area of land use (forest land – from 1990) (1000 Mha) and amount of N fertilizer use (million tonnes), and (b) number of livestock (million head) and poultry birds (billion head). Data presented by regions: 1) Asia, 2) Latin America (LAM), 3) Middle East and Africa (MAF), 4) OECD90 countries; 5) countries with reforming economies (REF) (FAOSTAT, 2012). The area extent of AFOLU land use categories, from (FAOSTAT, 2012): ''Cropland'' corresponds to the sum of FAOSTAT categories ''arable land'' and ''temporary crops'' and coincides with the IPCC category; ''Forest'' is defined according to FAO (FRA, 2010); countries reporting to UNFCCC may use different definitions. ''Permanent meadows and pasture'', are a subset of IPCC category ''grassland'', as the latter also includes unmanaged natural grassland ecosystems.

Since 1990, total forest area decreased by 3% (129.7 Mha) with the largest net loss of forests in Latin America (-8.5% or 88.8 Mha) followed by MAF countries, which lost 9.3% or 71.1 Mha. Oceania also reported a net loss of forest (about 700 kha yr^{-1} over the period 2000–2010), mainly due to large losses of forests in Australia, where severe drought and forest fires have exacerbated the loss of forest since 2000. The area of forest in OECD90 countries and Asia have slightly increased, while in REF countries, it was estimated to be almost the same in 2010 as in 1990 (FAO, 2012a).

11.2.2 Trends of non-CO_2 GHG emissions from agriculture

The agricultural sector is the largest contributor to global non-CO_2 GHGs, accounting for 56% of emissions in 2005 (U.S. EPA, 2011). Other important, albeit much smaller non-CO_2 emissions sources from other AFOLU categories, and thus not treated here, include fertilizer applications in forests. Cumulative non-CO_2 GHG emissions from agriculture in 2010 were estimated to be 5.4-5.8 $GtCO_2$eq./yr (Tubiello et al., 2013); (FAOSTAT, 2012) and comprised about 10-12% of global anthropogenic emissions (Linquist et al., 2012). Fossil fuel CO_2 emissions on croplands added another 0.4-0.5 $GtCO_2$eq./yr in 2010 from agricutural use in machinery, such as tractors, irrigation pumps, etc. (Ceschia et al., 2010) (FAOSTAT, 2012), but these emissions are not accounted for in the AFOLU sector. Between 1990 and 2010, agricultural emissions of CH_4 and N_2O grew by 0.9%/yr, with a slight increase in growth rates after 2005 (Tubiello et al., 2013). Three independent sources of disaggregated non-CO_2 GHG emissions estimates from agriculture at global, regional and national levels are available. They are mostly based on FAOSTAT activity data and IPCC Tier 1 approaches (IPCC, 2006a): (FAOSTAT, 2012); JRC/PBL (2012) and US EPA (2013). EDGAR and FAOSTAT also provide data at country level. Additional estimates of global emissions for enteric fermentation, manure management and manure are available at Tier 2 / 3 (e.g. Herrero et al., 2013). The three database estimates are slightly different, although statistically consistent given the large uncertainties in IPCC default methodologies (Tubiello et al., 2013). They cover emissions from key categories, including: enteric fermentation; manure deposited onto pasture; synthetic fertilizers; rice cultivation; manure management; crop residues; biomass burning; and manure applied to soils. Enteric fermentation, biomass burning and rice cultivation are reported separately under IPCC reporting guidelines, with the remaining categories aggregated into ‘’agricultural soils.’’ According to EDGAR and FAOSTAT, CH_4 emissions from enteric fermentation are the largest emission source, while EPA estimates N_2O emissions from agricultural soils to be the dominant source (Figure 11.4). All three databases nonetheless agree that combined, the two emission categories represent about 70% of the total, with emissions from rice cultivation (9-11%), biomass burning (10-12%) and manure management (6-8%) constituting the remaining non-CO_2 emissions from the agricultural sector. If all emission categories are disaggregated, both EDGAR and FAOSTAT agree that the largest emitting categories after enteric fermentation (32-37% of total agriculture emissions) are manure deposited on pasture by livestock (15%) and synthetic fertilizer (14%). Rice cultivation (11%) is a major source of global CH_4 emissions, which in 2010 were estimated to be 493-723 $GtCO_2$eq./yr. The lower range corresponds to estimates by (Herrero et al., 2013) and FAO (FAOSTAT, 2012), with EDGAR and EPA data at the higher end of the range. Other analyses suggest that emissions from rice may be at the lower end of these estimates (Yan et al., 2009).

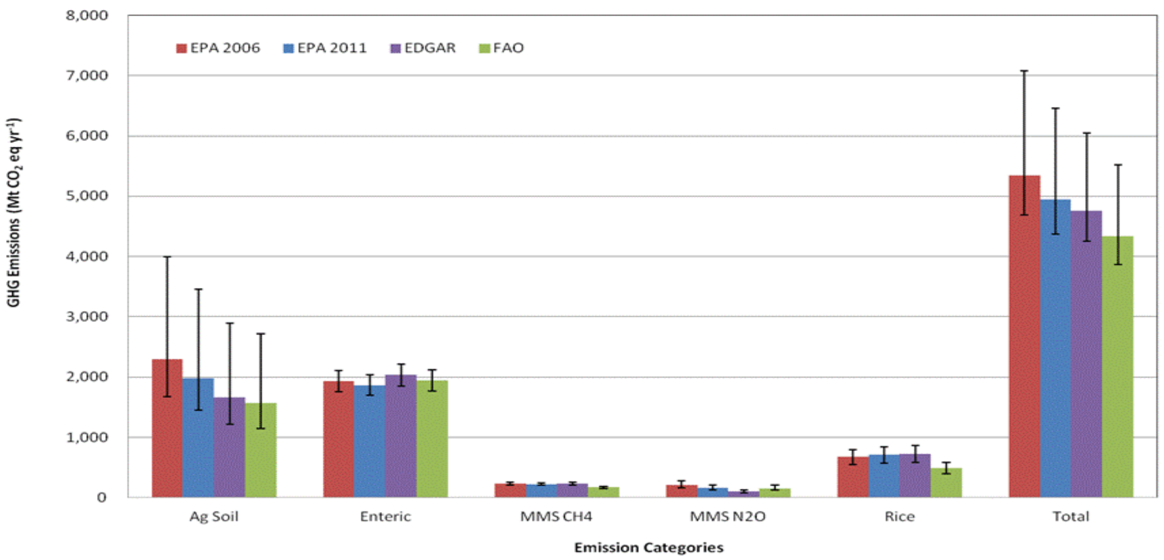

Figure 11.4. Data comparison between FAOSTAT, EPA (2006 and 2012) and EDGAR databases for key agricultural emission categories, grouped as: agricultural soils, enteric fermentation, manure management and rice cultivation, for 2005. Error bars represent 95% confidence intervals of global aggregated categories, computed using IPCC guidelines (IPCC, 2006a) for uncertainty estimation (from (Tubiello et al., 2013).

Enteric Fermentation. Global emissions in this key category grew from 1.3 to 2.0 $GtCO_2$eq./yr during the period 1961-2010, with average annual growth rates of 0.95% (FAOSTAT, 2012). During the 1990s, emission growth slowed compared to the long-term average, quickened again from the year 2000. In 2010, 1.0-1.5 $GtCO_2$eq/yr (75% of the total emissions), were estimated to come from developing countries. Averaged over the period 2000-2010, Asia and the Americas were the largest contributors, followed by Africa and Europe (FAOSTAT, 2012); see Figure 11.5). Emissions growth rates were largest in Africa, on average 2.4%/yr. In both Asia and the Americas, emissions grew at a slower pace (1-1.2%/yr), while they decreased in Europe (-1.7%/yr). In the previous decade (1990-2000), Europe's contribution had been larger than Africa's. Over the period 2000-2010, emissions were dominated by cattle, responsible for 75% of the total, followed by buffalo, sheep and goats.

Manure. Global emissions from manure, as either organic fertilizer on cropland or manure deposited on pasture, grew during 1961-2010 from 0.44 to 0.88 $GtCO_2$eq./yr. Average annual growth rates were 2%/yr, with a slow-down in recent decades. Emissions from manure deposited on pasture were far larger than those from manure applied to soils as organic fertilizer (FAOSTAT, 2012), (Herrero et al., 2013), with 80% of emissions from deposited manures coming from developing countries. (FAOSTAT, 2012), as also confirmed by (Herrero et al., 2013). During the period 2000-2010, the Americas, Asia and Africa were the largest contributors. Growth rates over the same period were largest in Africa, on average 2.4%/yr. Emissions grew at a slower pace in both Asia and the Americas (about 1.5%/yr), while they decreased in Europe (-1.4%/yr). Grazing cattle were responsible for two-thirds of the total, followed by sheep and goats. By contrast, over the same 2000-2010 period, emissions from manure applied to soils as organic fertilizer were larger in developed compared to developing countries. Largest emitters were Europe, followed by Asia and Americas. Africa contributed little to the total, albeit with high growth rates of 3.4%/yr. Swine and cattle contributed 95% of the total in this sub-category. Compared to manure applied to soils, emissions from manure management grew more slowly, i.e., from 0.28 to 0.35 $GtCO_2$eq./yr during the period 1961-2010, with average annual growth rates of only 0.5%/yr. Over the period 2000-2010, emissions were dominated by Asia, Europe and the Americas (Figure 11.5).

Synthetic Fertilizer. Emissions from synthetic fertilizers grew at an average of 19%/yr during 1961-2010, with absolute values increasing 10 fold, i.e. from 0.07 to 0.68 $GtCO_2$eq./yr (Tubiello et al., 2013). Growth slowed in recent decades, to about 2%/yr. At the current pace, emissions from synthetic fertilizers will overtake those from manure deposited on pasture within a decade, becoming the second largest agricultural emission category after enteric fermentation. In 2010, 70% of emissions from synthetic fertilizer were from developing countries. On average, during the period 2000-2010, Asia was by far the largest emitter, followed by the Americas and Europe (FAOSTAT, 2012). Emission growth rates over the same period were positive in Asia (5.3%/yr) and Europe (1.7%/yr), but negative in Africa (-3.3%/yr).

Rice. During the period 1961-2010, global emissions grew from 0.37 to 0.49 $GtCO_2eq./yr$, with average annual growth rates of 0.7%/yr (FAOSTAT, 2012). Global emission growth has slowed in recent decades, consistent with trends in rice cultivated area, and have decreased on a year-on-year basis during the period 2000-2010. Emissions from rice were dominated by developing countries, which contributed over 94% of emissions during 2000-2010. Asia was responsible for almost 90% of the total (Figure 11.5). Emission growth rates were nonetheless largest in Africa (1.8%/yr), followed by Europe (1.4%). Growth rates in Asia and the Americas were much smaller over the same period (0.2%/yr).

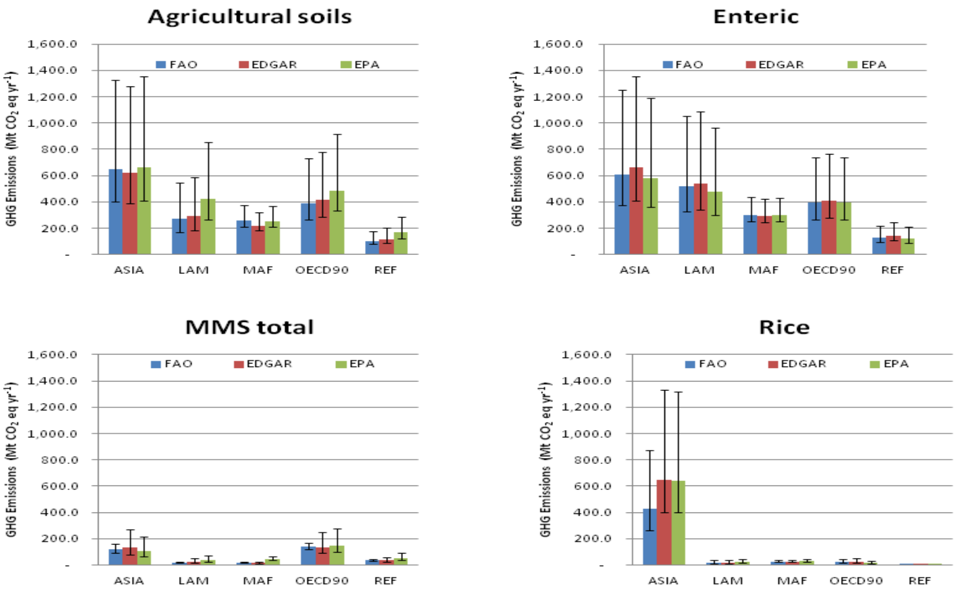

Figure 11.5. Regional data comparisons for key agricultural emission categoriesin 2010. Error bars represent 95% confidence intervals computed using IPCC guidelines (IPCC, 2006b) (from (Tubiello et al., 2013). The data show that most of the differences between regions and databases are of the same magnitude as the underlying emission uncertainties.

11.2.3 Trends of C fluxes from forestry and other land use (FOLU)[1] change

Plants take up CO_2 from the atmosphere when they grow. CO_2 is released from dead plant biomass and soils during decomposition, and by fires. Such fluxes are in equilibrium over decadal time-scales and in the absence of changing drivers such as human activity. Changes in land use and management can be both sources of CO_2 to the atmosphere (e.g. deforestation and other fires, and decomposition of soil carbon and dead plant material including timber products, when vegetation is

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[1] Rather than LULUCF (IPCC, 2003), the term FOLU used here, is consistent with AFOLU in the (IPCC, 2006b) Guidelines. However the data and methods assessed in this section deal mostly with land use change (LUC – e.g. changes between forests, grasslands and agricultural land) and forest management (F). Croplands and grasslands are generally assumed to be in balance with respect to CO2, i.e. regrowth offsets harvest. While this may not be true at the site level, results are very variable and there is a lack of global-scale assessment. Peatlands are dealt with in Box 11.2.

burnt, or when cut biomass, soil carbon and forest products decay) as well as sinks of atmospheric CO_2 (e.g. vegetation regrowth and afforestation). The combination of gross sources and sinks gives the net flux that affects atmospheric CO_2 concentration. The direct effects of human activity on the land in terms of land use change and forestry management have resulted in net FOLU emissions of 660 ± 295 $GtCO_2$ from 1750 to 2011, with annual emissions declining from 5.1 ± 2.9 $GtCO_2$/yr in the 1980s to 4.0 ± 2.9 $GtCO_2$/yr from 2000 to 2009 (IPCC AR5 WGI ch.6 Ciais et al.; Table 11.1). These correspond to a third of cummulative anthropogenic CO_2 emissions since 1750, and 12.5% of emissions in 2000 to 2009, mostly due to deforestation; occurring first primarily in temperate and boreal zones, and more recently in tropical zones (Table 11.1). The proportional contribution of FOLU to total emissions has declined over recent decades because of continuing rapid growth in fossil fuel emission rates, while FOLU emissions have likely declined (Figure 11.6).

Ecosystems also respond to environmental variability and change. Increased levels of CO_2 and N in the atmosphere have a fertilising effect on plants. Prolonged growing seasons in northern extra-tropical regions have likely enhanced net CO_2 uptake, while higher soil temperatures, and reduced rainfall and droughts in other areas, may reduce it. A full assessment of climate, N and CO_2 effects is dealt with in IPCC AR5 WGI (Ciais et al., section 6.3.2.6.5). Ground-based inventory measurements of forest stocks cannot separate out management from environmental effects, but increase in mature forest biomass or growth rates have been identified in inventory measurements from both managed and unmanaged lands in temperate and tropical regions (Phillips et al., 1998; (Luyssaert et al., 2008; Lewis et al., 2009; Pan et al., 2011). Globally, the net effect of the natural response of ecosystems to environmental change is a sink, often termed the “residual terrestrial sink” as it is calculated as the residual of other better-quantified CO_2 fluxes. This natural residual sink response of ecosystems to environmental change is an estimated -550 ± 330 GtC from 1750 to 2011, and -9.2 ± 4.4 GtC/yr in 2000 to 2009 (IPCC AR5 WGI ch.6 Ciais et al.; Table 11.1; minus sign denotes removal from the atmosphere). Therefore the natural residual land sink resulted in an offset of human-induced emissions from land, resulting in a net land sink in recent decades.

Table 11.1: Global anthropogenic carbon budget (From IPCC AR5 WGI, Chapter 6, Table 6.1, converted to $GtCO_2$/yr). Accumulated since the Industrial Revolution (onset in 1750) and averaged over the 1980s, 1990s, 2000s. Note that, by convention, a negative ocean or land to atmosphere CO_2 flux is equivalent to a gain of carbon by the ocean or land reservoirs. The uncertainty range of 90% confidence interval presented here differs from how uncertainties were reported in AR4 (68%).

	1750 to 2011 cumulative $GtCO_2$			1980–1989 $GtCO_2$/yr			1990–1999 $GtCO_2$/yr			2000–2009 $GtCO_2$/yr		
Atmospheric Increase[a]	880	±	37	12.47	±	0.73	11.37	±	0.73	14.67	±	0.73
Fossil fuel combustions and cement production[b]	1338	±	110	20.17	±	1.47	23.47	±	1.83	28.23	±	2.20
Ocean-to-atmosphere flux[c]	-568	±	110	-7.33	±	2.57	-8.07	±	2.57	-8.43	±	2.57
Land-to-atmosphere flux: Partitioned as follows:	110	±	165	-0.37	±	2.93	-4.03	±	3.30	-5.13	±	3.30
Net land use change[d]	660	±	293	5.13	±	2.93	5.50	±	2.93	4.03	±	2.93
Residual terrestrial sink[e]	550	±	330	-5.50	±	4.03	-9.53	±	4.40	-9.17	±	4.40

Notes:

(a) Data from Charles .D. Keeling, (http://scrippsco2.ucsd.edu/data/data.html), Thomas Conway and Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) using a conversion factor of 2.123 GtC per ppm.

b) CO_2 emissions are estimated by the Carbon Dioxide Information Analysis Center (CDIAC) based on UN energy statistics for fossil fuel combustion and US Geological Survey for cement production (Boden et al., 2011).

(c) Averaged from existing global estimates. This flux does not include the natural river flux of carbon and the associated natural outgas of CO_2 to the atmosphere.

(d) Based on the bookkeeping land use change flux accounting method of Houghton (2003) (2012).

(e) Sum of the Land-to-atmosphere flux minus Net Land Use Change, assuming the errors on each term are independent and added quadratically.

A variety of data and methods have been applied in calculating FOLU fluxes, trying where possible to factor out the direct effects of human activity from the indirect environmental change effects. A typical approach is to calculate the effects of changing land use and forest management on carbon stock/flux, often inherently, including environmental change effects on managed lands depending on the data and method used. While environmental effects (residual sink) on non-managed lands are either not included, or caluclated separately.

Several global FOLU flux estimates are shown in Figure 11.6. These are only an illustrative selection, including model results that were updated for IPCC WGI Chapter 6. Many of these approaches have been described in more detail in the meta-analysis of Houghton et al. (2012), and in the latest annual updates of the carbon budget produced by the Global Carbon Project (Le Quéré et al., 2012), summarised below. These estimates are based on different data sources, and include different processes and approaches to calculating emissions. For example, some assume instantaneous emissions of all carbon that will be eventually lost from the system following human action, while others take into account the rate of decomposition, fate of products, and rate of regrowth of replacement vegetation (legacy effects). Some account for forest management in terms of forest harvest and shifting cultivation (where forest is burnt, cultivated for a number of years until fertility declines, then left to regrow to forest), while others account for land use change only. Some include the dynamic (changing with time) effects of climate and CO_2 on land subject to FOLU (affecting biomass and decomposition and regrowth rates), while others use inventory/literature measurements of biomass or rate of growth/decay that are fixed through time. The different data and approaches lead to a large uncertainty in estimating the FOLU flux and difficulty in interpreting results. However most approaches agree that there has been a decline in FOLU emissions over the most recent years. For the range of 13 models included in Houghton et al. (2012), emissions declined from 4.18 to 4.11 $GtCO_2$/yr from the 1980s to 1990s with an uncertainty of ± 1.83 $GtCO_2$/yr. IPCC WGI used the Houghton bookeeping estimate (see below) for the carbon budget (Table 11.1), but gave the range across 12 process models, some updated to 2009, as 5.13 $GtCO_2$/yr for the 1980s, 4.40 $GtCO_2$/yr for the 1990s and 2.93 $GtCO_2$/yr for the 2000s, with an uncertainty of up to ± 2.93 $GtCO_2$/yr (IPCC, WGI, Chapter 6, Table 6.2).

Box 11.1 Different approaches to calculating the FOLU flux

a) IPCC/UNFCCC reporting and accounting methods. There are three databases available to the public and containing partial data on GHG emissions from AFOLU. These are the UNFCCC, FAOSTAT and EDGAR databases. They are all based on IPCC GHG Reporting guidelines (e.g. IPCC 2003, 2006). Parties to the UNFCCC report data in fulfillment of their climate policy obligations. Specifically, Annex I parties to the Kyoto Protocol mandatorily report and account annually their GHG sources and sinks due to afforestation, reforestation and deforestation activities since 1990, as well as optionally report those related to cropland and other forms of land management, with mandatory reporing of forest management from 2013. Reporting uses a range of methods and approaches dependent on available data and capabilities from using generalised emission factors (tier 1) to detailed inventory and satellite data and models (tier 3), with non-Annex I countries reporting at less frequent intervals. Inconsistencies and gaps in space and time in the UNFCCC data are addressed in part by EDGAR and FAOSTAT. These databases report data globally and at country detail, over a continuous time interval, using tier1 IPCC GHG Guidelines.

b) EDGAR covers the period 1970-2008, but is limited to GHG emissions from biomass fires based on GFED 2.0 data (Van Der Werf et al., 2006). These data do not distinguish FOLU fires from other fires, or capture significant additional LULUCF emissions due to forest harvest (Box 11.3).

c) The FAOSTAT database covers the period 1990-2010. It includes area of cropland, pastureland (annual FAOSTAT data from annual country reports, available from 1960) and forest (annual FAOSTAT data from FRA reports, published every 5 years). From these data, *net land use change* data can be computed. In addition, FAOSTAT data include annual estimates of wood harvest fluxes, and periodic estimated of forest C stock, including total biomass and soil C data. (FAOSTAT, 2012)[2] now includes GHG emissions due to net forest conversion, assuming instantaneous emissions, with an estimated net flux of 2.6 $GtCO_2$/yr in 2010 (Tubiello et al., 2013) as well as CO_2 emissions from cultivated organic (peatland) soils of 0.7 $GtCO_2$/yr. Increasing use of satellite data in recent years to support country estimates has resulted in a downward revision of estimated deforestation rates between FAO FRA 2000, 2005 and 2010. Therefore FOLU emissions estimates based on older FAO FRA data, including those summarised in IPCC fourth assessment report, have since been revised downward.

d) "Book-keeping" model method (Houghton et al., (2003) updated for (Friedlingstein et al., 2010): Tracks carbon in living vegetation, dead plant material, woods products and soils. Based primarily on FAO FRA data since 1970, with regional assumptions made about conversion to different land use (cropland, pasture), mode of clearing (fire/harvest/mechanical clearing) and fate of products. Uses regional biomass, growth and decay rates from literature, no dynamic CO_2 and climate effects. Includes forest management in terms of shifting cultivation and harvest and regrowth.

e) Process-based terrestrial ecosystem models: Simulate changing plant biomass and carbon fluxes between vegetation, soils and the atmosphere using spatially explicit (girdded) data on climate and soils. Change in land cover from a variety of data sets (primarily HYDE – (Goldewijk et al., 2011; Hurtt et al., 2011); but also SAGE – (Ramankutty and Foley, 1999) based mostly on FAOSTAT agricultural area change data, with assumptions about what the previous land cover was. Vary according to approach as to whether and how climate and CO_2 effects are calculated, few include N (Zaehle et al., 2011; Jain et al., 2013). Generally, they include fate of products in legacy effects, only a few explicitly include forest management (e.g. (Shevliakova et al., 2009a).

f) Satellite data approaches: Used to detect change in forest cover (e.g. (Hansen et al., 2010) have been combined with the book-keeping model approach to calculate tropical forest emissions (e.g. (deFries et al., 2002); (Achard et al., 2004). The data is high resolution and verifiable but only covers recent decades. Satellite data alone cannot distinguish the cause of change in forest area (deforestation, natural disturbance, management). Analyses typically assume instantaneous emissions. A recent development is the use of satellite-based forest biomass estimates (e.g. (Saatchi et al., 2011), and combining this with satellite land cover change to estimate instantaneous emissions from loss of forest cover (Harris et al., 2012a) or combining it with FAO and other activity data in the Houghton model approach including forest management and regrowth (Baccini et al., 2012), see Table 11.2. (Satellite-fire approaches are described in Box 11.3).

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[2] http://faostat.fao.org/

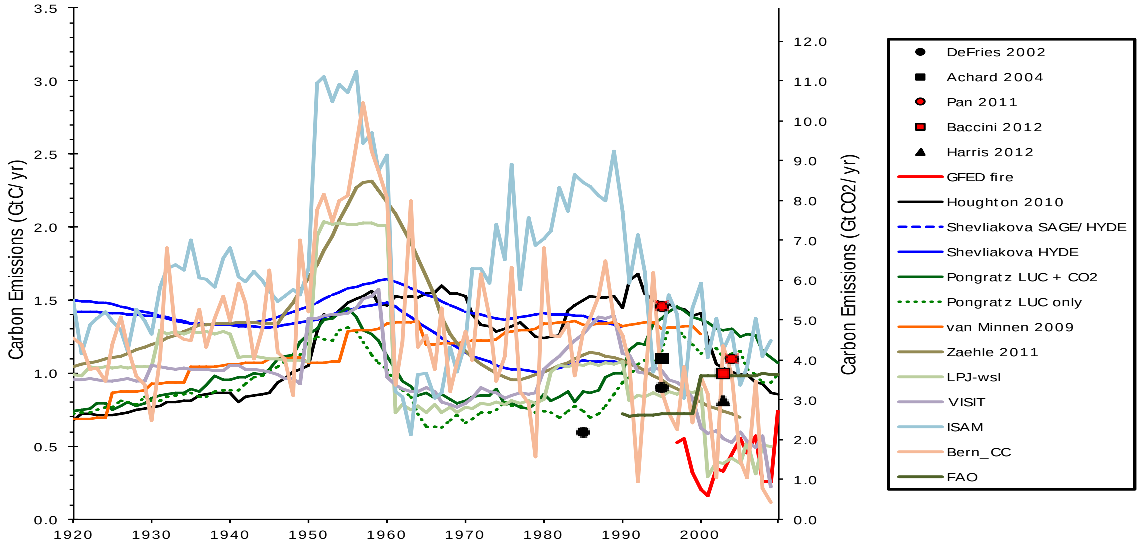

Figure 11.6 Global carbon emissions from land use change and forestry. The various approaches to estimating land use change emissions are described in the text in more detail. The symbols represent decadal mean satellite-based analyses of tropical flux (deFries et al., 2002) (Achard et al., 2004; Pan et al., 2011) – tropical only up to 2007; (Baccini et al., 2012; Harris et al., 2012b). GFED fire: satellite fire data (Van der Werf et al., 2010): GFED 3.0 database). (Houghton, 2010): bookeeping model approach (Houghton, 2003) updated to 2010 as in (Houghton et al., 2012); (Le Quéré et al., 2012) and IPCC WGI). An illustrative selection of process model results: (Shevliakova et al., 2009b) comparing SAGE and HYDE data sets; (Pongratz et al., 2009) results with and without CO_2 fertilisation effects; (Zaehle et al., 2011). The remaining process models putputs were updated for IPCC WGI using a common land use data set (Goldewijk et al., 2011): LPJ-wsl (Poulter et al., 2010); VISIT (Kato et al., 2011); ISAM (AK Jain et al., subm); BernCC (Stocker et al., 2011); IMAGE (Van Minnen et al., 2009); **note data shown from published paper, while checking issues with new results*).

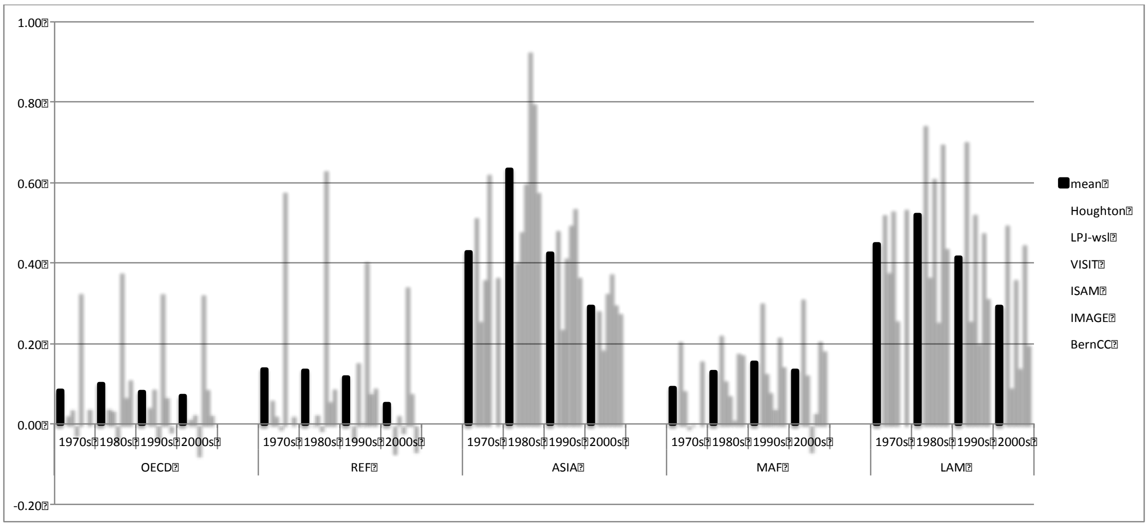

Figure 11.7 Regional trends in carbon fluxes from land use change and forestry (GtCO2/yr). Houghton book-keeping model (Houghton, 2003), updated as in and (Houghton et al., 2012); IPCC WGI) and 5 vegetation models (IMAGE: (Van Minnen et al., 2009) *note data from this model are preliminary; LPJ-wsl: (Poulter et al., 2010); BernCC: (Stocker et al., 2011); VISIT: (Kato et al., 2011); ISAM: (AK Jain et al., subm) using the HYDE land-cover data (Goldewijk et al., 2011; Hurtt et al., 2011) updated to 2010 for IPCC WGI.

Regional trends in FOLU emissions are shown in Figure 11.7. Uncertainties due to model and data differences become more apparent than in global numbers. Regional trends from all modelling studies indicate FOLU emissions peaked in the 1980s in ASIA and LAM regions and declined thereafter. This is consistent with a reduced rate of deforestation and some areas of afforestation most notably in India and China (FAO (FRA, 2010). In MAF the picture is mixed with Houghton showing a continuing increase from the 1970s to the 2000s, while the VISIT model indicates a small sink in the 2000s. The results for temperature and boreal areas represented by OECD and REF regions are very mixed ranging from large net sources (ISAM) to small net sinks. These regions include large areas of managed forests subjected to harvest and regrowth, and areas of reforestation (e.g. following crop abandonment in the USA and Europe). The ISAM model is the only one to include an N cycle – atmospheric N has a fertilising effect on forest regrowth, however N limitation due to harvest removals limits forest regrowth rates causing 70% higher modelled net emissions in temperate and boreal forests, and 40% globally, than when the N-cycle effects are not considered (AK Jain et al., subm). The general picture in these regions is of declining emissions or increasing sinks.

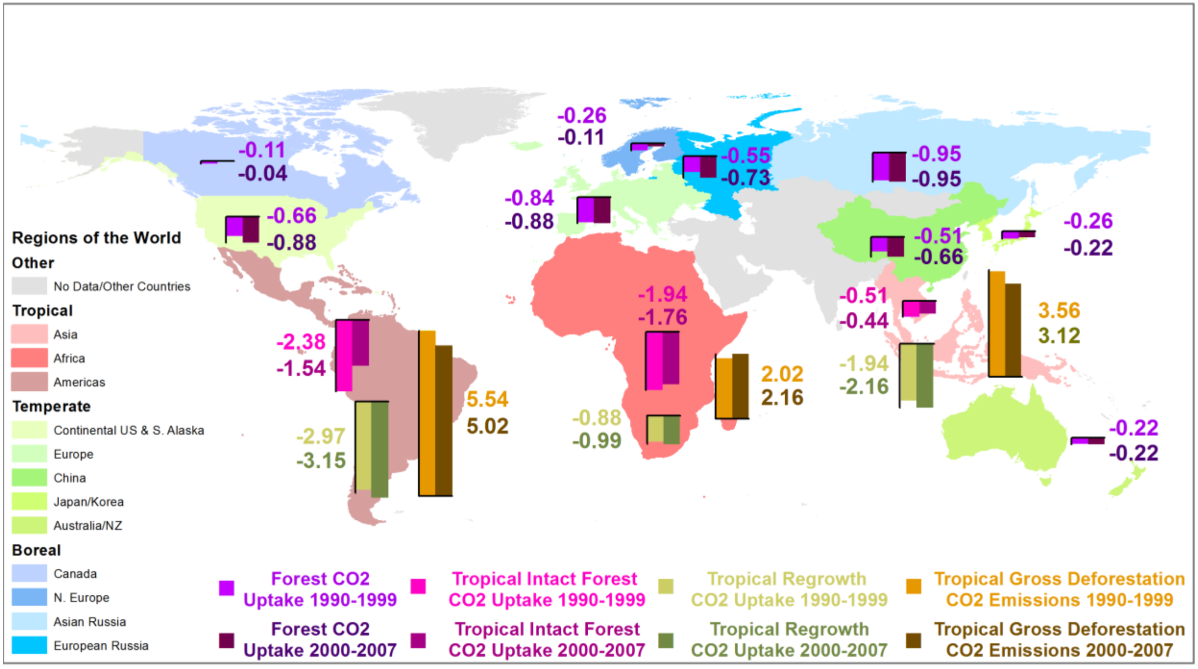

Figure 11.8 Carbon sinks and sources in world's forests (GtCO2/yr) (converted from C to CO2 and redrawn from (Pan et al., 2011) by Kevin F.S. McCullough). Negative bars (below the x axis) and negative fluxes represent sinks; positive bars (above the axis) represent sources. In the tropics, brown bars represent "gross" deforestation emissions (loss of forest both due to net deforestation and due harvesting/shifting cultivation) and green bars represent forest regrowth (following harvest, shifting cultivation or due to reforestation), calculated by (Houghton, 2003) model using FAO (FRA, 2010) data. Combining green and brown gives the net FOLU flux. In the tropics, pink bars represent net uptake in "intact" forests only (i.e. no deforestation, reforestation or forest management) from forest inventory measurements, representing the natural response to environmental change (residual) flux. In the temperate and boreal regions, purple bars represent the net flux from all forests (managed and unmanaged due to FOLU and environmental change) from forest inventory data.

Figure 11.8 (Pan et al., 2011) brings together global forest inventory data, and uses different approaches to breakdown the flux in different regions and also to different components. In the tropics "gross deforestation" is permanent forest loss[3] plus temporary loss of forest for shifting cultivation and harvest, with the temporary forest loss compensated by "tropical regrowth" (as in (Baccini et al., 2012), Table 11.2). Net FOLU emissions declined between the 1990s and 2000 to 2007 from 2.6 to 1.9 $GtCO_2$/yr in LAM regions, and 1.6 to 1.0 $GtCO_2$/yr in ASIA, but increased slightly in Africa from 1.1 to 1.2 $GtCO_2$/yr. Tropical "gross deforestation" emissions of 10.3 $GtCO_2$/yr from 2000 to 2007 in (Pan et al., 2011) and 8.4 $GtCO_2$/yr from 2000 to 2005 in (Baccini et al., 2012); Table

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[3] Note this is from based on FAO FRA data on "NET" change in forest area so is not technically "gross" deforestation

11.2) are higher than “gross deforestation” emissions of 3.0 $GtCO_2$/yr from 2000 to 2005 in (Harris et al., 2012a) because the latter estimate does not include temporary forest loss due to management, highlighting the importance of careful interpretation of different results, with different approaches and definitions. Where there is permanent forest loss, “gross” emissions from loss of biomass and soil carbon and “net” emissions accounting for any replacement vegetation are virtually the same, and this is the amount that can be mitigated. Where there is temporary forest loss through management, “gross” forest emissions can be as high as for permanent forest loss, but are largely balanced by uptake in regrowing forest and the net emissions are much smaller (amounting to forest degradation) as is the potential for mitigation. (Huang and Asner, 2010) estimated forest degradation in the Amazon, particularly selective logging, is responsible for 15-19% higher C emissions than reported from deforestation alone using high resolution satellite imagery and modelling. This is similar to Baccini et al. (2012) who found degradation to be responsible for 15% of total emissions in the tropics as a whole (Table 11.2). Figure 11.9 shows a global breakdown into component fluxes.

Table 11.2: Gross and net emissions of carbon ($GtCO_2$/yr) from LULCC activities in the tropics for the period 2000-2005. Detailed results from the analyses included in (Baccini et al., 2012): forest area loss from FAO (FRA, 2010), spatial location and biomass of forest loss from satellite data, flux calculation from (Houghton, 2003) book-keeping model. In this case “gross” refers to loss of soil and biomass C when forest is harvested or burnt, “net” accounts for C uptake in regrowing vegetation from activities that occurred during the period 2000 to 2005, but also accounting for legacy fluxes from activities prior to this period.

	Gross emissions	Net emissions
Deforestation	3.52	3.52
Afforestation		-0.06
Sub-total forest area change	**3.52**	**3.46**
Wood harvest (industrial) [1]	1.65	0.01
Fuelwood harvest[2]	0.84	0.31
Shifting cultivation[3]	2.35	0.30
Sub-total for degradation	**4.84**	**0.62**
Total	**2.280**	**4.09**

1. Emissions from logging debris and wood products, and uptake by recovering forests
2. Traditional subsistence activity, emissions and uptake by recovering forests
3. Emissions from the re-clearing and regrowth of fallows

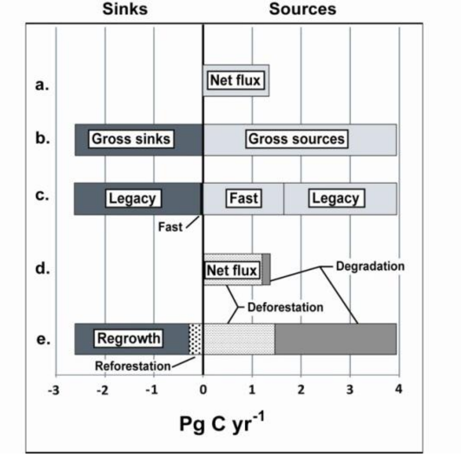


Figure 11.9. Breakdown of mean annual global carbon emissions from land use change and forestry into component fluxes for the meriod 2000 to 2009. (note: units are GtC/yr; to convert to $GtCO_2$

multiply by 3.667 [redraw for FD]). Figure reproduced from Houghton et al., (2012). Data from Houghton bookeeping model as reported in (Friedlingstein et al., 2010); (Houghton et al., 2012); IPCC WGI. "Legacy" in 2C refers to the sinks (regrowth) and sources (decomposition) from activities carried out before 2000; "fast" refers to sinks and sources from the current years activities.

Box 11.2 Peatlands, wetlands

Undisturbed peatlands and mangrove forests store a large amount of carbon and act as small net sinks, as decomposition in waterlogged soils is slower than plant inputs, thus leading to a build-up of soil organic carbon (Hooijer et al., 2010). Drainage and burning of peatlands for agriculture and forestry use result in a rapid increase in decomposition and vulnerability to further fire. In Southeast Asia emissions from drained peatlands in 2006 were 0.61 ± 0.25 $GtCO_2$/yr (Hooijer et al., 2010), adding emissions from peatland burning of 0.39 $GtCO_2$/yr (Van der Werf et al., 2010), Box 11.3), gives a total of 1.0 $GtCO_2$/yr in this region alone. There is a lack of global peatland emission estimates in the peer-reviewed literature. The FAO emissions database indicates a global contribution of drained organic soils under cropland of 0.75 Gt CO_2/yr with the largest contributions from Asia (0.4 Gt CO_2/yr) and Europe (0.15 Gt CO_2/yr) (FAOSTAT, 2012). (Joosten, 2010) estimates that the CO_2 emissions from more of 500,000 km^2 of drained peatlands in the world, including both croplands and grasslands, have increased from 1.1 Gt CO_2 /yr in 1990 to 1.3 Gt CO_2/yr in 2008 (an increase of more than 20%), with a decreasing trend in developed countries due to natural and artificial rewetting of peatlands. Mangrove ecosystem areas have declined by 20% (36Mha) since 1980, although the rate of loss has been declining in recent years, reflecting an increased awareness of the value of these scosystems (FAO, 2007). A recent study estimated that deforestation of mangroves released 0.02 to 0.12 GtC/yr. Peatland and mangrove emissions are not explicitly included in any of the estimates presented in Figure 11.6.

Box 11.3. Fires

Burning vegetation releases CO2, CO, CH4 and aerosols to the atmosphere. When vegetation regrows after a fire it takes up CO2. Therefore where fires are part of a burning and regrowth cycle (e.g. savanna burning and shifting cultivation) carbon emissions are balanced by uptake over decadal timescales or regional scales. Only fires where land is permanently cleared (e.g. deforestation, drained peatlands), or has increasing levels of disturbance resulting in degradation of soil and vegetation carbon stocks, are there net emissions of carbon to the atmosphere. Satellite-detection of fire occurrence and persistence has been used to estimate fire emissions (van der Werf et al., 2006: GFED 2.0 database, basis of EDGAR 4.0 data). It is hard to separate the causes of fire as natural or anthropogenic, especially as the drivers are often combined e.g. places may be more vulnerable to fires due to anthropogenic activity or climate conditions or a combination of the two. Both natural and anthropogenic fire activity is greater in dry years, particularly after previous wet years have led to a build up of fuel (biomass to burn). More recent estimates distinguish FOLU deforestation and degradation fires from other fires that do not result in net carbon emissions (van der Werf et al., 2010: GFED 3.0 database; see Figure 11.6), but do not detect emissions where land clearing is not by fire. Tropical deforestation and degradation fires emitted 0.38 GtC/yr (total carbon including CO2, CH4, CO and black carbon, roughly equivalent to 1.4 GtCO2/yr), 20% of all fire emissions during 1997 to 2009, and peat fires in equatorial Asia emitted 0.39 GtCO2/yr (0.4 GtCO2) . Fire management can lead to a terrestrial sink, e.g. of -0.2 GtCO2/yr in the USA in the 1980s (Houghton et al., 1999). FOLU deforestation fire emissions are inherently incorporated in model-based estimates.

FAQ 11.1 How much does AFOLU contribute to GHG emissions and how is this changing?

Agriculture and land use change, mainly deforestation of tropical forests, contribute greatly to anthropogenic greenhouse gas emissions and are expected to remain important during the 21st century. At present, cumulative GHG emissions (mainly CH_4 and N_2O) from agricultural production comprise about 10-12% of global anthropogenic emissions. Annual C flux from land use and land use change activities accounted for approximately 12 - 20% of total anthropogenic greenhouse gas emissions with mean values of about 1.1± 0.9 Gt C / yr in the 1990s. The total contribution of the AFOLU sector to anthropogenic emissions is therefore 24-34% of the global total.

11.3 Mitigation technology options and practices, and behavioural aspects

Greenhouse gases can be reduced by supply-side mitigation measures (i.e. by reducing GHG emissions per unit of land, animal or per unit of product), or by demand-side options (i.e. by reducing demand for food and fibre products). In IPCC AR4 the forestry chapter considered some demand-side measures but the agriculture chapter focussed on supply-side measures (Nabuurs et al., 2007; Smith, et al., 2007). In this section we discuss only supply-side measures (11.3.1). Demand-side options are discussed in section 11.4.

Mitigation activities in the AFOLU sector can reduce climate forcing in different ways:

- Reductions in CH_4 or N_2O emissions from cropping and animal husbandry systems.
- Reductions of direct (e.g. tractors) or indirect (e.g. production of fertilizers) emissions resulting from fossil energy use in agriculture or forestry or from production of inputs.
- Reductions of carbon losses from biota and soils, e.g. through management changes within the same land-use type (e.g. switch from tillage to no-till cropping, removal of factors such as N or P deficiency that limit soil carbon) or through reductions in the loss of carbon-rich ecosystems, e.g. reduced deforestation, increased soil carbon storage.
- Enhancement of carbon sequestration in biota and soils through increases in the area of carbon-rich ecosystems such as forests (afforestation, reforestation), or through increased carbon storage per unit area, e.g. increased stocking density in forests.
- Changes in albedo that increase reflection of visible light.
- Provision of bioenergy with low GHG emissions that can replace high-GHG energy (e.g. fossil fuels) in the energy, industry and transport sectors, thereby reducing their GHG emissions.

11.3.1 Supply-side mitigation measures

Per-area and per-animal mitigation potentials for agricultural mitigation options were given in (Smith, et al., 2007; Smith et al., 2008). All measures are summarised in Table 11.3. These mitigation options can have additive positive effects, but can also work in opposition, e.g. improved agroforestry with legume trees can have a negative impact on N_2O emissions. Measures that were described in detail in AR4 are not decribed further but updated references ae provided; additional practices, not considered in AR4 (e.g. biochar and bioenergy) are described in Box 11.4 and Annex, respectively.

Table 11.3: Summary of supply-side mitigation options in the AFOLU sector. Measures are for carbon (C) unless the impact upon other gases (N2O and CH4), and this is stated where relevant

Option	**Description**	**References**
Forestry		
Afforestation, Reforestation and Deforestation (ARD)		
Reduced deforestation	Deforestation is the conversion of forest to another land use or the long-term reduction of the tree canopy cover below the minimum 10 percent threshold.	(FAO, 2001)
Reduced Forest degradation	Changes within the forest which negatively affect the structure or function of the stand or site, and thereby lower the capacity to supply products and/or services.	(FAO, 2006b)
Afforestation	Establishment of forest plantations on land that, until then, was not classified as forest. Implies a transformation from non-forest to forest.	(UNFCCC, 2006)
Reforestation	Establishment of forest plantations on temporarily unstocked lands that are considered as forest.	(UNFCCC, 2006)
Forest Management		
Forest management in plantations	The process of planning and implementing practices for stewardship and use of the forest aimed at fulfilling relevant ecological, economic and social functions of the forest.	FAO 2012
Sustainable forest management in native forest	The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biological diversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological economic and social functions, at local, national and global levels, and that does not cause damage on other ecosystems.	FAO 2012
Land-based Agriculture		
Cropland management		
Croplands – agronomy	**C**: High input carbon practices, e.g. improved crop varieties, crop rotation, use of cover crops, perennial cropping systems, agricultural biotechnology	(Godfray et al., 2010); Burney et al., 2010; Conant et al., 2007
	N_2O: Improved plant N use efficiency	Huang and Tang, 2010
Croplands – nutrient management	**C**: Fertilizer input to increase yields and residue inputs (esp. important in low-yielding agriculture)	Denef et al., 2011. Eagle et al., 2012
	N_2O: N fertilizer application rate, fertiliser type, timing, precision application, inhibitors	Snyder et al., 2009; Akiyama et al., 2010; Barton et al., 2011; (Powlson et al., 2011); van kessel et al., 2012
Croplands –	**C**: Reduced tillage intensity; Residue retention	Conant et al., 2007; (Farage et al., 2007); (Powlson et al., 2011; Smith,

tillage/residues		2012a)
	N_2O:	Swan et al., 2011
Croplands – water management	**C**: Improved water availability in cropland including water harvesting and application	(Bayala et al., 2008)
	CH_4	
	N_2O: Drainage management to reduce emissions	
Croplands – rice management	**C**: Straw retention,	Yagi et al., 1997
	CH_4: Water management, mid-season paddy drainage	Itoh et al., 2011; Feng et al., 2013
	N_2O: Water management, N fertilizer application rate, fertiliser type, timing, precision application	Feng et al., 2013
Rewet peatlands drained for agriculture	**C**: Ongoing CO_2 emissions from drainage reduced (but CH_4 emissions can then increase)	(Lohila et al., 2004)
Croplands – set-aside & LUC	**C**: Long term fallow and community forestry.	(Seaquist et al., 2008; Mbow and C, 2010; Assogbadjo et al., 2012) Laganière et al., 2010;
	N_2O	
Biochar	**C**: Soil amendment to increase biomass productivity, and sequester C (Biochar was not covered in AR4 so is described in Box 11.4).	Singh et al. 2010; Taghizadeh-Toosi et al., 2011; (Woolf et al., 2010); Lehmann et al. 2003
	N_2O	Singh et al., 2010
Grazing Land Management		
Grasslands – management	**C:** Improved grass varieties / sward composition, e.g. deep rooting grasses, increased productivity and nutrient management. Appropriate stocking densities, carrying capacity, fodder banks and improved grazing management	Franzluebbers and Stuedemann, 2009; Follett and Reed, 2010; McSherry and Richtie 2013
	CH_4	Saggar et al., 2004
	N_2O	Saggar et al., 2004
Grasslands – grazing	Appropriate stocking densities, carrying capacity management, fodder banks and improved grazing management, fodder production and fodder diversification	(Conant et al., 2001); Freibauer *et al.*, 2004; Conant and Paustian, 2002; Reeder *et al.*, 2004 Franzluebbers and Stuedemann 2009; Conant *et al.*,2005, (Thornton and Herrero, 2010)
Grasslands- fire mgt	Improved use of fire for sustainable grassland management. Fire prevention and improved	(Ehrlich, D. et al. 1997; Ayoub and A.T. 1998; Fearnside and P.M. 2000;

	prescribed burning	Mbow, C. et al. 2000; Murdiyarso, D. et al. 2002; Haugaasen, T. et al. 2003; Saarnak, C. et al. 2003; Zhang, Y.H. et al. 2003; Barbosa, R.I. et al. 2005; Ito and A. 2005)
Revegetation		
Revegetation	The establishment of vegetation that does not meet the definitions of afforestation and reforestation (e.g. *Atriplex* spp.)	(Harper et al., 2007)
Other		
Organic soils – restoration	Soil carbon restoration on peatlands; and avoided net soil carbon emissions using improved land management	(Smith and Wollenberg, 2012)
Degraded soils – restoration	Land reclamation (afforestation, soil fertility reduction, water conservation soil nutrients enhancement, improved fallow, etc.)	(Hardner, J.J. et al. 2000; Batjes and N.H. 2003; Sands, R.D. et al. 2003; Arnalds and A. 2004; May, P.H. et al. 2004; Zhao, W.Z. et al. 2004)
Biosolid applications	Use of animal manures and other biosolids for improved managment of nitrogen; integrated livestock agriculture techniques	(Farage et al., 2007)
Livestock		
Livestock – feeding	**CH_4**: Improved feed and dietary additives to reduce emissions from enteric fermentation; including improved forage, dietary additives (bioactive compounds, fats), ionophores / antibiotics, propionate enhancers, archaea inhibitors, nitrate and sulphate supplements	(Newbold et al., 2002; Machmuller et al., 2003; Odongo et al., 2007; Anderson et al., 2008; Beauchemin et al., 2008; Martin et al., 2008; Waghorn, 2008; Grainger et al., 2008, 2010; Foley, Kenny, et al., 2009; Nolan et al., 2010; Van Zijderveld et al., 2010; Ding et al., 2010; Mao et al., 2010; Brown et al., 2011; Eugene et al., 2011); Waghorn *et al*., 2007; Kumar, 2011; Wood *et al*., 2006; (Van Zijderveld et al., 2011), Hristov et al 2011, (Bryan et al., 2013), Blummel et al 2010
Livestock – breeding and other long term management	**CH_4**: Improved breeds with higher productivity (so lower emissions per unit of product) or with reduced emissions from enteric fermentation; microbial technology such as archaeal vaccines, methanotrophs, acetogens, defaunation of the rumen, bacteriophages and probiotics	(Boadi et al., 2004; Alford et al., 2006; Nkrumah et al., 2006; Hegarty et al., 2007; Attwood and McSweeney, 2008; Cook et al., 2008; Morgavi et al., 2008; Janssen and Kirs, 2008; Chagunda et al., 2009; Williams et al., 2009; Wedlock et al., 2010; Yan et al., 2010) Emma et al., 2010; Newbold and Rode, 2006, (Thornton and Herrero, 2010)
Manure management	**CH_4**: Manipulate bedding and storage conditions, anaerobic digesters; biofilters, dietary additives.	(Chadwick et al., 2011), Echard et al. 2010, Hristov et al. 2012, Kebreab et al. 2006, (Monteny, et al., 2006), (Petersen and Sommer, 2011)

	N_2O: Manipulate livestock diets to reduce N excreta, soil applied and animal fed nitrification inhibitors, urease inhibitors, fertilizer type, rate and timing, manipulate manure application practices, grazing management	Chadwick et al. 2012, de Klein and Eckard 2008, de Klein and Monaghan 2011, Dijkstra et al 2011, Hristov et al. 2012, Kebreab et al. 2006, (Monteny, et al., 2006), (Petersen and Sommer, 2011), Pinares-Patino et al 2009, Schils et al 2011, (VanderZaag et al., 2011) (Wright and Klieve, 2011)
Integrated Systems		
Agroforestry (including agropastoral and agrosilvopastoral systems)	Agro-forestry is the production of livestock or food crops on land that also grows trees for timber, firewood, or other non wood products. It includes shelter belts and riparian zones/buffer strips with woody species. Incorporating trees into cropland management through rotation of woody cropsor by enabling trees to grow on farming lands	(Vagen et al., 2005; Oke and Odebiyi, 2007; Rice, 2008; Takimoto et al., 2008; Lott et al., 2009; Sood and Mitchell, 2011; Assogbadjo et al., 2012; Wollenberg et al., 2012; Semroc et al., 2012) (Souza et al. 2012)
Other mixed biomass production systems	Mixed production systems such as double-cropping systems and mixed crop-livestock systems can increase land productivity and efficiency in the use of water and other resources as well as serve carbon sequestration objectives. Grasses can in the same way as woody plants be cultivated in shelter belts and riparian zones/buffer strips provide environmental services	Heggenstaller et al., 2008; Herrero et al., 2010
Integration of biomass production with subsequent processing in food and bioenergy sectors	Integrating feedstock production with conversion, typically producing animal feed, that can reduce demand for cultivated feed such as soy and corn and can also reduce grazing requirements.	Dale et al., 2009, 2010; (Sparovek et al., 2007)
Bioenergy (see Annex I for full details)		
Bioenergy from plant residues	**Forest**: Biomass from silvicultural thinning and logging, and wood processing residues such as sawdust, bark and black liquor. Dead wood from natural disturbances, such as storms and insect outbreaks. Environmental effects of primary residue removal depend on land management practice and local conditions, and removal rates need to be controlled considering local ecosystem, climate, topography, and soil factors.	Chum et al., 2011; Näslund and Gustavsson 2008; Eriksson and Gustavsson 2010; Lattimore et al. 2009
	Agriculture: By-products associated with production and processing, both primary (e.g., cereal straw from harvesting) and secondary residues (e.g., rice husks from rice milling)	(Rogner et al., 2012), (Hakala et al., 2009); (Haberl et al., 2010); Chum et al., 2011; (Gregg and Smith, 2010)

Bioenergy from unutilized forest growth	Biomass from growth occurring in forests judged as being available for wood extraction, which is above the projected biomass demand in the forest industry. Includes both biomass suitable for, e.g., pulp and paper production and biomass that is not traditionally used by the forest industry.	(Chum, Faaij, Moreira, Berndes, Dhamija, Gabrielle, et al., 2011); Alam et al. 2012; (Sathre et al., 2010; Routa et al., 2012); Berg et al. 2005; Pyörälä et al 2012; Poudel et al. 2012; (Böttcher et al., 2012); Hotsmark, 2012; (Hudiburg et al., 2011a)
Bioenergy from dedicated plants	**Forests**: Biomass from short-rotation coppice or single stem plantations (e.g., willow, poplar, eucalyptus, pine).	Kursten, 2000; Tamubula and Sinden, 2000; Ravindranath et al., 2001; Rice 2008; Sood and Mitchell 2011
	Agriculture: Cultivation of high yielding crops such as oil crops (e.g. Jatropha), grasses (e.g. switchgrass, Miscanthus).	Chum et al., 2011;Sims et al., 2006; Haberl et al., 2011; Beringer et al., 2011); Popp, et al., 2011; Karl-Heinz Erb et al., 2012a
Bioenergy from Organic Wastes	Manure converted to biogas in biodigesters.	(Rogner et al., 2012); (Haberl et al., 2010); Chum et al., 2011; (Amon et al., 2006); Börjesson and Berglund 2006; Möller 2009
	Waste from households and restaurants, discarded wood products such as paper and demolition wood, and wastewaters suitable for anaerobic biogas production	Chum et al., 2011; (Rogner et al., 2012)

Box 11.4 Biochar

Since biochar was not considered in AR4, this box summarises available biochar technologies. Biomass stabilisation can be an alternative or enhancement to bioenergy in a land-based mitigation strategy. Heating biomass with exclusion of air / oxygen (pyrolysis) eliminates H and O preferentially over C, producing in addition to energy-containing volatiles and gases, a stable C-rich co-product (char). Added to soil as 'biochar', a system is created that has greater abatement potential than typical bioenergy (Woolf et al., 2010) and probably highest where efficient bioenergy (with use of waste heat) might be constrained by a remote, seasonal or diffuse biomass resource (Shackley et al., 2012). The relative benefit of pyrolysis–biochar systems (PBS) is increased if assumptions are made for the durability of positive effects of biochar on crop (and thus biomass) productivity and impacts on soil-based emission of trace gases (N_2O and CH_4). Realising the potential for biochar technology will be constrained by economics and the sustainability of feedstock aquisition. Focusing on deployment on less fertile land but not accounting explicitly for cost, but limiting feedstock to sources considered sustainable, (Woolf et al., 2010) calculated maximum abatement potential of 6.6 $GtCO_2$eq./yr from 2.27 Gt biomass C. With competition for virgin non-waste biomass this was lower (3.67 $GtCO_2$eq./yr from 1.01 Gt biomass C), accruing 240-480 Gt CO_2-eq. abatement within 100 years, assuming favourable adoption rates. Meta-analysis of available experimental data suggests that crop productivity is typically enhanced by ca. 15% at least over the short-term, but with a wide range of effect that probably relates to pre-existing soil constraints (Jeffery et al., 2011b). The (Woolf et al., 2010) analysis assumed relative yield increases ranging from 0 to 90%, an effect that feeds back into carbon abatement, though when the assumption is relaxed by one-half projected abatement was decreased only 10%. Similarly decreasing an assumed 25% suppression on soil N_2O flux had a smaller effect. Although the interaction of biochar and the soil N cycle are not fully understood, effects on mineralisation, nitrification, immobilisation and sorption have all been inferred for periods of days to years after biochar amendment. The occasionally dramatic suppression of soil N_2O flux while explainable are not certain, at least over the long-term, and not predictable. The potential to enhance mitigation by using biochar to tackle gaseous emissions from organic fertilisers before as well as after application to soil (Steiner et al., 2010) – and spatial strategies to maximise the effect – have been barely explored. The abatement potential for the whole system remains, however, most sensitive to the absolute stability of the C stored in biochar. Estimates of 'half-life' have been inferred from wildfire charcoal (Lehmann, 2007) or extrapolatedfrom direct short-term observation, estimates ranging from <50 to >10,000 years (Spokas, 2010). The (Woolf et al., 2010) analysis makes optimistic assumptions on the yield of stabilised carbon (biochar) and energy product from biomass pyrolysis that would require efficient as well as clean technology and access to energy infrastructure. Most importantly, the economic factors that currently constrain biochar production are not considered; currently the feasibility of meeting the break even cost of biochar production (location specific) depends on a predictable return on benefits to crop production – and this will remain the case until stabilised C can be monetised. Standards to ensure that biochar is produced in a way that does not conserve or create toxic contaminants are also required, to regulate deployment.

11.3.2 Mitigation effectiveness (non-permanence: saturation, human and natural impacts, displacement)

Since carbon sequestration in soil and vegetation and the retention of existing carbon stocks forms a significant component of the mitigation potential in the AFOLU sector, this section considers the factors affecting this strategy compared to avoided GHG emissions.

Non-permanence / reversibility. Reversals are the release of previously sequestered carbon, which negates some or all of the benefits from sequestration that has occurred in previous years. This issue is sometimes referred to as "permanence" (Smith, 2005). Various types of carbon sinks (e.g., forestry, agricultural soil C) have an inherent risk of future reversals of sequestered C. Various mechanisms have been used in emissions trading schemes (e.g. buffer pool, insurance) to compensate for reversals that may occur.

Some activities that reverse carbon sequestration are relatively easy to track visually, such as deforestation (Gibbs et al., 2007) and some changes in land-use such as the removal of residues from a ploughed field. Obviously, such an approach cannot assess all carbon pools (e.g. below ground), and these techniques, which often rely on remote sensing (Gibbs et al., 2007) are essentially reliant on the development of calibration equations between the land-use change and carbon mitigation impacts rather than detailed on-ground measurements.

There are relatively few data on how much carbon is lost when reversals occur and estimates will depend on a range of factors such as the carbon storage within the system and the nature of the disturbance. A first order estimate of the effects of plantation deforestation and conversion to pasture could be achieved from the reverse (e.g. reforestation from pasture).

Certain types of mitigation activities (e.g. avoided N_2O from fertilizer, emission reductions from changed diet patterns or reduced food-chain losses) are effectively permanent since the emissions, once avoided, cannot be re-emitted. The same applies to the use of bioenergy to displace fossil-fuel emissions (see Annex I for full discussion).

Unintentional reversals are usually caused by natural events that affect yields / growth (e.g. frost damage, pest infestation, fire) and although these will affect the annual increment of C sequestration or N_2O flux, the resulting change is not a reversal. With respect to annual crops, wildfire would only affect the current year's carbon storage, unless it burns into the organic soil layer. However, wildfire in systems with tree or shrub crops or windbreaks could see substantial loss of aboveground stored carbon; however whether this is considered a loss depends on what happens following the fire and whether the forest recovers, or changes to a lower carbon storage state (see Box 11.3). Some systems are naturally adapted to fire and carbon stocks will recover following fire, whereas in other cases the fire results in a change to a system with a lower carbon stock (e.g. (Brown and Johnstone, 2011).

The permanence of a soil carbon sink is defined as the longevity of the sink, i.e. how long it continues to remove carbon from the atmosphere. The permanence of the soil carbon stock relates to the longevity of the stock, i.e. how long the increased carbon stock remains in the soil or vegetation, and is linked to consideration of the reversibility of the increased carbon stock (Smith et al., 2005). (Kim et al., 2008) estimated the impact of differences in permanence on the value of carbon offsets using examples from cropland management and forest management, and developed a discounting function.

Saturation. Avoided emissions (e.g. through fossil fuel substitution with bioenergy) can continue in perpetuity, but it is often considered that carbon sequestered in soils (Guldea et al., 2008) or vegetation cannot continue indefinitely. In this model, the carbon stored in trees and vegetation reaches a new equilibrium (as the trees mature or as the soil carbon stock saturates). As the soils / vegetation approach the new equilibrium, the annual removal (sometimes referred to as the sink strength) decreases until it becomes zero at equilibrium. This process is called saturation (Smith et al., 2005)(Körner, 2006, 2009) and the uncertainty associated with saturation has been estimated by (Kim and McCarl, 2009). An alternative view is that saturation does not occur, with studies from old-growth forests for example showing that they can continue to sequester C in soil and dead organic matter even if net living biomass increment is near zero (e.g. (Luyssaert et al., 2008). Peatlands are unlikely to saturate in carbon storage, but the rate of C uptake may be very slow (see Box 11.2).

Human and natural impacts. Soil and vegetation carbon sinks can be impacted upon by direct human induced, indirect human induced and natural change (Smith, 2005). Direct human induced changes are deliberate management practices, designed to influence the land. All of the mitigation practices discussed in section 11.3.1 are direct human-induced changes. Sinks can also be affected by natural factors, for example, carbon stocks can be affected by soil and hydrological conditions. Between the direct human-induced changes and the natural changes are indirect human-induced changes. These changes can impact carbon sinks and are induced by human activity, but are not directly related to management of that piece of land; examples being induced climate change or atmospheric nitrogen deposition. Natural changes that threaten to impact the efficacy of mitigation measures are discussed in section 11.5.

Displacement / leakage. Displacement / leakage can occur within or across national boundaries and the efficacy of mitigation practices must consider the potential for displacement of emissions. If reducing emissions in one place leads to increased emissions elsewhere, no net reduction occurs; the emissions are simply displaced (Kastner, Kastner, et al., 2011; Kastner, Erb, et al., 2011), however this assumes a one to one correspondence. (Murray et al., 2004) estimated the leakage from different forest carbon programs and this varied from <10% to >90% depending on the nature of the activity. Trade statistics may give information on net imports and exports of agricultural products and timber (and other forest products) and can be used as a proxy for possible emission displacement. Indirect land use change (iLUC) is an important component to consider for displaced emissions and assessments of this are an emerging area. iLUC is discussed further in section 11.4 and in in relation to bioenergy in Annex I.

The timing of mitigation benefits from actions (e.g. bioenergy, forest management, forest products use/storage) can vary and the timing of benefits needs to be considered when judging the effectiveness of a mitigation action. (Cherubini, Guest, et al., 2012) modelled the impact of timing of benefits varies for three different wood applications (fuel, non-structural panels and housing construction materials) that provide mitigation over different time-frames. and thus have different impacts on CO_2 contents and radiative forcing.

Additionality: An additional consideration for gauging the effectiveness of mitigation is determining whether the activity would have occurred anyway, with this encompassed in the concept of "additionality" (see Glossary).

Impacts of climate change: An area of emerging activity is predicting the likely impacts of climate change on mitigation potential, both in terms of impacts on existing carbon stocks, but also on the rates of carbon sequestration. Components of change include the impacts of changed temperatures and water balances on forests (Allen et al., 2010) and soils (Hopkins et al., 2012), the effects of increased CO_2 on plant growth (Field et al., 1995) and decomposition (Groenigen et al., 2011), the interactions of these factors (e.g. Woldendorp et al. 2008; (Knohl and Veldkamp, 2011) and the impacts of climate induced pests and diseases on carbon stocks (Kurz, Dymond, et al., 2008).

11.4 Infrastructure and systemic perspectives

Section 11.3 considered only supply-side mitigation measures. In this section, we consider intrastructure and system perspectives, which include potential demand-side mitigation measures in the AFOLU section.

11.4.1 Land: a complex, integrated system

Mitigation in the AFOLU sector is embedded in the complex interactions between socioeconomic and natural factors simultaneously affecting land systems (Turner et al., 2007). Land is used for a variety of purposes, including housing and infrastructure, production of goods and services through agriculture and forestry and absorption or deposition of wastes and emissions (Dunlap and Catton, Jr., 2002). Agriculture and forestry are important for rural livelihoods and employment (Coelho, Agbenyega, Agostini, Erb, Haberl, Hoogwijk, Lal, Lucon, Masera, Moreira, et al., 2012). More than half of the planet's total land area (134 M km^2) is used for urban and infrastructure land, agriculture and forestry; less than one quarter shows relatively minor signs of direct human use (Ellis et al., 2010), (Erb et al., 2007), Figure 11.10); even the latter areas may be inhabited by indigenous populations (Read et al., 2010).

Land use change is a pervasive driver of global environmental change, associated with various positive and negative effects (Foley et al., 2005, 2011). From 1950 to 2005, farmland (cropland plus pasture) increased from 28% to 38% of the global land area excluding ice sheets and inland waters (Hurtt et al., 2011). Farmland growth (+33%) was lower than that of population, food production and GDP due to increases in yields and biomass conversion efficiency (Krausmann et al., 2012). Currently, almost one quarter of the global terrestrial net primary production (one third of the aboveground part) is foregone due to land use related losses in NPP, harvested for human purposes or destroyed during harvest or in human-induced fires (Haberl et al., 2007), (Imhoff et al., 2004). The fraction of terrestrial NPP appropriated by humans doubled in the last century (Krausmann and others, subm), underlining that humans increasingly dominate terrestrial ecosystems (Ellis et al., 2010). Growth in the use of food, energy and other land-based resources, urbanization and infrastructure development are affected by increasing population and GDP, as well as the ongoing agrarian-industrial transition (Haberl, Fischer-Kowalski, et al., 2011),(Kastner et al., 2012)Seto, Güneralp, et al., 2012)
[173]. Increasing resource use as well as growing land demand for biodiversity conservation and carbon sequestration (Soares-Filho et al., 2010), result in increasing competition for land (Harvey and Pilgrim, 2011a), subsection 11.4.2). Influencing ongoing transitions in resource use is a major challenge (Fischer-Kowalski, 2011; WBGU, 2011). Changes in cities, e.g. in terms of infrastructure, governance and demand, can play a major role (Seto, Reenberg, et al., 2012; Seitzinger et al., 2012); see Chapter 12.

Most GHG mitigation activities in the AFOLU sector affect land use or land cover and, therefore, have socioeconomic as well as ecological consequences, e.g. on food security, livelihoods, ecosystem services or emissions (sections 11.1, 11.4.5, 11.7). Feedbacks involved in implementing mitigation in AFOLU may influence different, sometimes conflicting social, institutional, economic and environmental goals (Madlener et al., 2006a). Climate change mitigation in the AFOLU sector faces a complex set of interrelated challenges (see sections 11.4.5 and 11.7):

- Full GHG impacts, including those from feedbacks (e.g. 'indirect' land use change) or leakage, are often difficult to determine (Searchinger et al., 2008b).
- Feedbacks between GHG reduction and other important objectives such as provision of livelihoods and sufficient food or the maintenance of ecosystem services and biodiversity are not completely understood.
- Maximizing synergies and minimizing negative effects involves multi-dimensional optimization problems involving various social, economic and ecological criteria or conflicts of interest between different social groups (Martinez-Alier, 2002).
- Many phenomena are scale-dependent and processes may proceed at different speeds, or perhaps even move in different directions, at different scales.

11.4.2 Mitigation in AFOLU – feedbacks with land use competition

Driven by economic and population growth, changing consumption patterns, increased demand for bioenergy as well as land demand for conservation, competition for land is expected to intensify (Smith et al., 2010; Woods et al., 2010). Maximization of one output or service (e.g. crops) often excludes, or at least negatively affects, others (e.g., conservation; (Phalan et al., 2011a). Mitigation in the AFOLU sector may affect land use competition. Figure 11.10 shows why these feedbacks are different for demand-side and production-side measures (Smith et al., 2013).

Demand-side measures generally reduce inputs (fertilizer, energy, machinery) and land demand. The ecological feedbacks of demand-side measures are mostly beneficial since they reduce competition for land and water (Smith, et al., 2013). Some production-side measures, though not all, may intensify competition for land and other resources. Based on Figure 11.10 one may distinguish several cases:

- **Optimization of biomass-flow cascades** through use of residues and by-products, recycling and energetic use of wastes (Haberl and Geissler, 2000); (Haberl et al., 2003); (WBGU, 2009). Such measures increase resource use efficiency and may reduce competition, but there are may also be trade-offs; e.g., using crop residues for bioenergy or roughage supply may leave less C and nutrients on cropland, reduce soil quality and C storage in soils and increase the risk of losses of carbon through soil erosion; residues are also often used as forage, particularly in the tropics (e.g. see (Blanco-Canqui and Lal, 2009), (Ceschia et al., 2010), (González-Estrada et al., 2008; Muller, 2009); Giller et al 2010).
- **Increases in yields of cropland** (Burney et al., 2010a); (Tilman et al., 2011), grazing land or forestry and improved livestock feeding efficiency (Steinfeld et al., 2010), (Thornton and Herrero, 2010) can reduce land competition but may also result in trade-offs with other ecological, social and economic costs (IAASTD, 2009) although these can to some extent be mitigated (Tilman et al., 2011). Increases in yields may result in rebound effects that increase consumption (Lambin and Meyfroidt, 2011)(Erb, 2012) or provide incentives to farm more land (Matson and Vitousek, 2006), and may hence fail to result in land sparing if effective land use policies are missing (section 11.10).
- **Land-demanding measures** harness the production potential of the land for either C sequestration or growing energy crops. These options result in competition for land (and sometimes other resources such as water) that may have substantial social, economic and ecological effects (positive or negative) (Chum, Faaij, Moreira, Berndes, Dhamija, Gabrielle, et al., 2011);(Coelho, Agbenyega, Agostini, Erb, Haberl, Hoogwijk, Lal, Lucon, Masera, Moreira, et

al., 2012);(WBGU, 2009);(UNEP, 2009). Such measures may result in pressures on forests and GHG emissions related to direct and indirect land use change, contribute to price increases of agricultural products, or negatively affect livelihoods of rural populations. These possible impacts need to be balanced against possible positive effects such as GHG reduction, improved water quality (Townsend et al., 2012), land (Harper et al., 2007) and biodiversity protection (Swingland et al., 2002) or job creation (Chum, Faaij, Moreira, Berndes, Dhamija, Gabrielle, et al., 2011);(Coelho, Agbenyega, Agostini, Erb, Haberl, Hoogwijk, Lal, Lucon, Masera, Moreira, et al., 2012).

- **Competing uses of biomass** such as the use of grains for food, feed and as feedstock for biofuels, or the use of wood residues for chipboards, paper and bioenergy, can result in increased land demand with the above-mentioned effects and may prevent the return of nutrients and C to the soil.

Therefore, an integrated energy/agriculture/land-use approach for mitigation in AFOLU has to be implemented in order to optimize synergies and mitigate negative effects (Popp, et al., 2011);(Creutzig et al., 2012a);(Smith, 2012a).

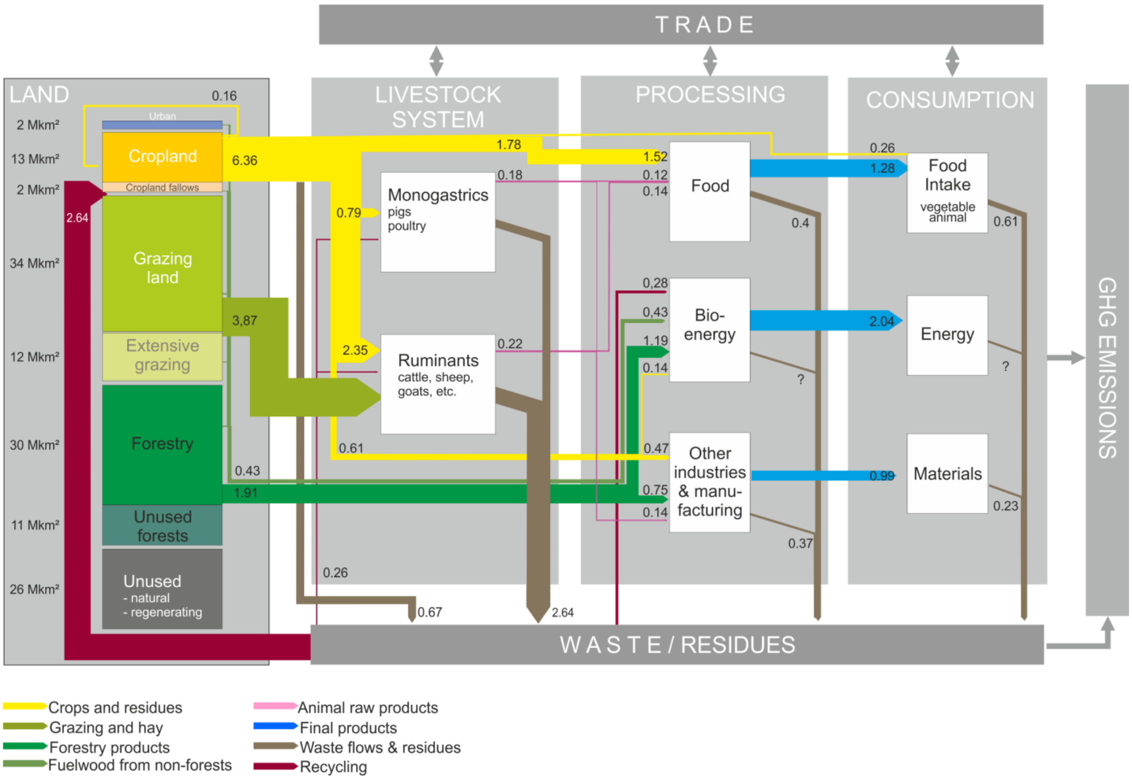


Figure 11.10 Global land use and biomass flows in 2000 from the cradle to the grave. Values in Gt dry matter biomass/yr. Figure source: (Smith, et al., 2013). Assumed gross energy value of dry-matter biomass 18.5MJ/kg. The difference between inputs and outputs in the consumption compartment is assumed to be directly released to the atmosphere (respiration, combustion). Data sources: Area: (Erb et al., 2007; FAO, 2010) Schneider et al., 2009; biomass flows: (Wirsenius, 2003; Sims et al., 2006; Krausmann et al., 2008; Kummu et al., 2012) (FAOSTAT, 2012).

11.4.3 Demand-side options for reducing GHG emissions from AFOLU

Changes in demand for food and fibre can reduce GHG emissions in the production chain. They save GHG emissions (i) by reducing the use of inputs required during production (e.g. CH_4 from enteric fermentation of feed, N_2O from fertilizers, or CO_2 from tractor fuels) and (ii) by making land available for e.g. afforestation or bioenergy (section 11.4.4). Food demand change is a sensitive issue due to the prevalence of hunger, malnutrition and the lack of food security in many regions (Godfray et al., 2010). Sufficient food production and equitable access to food are both critical for food security

(Misselhorn et al., 2012). GHG emissions may be reduced through changes in food demand without jeopardizing health and well-being by (1) reducing losses and wastes of food in the supply chain as well as during final consumption and (2) changing diets towards less GHG intensive food, e.g. substitution of animal products with of plant-based food with adequate protein content, and reduction of overconsumption in regions where this is prevalent. Demand-side options also relate to forestry products and socioeconomic C stocks (Table 11.4). Certification schemes for agricultural products and wood from sustainable forestry, and avoidance of wood from illegal logging or destructive harvest are discussed in section 11.10.

Table 11.4: Overview of demand-side mitigation options in the AFOLU sector

Changes in diet	Reduced consumption of food derived from agricultural products with high greenhouse gas emissions per unit product, e.g. livestock products, food transported via airfreight or from heated greenhouses; switch to low GHG local and seasonal products.	(Stehfest et al., 2009a); (Popp et al., 2010); (Smith, 2012b) (González et al., 2011), (Garnett, 2011) Smith et al. submitted.
Reduced losses in the food supply chain	Reduced losses in the food supply chain and in final consumption reduces energy use and GHG emissions from agriculture, transport, storage and distribution, and makes area available for bioenergy or C sinks.	(Godfray et al., 2010) (Gustavsson et al., 2011) (Hodges et al., 2011) (Parfitt et al., 2010), Smith et al. (2013)
Change consumption of wood products	Wood consumption can be reduced by conserving wood and using alternative and recycled fibers to substitute for wood in various products. Reduced wood harvest can help to conserve C pools in forests. Forest protection can be promoted through use of certified sustainable wood (section 11.10) from forestry where harvest does not exceed increments.	(Holtsmark, 2012) (Werner et al., 2010)
Substitution of wood for C intensive products	GHG emissions from fossil fuels or non-renewable materials can be reduced by switching to forest products from sustainably managed forests. The efficiency of emissions displacement depends on the product, its lifecycle, use of by-products and the fossil-fuel based reference system that is substituted. Emission reductions per unit of biomass are generally higher if harvested biomass can be used both for material and energy substitution; and in most cases even higher if wood can be materially recycled during its lifetime and only finally used for energy.	(Pingoud et al., 2010), (Sathre and O'Connor, 2010), (Werner et al., 2010)
Increased C stocks in wood products	C in wood and paper products remains sequestered and is emitted to varying degrees depending on how products are made, used, and disposed of. Sequestration in products and uses can be increased by altered processing methods, shifts in products used, end-use durability, and landfill management. Sequestration in forests and products can be maximized by optimizing forest management and wood use.	(Laturi et al., 2008), (Gustavsson and Sathre, 2011), (Holtsmark, 2012)

Reductions of losses in the food supply chain – Globally, ~30-40% of all food produced is lost in the supply chain from harvest to consumption (Godfray et al., 2010). Energy embodied in wasted food is estimated at ~36 EJ/yr (FAO, 2011). In developing countries, losses of up to 40% occur on farm or during distribution due to poor storage, distribution and conservation technologies and procedures. In developed countries, less is lost on farm or during distribution, but up to 40% is lost or wasted in service sectors and at the consumer level (Foley et al., 2005; Godfray et al., 2010; Parfitt et al., 2010; Gustavsson et al., 2011; Hodges et al., 2011).

Not all losses are (potentially) avoidable because losses in households also include parts of products normally not deemed edible (e.g. peels of some fruits). In the UK, 18% of the food waste was classified as unavoidable, 18% as potentially avoidable and 64% as avoidable (Parfitt et al., 2010). According to recent data for Austria, Netherlands, Turkey, the UK and the USA, food wastes at the household level in industrialized countries are 150-300 kg per household per year (Parfitt et al., 2010). A mass-flow modelling study based on FAO commodity balances that covered the whole food supply chain, but excluded non-edible fractions, found per-capita food loss values ranging from 120-170 kg/cap/yr in Subsaharan Africa to 280-300 kg/cap/yr in Europe and North-America. Calculated losses ranged from 20% in Subsaharan Africa to >30% in the industrialized regions (Gustavsson et al., 2011).

A range of measures exists to reduce wastes and losses in the supply chain: investments into harvesting, processing and storage technologies in the developing countries, and awareness raising or taxation to reduce retail and consumer-related losses primarily in the developed countries. Different measures are needed to reduce losses (i.e. increase efficiency) in the supply chain and at the household level. Substantial GHG savings could be realised by saving one quarter of the wasted food according to (Gustavsson et al., 2011), see Table 11.5.

Changes in diets – Land use and GHG effects of changing diets require widespread behavioural changes to be effective; i.e. a strong deviation from current trajectories (increasing demand for food, in particular for animal products). Cultural, socioeconomic and behavioural aspects of implementation are discussed in sections 11.4.5. and 11.7.

Studies based on Life-Cycle Analysis (LCA) methods show substantially lower GHG emissions for most plant-based food than for animal products in many regional settings (Carlsson-Kanyama and González, 2009; Pathak et al., 2010; Bellarby et al., 2012; Berners-Lee et al., 2012). Exceptions include vegetables grown in heated greenhouses or transported by airfreight (Carlsson-Kanyama and González, 2009). A comparison of three meals served in Sweden with similar energy and protein content based on (1) soy, wheat, carrots and apples, (2) pork, potatoes, green beans and oranges, and (3) beef, rice, cooked frozen vegetables and tropical fruits revealed GHG emissions from 0.42 $kgCO_2eq$ for the first option, 1.3 $kgCO_2eq$ for the second and 4.7 $kgCO_2eq$ for the third, i.e. a factor of >10 difference (Carlsson-Kanyama and González, 2009). Most LCA studies quoted here use attributional LCA which calculates impacts related to current production systems. Changes in demand would need to be assessed with consequential LCA, but differences of both approaches (Thomassen et al., 2008) are generally not large enough to reverse the picture. GHG benefits of plant-based food over animal products hold when compared per unit of protein (González et al., 2011). GHG emissions of livestock products per unit of protein are highest for beef and lower for pork, chicken meat, eggs and dairy products (De Vries and De Boer, 2010) due to their feed and land use intensities. Figure 11.11 presents a comparison between milk and beef for different production systems and regions of the world (Herrero et al., 2013). Beef production can use up to five times more biomass for producing 1 kg of animal protein than dairy. In addition emissions intensities for the same livestock product vary largely between different regions of the world due to differences in agroecology, diet quality and intensity of production (Herrero et al., 2013; Figure 11.12). In overall terms, Europe and North America have lower emissions intensities per kg of protein that Africa, Asia and Latin America. However, livestock can be fed on plants not suitable for human consumption which can be grown on land not suitable for cropping; hence, food production by grazing animals can contribute to food security (Wirsenius, 2003); (Gill et al., 2010).

Studies based on integrated modelling show that changes in diets strongly affect future GHG emissions from food production (Stehfest et al., 2009a; Popp et al., 2010; Davidson, 2012). Using a coupled model system comprising the land use allocation model MAgPIE and the dynamic global vegetation model LPJmL (Popp et al., 2010) estimated that agricultural non-CO_2 emissions (CH_4 and N_2O) would triple until 2055 to 15.3 $GtCO_2$-eq/yr if current dietary trends and population growth were to continue. Technical mitigation measures alone could reduce that value to 9.8 $GtCO_2$-eq/yr whereas emissions were reduced to 4.3 $GtCO_2$-eq/yr in a ‘decreased livestock product’ scenario and to 2.5 $GtCO_2$-eq/yr if both mitigation and dietary change was assumed. Hence, the potential to reduce GHG emissions through changes in consumption was found to be substantially higher than that of technical GHG mitigation measures. Stehfest et al. (2009a) evaluated effects of dietary changes on CO_2 (including C sources/sinks of ecosystems), CH_4 and N_2O emissions using the IMAGE model. In a 'business as usual' scenario largely based on FAO (2006c), total GHG emissions were projected to reach 11.9 $GtCO_2$-eq/yr in 2050. The analysis of effects of changes in diet always assumed nutritionally sufficient diets; reduced supply of animal protein was compensated by plant products (soy, pulses, etc.). The following changes were evaluated: no ruminant meat, no meat and a diet without any animal products. Changed diets resulted in GHG emission savings of 34-64% compared to the 'business as usual' scenario; a switch to the 'healthy diet' would save 4.3 $GtCO_2$-eq/yr (-36%). Adoption of the 'healthy diet' recommended by the Harvard Medical School would reduce global GHG abatement costs to reach a 450 ppm CO_2eq concentration target by ~50% compared to the reference case ((Stehfest et al., 2009a).

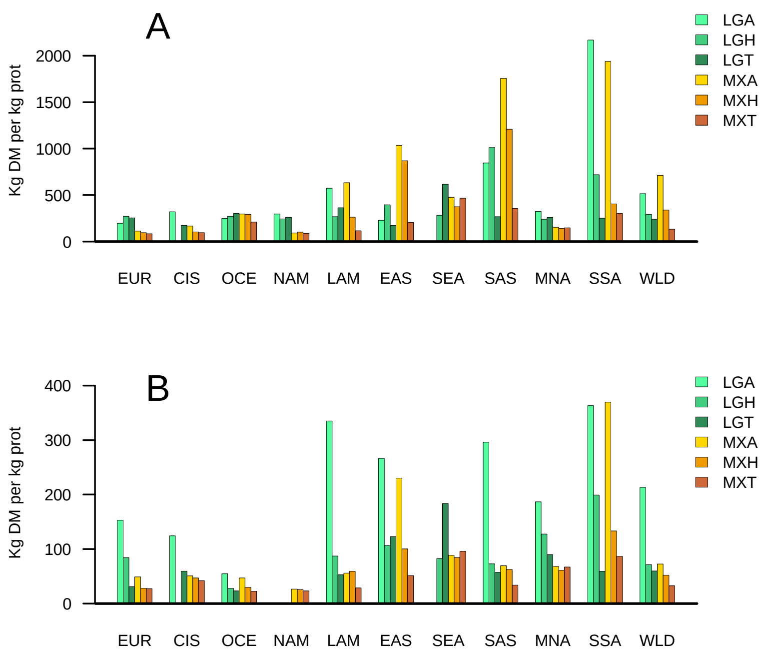


Figure 11.11. Biomass use efficiencies for the production of edible protein from beef and milk for different production systems and regions of the world (Herrero et al., 2013). LG=grazing livestock, MX= mixed crop/livestock system, A=arid region H=humid region, T= temperate/highland region.

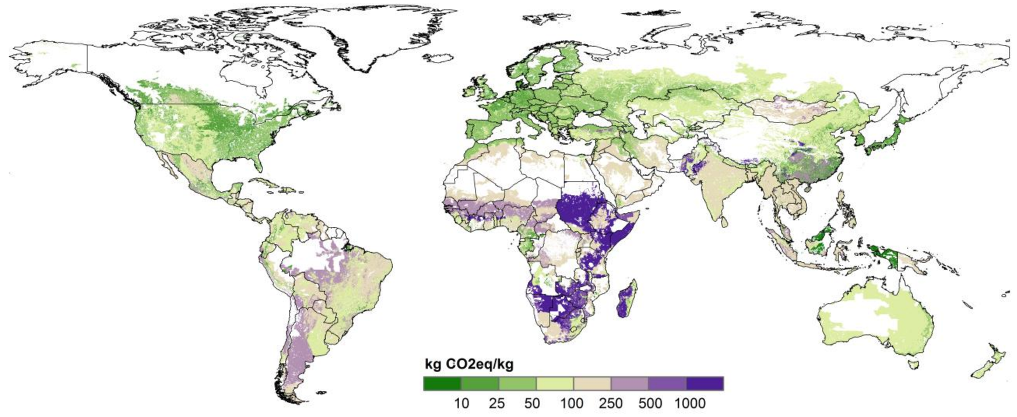


Figure 11.12. Global non-CO_2 greenhouse gas efficiency per kilogram of protein produced from livestock (Herrero et al., 2013)

A limitation of food-related LCA studies is that they have so far seldom considered the emissions resulting from land-use change induced by food production (Bellarby et al., 2012). A recent study found that the foregone C sequestration potential of cropland and pastures required for the production of beef, lamb, calf, pork, chicken and milk is 25%-470% of the GHG emissions usually considered in LCA of food products. The land-related GHG emissions differ strongly between products and depend on the time horizon (30-100 yr) assumed (Schmidinger and Stehfest, 2012). If cattle production contributes to tropical deforestation (Zaks et al., 2009; Bustamante et al., 2012) (Houghton et al., 2012), emissions are particularly high (Cederberg et al., 2011). These findings underline the importance of diets for GHG emissions in the food supply chain (Garnett, 2011; Bellarby et al., 2012), (Reay et al., 2012). Considering potential co-benefits, reduced consumption of animal products may alleviate some of the concerns expressed around animal welfare (Keeling et al., 2011), and mitigate diet-related health risks in regions where overconsumption of animal products is prevalent (McMichael et al., 2007).

Demand-side options related to wood and forestry – Global carbon stocks in long-lived wood products in use (excluding landfills) were approximately 2.2 GtC in 1900 and increased to 6.9 GtC in 2008. Per-capita, carbon stored in wood products amounted to ~1.4 t C / capita in 1900 and ~1.0 t C / capita in 2008 (Lauk et al., 2012). The net yearly accumulation of long-lived wood products in use varied between 35 and 91 MtC / yr in the period 1960-2008 (Lauk et al., 2012); the yearly accumulation of C in products and landfills was ~200 MtC / yr in the period 1990-2008 (Pan et al., 2011). If inflows would rise through increased use of long-lived wood products, C sequestration in wood-based products could be enhanced, thus contributing to GHG mitigation.

Increased wood use does not always reduce GHG emissions because changes in wood harvest affect the carbon balance of forests (Böttcher et al., 2012; Holtsmark, 2012). (Werner et al., 2010) show that GHG benefits are highest when wood use for long-lived products, as well as the lifetime of products, are maximized and energy use is focused on by-products and wood wastes. Recent studies suggest that substitution of wood from sustainably managed forests for non-wood materials in the construction sector (concrete, steel, etc.) in single family homes, apartment houses and industrial buildings, reduces GHG emissions in most cases (Werner et al., 2010; Sathre and O'Connor, 2010). Most of the emission reduction results from reduced production emissions, whereas the role of carbon sequestration is relatively small (Sathre and O'Connor, 2010).

Substitution of steel and concrete in buildings with wood is discussed in detail in Chapter 9. Analyses of the net CO_2 emissions over a 100 year lifetime of buildings revealed that buildings constructed with wood frames have lower emissions than buildings with steel and concrete frames and sequester carbon in the building (Gustavsson et al., 2006)(Gustavsson and Sathre, 2011). A scenario analysis with an integrated modelling framework showed that construction of one million flats per year in the next 23 years would reduce GHG emissions in the EU-27 by 0.2-0.5% (Eriksson et al., 2012). A study for the US also found substantial GHG benefits of substituting concrete or steel frames with wood (Upton et al., 2008); however, this study also showed that the results were sensitive to assumptions on the alternative use of land (e.g. for C sequestration) in case of lower wood use. (Nässén et al., 2012) confirmed that under current conditions, buildings with wood frames have lower GHG emissions than those with concrete frames.

11.4.4 Feedbacks of changes in land demand

Mitigation options in the AFOLU sector are highly interdependent due to their direct and indirect impacts on land demand. Indirect interrelationships, mediated *via* area demand for food production, which in turn affects the area available for other purposes, are difficult to quantify and require systemic approaches. Table 11.5 shows the magnitude of possible feedbacks in the land system in 2050. It first reports the effect of single mitigation measures compared to a reference case, and then the combined effect of all measures. The reference case is similar to the FAO (2006c) projections for 2050. The diet change case assumes a global contract and converge scenario towards a nutritionally sufficient low animal product diet. The yield growth case assumes higher yield growth according to the 'Global Orchestration' scenario in (MEA, 2005). The feeding efficiency case assumes on average 17% higher livestock feeding efficiencies than the reference case. The waste reduction case assumes a reduction of the losses in the food supply chain by 25% (section 11.4.3). The combination of all measures results in a substantial reduction of cropland and grazing areas (Smith et al., 2011), even though the individual measures cannot simply be added up due to the interactions between the individual compartments shown in Figure 11.6.

Table 11.5: Changes in global land use and related GHG reduction potentials in 2050 assuming the implementation of measures to increase C sequestration on farmland, and use of spare land for either bioenergy or afforestation. Afforestation and bioenergy are both assumed to be implemented on spare land, i.e. are mutually exclusive. Source: (Smith et al., 2011).

Cases	Food crop area	Livestock grazing area	C sink on farm-land*	Afforestation of spare land**,[1]	Bioenergy on spare land**,[2]	Total mitigation potential	Difference in mitigation from Reference case
	[Gha]		$GtCO_2eq.yr^{-1}$				
Reference	1.60	4.07	3.5	6.1	1.2-9.4	4.6-12.9	0
Diet change	1.38	3.87	3.2	11.0	2.1-17.0	5.3-20.2	0.7-7.3
Yield growth	1.49	4.06	3.4	7.3	1.4-11.4	4.8-14.8	0.2-1.9
Feeding efficiency	1.53	4.04	3.4	7.2	1.4-11-1	4.8-14.5	0.2-1.6
Waste reduction	1.50	3.82	3.3	10.1	1.9-15.6	5.2-18.9	0.6-6.0
Combined	1.21	3.58	2.9	16.5	3.2-25.6	6.1-28.5	1.5-15.6

* Cropland for food production and livestock grazing land. Potential C sequestration rates with improved management derived from global technical potentials in (Smith et al., 2008)

** Spare land 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, Erb et al., 2012.

1 Assuming 11.8 $tCO2eq/ha/yr$ (Smith et al., 2000).

2 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 (Smith, Zhao, et al., 2012). Low bioenergy value: ethanol from maize replaces gasoline and reduces GHG by 45%, energy yield 75 GJ/ha/yr (Chum, Faaij, Moreira, Berndes, Dhamija, Gabrielle, et al., 2011).

Table 11.5 shows that demand-measures save GHG by creating spare land that can be used for bioenergy or C-sequestration through afforestation. The effect is strong and non-linear, and cancels out reduced C sequestration potentials on farmland. Demand-side potentials are substantial compared to production-based mitigation potentials (section 11.3), but implementation may be difficult (sections 11.7 and 11.8). Uncertainties related to the possible GHG savings from bioenergy are large and strongly depend on assumptions regarding energy plants, utilization pathway, energy crop yields, and effectiveness of sustainability criteria (see 11.4.5, 11.7 and Annex I).

Conversely, the systemic effects of land-demanding GHG mitigation measures such as bioenergy or afforestation depend not only on their own area demand, but also on land demand for food and fibre supply (Chum, Faaij, Moreira, Berndes, Dhamija, Gabrielle, et al., 2011; Coelho, Agbenyega, Agostini, Erb, Haberl, Hoogwijk, Lal, Lucon, Masera, Moreira, et al., 2012; Erb, Mayer, et al., 2012). In 2007, energy crops for transport fuels covered about 26.6 Mha or 1.7% of global cropland (UNEP, 2009). Assumptions on energy crop yields (see Annex I) are the main reason for the large differences in estimates of future area demand of energy crops in the next decades, which vary from <100 Mha to >1000 Mha, i.e. 7%-70% of current cropland (Sims et al., 2006; Smeets et al., 2007a; Pacca and Moreira, 2011; Coelho, Agbenyega, Agostini, Erb, Haberl, Hoogwijk, Lal, Lucon, Masera, Moreira, et al., 2012). Increased pressure on land systems may also emerge when afforestation claims land or avoided deforestation restricts farmland expansion (Murtaugh and Schlax, 2009; Popp, Dietrich, et al., 2011).

Land-demanding mitigation measures may result in feedbacks such as GHG emissions from land expansion or agricultural intensification, higher yields of food crops, higher prices of agricultural products, reduced food consumption, displacement of food production to other regions and consequent land clearing as well as impacts on biodiversity and non-provisioning ecosystem services (Plevin, et al., 2010), (Popp et al., 2012).

Drivers of rising food prices are weather conditions that decrease crop productivity, speculation on food commodities, rising energy costs, decades of under-investment in agriculture, impacts of climate change, export restrictions and rising demand for higher value food products (such as livestock products) (Koh and Ghazoul, 2008; Alston et al., 2009; Gilbert and Morgan, 2010) Ajanovic 2011, Heady 2011). However, restrictions to agricultural expansion due to avoided deforestation, increased energy crop area, afforestation or reforestation may increase costs of agricultural production and food prices. In a modeling study, conserving C-rich natural vegetation such as tropical forests was found to increase food prices by a factor of 1.75 until 2100, due to restrictions of cropland expansion, even if no growth of energy crop area was assumed (Wise et al., 2009b). Food price indices (weighted average of crop and livestock products) are estimated to increase until 2100 by 82% in Africa, 73% in Latin America and 52% in Pacific Asia if large scale bioenergy deployment is combined with strict forest conservation, compared to a reference scenario without forest conservation and bioenergy (Popp, Dietrich, et al., 2011). Further trade liberalisation can lead to lower costs of food, but also increases the pressure especially on tropical forests (Schmitz et al., 2011).

Increased land demand for GHG mitigation can be partially compensated through higher agricultural yield increases (Popp, Dietrich, et al., 2011). While yield increases can help to reduce competition for land and alleviate environmental pressures (Smith et al., 2010; Burney et al., 2010b), agricultural intensification incurs economic costs (Lotze-Campen et al., 2010) and may also create social and environmental problems such as nutrient leaching, soil degradation, toxic effects of pesticides, worsening of animal welfare and many more (IAASTD, 2009). Maintaining yield growth while reducing negative environmental effects of agricultural intensification is, therefore, a central challenge (DeFries and Rosenzweig, 2010). Both increased land-use intensity and land expansion into new areas may entail higher greenhouse gas emissions from the agricultural sector, and result in increased water use for irrigation (IAASTD, 2009). Negative impacts such as increases in flows of reactive nitrogen can be reduced through technology dissemination to developing countries, in order to intensify agriculture in regions with the highest yield gaps (Tilman et al., 2011).

Additional land demand may put pressures on biodiversity, as land-use change is one of the most important drivers of biodiversity loss (Sala et al., 2000). Large-scale bioenergy may therefore negatively affect biodiversity (Groom et al., 2008) which is a key prerequisite for the resilience of ecosystems, i.e. for their ability to adapt to changes such as climate change, and to continue to deliver ecosystem services in the future (Díaz et al., 2006); (Landis et al., 2008)). Because climate change is also an important driver of biodiversity loss (Sala et al., 2000), bioenergy may also be beneficial for biodiversity if it slows down climate change (see Annex I).

Trade-offs related to land demand may be reduced through multifunctional land use, i.e. the optimization of land to generate more than one product or service such as food, animal feed, energy or materials, soil protection, wastewater treatment, recreation, or nature protection (De Groot, 2006); (DeFries and Rosenzweig, 2010). Appropriate, multifunctional land management can alleviate trade-offs or even achieve synergies, (e.g. (Swingland et al., 2002), enhancing biomass production while reducing environmental pressures, in particular when combined with ecological zoning approaches (Coelho, 2012).

11.4.5 Sustainable development and behavioural aspects

The relation between AFOLU measures and sustainable development works in two directions (see Figure 11.13).

(1) The development context creates the conditions, positive or negative, for undertaking AFOLU measures. Thus, the development context provides opportunities or barriers for AFOLU (May et al., 2005; Madlener et al., 2006; Smith and Trines, 2006; Smith, 2007; Angelsen, 2008; Howden et al., 2008; Corbera and Brown, 2008; Cotula et al., 2009; Cattaneo et al., 2010; Junginger et al., 2011). Section 11.8 discusses the specific barriers and opportunities in the AFOLU sector.

(2) AFOLU measures have additional effects on the development process, beyond improving the GHG balance (Foley et al., 2005; Alig et al., 2010; Calfapietra et al., 2010; Busch et al., 2011; Albers and Robinson, 2012; Smith, Haberl, et al., 2013; Branca et al., 2013). These effects can be positive (co-benefits) or negative and do not necessarily overlap geographically, socially or in time. This creates the possibility of trade-offs, because an AFOLU measure can bring co-benefits for one social group in one area (e.g. increasing income), while bringing adverse effects to others somewhere else (e.g. reducing food availability). Co-benefits, adverse effects and spillovers of AFOLU are discussed in section 11.7. Potential interactions between AFOLU mitigation options and the development context under the transformation pathways are discussed in section 11.9.

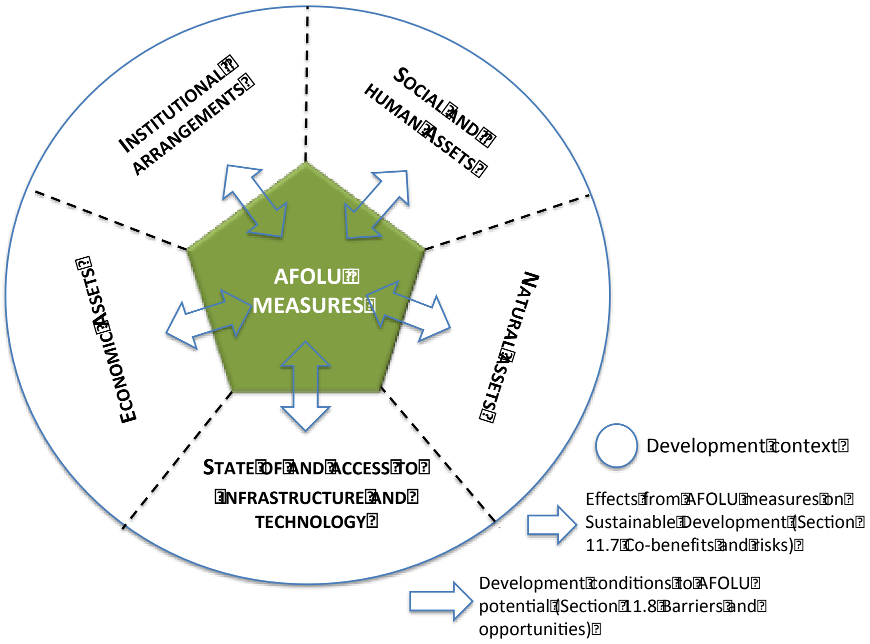


Figure 11.13. Dynamic interactions between the development context and AFOLU

Table 11.6 summarizes the issues commonly considered in scientific research when assessing the interactions between the development context and AFOLU.

Table 11.6: Issues related to AFOLU mitigation options and sustainable development

Dimensions	Issues
Social and human assets	Population growth and migration, level of education, human capacity, existence and forms of social organization, individual skills, indigenous and traditional knowledge, cultural values, equity and health
Natural assets	Availability of natural resources (land, forest, water, agricultural land, minerals, fauna), GHG balance, ecosystem integrity, biodiversity conservation, ecosystem services, ecosystem productive capacity, ecosystem health and resilience
State of infrastructure and technology	Availability of infrastructure and technology, technology development, appropriateness, acceptance
Economic factors	Credit capacity, employment creation, income, wealth distribution/distribution mechanisms, carbon finance, available capital/investments
Institutional arrangements	Land tenure and land use rights, participation and decision making mechanisms (e.g. through FPIC), sectoral and cross-sectoral policies, investment in research

Based on (Pretty, 2008)(Sneddon et al., 2006)(Macauley and Sedjo, 2011a)(Madlener et al., 2006a)(Steinfeld et al., 2010)

Scale of the implementation of an AFOLU measure is relevant for understanding its impact on sustainable development. The scale of the intervention includes the geographical size (i.e. area), as well as the size of interactions among social groups, and between human and natural systems (Trabucco et al., 2008)(Madlener et al., 2006b)(Pretty, 2008). Social interactions tend to become more complex the bigger the geographic scale used. One can identify a “social scale-line” that goes from individuals to the global society. Intermediate scales would be e.g. family – neighborhood – community – village – city - province – country – region – globe. Impacts on sustainable development are different along this scale-line. For example, bio-fuels have been identified as one option for substituting fossil fuels at a global scale (see section 11.3; Annex I). It can promote innovation or economic activity (Junginger et al., 2011). However, large-scale energy plantations can have negative impacts on livelihoods or on a specific region, e.g. on food or water availability (Alves Finco and Doppler, 2010a; Gallardo and Bond, 2011) (see Annex I).

Temporal consideration: As the concept of sustainable development includes current and future generations, the impacts of AFOLU over time also need to be considered. Further, the impact of AFOLU measures can be realized at differenttimes, e.g. while reducing deforestation has an immediate impact on GHG emissions, reforestation will have an increasing impact on C sequestration over time. Section 11.9 discusses the AFOLU mitigation options in different future scenarios, and with future drivers such as population growth.

Behavioural aspects: Behavioural aspects with regard of AFOLU are important at different levels in terms of a) land management decisions, b) production patterns over different value chains and c) consumption patterns. Besides economic considerations *Land management decisions* can be influebced by cultural values, especially from local actors (including indigenous peoples or local communities). However, when land use decisions are taken at a higher level e.g. by corporations or states, behaviour is also directed by other factors or values, including national and international market considerations or corporate image. Different values regarding developmental benefits or risks from AFOLU result in different perceptions, and lead to different behaviours. Regarding *production patterns* along the value chain, behaviour can be influenced through information, incentives and technology regarding markets and consumer preferences. The extent to which low-carbon production patterns will be used in a specific context, needs to be better understood (Muys, et al. forthcoming (Fraser, 1999; Primmer and Karppinen, 2010; MacMillan Uribe et al., 2012). Looking at *consumption patterns*, behavioural changes can have an impact on type of food, food preparation and consumption or energy consumption patterns (Popp et al., 2010). Understanding behavioural aspects for land use decisions includes the assessment of four survival dilemmas, including the benefit-risk dilemma, the temporal survival dilemma, the spatial survival dilemma and the social survival dilemma (Vlek and Keren, 1992; Vlek, 2004). The resolution of such dilemmas and the corresponding behavioural patterns by different agents are becoming an important research area in the AFOLU sector and for all actors (Villamor et al., 2011; Le et al., 2012) (see section 11.10).

Examples of factors affecting land management decisions include influence from land managers regarding a holistic land use or forest conservation (Gilg, 2009; Bhuiyan et al., 2010; Primmer and Karppinen, 2010). Labelling, certification or other information-based instruments have been developed for promoting more sustainable products (including wood or biofiels). Recently, the role of certification in reducing GHG while improving sustainability has been explored, especially for bioenergy (Schubert and Blasch, 2010; van Dam et al., 2010b). Concrete examples of behavioral change on the consumption side that could help to mitigate climate change, include dietary change ((Stehfest et al., 2009b; Popp et al., 2012) (more detailed information regarding these mitigation options is included in section 11.4 above and Annex I).

11.5 Climate change feedback and interaction with adaptation (includes vulnerability)

Climate regulation is one of many services provided by land (section 11.1) and hence AFOLU mitigation options will depend on the synergies and trade-offs with other environmental, social and economic concerns over space and time (section 11.4.). Mitigation and adaptation in land based ecosystems are closely interlinked through a web of feedbacks, synergies and risk-tradeoffs (see section 11.8). The mitigation measures themselves may be vulnerable to climatic change or there may be possible synergies or trade-offs between mitigation and adaptation options within or across AFOLU sectors.

Land-use changes can either help mitigate or contribute to climate change by affecting biophysical processes (e.g. evapotranspiration, albedo) and/or change in carbon fluxes to and from the atmosphere (WG1 and 2). Whether a particular ecosystem is functioning as sink or source of greenhouse gas emission may change over time, depending on its vulnerability to climate change and other stressors and disturbances. Hence, mitigation options available today in the AFOLU sectors may no longer be available with further warming.

IPCC WG II reviews in detail the observed and projected impacts of climate change on species, biomes and ecosystems. Biological systems exhibit different vulnerabilities depending on the type, magnitude and rate of climatic changes, the system’s sensitivity to this exposure and its adaptive capacity (see IPCC TAR). Building on the findings of the SREX, physical and biological systems appear to be more sensitive to extreme events than to changes in average climatic conditions. Climate related vulnerabilities of ecosystems may further be compounded by other stressors (see WGII).

Mitigation choices taken in a particular land-use sector may further enhance or reduce resilience to climate variability and change within or across sectors (Locatelli et al, 2008). For example, reducing emissions from deforestation and degradation may also yield co-benefits for adaptation by maintaining biodiversity and other ecosystem goods and services, while bioenergy plantations, by reducing biological diversity may diminish, adaptive capacity of climate change (e.g. Edenhofer et al., 2011). There may also be ripple effects across sectors, as land is finite and hence land use choices driven by mitigation concerns (forest conservation, afforestation) may have consequences for adaptive responses and/or development objectives of other sectors (e.g. expansion of agricultural areas).

The focus of this section is on assessing the impacts of climate change on mitigation potential of land use sectors. The broader impacts of climate change on the land use sectors, terrestrial ecosystems and crop production systems are further addressed in Working Group II (Chapter 4 and 6). Similarly, the implications of climate change feedbacks to carbon cycle are addressed in Working Group I, Chapter 6. Thus this section provides a brief account of these issues and refers to the WG I and II chapters for details.

11.5.1 Feedbacks between land use and climate change

When reviewing the interlinkages between climate change mitigation and adaptation within the natural resource sector the following issues need to be considered: (i) the impact of climate change on the mitigation potential of a particular sector (e.g. forestry and agricultural soils) over time, (ii) potential synergies / risk-tradeoffs within a land-use sector between mitigation and adaptation objectives, and (iii) potential risk-tradeoffs across sectors between mitigation and adaptation objectives. This discussion needs to be further placed within the broader development context in recognition of relevance of natural resources for many livelihoods and economies (see section 11.4.5 and 11.7.1). This also implies that synergies/ risk-tradeoffs associated with land-use choices need to be considered across different scales in their economic, social and environmental consequences.

Climate change and forests interact strongly. Climate and atmospheric CO_2 concentrations are major drivers of forest productivity and dynamics. At the same time forests play an important role in controlling climate and atmospheric CO_2 throughthe large amounts of carbon they can store or release, and through direct effects on the climate such as the absorbtion or reflection of solar radiation (albedo), cooling through evapotranspiration and the production of cloud-forming aerosols (Arneth et al., 2010; Pan et al., 2011; Pielke et al., 2011 from chapter 4, WGII).

Climate feedbacks of forest ecosystems differ from each other depending on the location and forest types. For example, tropical forests mitigate warming through evaporative cooling, but the low albedo of boreal forests privide a positive climate forcing (Bonan, 2008b). Deforestation in mid- to high latitudes is hypothesized to have the potential to cool the Earth’s surface by altering biophysical processes (Bala et al., 2007b; Bonan, 2008b). Several studies show that there will be an expansion of deciduous woodlands (Edwards et al., 2005; Peros et al., 2008). In this context, (Swann et al., 2010) suggest that the expansion of deciduous forest has a positive feedback on regional climate change.

According to Chapter 6 of Working Group 1, projections of the global carbon cycle to 2100 using ‘CMIP5 Earth System Models’ that represent a wider range of complex interactions between the carbon cycle and the physical climate system, consistently estimate a positive feedback between climate and the carbon cycle, i.e. reduced natural sinks or increased natural CO_2 sources in response to future climate change.

11.5.2 Implications of climate change on land use carbon sinks and mitigation potential

According to Chapter 6 of WGI the terrestrial biosphere pools in which carbon is currently being stored are vulnerable to climate change, changes in disturbance regime and other ecosystem stressers and changes, including landuse change. Carbon sinks in tropical ecosystems are vulnerable to climate change. However landuse, landuse change and land management are emerging as key drivers of future terrestrial carbon cycle, modulating both emissions and sinks. This highlights the importance of landuse change and other anthropogenic pressures on forests impacting the mitigation potential of landuse sectors.

Most model based studies suggest that rising temperatures, drought and fires will lead to forests becoming a weaker sink or a net carbon source before the end of the century (Sitch et al., 2008) and Bowman et al., 2009). Pervasive droughts, disturbances such as fire and insect outbreaks, exacerbated by climate extremes and climate change further put the mitigation benefits of the forests at risk (Canadell and Raupach, 2008a; Phillips et al., 2009; Herawati and Santoso, 2011). Forest disturbances and climate extremes have associated carbon balance implications (Millar et al., 2007; Zhao and Running, 2010; Potter et al., 2011);(Davidson, 2012);(Kurz, Stinson, et al., 2008). Forest disturbances affect roughly 100 million ha of forests annually (FRA, 2010). The emissions resulting from forest fires are presented in section 11.2.1.

Arcidiacono-Bársony (2011) suggest a possibility that the mitigation benefits from deforestation reduction under REDD (see section 11.10.1) could be reversed due to increased fire events, and climate-induced feedbacks. While Gumperberger (2010) conclude that the protection of forests under the forest conservation (including REDD) programmes could increase carbon uptake in many tropical countries, mainly due to CO_2 fertilization effects, even under climate change conditions. Similarly, according to dynamic global vegetation modelling an increase in forestry mitigation potential is projected in India under the changed climate, primarily due to CO_2 fertilization, however this study does not consider the impact of increased fire and pest occurrences and nutrient deficiency on the mitigation potential (Ravindranath et al., 2011).

Carnicer et al. (2011) suggest that climate change is increasing severe drought events in the Northern Hemisphere, and causing regional tree die-back events and global reduction of carbon sink efficiency of forests. Ma et al. (2012) provide the observational evidence of the weakening of the terrestrial carbon sinks in the northern high latitude regions, based on observations from the long-term forest permanent sample plots in Alberta, Saskachetwan and Manitoba. Climate change impacts on agriculture will affect not only yields, but also SOC levels in agricultural soils. Such impacts can be either positive or negative, depending on the particular effect considered. Elevated CO_2 alone will have positive effects on soil carbon storage, because increased above and belowground biomass production in the agro-ecosystem. Likewise, the lengthening of the growing season under warmer climates will allow for increased carbon inputs into soils. Warmer temperatures may also have negative effects on SOC, by increasing decomposition rates as well as by reducing inputs by shortening crop life cycles (Rosenzweig and Tubiello, 2007). (Hopkins et al., 2012) project accelerated soil organic carbon loss from forests with warming, and the losses are estimated to be high, especially in the younger soil carbon that is years-to-decade old, that comprises of large fraction of total soil carbon in forest soils globally.

11.5.3 Implications of climate change on peat lands, pastures/grasslands and rangelands

Peatlands: Wetlands, peatlands and permafrost soils contain higher carbon densities than mineral soils, and together they comprise extremely large stocks of carbon globally (Davidson and Janssens, 2006). According to (Schuur et al., 2008), the thawing permafrost and the resulting microbial decomposition of previously frozen organic carbon (C) is one of the most significant potential feedbacks from terrestrial ecosystems to the atmosphere in a changing climate. According to Chapter 6 of Working Group 1, large areas of permafrost will experience thawing, but uncertainty over the magnitude of frozen carbon losses through CO_2 or CH_4 emissions to the atmosphere are large, although most of AR5 model results produce significantly increased CO_2 emissions by the end of the 21st century. Peatlands cover approximately 3% of the earth's land area and are estimated to contain 350-550 Gt of carbon, roughly between 20 to 25% of the world's soil organic carbon stock (Gorham, 1991) (Fenner et al., 2011). Peatlands can lose CO_2 through plant respiration and aerobic peat decomposition (Clair et al., 2002) and with the onset of climate change, may become a source of CO_2 (Koehler et al., 2010). A study by Fenner et al (2011) suggests that climate change is expected to increase the frequency and severity of drought in many of the world's peatlands which, in turn, will release far more GHG emissions than thought previously. Climate change is projected to have a severe impact on the peatlands in northern regions where most of the perennially frozen peatlands are found (Tarnocai, 2006). Recent studies on nitrous oxide (N_2O) emissions from permafrost peatlands have shown that tundra soils can support high N_2O release, which is on the contrary to what was thought previously (Marushchak et al., 2011).

Grasslands, Pastures and Rangelands: Carbon stocks in permanent grassland are influenced by human activities and natural disturbances, including harvesting of woody biomass, rangeland degradation, grazing, fires, and rehabilitation, pasture management, etc.

The most important impacts of climate change on rangelands will likely be through changes in pasture productivity. Climate change may also affect grazing systems by altering species composition; for example, warming will favour tropical (C4) species over temperate (C3) species (Howden et al., 2008). Projected increases in rainfall intensity (WGI, Chapter 12) are likely to increase the risks of soil erosion, leading to losses in carbon stocks from the grassland and rangelands.

11.5.4 Potential adaptation measures to minimize the impact of climate change on carbon stocks in forests and agricultural soils

Forests: Adaptation to climate change in forest ecosystems and agriculture systems are discussed in detail in WG II chapters. Adaptation practice is basically a framework for managing future climate risks and offers the potential of reducing future economic, social, and environmental costs (Murthy et al., 2011). Forest ecosystems require the longer response time to adapt and a further long period is involved in developing and implementing adaptation strategies (Leemans and Eickhout, 2004; Ravindranath, 2007). Some examples of the 'win-win' adaptation practices are as follows: (Murthy et al., 2011): anticipatory planting of species along latitude and altitude, assisted natural regeneration, mixed species forestry, species mix adapted to different temperature tolerance regimes, fire protection and management practices, thinning, sanitation and other silvicultural practices, *in situ* and *ex situ* conservation of genetic diversity, drought and pest resistance in commercial tree species, adoption of sustainable forest management practices, increase Protected Areas and link them wherever possible to promote migration of species, forests conservation and reduced forest fragmentation enabling species migration and energy efficient fuelwood cooking devices to reduce pressure on forests.

Agricultural soils: (Smith and Olesen, 2010) identified a number of synergies between measures that deliver climate mitigation in agriculture, and that also enhance resilience to future climate change, the most prominent of which was enhancement of soil carbon stocks.

On current agricultural land, interactions between mitigation and adaptation can be mutually re-enforcing, especially in view of increased climate variability under climate change. By increasing the ability of soils to hold soil moisture and to better withstand erosion, and by enriching ecosystem biodiversity through the establishment of more diversified cropping systems, many mitigation techniques implemented locally for soil carbon sequestration may also help cropping systems to better withstand droughts and/or floods, both of which are projected to increase in frequency and severity in future warmer climates (Rosenzweig and Tubiello, 2007).

11.5.5 Mitigation and adaptation synergy and risk-tradeoffs

Mitigation policies and measures may exhibit synergies and risk-tradeoffs with adaptation (Bates et al., 2008). Examples which successfully combine forest-based adaptation with mitigation options include ecosystem-based adaptation policies and measures that conserve, (e.g. natural forests) and at the same time provide significant climate change mitigation benefits by maintaining existing carbon stocks and sequestration capacity, and by preventing future emissions from deforestation and forest degradation. Adaptation projects that prevent fires and prevent release of GHG and restore degraded forest ecosystems also enhance carbon stocks (CBD and GiZ, 2011). Many strategies and practices developed to advance sustainable forest management (SFM) also help to achieve the objectives of climate change adaptation and mitigation (Van Bodegom et al., 2009). Use of organic soil amendments as a source of fertility could potentially increase soil carbon (Brown et al., 2011, (Gattinger et al., 2012) Similarly, forest and biodiversity conservation, protected area formation and mixed species forestry based afforestation are practices that can help to maintain or enhance carbon stocks, while also providing adaptation options to reduce vulnerability of forest ecosystems to climate change (Ravindranath, 2007).There could be potential tradeoffs, for example afforestation with exotic high yielding monoculture plantations could sequester carbon at higher rates, but such plantations could be vulnerable to climate change related droughts and pests. Most categories of adaptation options for climate change have positive impacts on mitigation. Adaptation measures will in general, if properly applied, reduce GHG emissions, by improving nitrogen use efficiencies and improving soil carbon storage (Smith and Olesen, 2010). In the agriculture sector cropland adaptation options that also contribute to mitigation are: soil management practices that reduce fertilizer use and increase crop diversification; promotion of legumes in crop rotations; increasing biodiversity, the availability of quality seeds and integrated crop/livestock systems; promotion of low energy production systems; improving the control of wildfires and avoiding burning of crop residues; and promoting efficient energy use by commercial agriculture and agro-industries (FAO 2008, FAO 2009a). It has to be noted that mitigation-adaptation practices should not lead to reduction in crop yields and could potentially enhance. Agroforestry is an example of mitigation adaptation synergy in agriculture sector since trees planted sequester carbon and tree products provide livelihood to communities, especially during drought years (Verchot et al., 2007).

FAQ 11.2 How will decisions in AFOLU affect GHG emissions over different timescales?

There are many mitigation options in the AFOLU sector which are already being implemented, for example afforestation, avoided deforestation, cropland and grazing land management and improved livestock breeds and diets. These can be implemented now. Others (such as some forms of biotechnology and livestock dietary additives) are still in development and may not be applicable for a number of years. In terms of the mode of action of the measures, in common with other sectors, non-CO_2 greenhouse gas emission reduction is immediate and permanent. However, a large portion of the mitigation potential in the AFOLU sector is carbon sequestration in soils and vegetation. This mitigation potential differs, in that the measures are time-limited (the potential saturates), and the enhanced carbon stocks created are reversible and non-permanent. There is, therefore, a significant time component in the realisation and the duration of much of the mitigation potential available in the AFOLU sector.

11.6 Costs and potentials

This section deals with economic costs and potentials of greenhouse gas (GHG) mitigation (reduction for emissions or sequestrationof carbon) within the AFOLU sector. Economic mitigation potentials are distinguished from technical or market mitigation potentials (Smith, 2012a). Technical mitigation potentials represent the full biophysical potential of a mitigation measure, without accounting for economic or other constraints. These estimates account for constraints and factors such as land availability and suitability (Smith, 2012a), but not any associated costs (at least explicitly). By comparison, economic potential refers to mitigation that could be realised at a given carbon price over a specific period, but does not take into consideration any socio-cultural (for example, life-style choices) or institutional (for example, political, policy and informational) barriers to practice or technology adoption. Economic potentials are expected to be lower than the corresponding technical potentials. Also, policy incentives (e.g. a carbon price) and competition for resources across various mitigation options, tends to affect the size of economic mitigation potentials in the AFOLU sector (McCarl and Schneider, 2001). Finally, market potential is the realised mitigation outcome under current or forecast market conditions encompassing biophysical, economic, socio-cultural and institutional barriers to, as well as policy incentives for, technological and/or practice adoption, specific to a sub-national, national or supra-national market for carbon. Figure 11.14 (Smith, 2012a) provides a schematic view of the three types of mitigation potentials.

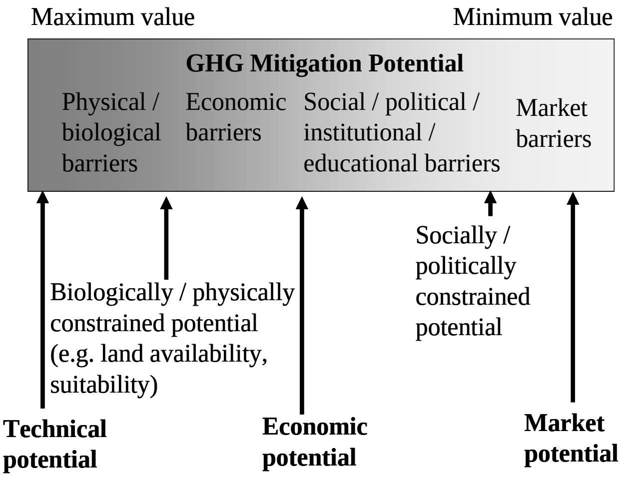


Figure 11.14. Relationship between technical, economic and market potential (after (Smith, 2012a))

Economic (as well as market) mitigation potentials also tend to be context-specific and are likely to vary across spatial and temporal scales. Unless otherwise stated, in rest of this section, economic potentials are expressed in million tonnes (Mt) of GHG mitigation in carbon dioxide equivalent (CO_2-eq.) terms, that can arise from an individual mitigation option or from an AFOLU sub-sector at a given cost per tonne of carbon dioxide equivalent (US$/t$CO_2$-eq.) over a given period to 2030, which is 'additional' to the corresponding baseline or reference case levels.

Section 11.3 describes various supply-side mitigation options (also called 'measures') within the AFOLU sector, and section 11.4 considers a number of potential demand-side measures. Estimates for costs and potentials are not always available for the individual options described. Also, aggregate estimates covering both the supply- and demand-side options for GHG mitigation within the AFOLU sector are lacking so this section mostly focuses on the supply-side options which are expected to account for most of the economic mitigation potentials in the sector. Key uncertainties and sensitivities around mitigation costs and potentials in the AFOLU sector are (1) the carbon price, (2) prevailing biophysical and climatic conditions, (3) existing management heterogeniety (or differences in the baselines), (4) management interdependencies (arising from competition or co-benefits across tradition production, environmental outcomes and mitigation strategies or competition/co-benefits across mitigation options), (5) the extent of leakage, (6) multiple gas emissions associated with a particular mitigation option, and (6) timeframe for abatement activities and the discount rate. In this section we a) provide aggregate mitigation potentials for the AFOLU sector (since IPCC AR4 provided these separately, for agriculture and forestry), b) provide estimates of global mitigation costs and potentials published since AR4, for comparison with AR4 estimates, and c) provide a regional disaggregation of the potentials to show how potential, and the portfolio of available measures varies in different world regions.

11.6.1 Approaches to estimating economic mitigation potentials

Bottom-up and top-down modelling approaches are used to estimate AFOLU mitigation potentials and costs. While both approaches provide useful estimates for mitigation costs and potentials, comparing bottom-up and top-down estimates is not straightforward.

Bottom-up estimates are typically derived for discrete abatement options in agriculture at specific location or time, and are often based on detailed technological, engineering and process information and data on individual technologies (e.g. DeAngelo et al., 2006). These studies provide estimates of how much technical potential of particular agricultural mitigation options will become economically viable at certain carbon dioxide-equivalent prices. Bottom-up mitigation responses are typically restricted to input management (for example, changing practices with fertiliser application and livestock feeding) and mitigation costs estimates are considered 'partial equilibrium' in that the relevant input-output prices (and, sometimes, quantities such as area or production levels) are held fixed. As such, unless adjusted for potential overlaps and trade-offs across individual mitigation options, adding up various individual estimates to arrive at an aggregate for a particular landscape or at a particular point in time could be misleading.

With a 'systems' approach, top-down models typically take into account possible interactions between individual mitigation options. These models can be sector-specific or economy-wide, and can vary across geographical scales: sub-national, national, regional and global. Mitigation strategies in top-down models may include a broad range of management responses and practice changes (for example, moving from cropping to grazing or grazing to plantation) as well as changes in input-output prices (for example, land and commodity prices). Such models can be used to assess the cost competitiveness of various mitigation options and its implications across input-output markets, sectors, and regions over time for large-scale domestic or global adoption of mitigation strategies. In top-down modelling, dynamic cost-effective portfolios of abatement strategies are identified incorporating the lowest cost combination of mitigation strategies over time from across sectors, including agricultural and other land-based sectors, across the world that achieve the climate stabilisation target. Top-down estimates for 2030 are included in this section, and are revisited in section 11.9 when considering the role of the AFOLU sector in transformation pathways.

Providing consolidated estimates of economic potentials for GHG mitigation within the AFOLU sector as a whole is complicated because of complex interdependencies largely stemming from competing demands on land for various agricultural and forestry (production and mitigation) activities as well as for the provision of many ecosystem services (Smith et al., 2013). These interactions are discussed in more detail in section 11.4.

11.6.2 Global estimates of costs and potentials in the AFOLU sector

Through combination of forestry and agriculture potentials from IPCC AR4, total mitigation potentials for the AFOLU sector are estimated to be ~3 to ~7.2 $GtCO_2$-eq./yr in 2030 at 20 and 100 US\$/tCO_2.-eq., respectively (Figure 11.15), including only supply-side measures in agriculture (Smith, et al., 2007) and a combination of supply- and demand-side measures for forestry (Nabuurs et al., 2007). Estimates of global economic mitigation potentials in the AFOLU sector, published since AR4 are shown in Figure 11.16, with AR4 estimates shown for comparison (denoted IPCC AR4, 2007).

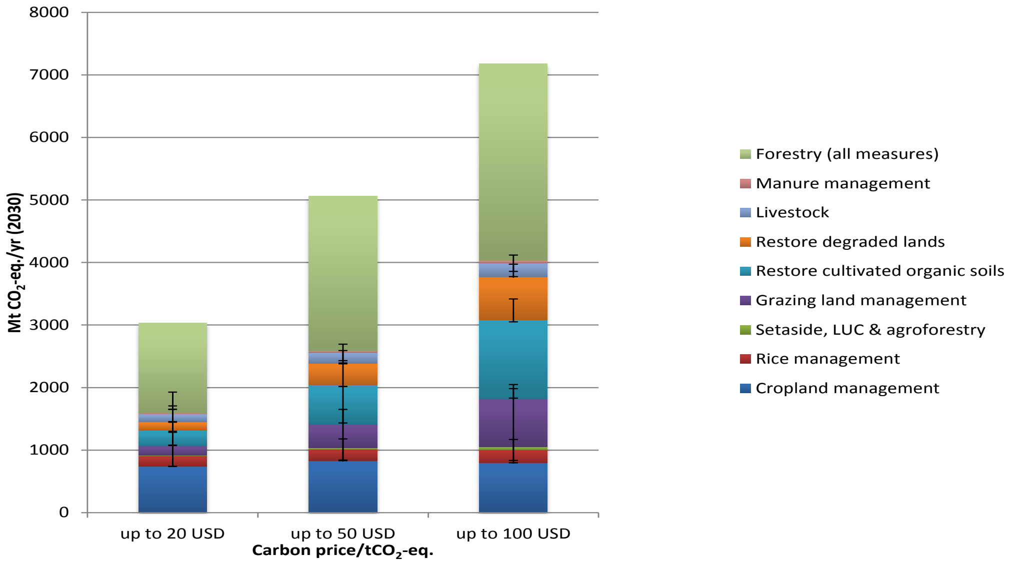


Figure 11.15. Mitigation potential for the AFOLU sector, plotted using data from IPCC AR4 (Nabuurs et al., 2007; Smith, Martino, Cai, Gwary, Janzen, Kumar, McCarl, Ogle, O'Mara, Rice, Scholes, et al., 2007). Error bars show the range of estimates (+/- 1 standard deviation) for agricultural measures for which estimates are available.

Figure 11.16 presents global estimates for economic mitigation potentials in AFOLU in 2030 at various carbon prices. The range of global estimates at a given carbon price partly reflects uncertainty surrounding AFOLU mitigation potentials in the literature, and the underlying assumptions about land use driving the scenarios considered. The ranges of estimates also reflect differences in the GHGs and measures considered in the studies. For example, ~90% of the mitigation potential found in some bottom up studies such as (Smith, Martino, Cai, Gwary, Janzen, Kumar, McCarl, Ogle, O'Mara, Rice, Scholes, et al., 2007; Smith et al., 2008) derive from soil carbon sequestration, whereas soil carbon sequestration is not considered in most top-down studies collated by (Rose et al., 2012) – if only the non-CO_2 potentials in agriculture from IPCC AR4 are considered, the estimates from (Rose et al., 2012) are much closer. Other differences include the consideration of multiple sectors in the top-down models. This means that mitigation options in the AFOLU sector are in competition in terms of cost-effectiveness with many sectors. Most of the bottom-up studies consider only agriculture, or forestry and rarely the whole land sector together (but not other sectors). For this reason, the studies shown in Figure 11.16 are not comparable on a like-for-like basis, but nevertheless show the range of estimates of AFOLU mitigation potential published since AR4. Most mitigation potentials in the AFOLU sector are close to the ranges suggested in IPCC AR4 or lower in top-down studies (due to consideration of only non-CO_2 GHGs in agriculture). Exceptions are from the study estimating forestry potentials of (Sohngen, 2009), which are larger than other estimates. Demand-side options in agriculture also show a large mitigation potential compared to estimates of supply-side only from AR4, but they are not assessed at a specific carbon price and should be regarded as technical potentials. Economic potentials are likely to be much lower, so as such, they are not directly comparable with the economic potentials shown of Figure 11.16.

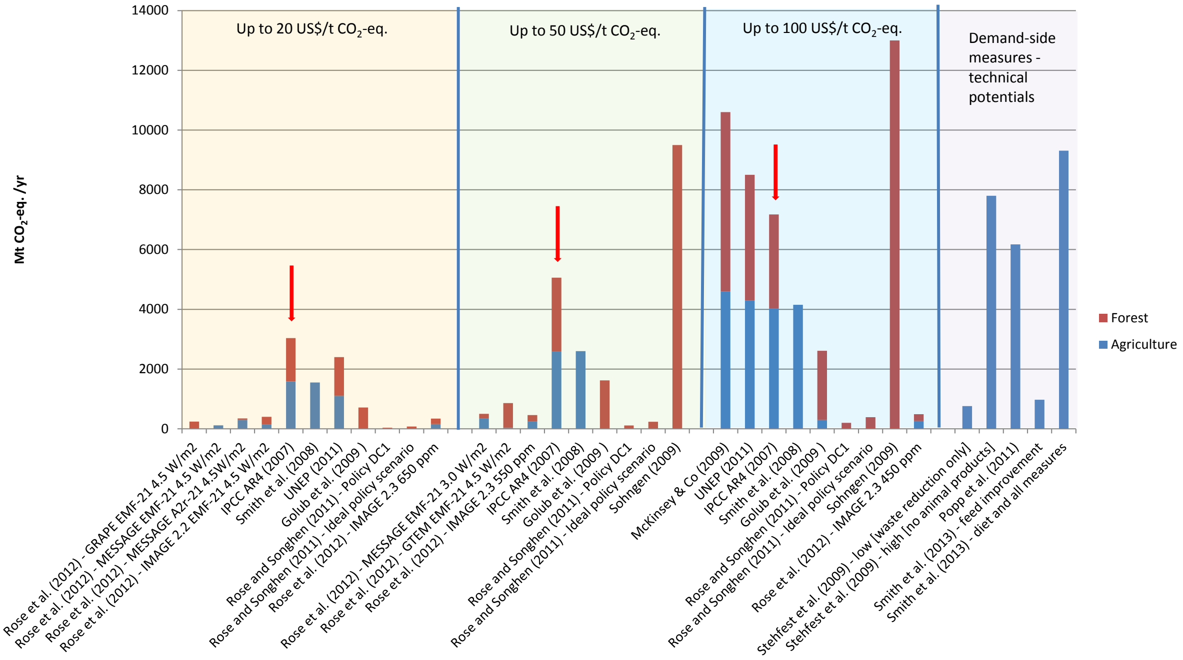


Figure 11.16. Estimates of economic mitigation potentials in the AFOLU sector published since AR4, (AR4 estimates shown for comparison, denoted by red arrows), including bottom-up, sectoral stidies, and top-down, multi-sector studies. Some studies estimate potential for agriculture and forestry, others for one or other sector. Mitigation potentials are estimated for around 2030, but studies range from estimates for 2025 (Rose et al., 2012) to 2035 (Rose and Sohngen, 2011). Studies are collated for those reporting potentials at up to ~20 US$/t$CO_2$-eq. (actual range 1.64-21.45), up to ~50 US$/t$CO_2$-eq. (actual range 31.39-50.00), and up to ~100 US$/t$CO_2$-eq. (actual range 70.0-120.91). Demand-side measures (shown on the right hand side of the figure) are not assessed at a specific carbon price, and should be regarded as technical potentials. Not all studies consider the same measures or the same GHGs; further details are given in the text.

Table 11.7 shows the ranges of global ecomonic mitigation potentials from AR4 (Nabuurs et al., 2007; Smith, Martino, Cai, Gwary, Janzen, Kumar, McCarl, Ogle, O'Mara, Rice, Scholes, et al., 2007), and studies published since AR4 that are shown in full in Figure 11.16, for agriculture, forestry and AFOLU combined.

Table 11.7: Ranges of global mitigation potential (Mt CO_2-eq./yr in 2030) reported since IPCC AR4 (full data shown in Figure 11.16)

	up to 20 US$/t CO_2-eq.	up to 50 US$/t CO_2-eq.	up to 100 US$/t CO_2-eq.	Technical potential only
Agrriculture[1]	0-1585	30-2600	260-4600	▨
Forestry	10-1450	112-9500	198-13000	▨
AFOLU total[1,2]	120-3034	500-5058	490-10600	▨
Demand-side measures	▨	▨	▨	760-9311

1 All lower range figures for agriculture are for non-CO2 GHG mitigation only

2 AFOLU total includes only estimates where both agriculture and forestry have been considered together.

In forestry, in the short term, the economic potentials of carbon mitigation from reduced deforestation are expected to be greater than the economic potentials of afforestation, since deforestation is the single most important source of GHG emissions within the forestry sector, with a net loss of forest area between 2000 and 2010 estimated at 5.2 million ha/yr (FAO, 2012b).

Kindermann et al. (2008) presented details on the modelling methodologies and assumptions and suggested that the baseline carbon emissions projections, as well as the economic potentials and costs for emissions mitigation, differ between models because of, among other things, model-specific economic assumptions (including population, technology, trade, and alternative use and opportunity costs of land) and assumptions regarding biological conditions (for example, quantity of carbon in forest biomass). Forest mitigation potential and costs are projected to vary over time as the lowest-cost options are adopted first, moving to the high-cost land associated with high agricultural productivity and, hence, higher opportunity costs for afforestation or avoided deforestation activities (Kindermann et al., 2008).

11.6.3 Regional disaggregation of global costs and potentials in the AFOLU sector

Figure 11.17 shows the economically viable mitigation opportunities in AFOLU in 2030 by region and by main mitigation option at carbon prices of up to US$20, 50 and 100/t$CO_2$-eq. The composition of the agricultural mitigation portfolio varies greatly with the carbon price (Smith, 2012a), with low cost options such as cropland management being favoured at low carbon prices, but higher cost measues such as restoration of cultivated organic soils being more cost effective at higher prices.

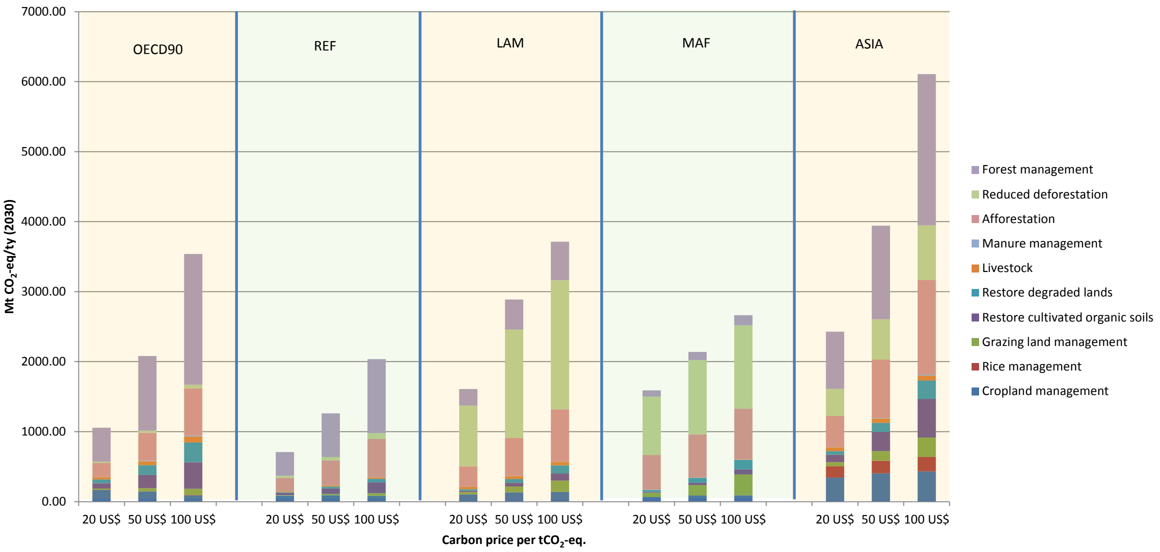


Figure 11.17. Economic mitigation potentials in the AFOLU sector by region. Global forestry activities (annual amount sequestered or emissions avoided above the baseline for forest management, reduced deforestation and afforestation), at carbon prices up to 100 US$/tCO$_2$ are aggregated to regions from results from three models of global forestry and land use: the Global Timber Model (GTM; (Sohngen and Sedjo, 2006), the Generalized Comprehensive Mitigation Assessment Process (GCOMAP Sathaye et al., 2006), and the Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA; Benítez et al., 2007) see Kindermann et al. (2008) for the modelling methodologies and assumptions.

Figure 11.17 also reveals some very large differences in mitigation potential, and different ranking of most effective options, between regions. Across all AFOLU measures, ASIA has the largest mitigation potential, with the largest mitigation in both forestry and agriculture, followed by LAM, OECD90, MAF then REF. Differences between the most effective options are particularly striking, with reduced deforestation dominating the forestry mitigation potential LAM and MAF, but very little potential in OECD90 and REF. Forest management, followed by afforestation, dominate in OECD90, REF and ASIA. Among agricultural measures, among the most striking of regional differences are the rice management practices for which almost all of the global potential is in ASIA, and the large potential for restoration of organic soils also in ASIA (due to cultivated south east Asian peats), and OECD90 (due to cultivated northern peatlands). A number of other regional differences can be seen.

Estimates for economic potential for carbon mitigation from forestry are also available for particular regions or programs (e.g. Coren et al., 2011; Busch et al., 2012; Merger et al., 2012). Table 11.8 presents the consolidated estimates based on regional bottom up models. The forestry mitigation options are estimated to contribute between 1.27 and 4.23 GtCO$_2$/yr economically viable abatement in 2030 at carbon prices of up to 100 US$/t CO$_2$, the amount of estimated abatement much lower than the corresponding global estimate of 13.8 Gt CO$_2$/yr based on the global forest sector models shown in Figure 11.17. This reflects the uncertainty surrounding forestry mitigation potentials in the literature drawn from a variety of studies relying on different modelling methodologies and assumptions and, in some instances, not taking into account possible leakages. Bottom-up estimates of economically viable mitigation generally include numerous activities in one or more regions represented in detail. One important reason that bottom-up results yield a lower potential consistently for every region, is that this type of study takes into account (to some degree) barriers to implementation.

Table 11.8: Economic mitigation potential by world region in forestry sector, excluding bioenergy, based on regional bottom up models: Mt CO2eq./yr for prices up to 100 US$/tCO2eq. for 2030.

	Regional bottom-up estimate		
	Mean	**Low**	**High**
OECD	700	420	980
Economies in transition	150	90	210
Non-OECD	1,900	760	3,040
Global	2,750[a]	1,270	4,230

a Excluding bio-energy

FAQ 11.3 What are the main mitigation options in AFOLU and what is the potential for reducing GHG emissions?

In general, available top-down estimates of costs and potentials suggest that AFOLU mitigation will be an important part of a global cost-effective abatement strategy. However, potentials and costs of these mitigation options differ greatly by activity, regions, system boundaries and the time horizon. Especially, forestry mitigation options - including reduced deforestation, forest management, afforestation, and agro-forestry - are estimated to contribute between 1.27 and 4.23 $GtCO_2$/yr of economically viable abatement in 2030 at carbon prices up to 100 US$/t CO_2-eq. About 50% of the mean estimates are projected to occur at a costs under 20 US$/t$CO_2$-eq. (= 1.55 $GtCO_2$/yr). Global economic mitigation potentials in agriculture in 2030 are estimated to be up to 1.10-4.60 $GtCO_2$-eq/yr. Besides supply side based mitigation, demand side mitigation options can have a significant impact on GHG emissions from food production. Changes in diet towards plant-based and hence less GHG intensive food can result in GHG emission savings of 4.3-11.0 $GtCO_2$eq./yr in 2050, depending on which GHGs and diets considered. Reducing food losses and waste in the supply chain from harvest to consumption can reduce GHG emissions by 0.76-1.5 $GtCO_2$eq./yr.

11.7 Co-benefits, risks and spillovers

The implementation of the AFOLU mitigation options (Section 11.3) will result in a range of outcomes beyond changes in GHG balances. Some of these outcomes can be beneficial (co-benefits) whereas others are potentially detrimental (adverse side effects). Assessing the effect of co-benefits and adverse effects of AFOLU measures on sustainable development is a great challenge because these effects do not necessarily overlap geographically, socially or with regard to the timeline (see section 11.4.5). Further, there are many uncertainties and research gaps regarding the attribution of both co-benefits and potential adverse effects. Some of these potential outcomes can be quantified, whereas metrics for others (e.g. biodiversity or social effects) are less clear. Modelling frameworks are being developed which allow an integrated assessment of multiple outcomes at project (Townsend et al., 2011) and smaller (Smith et al 2013) scales. Co-benefits, risks and uncertainties, and spillovers in the AFOLU sector are summarised in Table 11.9.

Least developed countries (LDCs) are dependent upon natural assets and highly vulnerable to climate change (Patt et al., 2010). This makes it very relevant to understand the potential co-benefits and risks of AFOLU mitigation options for these countries under specific contexts (see Box 11.5)

Box 11.5 The role of Least Developed Countries (LDCs) in mitigation in the AFOLU sector

[COMMENTS ON TEXT BY TSU TO REVIEWER: Boxes highlighting further LDC-specific issues are included in other chapters of the report (see chapter sections 1.3.1, 2.1, 6.3.6.6, 7.9.1, 8.9.3, 9.3.2, 10.3.2, 11.7, 12.6.4, 16.8) and a similar box may be added to the Final Draft of chapters, where there is none in the current Second Order Draft. In addition to general comments regarding quality, reviewers are encouraged to comment on the complementary of individual boxes on LDC issues as well as on their comprehensiveness, if considered as a whole.]

The contribution of LDCs to future GHG emissions is likely to be substantial, as it is expected to rise by 30-40% above 2005 levels in line with the projected unprecedented increase in food production by 2030. The need for intensification with increased fertilizer use will exacerbate LDCs' share of emissions. The contribution of LDCs to the global effort on mitigation relies mainly on carbon sequestration in agriculture, forestry and other land uses by decreasing GHG emissions, and/or improving carbon uptake. Potential activities include reducing deforestation, increasing forest cover, agroforestry, agriculture that includes livestock management, and producing sustainable renewable energy. Although agriculture and forestry are important sectors for GHG abatement, technology will not be sufficient to deliver the necessary transitions to a low GHG future. Other barriers include access to market and credits, technical capacities, and institutional framework and regulations. Additionally, LDC population diversity makes it difficult to establish the relationships between GDP and CO_2 emissions per capita as suggested by the Kaya model. This partly arises from the wide gap between rural and urban communities, and the difference in livelihoods (e.g. the use of fuel wood, farming practices in various agroecological conditions, dietary preferences with a rising middle class in LDCs, development of infrastructure, behavioural change, etc.). Also, addressing non-permanence and leakage induced by new mitigation pathways (old conservation paradigm) leads to the transfer of ecosystem services extraction around non-protected areas that threatens conservation areas in countries with low capacities.

On the policy side, the chapter underlines issues of co-benefits or trade-offs from improved agricultural production and the necessary link between mitigation and adaptation, and how to manage incentives for a substantial GHG abatement initiative nested in agricultural activities. The question is how to strike a viable balance in a poverty context while accounting for development priorities. Mitigation pathways in LDCs should be assessed in terms of performance to address the dual need for mitigation and adaptation through clear guidelines to manage multiple options. Safeguarding, nesting, and *a priori* consent of small holders is central, and demands extra effort to address equity issues including gender, challenges, prospects and prerequisites for carbon sequestration projects. Unless mitigation projects address this duality, they could become drivers of subsequent harm that might deepen poverty instead of alleviating it.

One sector where the co-benefits and trade-offs are timely and relevant is for bioenergy. Some bioenergy options in LDCs include perennial cropping systems, use of biomass residues and wastes, and advanced conversion systems. Agricultural and forestry residues represent a potential low cost and low carbon source for bioenergy. Nevertheless, the large-scale use of bioenergy can be controversial in the LDC context because of its implication on land use change and the threats to food security. Efficient biomass production for bioenergy requires the safeguarding of food production, biodiversity, and terrestrial carbon storage while controlling potential emission of N_2O from agricultural soils. When bioenergy products are acquired through land use conversion, this process can lead to a loss of carbon stocks that negate the net positive GHG mitigation impacts. In addition, the growing fuel-wood market in cities requires sustainable land-use systems that must integrate trees on arable or pasture land (agroforestry) rather than relying on forest extraction.

It is critical that data gaps be identified to foster a better understanding of productive systems. This process could culminate in a common understanding that represents regional practices across LDCs. Through the identification of crucial areas within those production systems where region/country-specific emission factors should be developed via measurements, LDCs can share knowledge on resilient and resource efficient farming systems, including the identification of critical needs for measurement guidance and methodologies.

11.7.1 Socio-economic effects

The implementation of AFOLU measures may have important impacts on the living conditions of the various social groups involved, including indigenous peoples, farmers, rural communities or landless peoples. Maximising co-benefits of AFOLU mitigation options can help to achieve the objectives of other international agreements, including the United Nations Convention to Combat Desertification (UNCCD,2011) or Convention on Biological Diversity (CBD), and mitigation action may also contribute to a broader global sustainability agenda (Koziell and Swingland, 2002; Swingland et al., 2002; Harvey et al., 2010; Gardner et al., 2012). In many cases, implementation of these agendas is limited by capital, and mitigation may provide a new source of finance (Tubiello et al.).

AFOLU mitigation measures can promote increases in food and fibre production, improve watershed conditions, provide financial incentives or generate local employment, thus having a positive impact on livelihoods. In some situations, one or more of these co-benefits can be sold (e.g. timber and non-timber forest products, water), thus providing additional cash-flow for land-holders. An emerging area is the payment for several environmental services from reforestation or forest management (Deal and White, 2012; Deal et al., 2012). Further considerations on economic co-benefits are related to the access to carbon payments either within or outside UNFCCC agreements (see section 11.10). Several recent studies have examined carbon markets, their potentials and constraints as means for promoting AFOLU measures in developed and developing countries (P. Combes Motel et al., 2009; Alig et al., 2010; Asante et al., 2011; Asante and Armstrong, 2012, see section 11.6). In some cases mitigation payments can fulfil the gap for a sustainable production of non-timber forest products (NTFP), further diversifying income at the local level (Singh, 2008). The realisation of economic co-benefits seems to be related to the design of the specific mechanisms (Corbera and Brown, 2008) and depend upon three main variables a) the amount and coverage of these payments, b) the recipient of the payments and c) timing of payments (*ex-ante* or *ex-post)* (Skutsch et al., 2011).

Some attention has been given to the potential impacts of AFOLU mitigation measures on land tenure and land use rights for indigenous peoples, local communities and other forest dependant groups (Sunderlin et al., 2005; Chhatre and Agrawal, 2009; Blom et al., 2010; Sikor et al., 2010; Larson, 2011; Rosendal and Andresen, 2011) (See 11.10). Whether an impact on a specific group is positive (co-benefit) or negative seems to depend upon two factors: a) the institutions regulating land tenure and land use rights and b) the level of enforcement by such institutions (Corbera and Brown, 2008; Araujo et al., 2009; Albers and Robinson, 2012). Research on specific tenure forms that enable AFOLU mitigation measures in different regions or under more specific circumstances is still needed (Robinson et al., 2011).

Financial concerns including reduced access to loan and credits, high transaction costs or reduced income due to price changes of carbon credits over the project length appear as potential risks for AFOLU measures, especially in developing countries and when land holders use market mechanisms (e.g. A/R CDM) (Madlener et al., 2006b). According to some authors, a wider scheme for payments of environmental services could contribute to increased economic feasibility of AFOLU mitigation measures (Wünscher and Engel, 2012).

Perceived potential socio-economic risks include the possibility to further promote corruption or to jeopardize the decentralisation efforts made in the last decades in the forest sector, or to increase land rents and food prices due to a reduction in land availability for agriculture in developing countries. Further, land based mitigation options could increase inequity and land conflicts or marginalize small scale farm/forests owners (Huettner, 2012)(Robinson et al., 2011).

An emerging area of concern is related to food security, particularly with increased demand on food with global population increase, intensification of diets, stresses on water supply and impacts of climate change on crop yields (see also Annex I). These interactions are discussed in a recent review (Smith, Haberl, et al., 2013) as well as in section 11.4 and Annex I.

11.7.1.1 Environmental and health effects

The impacts of greenhouse gas mitigation in the AFOLU sector on other climate drivers (such as albedo and water balance) are discussed in detail in section 11.5 so are not discussed further here.

In addition to potential climate impacts, land-use intensity drives the three main fractionating N loss pathways (nitrate leaching, denitrification and ammonia volatilization) and typical N balances for each land use indicate that total N loss also increase with increasing land-use intensity (Stevenson et al., 2010). Leakages from N cycle can cause air (e.g. NH_3, NO_x), soil (nitrate) and water pollution (e.g. eutrophication) and agricultural intensification can lead to a variety of other adverse environmental impacts (Smith, Ashmore, et al., 2013; Smith, Bustamante, et al., 2013). Multi-process practices (diversified crop rotations and organic N sources) can significantly improve total N retention compared to three common single-process strategies (reduced N rates, nitrification inhibitors, and changing chemical forms of fertilizer) (Gardner and Drinkwater, 2009) (Bambo et al., 2009). Integrated systems can be an alternative to attempt to reduce leaching.

AFOLU mitigation options can promote conservation of biological diversity (Smith, Ashmore, et al., 2013). Biodiversity conservation can be improved both by reducing deforestation (Murdiyarso et al., 2012)(Chhatre et al., 2012; Murdiyarso et al., 2012; Putz and Romero, 2012; Visseren-Hamakers et al., 2012), and by using reforestation/afforestation to restore biodiverse communities on previously developed farmland (Harper et al., 2007). Reforestation may also provide a mechanism to fund translocation of biodiverse communities in response to climate change. Financial flows supporting AFOLU mitigation measures (e.g. those resulting from the REDD+ mechanism) can have positive effects on conserving biodiversity, but could eventually create competition against conservation of biodiversity hotspots, when carbon stocks are low (Gardner et al., 2012) (see section 11.10 for policy considerations). Some authors propose that carbon payments be complemented with biodiversity payments as an option for reducing trade-offs against biodiversity conservation (Phelps, Guerrero, et al., 2010). Bundling of ecosystem service payments is an emerging area (Deal and White, 2012).

Stubble retention and minimum tillage may also increase crop yields and reduce the amount of wind and water erosion due to an increase in surface cover (Lal, 2001); agroforestry systems will reduce wind erosion by acting as wind breaks and may increase crop production, and reforestation or bioenergy systems can be used to restore degraded or abandoned land (Yamada et al., 1999; Wicke et al., 2011; Sochacki et al., 2012).

Reduced emissions from agriculture and forestry may also improve air, soil and water quality (Smith, Ashmore, et al., 2013), thereby indirectly providing benefits to human health and well being. Demand-side measures to reduce livestock product consumption in the diet are also known to be associated with multiple health benefits (Stehfest et al., 2009a). Other authors have studied the potential impacts from AFOLU mitigation strategies on human health (Cançado et al., 2006; Hilber et al., 2012). In this area more research is needed to make more conclusive recommendations.

Besides, AFOLU mitigation measures can have various impacts on water resources. In a synthesis of global data, Jackson et al. (2005) documented several effects of afforestation/ reforestation on the water cycle. Stream flow decreased within a few years of planting and 13% of streams dried up completely for at least 1 year, with eucalyptus more likely to dry up streams than pines. The reduction in runoff is greater in drier regions (<1000 mm mean annual precipitation – (Farley et al., 2005). Forestry projects can result in reduced water yields (Jackson et al., 2005) in either groundwater or surface catchments, or where irrigation water is used to produce bioenergy crops. In other situations, reforestation can result in a restoration of water quality albeit with reduced water yields (e.g. Townsend et al., 2012).

Finally, in afforestation/reforestation activities there is a risk of increased release into the atmosphere of volatile organic compounds (VOC) emitted in large amounts by most of the commonly used species (Calfapietra et al., 2010).

11.7.1.2 Technological considerations

AFOLU mitigation options can promote innovation, and many technological supply-side mitigation options outlined in section 11.3, also increase agricultural and silvicultural efficiency. At any given level of demand for agricultural products, intensification increases output per unit area and year and would therefore - *ceteris paribus*- allow the reduction in farmland area which would in turn free land for C sequestration and/or bioenergy production. For example, a recent study calculated impressive GHG reductions from global agricultural intensification by comparing the past trajectory of agriculture (with substantial yield improvements) with a hypothetical trajectory with constant technology (Burney et al., 2010b). An empirical long-term study for Austria 1830-2000 also suggested that increased agricultural yields contributed to the emergence of a substantial terrestrial carbon sink in biota and soils (e.g.,Erb et al., 2008).

Since a large proportion of the mitigation potential in the AFOLU sector arises from carbon sequestration in soils and vegetation and the maintenance of existing carbon stocks (e.g. by avoiding deforestation), there are significant risks associated with the future maintenance of the C stocks, which may be affected by management (see section 11.3.3 for discussion of non-permanence / reversal) or by natural factors (see section 11.5 for discussion of future climate impacts on C sinks / stocks). A number of the technologies also present apparent risks; certain types of biotechnology and animal feed additives, for example, are banned in parts of the world.

11.7.1.3 Public perception

Mitigation measures which support sustainable development are likely to be viewed positively in terms of public perception, but a large scale drive towards mitigation without inclusion of the key stakeholder communities involved would likely not be greeted favourably (Smith and Wollenberg, 2012).

However, there are concerns about competition between food and AFOLU outcomes either because of an increasing use of land for biofuel plantations (Fargione et al., 2008; Alves Finco and Doppler, 2010b), or afforestation/reforestation (Mitchell et al., 2012) or by blocking the transformation of forest land into agricultural land (Harvey and Pilgrim, 2011b). Further, lack of clarity regarding the architecture of the future international climate regime and the role of AFOLU mitigation measures is perceived as a potential threat for long-term planning and long-term investments. As noted in Section 11.7.1.2, certain technologies are banned in some jurisdictions due to perceived health and/or environmental risks. Public perception is often as important than scientific evidence of hazard / risk in considering government policy regarding such technologies (Royal Society, 2009).

11.7.2 Spillovers

The section on systemic perspectives (11.4) largely deals with spill over effects so the details will not be repeated here. There are two additional socio-economic spill-over that are very specific for the AFOLU sector and therefore relevant in this section.

Ecosystem markets - In some jurisdictions ecosystem markets are developing (Engel et al., 2008; Wünscher and Engel, 2012)(MEA, 2005)(Deal and White, 2012) and these allow valuation of various components of land-use changes, in addition to carbon mitigation (Mayrand and Paquin, 2004; Barbier, 2007). Different approaches are used; in some cases the individual components (both co-benefits and tradeoffs) are considered singly (bundled), in other situations they are considered *in toto* (stacked) (Deal and White, 2012). Ecosystem market approaches provide a framework to value the overall merits of mitigation actions at both project, regional and national scales (Farley and Costanza, 2010). The ecosystem market approach also provides specific methodologies for valuing the individual components (e.g. water quality response to reforestation, timber yield); and for other types of ecosystem service (e.g. biodiversity, social amenity) these methodologies are being developed (Bryan et al., 2013).

Scale of impacts - It is also important to consider the scale of any impacts. The co-benefits and trade-offs from mitigation measures will be largely scale dependent. Thus if the uptake of mitigation is poor, then the co-benefits and trade-offs will likewise be poor, whereas large scale carbon mitigation investment may result in large-scale landscape change. Where this displaces other commodities, there are likely to be impacts on markets. Such analyses will also need to consider the impacts of climate change on mitigation, and associated co-benefits and trade-offs.

FAQ 11.4 Are there any co-benefits associated with mitigation actions in AFOLU?

In several cases, the implementation of AFOLU mitigation measures may result in an improvement in land management and therefore have socio-economic, health and environmental benefits: For example, reducing deforestation, reforestation and afforestation can improve local climatic conditions, water quality, biodiversity conservation and help to restore degraded or abandoned land. Minimum tillage for soil carbon sequestration may also reduce the amount of wind and water erosion due to an increase in surface cover. Further considerations on economic co-benefits are related to the access to carbon payments either within or outside the UNFCCC agreements and new income opportunities especially in developing countries (especially for labour intensive mitigation options such as afforestation).

Table 11.9: Summary of potential co-benefits, and risks from AFOLU measures. Note: Impacts from AFOLU-bioenergy are discussed in Annex I

	Institutional	Scale	Social	Scale	Environmental	Scale	Economic	Scale	Technological	Scale
Forestry	Improvement (+) or diminishing (-) tenure and use rights for local comm. and indigenous peoples (8, 4, 5, 9, 21)	Local to national	Increase (+) or decrease (-) participation of indigenous peoples and local communities (4, 5, 6, 21,8, 9)	Rather local	Increases (+) or reduction (-) of resilience, reduction of disaster risks t (s. section 11.5)	Local	Increase (+) in economic activity and income (6, 7,21, 8)	Local	Adoption of technologies by new users (+) (7,13, 26)	Rather local
	Promoting (+) or contradicting (-) the enforcement forest policies (5, 6, 9, 2, 21)	National	Reduce (+) or increase (-) existing conflicts or on social discomfort (4, 5, 6, 21, 9)	Local to trans-boundary	Positive impacts (+) on albedo and evaporation and interactions with ozone (s. section 11.5)	Local to global	Access (+) or lack of access (-) to new financing schemes (6, 8, 16, 21)	Local to global	Promote (+) or delete (-) technology development and transfer (7, 13, 26)	Local to global
	Harmonization (+) of tenure and use regimes (e.g. with customary rights) (4, 5, 6, 21, 8, 9)	Local to national	Increase (+) or decrease (-) on food and fiber availability as well as NTFP output (18,19)	Local to national	Monocultures can reduce (-) biodiversity and have negative impacts (-) on water and ecosystem services (1, 21, 19, 28)	Local to trans-boundary	Employment creation (+) (8, 21)	Local		
	Creation of participative mechanisms (+) for land management (4, 6, 21, 9)	Local to national	Recognition (+) or denial (-) of indigenous and local knowledge in managing forests (4, 5, 6, 21, 8)	Rather local	Ecological restoration increases biodiversity and ecosystem services (+) by 44 and 25% respectively (28)	Local to global	Increase (+) or decrease (-) income (16, 22, 23,	Local to national		

	Cross-sectoral coordination (+) or clashes (-) between forestry, agriculture, energy and/or mining (7, 21)	Local to national	Equal access to benefit-sharing mechanisms (+) (4, 5, 6, 21, 8, 9)	Rather local	Conservation and forest management can keep biodiversity and slow desertification (+) (1, 19, 22, 28, 31)	Local to trans-boundary				
	Creation of benefit-sharing mechanisms (+) (4, 5, 6, 21,8)	Local to national	Protection of (+) cultural habitat when conserving natural forests (4,5, 9)	Local	Competition with other land uses and risk of activity or community displacement (-)(5, 6, 15, 18, 21,30, 31)	Local to trans-boundary				
Land based agriculture	Enhance law enforcement (+) or create clashes (-) with policies in other sectors (7, 20, 21)	Local to national	Increase (+) or decrease (-) of food and fiber availability (7, 18, 19,15, 24, 29, 31)	Local to global	Impacts on N and P cycle in water, especially of monocultures or large agricultural areas (+/-) (19, 24,31)	Local to trans-boundary	Increase (+) or decrease (-) in economic activity and income diversification (16, 19, 21, 24, 29)	Local	Can facilitate technology transfer (+) (24,	Local to global
	Promotion (+) or reduction (-) of social participation (21, 33)	Local to national	Impacts on traditional practices and livelihoods (+/-) (21,29)	Local	Increase (+) or decrease (-) of biodiversity and pressure on other ecosystems (15,19, 21, 29, 31)	Local	Ensuring (+) or jeopardizing (-) access to new financing schemes (16, 21,)	Local to global	Promote (+) or delay (-) improvements in infrastructure (24)	Local
			Promoting (+) or reducing (-) equity along the value chain (20, 24, 33)	Local to national	Soil conservation (+) and improvement of soil quality (+) (19, 24, 29, 31)	Local to trans-boundary	Employment creation (+) (21, 24)	Local		

			Competition for infrastructure for agriculture (-), can increase social conflicts (21)	Local	Sustainable practices, including organic agriculture and cropland restoration can have positive impacts on soil fertility (13, 19)	Local				
Livestock			Changes in the perception of animal welfare (due to cultural values) (32, 2	Local	Impacts on N cycle in water (+/-) (2, 3, 31)	Local to trans-boundary	Increase (+) or decrease (-) in economic activity and income diversification (2,3)	Local	Some technologies can reduce pollution while producing energy (+) (2, 3)	
			Impacts on traditional practices and livelihoods (2, 3)	Local	Reduction (+) or increase (+) of pressure for land use change (2, 3)	Local to national	Employment creation (+) (2, 3)	Local		
			Increase food supply (+) (2, 3, 19	Local to national	Impacts on soil quality (+/-) (2, 3, 31)	Local				
Integrated systems	Promote participatory systems (21, 35)		Increases (+) on food and fiber output including NTFP (18,19)	Local to national	Improve (+) or harm (-) biodiversity and water availability (21, 19, 31, 34)	Local to trans-boundary	Income diversification (+) and new markets’ access (+) or hindering (-) (7,21	Local		
			Can favor the use of local knowledge (+) (2	Local	Disaster risk reduction (+) (34, see 11.5)	Local	Job creation (7, 21)	Local to national		
Biochar			Food availability through improved agricultural productivity (+/-) (17, 27	Local	Interactions with soil are not clear (+/-) (17, 27)	Local	Improvement in income, if linked to climate payment/transfer (25)			

			Use of traditional knowledge (+) (17)		Potential for countering land degradation (17)					
Changes in demand patterns			Impacts on health due to dietary changes specially in societies with a high consume of animal protein (+) (32,	Local to global	Changes in diet can reduce (+) or increase (-) pressure for land transformation (29, 30, 31)		Due to dietary changes livestock producers can lose markets (-) (2)	Local to global		

Sources: 1) (Trabucco et al., 2008); 2) (Steinfeld et al., 2010); 3)(Gerber et al., 2010); 4); (Sikor et al., 2010);5)(Rosemary, 2011); 6)(Pettenella and Brotto, 2011); 7) (Jackson and Baker, 2010); 8)(Corbera and Schroeder, 2011); 9)(Carol J. Pierce, 2011); 10)(Blom et al., 2010); 11)(Halsnæs and Verhagen, 2007); 12)(Larson, 2011); 13) (Lichtfouse et al., 2009) ; 14)(Thompson, Baruah, et al., 2011) 15)(Graham-Rowe, 2011) 16)(Tubiello et al., 2009) 17) (Barrow, 2012)18)(Godfray et al., 2010); 19)(Foley, DeFries, et al., 2009)20)(Halsnæs and Verhagen, 2007) 21)(Madlener et al., 2006b)22)(Strassburg et al., 2012) ;23)(Canadell and Raupach, 2008b) ;24)(Pretty, 2008) ; 25)(Galinato et al., 2011) 26)(Macauley and Sedjo, 2011b) ; 27)(Jeffery et al., 2011a); 28)(Benayas et al., 2009); 29)(Foley et al., 2011) ;30) (Haberl et al., 2013) ; 31) (Smith, Haberl, et al., 2013) ; 32) (Stehfest et al., 2009a) ; 33) (Chhatre et al., 2012)34) (Seppälä et al., 2009) ; 35)(Murdiyarso et al., 2012)

11.8 Barriers and opportunities

Barriers and opportunities refer to the conditions provided by the development context. These conditions can hinder (barriers) or enable and facilitate (opportunities) the full use of the AFOLU mitigation measures. AFOLU programs can help to overcome barriers, but countries being affected by many barriers will need time, financing and capacity support. In some cases, the international negotiations have recognised these different circumstances among countries and have proposed corresponding approaches (e.g. phased approach in the REDD+ mechanism, Green Climate Fund; 11.10). The range of barriers and opportunities can cover a wide range of issues. Corresponding to the development framework we presented in section 11.4.5, we discuss the following types of barriers and benefits: socio-economic, environmental, related to institutional issues and related to the state of and access to technology and infrastructure.

11.8.1 Socio-economic barriers and opportunities

There are social and economical factors that could limit or enable the implementation or effectiveness of AFOLU mitigation measures.

Different financing and market mechanisms are set in place to promote AFOLU mitigation measures, both in developing (e.g. A/R CDM or the voluntary carbon markets, see 11.10) (Tubiello et al., 2009) and developed countries (e.g. formal and voluntary carbon markets, see 11.10). The ***design and coverage of these mechanisms*** is key to successfully use the AFOLU mitigation potential. Concerns have been expressed regarding which costs will be covered by such mechanisms. If financing mechanisms fail to cover at least transaction and monitoring costs, these mechanisms will become a barrier for the full implementation of AFOLU mitigation. According to some authors, opportunity costs also need to be fully covered by any financing mechanism for the AFOLU sector, especially in developing countries, because otherwise AFOLU mitigation measures would be less attractive compared to returns from other land uses (Angelsen, 2008; Cattaneo et al., 2010; Böttcher et al., 2012). Conversely, if financing mechanisms are designed to modify economic activity, these could be an opportunity for using the full mitigation potential in the AFOLU sector. Thus securing ***scale of financing*** sources can become either a barrier (if the financial volume is not secured) or create an opportunity (if financial sources for AFOLU suffice) for using AFOLU mitigation potential Streck (2012).

Another element is the ***accessibility to AFOLU financing*** for farmers and forest stakeholders. If land dependent communities (e.g. agriculturalists, pastoralists or forest dependent communities) do not have access to the financing/marketing mechanisms of AFOLU, these will not be used (Tubiello et al., 2009; Havemann, 2011; Carol J. Pierce, 2011).

Poverty, is characterized not only by low income but also by lower nutritional levels, limited access to decision making and social organization, low levels of education and reduced access to resources (e.g. land or technology) (United Nations Development Program and International Poverty Center, 2006). High levels of poverty can therefore limit the possibilities of using AFOLU mitigation options, because of short-term priorities. In addition, poor communities have limited skills and sometimes lack of social organization that can limit the use and scaling up of AFOLU mitigation options (Smith and Wollenberg, 2012; Huettner, 2012). This is especially relevant when forest land sparing competes with other development needs e.g. increasing agricultural land or promoting some types of mining (Forneri et al., 2006), or when large scale bioenergy compromises food security (Nonhebel, 2005) and Annex I.

11.8.2 Institutional barriers and opportunities

Transparent and accountable governance and swift institutional set up are paramount for sustainable implementation of AFOLU mitigation measures. This includes the need to have ***clear land tenure*** and land use regulations and a certain level of enforcement as well as clarity about carbon ownership (see 11.4.5.and 11.10). Countries and regions, where land tenure and user rights are clear and governance agreements between the civil society, the public and the private sector are enforced, will provide better opportunities for full use of the mitigation potential of the AFOLU sector. Conversely, countries suffering from corruption or weak governance in the forestry and agricultural sectors will need to overcome this barrier before achieving their full AFOLU potential (Palmer, 2011; Markus, 2011; Rosendal and Andresen, 2011; Murdiyarso et al., 2012)(Thompson, Baruah, et al., 2011).

Lack of social organization can reduce feasibility of AFOLU mitigation measures in the near future, especially in areas where small-scale farmers or forest users are the main stakeholders (Laitner et al., 2000; Madlener et al., 2006a; Thompson, Baruah, et al., 2011).

11.8.3 Ecological barriers and opportunities

Mitigation potential in the agricultural sector is highly site-specific, even within specific regions or cropping systems (Baker et al., 2007; Chatterjee and Lal, 2009). As pressure on natural resources is increasing, current land-use practices, while increasing the short-term supplies of material goods, may undermine many ecosystem services in the long term (Foley, DeFries, et al., 2009; Haberl et al., 2013). ***Availability of land and water*** for different uses need to be balanced considering short and long term priorities and mostly the global divide on resource use. Consequently, limited resources can become an ecological barrier and the decision of how to use it needs to balance ecological integrity and societal needs (Jackson, 2009).

At the local level, the ***specific soil conditions, water availability, N_2O emission reduction potential and natural variability and resilience*** to the specific systems will determine the size of the potential of each AFOLU mitigation option (Baker et al., 2007; Halvorson et al., 2011). Frequent droughts in Africa as well as changes in the hydro-meteorological events in Asia and Central and South America seem to be important variables defining the specific regional potential (Rotenberg and Yakir, 2010)(Bradley et al., 2006). Ecological saturation (soil carbon, productivity or yield after some threshold of intensification is reached) demonstrates that mitigation options have their own limits but many land use practices have a good potential for emission reduction or carbon sequestration.

The fact that many ***AFOLU measures can provide adaptation benefits*** provides an opportunity for increasing ecological efficiency (Guariguata et al., 2008; van Vuuren et al., 2009; Robledo et al., 2011).

11.8.4 Technological barriers and opportunities

Technological barriers refer to the limitation to generate, procure and apply science and technology to identify and solve an environmental problem. Some mitigation technologies are already applied now (e.g. afforestation, cropland and grazing land management, improved livestock breeds and diets) so for these there are no technological barriers, but others (e.g. some livestock dietary additives, crop trait manipulation) are still in the development stage. The ***ability to manage and re-use knowledge assets*** for scientific communication, technical documentation and learning is lacking in many areas where mitigation should take place. Future developments present opportunities for additional mitigation to be realised in the future if high levels of ease-of-use, range-of-use is guaranteed. There is also a real need to adapt technology to local needs by focussing for instance on opportunities, e.g. designing simple but robust dams that can be built from local products (to avoid transport emissions that are relatively large compared to the emissions that can be avoided through rewetting (Kandji et al., 2006).

Barriers and opportunities related to ***monitoring, reporting and verification*** of the progress of AFOLU mitigation measures need also to be considered here. Although monitoring forest carbon in forests with high spatial variation of tree density and species composition poses a technical barrier for the implementation of REDD (Baker et al., 2010) (see Section 11.10), the IPCC National Greenhouse Gas Inventory Guidelines (Paustian et al., 2006) provides one opportunity, because it offers standard scientific methods that countries already use to report AFOLU emissions and removals under the UNFCCC. Also, field research in high-biomass forests (Gonzalez et al., 2010) show that remote sensing data and Monte Carlo quantification of uncertainty offer a technical opportunity for implementing REDD.

FAQ 11.5 What are the barriers to reducing emissions in AFOLU and how can these be overcome?

There are many barriers to emission reduction. Firstly, mitigation practices may not be implemented for economic reasons (e.g. market failures, need for capital investment to realise recurrent savings), or a range of non-economic reasons including risk-related, political/bureaucratic, logistical and educational/societal barriers. Technological barriers can be overcome by research and development, logistical and political / bureaucratic barriers can be overcome by better governance and institutions, education barriers can be overcome through better education and extension work networks and risk-related barriers can be overcome, for example, through clarification of land tenure uncertainties.

11.9 Sectoral implications of transformation pathways and sustainable development

Many mitigation pathways will have implications for sustainable development, and corrective actions to move toward sustainability may be possible. Impacts on development are context specific and depend upon scale and institutional agreements of the AFOLU measures and not merely of the type of measure (see 11.4 for development context and systemic view, 11.7 for potential co-benefits and adverse effects and 11.8 for opportunities and challenges). To evaluate sectoral implications of transformation pathways, it is therefore useful to characterise them with respect to prevailing mitigation technologies and measures, potentials and policy assumptions.

11.9.1 Characterisation of transformation pathways

Uncertainty about reference AFOLU emissions is significant historically (see section 11.2) and in projections (see section 6.3.5). Climate policy transformation projections of the energy system, AFOLU emissions and land-use are defined by the reference scenario, as well as the abatement policy assumptions regarding eligible abatement options, regions covered, and technology costs over time. Many transformation scenarios suggest a substantial cost-effective mitigation role for land related mitigation. However, most transformation scenarios assume an idealized policy implementation, with immediate, global, and comprehensive availability of land related mitigation options. These scenarios also ignore mitigation risks and transaction costs or Monitoring Reporting and Verification (MRV) costs (Rose et al., 2012). Furthermore, other developmental issues including intergenerational debt or non-monetary benefits are not considered completely (Ackerman et al., 2009). Policy implementation of large-scale land-based mitigation will be challenging and actual implementation will affect costs, net emissions and will have other social implications (Rose and Lubowski, 2013).

In recent idealized implementation scenarios, land-related mitigation represents a significant share of emissions reductions (Table 11.10). In these cases, models assume an explicit terrestrial carbon stock incentive, or a global forest protection policy. Bioenergy is consistently deployed and agricultural emissions priced. The largest land emission reductions were in net CO_2 emissions, which also had the greatest variability across models. Some models exhibit increasing land CO_2 emissions under mitigation, as bioenergy feedstock production leads to land-use change, while other models exhibit significant reductions with protection of existing terrestrial carbon stocks and planting of new trees to increase carbin stocks. Land-related CO_2 and N_2O mitigation is more important in the nearer-term for some models. Land-related N_2O and CH_4 reductions are a significant part of total N_2O and CH_4 reductions, but a smaller fraction of baseline land emissions, suggesting that models are cost-effectively keeping N_2O and CH_4 emissions low. Land emissions reductions only increase slightly with the stringency of the target as energy and emissions reductions increase faster with target stringency. Land CO_2 reductions can be over 100% of baseline emissions from the expansion of forests for sequestration.

Table 11.10: Cumulative land-related emissions reductions of CH_4, CO_2, and N_2O in idealized implementation 550 ppm and 450 ppm scenarios. Source: Chapter 6.3.5. [AUTHORS: Results under review. Regard as preliminary]

			550			450		
			2010-2030	2010-2050	2010-2100	2010-2030	2010-2050	2010-2100
Cumulative global land-related emissions reductions (GtCO2eq)	**CH4**	min	3.5	17.2	50.8	0.0	4.5	51.5
	(n=5)	max	9.8	43.2	198.8	14.1	52.2	211.2
	CO2	min	-3.7	-17.7	-103.8	-7.9	-32.7	-137.6
	(n=12)	max	280.9	543.0	733.4	286.6	550.5	744.6
	N2O	min	3.1	8.4	25.5	3.1	8.4	25.5
	(n=4)	max	6.7	25.2	92.8	10.6	29.5	94.9
Land reductions share of total global emissions reductions	**CH4**	min	20%	20%	19%	23%	20%	16%
		max	37%	40%	42%	29%	31%	36%
	CO2	min	-8%	-5%	-3%	-8%	-5%	-3%
		max	74%	48%	17%	73%	47%	15%
	N2O	min	52%	56%	65%	53%	61%	65%
		max	78%	82%	84%	84%	84%	84%
Percent of baseline land emissions reduced	**CH4**	min	3%	8%	9%	0%	2%	10%
		max	8%	15%	28%	10%	18%	29%
	CO2	min	-8%	-36%	-16%	-16%	-67%	-16%
		max	373%	417%	504%	381%	423%	512%
	N2O	min	4%	6%	8%	4%	6%	8%
		max	8%	15%	21%	13%	17%	22%

The abatement role of individual land-related technologies, especially bioenergy, is not generally reported in transformation pathway studies. In part, this is due to emphasis on the energy system, but also other factors that make it difficult to uniquely quantify mitigation by technology. An exception is Rose et al. (2012) who reported agriculture, forest carbon, and bioenergy abatement levels for various climate stabilization policies. Over the century, bioenergy was the dominant strategy, followed by forestry, and then agriculture. Bioenergy generated 4.8 to 52.1 and 113.3 to 749.1 Gt CO_2-eq. mitigation by 2050 and 2100, respectively.

Within models, there is a positive correlation between reductions and GHG prices. However, across models, it is less clear, as some estimate large reductions with a low GHG price, while others estimate low reductions despite a high GHG price. For the most part, these divergent views are due to differences in modeling. Overall, while a tighter target and higher carbon price results in a decrease in land-use emissions, emissions decline at a decreasing rate. This is indicative of the rising relative cost of land mitigation, the increasing demand for bioenergy, and subsequent increasing need for overall energy system abatement and energy consumption reductions.

Models project increased deployment of, and dependence on, modern bioenergy, with some models projecting 100 EJ per year by 2030, and 250 EJ per year by 2050. Models universally project that the majority of agriculture and forestry mitigation, and bioenergy primary energy, will occur in developing and transitional economies. It is difficult to generalize on regional land cover effects of mitigation (Section 6.3.5). By 2030, in idealized implementation climate policy scenarios, there is expansion of energy cropland and forest land in many, but not all, regions, but the magnitude of expansion and the nature of the land conversion varies greatly across models. Like mitigation, there is relatively modest additional land conversion in 450 ppm scenarios compared to 550 ppm scenarios.

More recently, the literature has begun exploring more realistic fragmented policy contexts and identifies a number of policy coordination and implementation issues (Calvin et al., 2009; Rose and Sohngen, 2011; Lubowski and Rose, 2013 for a discussion). There are many dimensions to policy coordination: technologies, regions, climate and non-climate policies, and timing, trans-sectoral coordination. For instance, increased bioenergy incentives without global terrestrial carbon stock incentives (Wise et al., 2009b; Reilly et al., 2012) or global forest protection policy (Popp, Dietrich, et al., 2011), suggests a large potential for leakage with the use of energy crops. The leakage comes primarily in the form of displacement of pasture, grassland, and natural forest (see section 11.5). There is also food cropland conversion. However, providing bioenergy while protecting terrestrial carbon stocks could result in a significant increase in food prices and decrease of food availability (see also section 11.4.3 which explores such systemic perspectives). Further, the mitigation potential especially for reducing emissions from deforestation is very different across regions making a global assessment of development impact more difficult. Implementing and coordinating land mitigation policies will be challenging. Staggered adoption of land mitigation policies will likely have leakage implications (e.g. Calvin et al., 2009; Rose and Sohngen, 2011) as well as institutional and socioeconomic implications (Madlener et al., 2006a). Delayed forest policy could even accelerate deforestation (Rose and Sohngen, 2011). Bioenergy sustainability policies across sectors also need to be coordinated (Frank et al., 2013). Institutional issues, especially clarification of land tenure and property rights and equity issues will also be critical for successful land mitigation in forestry over time (Karsenty et al.; Palmer, 2011; Gupta, 2012). Finally, international land related mitigation projects are currently regarded as high risk carbon market investments, which may affect market appeal, and offset supplier voluntary participation incentives may affect the net GHG benefits of mitigation (Rose et al., 2013a).

11.9.2 Implications of transformation pathways for the AFOLU sector

Implications of transformation pathway scenarios that have large areas forest for C sequestration in given regions (e.g. see Figure 11.18) depend upon how the forest area increases. If natural forest areas increase, biodiversity and a range of other ecosystem services provided by forests could be enhanced. If afforestation occurs through large scale plantation, however, some negative impacts on biodiversity, water and other ecosystem services could arise, depending on what land cover the plantation replaces and the rotations time. The provisioning service of timber / fibre could increase with large forest area, unless wood harvest is reduced to enhance carbon storage. Food security could be threatened if land previously used for food is devoted to forest for sequestration Agroforestry systems could offer mitigation potential through sequestration while promoting food security. However the mitigation effect per area is lower for agroforestry than for plantations. Co-benefits and risk-tradeoffs are discussed in detail in section 11.7.

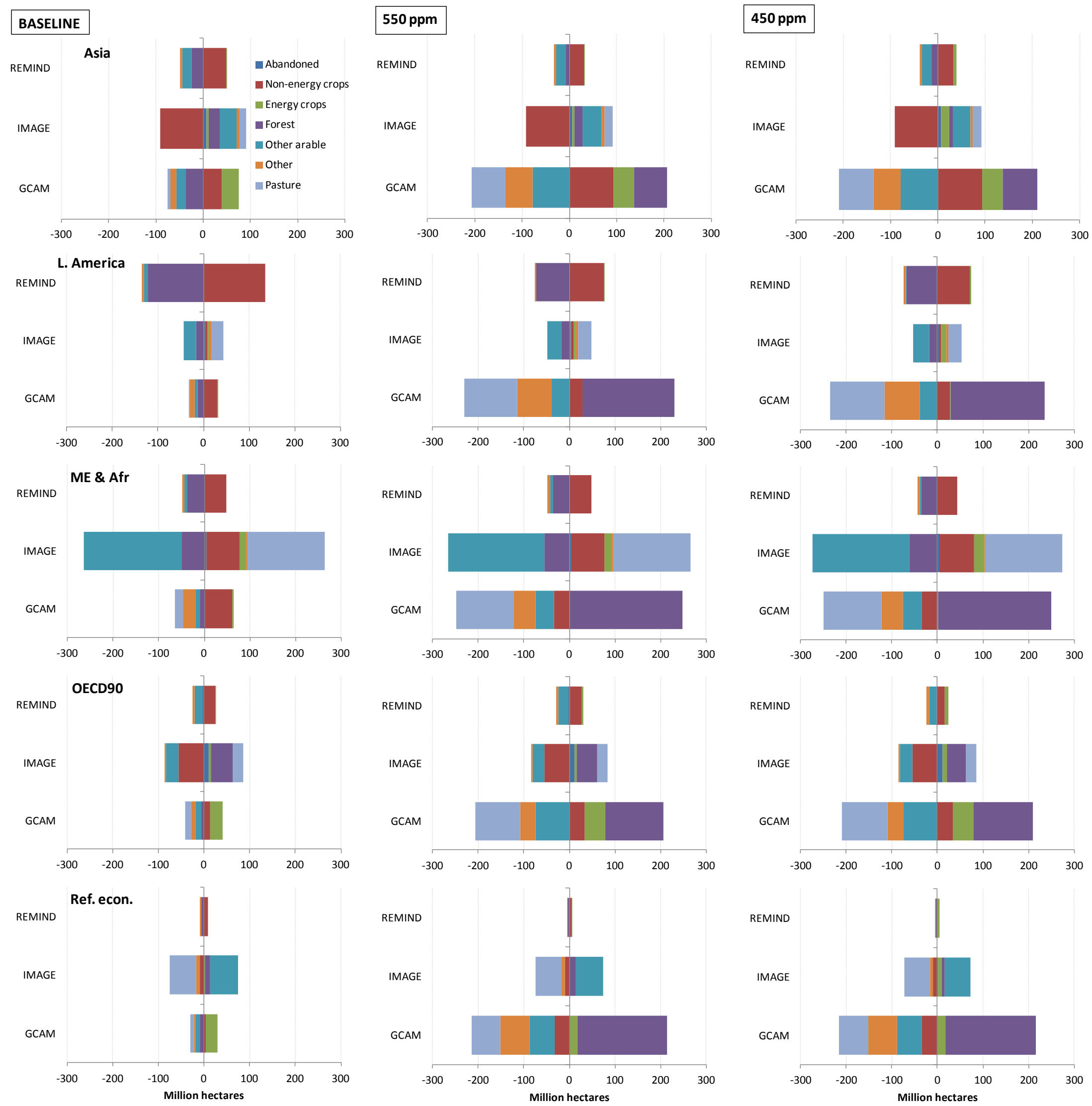


Figure 11.18. Regional land cover change by 2030 from 2005 from three models for baseline (left) and idealized implementation 550 ppm (center) and 450 ppm (right) scenarios.

Implications of transformation pathway scenarios that require large land areas for dedicated biomass feedstocks (e.g. see figure 11.18) are that food prices could increase if land normally used for food production is devoted to bioenergy. If natural forest or other natural land is used for bioenergy, ecosystem services provided by these natural lands could be lost and initial GHG emissions from land use change could be high. The environmental impacts of energy crop plantations largely depend upon where, how, and at which scale, they are implemented, and how they are managed (Davis et al., 2013). Impacts of bioenergy are discussed in more detail in the bioenergy annex.

Implications of transformation pathway scenarios that rely heavily of reduction of non-CO_2 GHGs from agriculture (e.g. see figure 11.18) are context specific. If agricultural mitigation is implemented according to best management practices (and many of the mitigation options described in section 11.3 deliver mitigation through reduced absolute emissions, or through reduced emissions per unit of agricultural product), environmental damage can be reduced and the ecosystem services provided by agriculture (including food supply) can be enhanced. If, however, the delivery of mitigation involves large scale industrial agriculture (large areas of monoculture crops or intensive livestock production), ecosystem services could be damaged. Co-benefits and risk-tradeoffs are discussed in detail in section 11.7.

11.9.3 Implications of transformation pathways for sustainable development

Implications of the four pathways on sustainable development are context and time specific. Section 11.4 provides a detailed discussion of the implications of large scale land use change, competition between different demands for land, and the feedbacks between land use change and other services provided by land, section 11.7 discusses the potential co-benefits and adverse effects and section 6.6 compares potential co-benefits and adverse effects across sectors while section 11.8 presents the opportunities and barriers for promoting AFOLU mitigation activities in future. Finally Annex I discusses the specific implications of increasing bioenergy crops.

Summarizing, there are major opportunities and concerns for sustainable development around the following issues:

Institutional: Clarification of land tenure, property rights and access to natural assets to all local stakeholders. Further, cross-sectoral coordination with the energy or mining sectors as well as within the sub-sectors in AFOLU including forestry and agricultre

Social: Use of participative schemes and equal benefit sharing mechanisms. Further consider potential competition with food security

Economic: Opportunities for income generation and clarification of income sharing mechanisms. There is still a need to internalize some social or environmental costs (e.g. intergenerational equity)

Natural assets and health: Direct and indirect impacts on natural assets especially biodiversity, water quantity and quality and soil quality.

Technology and infrastructure: technology transfer in the agricultural sector, and for MRV

11.10 Sectoral policies

Climate change is likely to influence, and be influenced by, the most diverse policy or management choices. This is particularly critical for agriculture and forests that are strongly dependent on climate phenomena but also contribute as sources of and sinks for greenhouse gases (Golub et al., 2009). Regional variability is one of the main drawbacks to fully assess the cost-effectiveness of different measures. National and international agricultural and forest climate policies have the potential to redefine the opportunity costs of international land-use in ways that either complement or counteract the attainment of climate change mitigation goals. Policy instruments can be complementary (e.g. economic incentives and regulatory approaches in the case of deforestation reduction) but in some case, policies interactions might cause trade-offs. Additionally, adequate policies are needed for orienting practices in agriculture and in forest conservation for global sharing of innovative technologies for efficient use of land resources.

Policies related to the AFOLU sector that directly or indirectly affect mitigation are discussed below according to the instruments through which they are implemented (economics incentives, regulatory and control approaches, information schemes, voluntary actions). Emphasis is given to REDD+ strategies, considering its development in recent years.

11.10.1 Economic Incentives

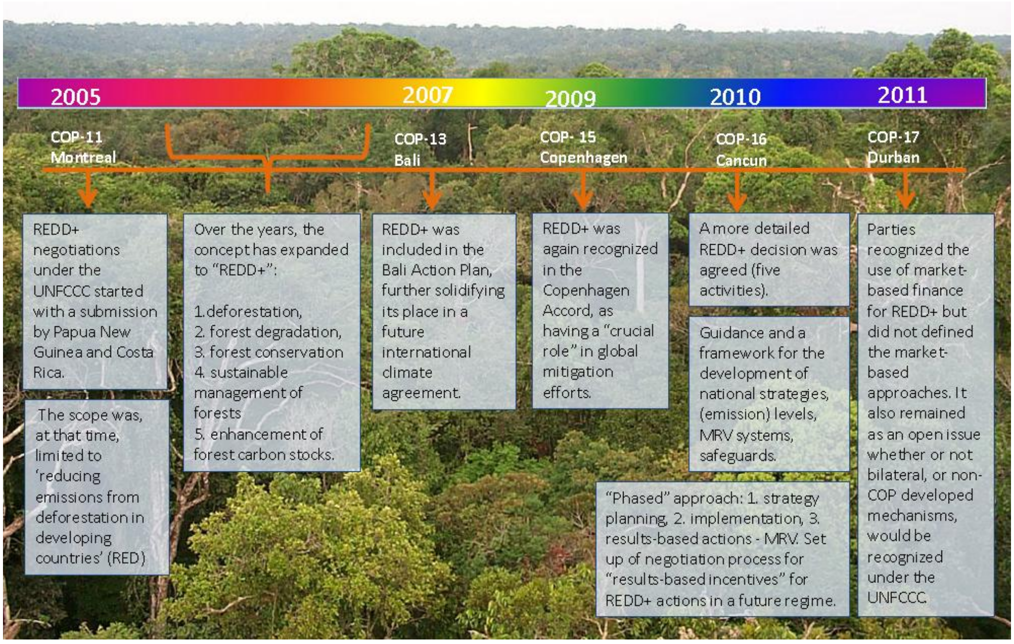
Tradable credits Flexible mechanisms (Clean Development Mechanism (CDM), Joint Implementation (JI) and Emissions Trading) were introduced for the mandatory market to reach the mitigation goals defined in the Kyoto Protocol with the least economic costs. The CDM and JI mechanisms create a supply of emission reduction instruments, while Emissions Trading allows those instruments to be sold on international markets. By 2012, 40 CDM projects (0.70%) were related to afforestation and reforestation while agriculture projects amounted to 158 (2.78%) (UNFCCC statistics). An analysis of A/R CDM projects suggested that ‘successful’ applications include: initial funding support, design and implementation guided by large organizations with technical expertise, occur on private land (land with secured property rights attached), and most revenue from Certified Emission Reductions (CERs) directed back to local communities (Thomas et al., 2010). On the other hand, forest projects are increasing in the voluntary markets and transactions of carbon credits from this sector amounted UD$133M in 2010 (Peters-Stanley et al., 2011), 95% of them in voluntary markets.

In 2011, Australia started the Carbon Farming Initiative (CFI) that allows farmers and investors to generate tradable carbon offsets from farmland and forestry projects. This followed several years of State-based and voluntary activity that had resulted in 65,000 ha of A/R projects (Mitchell et al., 2012). Also in Australia, the Western Arnhem Land Fire Abatement Project (WALFA), started in 2006, is a fire management project that produces a tradable carbon offset, through the application of improved fire management using traditional management practices of indigenous land owners (Whitehead et al., 2008; Bradstock et al., 2012). Focusing on N_2O emissions from agriculture, the Alberta Quantification Protocol for Agricultural N_2O Emissions Reductions issues C offset credits for on-farm reductions of N_2O emissions and fuel use associated with the management of fertilizer, manure, and crop residues for each crop type grown. Other N_2O emission reduction protocols (e.g., (Millar et al., 2010) are being considered for the Verified Carbon Standard, the American Carbon Registry, and the Climate Action Reserve (Robertson et al., 2012).

Reduced emissions by deforestation and forest degradation (REDD+) The most striking aspect of policies for the forest sector is the discussion of mechanisms associated with REDD and its variations. The evolution of discussions on REDD+ in the international community, particularly under the umbrella of the UNFCCC is presented in Figure 11.19. The mechanism will finance not only forest conservation and avoided deforestation but also sustainable forest management and enhancement of carbon stocks restoration / afforestation / reforestation. REDD+ mechanisms can be a very cost effective option for mitigating climate change (Strassburg et al. 2007, 2009) and the large share of global abatement of emissions from land-use sector would be from the extensive margin of forestry, especially through avoided deforestation in tropical regions (Golub et al., 2009).

Although the UNFCCC consider market-based instruments to support REDD+ activities, several issues (like environmental integrity, risk of leakage, non-permanence and excess supply of credits, difference in views on the use of private finance) have so far prevented the development of compensatory mechanisms in these activities supported under the UNFCCC. Meanwhile, different regional and global programs and partnerships address forest management and conservation and readniness for REDD+ (Table 11.10) and some national REDD+ strategies have been started in countries with significant forest cover (see Box 11.6).

A growing body of academic literature has been analysing different aspects related to the implementation, effectiveness and scale of REDD+ mechanisms, as well as the interactions with other social and environmental co-benefits. Crediting REDD+ activities requires internationally agreed rules for monitoring, reporting and verification (MRV). These technologies typically combine remotely sensed data with ground-based inventories, and the design of a REDD policy framework (and specifically its rules) can have a significant impact on monitoring costs (Angelsen et al. 2008). (Böttcher et al., 2009)Forest governance is another central aspect, including debate on decentralization of forest management, logging concessions in public owned commercially valuable forests, and timber certification, primarily in temperate forests. Although a majority of forests continue to be owned formally by governments, there are indications that the effectiveness of forest governance is increasingly independent of formal ownership (Agrawal et al., 2008). However, there are widespread concerns that REDD+ will increase costs on forest-dependent peoples and in this context, stakeholders rights, including rights to continue sustainable traditional land use practices, appear as a precondition for REDD development (Phelps, Webb, et al., 2010).



REDD+ negotiations under the UNFCCC started with a submission by Papua New Guinea and Costa Rica.

The scope was, at that time, limited to 'reducing emissions from deforestation in developing countries' (RED)

Over the years, the concept has expanded to "REDD+":

1. deforestation,
2. forest degradation,
3. forest conservation
4. sustainable management of forests
5. enhancement of forest carbon stocks.

REDD+ was included in the Bali Action Plan, further solidifying its place in a future international climate agreement.

REDD+ was again recognized in the Copenhagen Accord, as having a "crucial role" in global mitigation efforts.

A more detailed REDD+ decision was agreed (five activities).

Guidance and a framework for the development of national strategies, (emission) levels, MRV systems, safeguards.

"Phased" approach: 1. strategy planning, 2. implementation, 3. results-based actions - MRV. Set up of negotiation process for "results-based incentives" for REDD+ actions in a future regime.

Parties recognized the use of market-based finance for REDD+ but did not defined the market-based approaches. It also remained as an open issue whether or not bilateral, or non-COP developed mechanisms, would be recognized under the UNFCCC.

Figure 11.19. The evolution of REDD+ under the UNFCC (according to Climate Focus and Climate Advisers, 2012).

Another key issue for the implementation of REDD is how to address the "leakage" of emissions (i.e. a reduction of deforestation in a target area being compensated for an increase in other areas) (Santilli et al., 2005; UNFCCC, 2006; Nabuurs et al., 2007) Strassburg et al., 2007, 2009). A mechanism operating at the national level would solve the leakage problem within each country, a major drawback of project-based approaches (Herold and Skutsch, 2011) but the threat of international leakage would remain. There are also concerns about the impacts of REDD+ design and implementation options on biodiversity conservation (areas of high C content and high biodiversity are not necessarily coincident). Some aspects of REDD+ implementation that might affect biodiversity include site selection, management strategies and stakeholder engagement (Harvey et al., 2010). The way in which a REDD framework addresses leakage is also critical for biodiversity outcomes. While the climate community is mainly concerned with reducing the amount of leakage, the conservation community is also concerned about where leakage occurs, as deforestation and exploitation of natural resources could move from areas of low conservation value to those of higher conservation value, or to other natural ecosystems, threatening species native to these ecosystems (Harvey et al., 2010). Additionally, transnational leakage could lead deforestation to move into relatively intact areas of high biodiversity value or into countries which currently have little deforestation (Putz and Redford, 2009).

Box 11.6. Examples of REDD+ initiatives at national scale in different regions with significant forest cover

Amazon Fund - The Amazon Fund in Brazil was officially created in 2008 by a presidential decree. The Brazilian Development Bank (BNDES) was attributed with the responsibility to manage it. The Norwegian government played a key role in creating the fund by donating funds to the initiative in 2009. Since then, the Amazon Fund has received funds from two more donators: the Federal Republic of Germany and Petrobrás, Brazil's largest oil company. (www.amazonfund.gov.br)

UN-REDD Democratic Republic of Congo - The Congo Basin rainforests are the second largest after Amazonia. In 2009, Democratic Republic of the Congo (DRC) started, with support of UN-REDD Programme and FCPC, the planning to the implementation stages of REDD+ preparedness. The initial DRC National Programme transitioned into the full National Programme (Readiness Plan) after it was approved by the UN-REDD Programme Policy Board in 2010. (www.un-redd.org/UNREDDProgramme/).

Indonesia-Norway REDD+ Partnership3. In 2010, the Indonesia-Norway REDD+ Partnership was established through an agreement between governments of the two countries. The objective was to support Indonesia's efforts to reduce emissions from deforestation and degradation of forests and peat lands. Indonesia agreed to take systematic and decisive action to reduce its forest and peat related GHG emissions, whereas Norway agreed to support those efforts by making available up to one billion US dollars exclusively on a payment-for-results basis over the next few years. (www.un-redd.org/UNREDDProgramme/)

Taxes, charges, subsidies

Financial regulations are another approach to pollution control. A range of instruments can be used: pollution charges; taxes on emission; taxes on inputs and subsidies (Jakobsson et al., 2002). Nitrogen (N) taxes are one possible instrument since agricultural emissions of nitrous oxide mainly derive from the use of nitrogenous fertilizers. An analysis of the tax on the nitrogen content of synthetic fertilizers in Sweden indicated that direct N_2O emissions from agricultural soils in Sweden (the tax abolished in 2010) would have been on average 160 tons or 2% higher without the tax (Mahlin, 2012). Additionally, the study showed that removal of the N tax could completely counteract the decreases in CO_2 emissions expected from the future tax increase on agricultural CO_2. Low-interest loans can also support the transition to sustainable agricultural practices as currently implemented in Brazil, the second largest food exporter, through the national program Low Carbon Agriculture (launched in 2010).

11.10.2 Regulatory and Control Approaches

Deforestation control and land planning (protected areas and land sparing / set-aside policies): The rate of deforestation in the world's three largest tropical rainforest regions (Amazon basin, the Congo basin, and the forests of Southeast Asia) declined nearly 25% during the last decade compared with the net forest loss during the 1990s (see section 11.2). Public policies have had a significant impact by reducing deforestation rates in some tropical countries (see e.g. Box 11.7).

Box 11.7. Deforestation control in Brazil

Deforestation rates in Brazilian Amazon decreased by 77% from 2004-2011 (from 27,772 km2 to 6,418 km2 /year) (www.obt.inpe.br/prodes). The Brazilian Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) includes: coordinated efforts among federal, state, and municipal governments, and civil organizations, remote-sensing monitoring, significant increases of new protected areas (Soares-Filho et al., 2010) and combination of economic and regulatory approaches (municipalities with very high deforestation rates are under more stringent regulations and new credit policies introduced in 2008 made rural credit dependent on proof of compliance with deforestation legislation and the legitimacy of land claims.

Since agricultural expansion is one of the drivers of deforestation (especially in tropical regions), one central question is if intensification of agriculture reduces cultivated areas and results in land sparing by concentrating production on other land. Land sparing would allow released lands to sequester carbon, provide other environmental services and protect biodiversity (Fischer et al., 2008). In the United States, over 13 million ha of former cropland are enrolled in the US Conservation Reserve Program (CRP), with biodiversity, water quality, and carbon sequestration benefits (Gelfand et al., 2011).

Environmental regulation (water and air pollution control, emission targets): In many developed countries, environmental concerns related to water and air pollution since the mid-1990s, led to the adoption of laws and regulations that now mandate improved agricultural nutrient management planning (Jakobsson et al., 2002). Some policy initiatives deal indirectly with N leakages and thus promote the reduction of N_2O emissions. The Nitrates Directive (1991) sets limits on the use of fertilizer N and animal manure N in NO_{3-} vulnerable zones. Across the 27 EU Member States, 39.6% of territory is subject to related action programmes. However, in terms of the effectiveness of environmental policies and agriculture, there was considerable progress controlling point pollution, but that the efforts to control non-point pollution of nutrients have been less successful and potential synergies from various soil-management strategies should be better exploited (Henriksen et al., 2011). Emission targets for the AFOLU sector were also introduced by different countries (e.g. Climate Change Act, Scotland; European Union). Forty-three countries in total (as of December 2010) have proposed NAMAs to the UNFCCC. Agricultural and forestry sectors represented 59% and 91% respectively of the countries. For the least developed countries, the forestry sector is quoted in all the NAMAs, while the agricultural sector is accounted for in 70% of the NAMAs.

Bioenergy targets: In response to many different policy objectives, including climate change mitigation, energy security, and rural development, more than 50 countries worldwide have put in place targets and/or mandates for bioenergy (Petersen, 2008). Land use planning and governance is central to the implementation of sustainable biofuels (Tilman et al., 2009) as policy and legislation in related sectors, such as agriculture, forestry, environment and trade can have a profound effect on the development of effective bioenergy programs (Jull et al., 2007). A recent study analysed the consequences of renewable targets of EU member states on the CO_2 sink for the EU forests and indicated a decrease in the forest sink by 4–11% (Böttcher et al., 2012). Another possible trade-off of biofuel targets is related to international trade. Global trade in biofuels might have a major impact on other commodity markets (e.g. vegetable oils or animal fodder) and result in long trade disputes (Zah and Ruddy, 2009).

11.10.3 Information Schemes

Acceptability by the farmers and practicability of mitigation measures need to be considered because the efficiency of a policy is determined by the cost of achieving a given goal. Therefore costs related to education and implementation of policies should be taken into account (Jakobsson et al., 2002). In the agriculture sector, non-profit conservation organizations (e.g. The Sustainable Agriculture Network - SAN) and governments (e.g. Farming for a Better Climate, Scotland) promote the social and environmental sustainability of agricultural activities by developing standards and educational campaigns. Certification bodies certify farms or group administrators that comply with standards and policies (e.g. Rainforest Alliance Certified). In some cases, specific voluntary set of climate change adaptation and mitigation criteria were included (SAN Climate Module). In the forestry sector, many governments have worked towards a common understanding of sustainable forest management (Auld et al., 2008). Nine major regional and ecoregional processes (African Timber Organization-ATO, Dry-Zone Africa, Dru Forest in Asia, International Tropical Timber Association-ITTO, Lepaterique, Montrea, Near East, Pan-European and Tarapoto) have developed criteria and indicators by which sustainability can be assessed, monitored and reported.

11.10.4 Voluntary Actions and Agreements

In voluntary markets, different certification systems also consider improvements in forest management, avoided deforestation and carbon uptake by regrowth, reforestation, agroforestry and sustainable agriculture. In the last 20 years, forest certification has been developed as an instrument for promoting sustainable forest management. Certification schemes encompass all forest types but there is a concentration in temperate forests (Durst et al., 2006). Approximately 8% of global forest area has been certified under a variety of schemes and 25% of global industrial roundwood comes from certified forests (FAO 2009). Less than 2% of forest area in African, Asian and tropical American forests are certified and most certified forests (82%) are large and managed by the private sector (ITTO 2008).

1 **Table 11.11:** Some regional and global programs and partnerships related to illegal logging, forest management and conservation and REDD+

Program / Institution	**Context**	**Objectives and Strategies**
Forest Law Enforcement and Governance (FLEG) / World Bank	Illegal logging and lack of appropriate forest governance are major obstacle to countries to alleviate poverty, to develop their natural resources and to protect global and local environmental services and values	Support regional forest law enforcement and governance
Improving Forest Law Enforcement and Governance in the European Neighbourhood Policy East Countries and Russia (ENPI-FLEG) / EU	Regional cooperation in the European Neighborhood Policy Initiative East Countries (Armenia, Azerbaijan, Belarus, Georgia, Moldova and Ukraine), and Russia following up on the St Petersburg Declaration	Support governments, civil society, and the private sector in participating countries in the development of sound and sustainable forest management practices, including reducing the incidence of illegal forestry activities
Forest Law Enforcement, Governance and Trade (*FLEGT*) / European Union	Illegal Logging has a devastating impact on some of the world's most valuable forests. It can have not only serious environmental, but also economic and social consequences	Exclude illegal timber from markets, to improve the supply of legal timber and to increase the demand for responsible wood products. Central element are trade accords to ensure legal timber trade and support good forest governance in the partner countries. There is a number of countries in Africa, Asia, South and Central America currently negotiating FLEGT Voluntary Partnership Agreements (VPAs) with the European Union.
Program n Forests (PROFOR) / multiple donors including the European Union, European countries, Japan and the World Bank	Well-managed forests have the potential to reduce poverty, spur economic development and contribute to a healthy local and global environment	Provide in-depth analysis and technical assistance on key forest questions related to livelihoods, governance, financing and cross-sectoral issues. PROFOR activities comprise analytical and knowledge generating work that support the strategy's objectives of enhancing forests' contribution to poverty reduction, sustainable development and the protection of environmental services.
UN-REDD Programme / United Nations	The UN collaborative initiative on Reducing Emissions from Deforestation and forest Degradation (REDD) in developing countries was launched in 2008 and builds on the convening role and technical expertise of the FAO, UNDP and the UNEP.	The Programme supports national REDD+ readiness efforts in 46 partner countries (Africa, Asia-Pacific and Latin America) through: (i) direct support to the design and implementation of REDD+ National Programmes; and (ii) complementary support to national REDD+ action (common approaches, analyses, methodologies, tools, data and best practices). By July 2012, total funding for these two streams of support to countries amounted US$117.6 million.
REDD+ Partnership / International effort (50 different countries)	The UNFCCC has encouraged the Parties to coordinate their efforts to reduce emissions from deforestation and forest degradation. As a consequence, countries attending the March 2010 International Conference on the Major Forest	The REDD+ Partnership serves as an interim platform for its partner countries to scale up actions and finance for REDD+ initiatives in developing countries (including improving the effectiveness, efficiency, transparency and coordination of REDD+ and financial instruments), to

	Basins, hosted by the Government of France, agreed on the need to forge a strong international partnership on REDD+.	facilitate knowledge transfer, capacity enhancement, mitigation actions and technology development and transfer among others.
Forest Investment Program (FIP) / Strategic Climate Fund (a multi-donor Trust Fund within the Climate Investment Funds)	Reduction of deforestation and forest degradation and promotion of sustainable forest management, leading to emission reductions and the protection of carbon terrestrial sinks.	Support developing countries' efforts to REDD and promote sustainable forest management by providing scaled-up financing to developing countries for readiness reforms and public and private investments, identified through national REDD readiness or equivalent strategies.
Forest Carbon Partnership (FCPF) / World Bank	Assistance to developing countries to implement REDD+ by providing value to standing forests.	Builds the capacity of developing countries to reduce emissions from deforestation and forest degradation and to tap into any future system of REDD+.
Indonesia-Australia Forest Carbon Partnership	Australia's assistance on climate change, and builds on long-term practical cooperation between Indonesia and Australia.	The Partnership supports strategic policy dialogue on climate change, the development of Indonesia's National Carbon Accounting System, and implementing demonstration activities in Central Kalimantan.

In response to many different policy objectives, including climate change mitigation, energy security, and rural development, more than 50 countries worldwide have put in place targets and/or mandates for bioenergy (Petersen, 2008). Land use planning and governance is central to the implementation of sustainable biofuels (Tilman et al., 2009) as policy and legislation in related sectors, such as agriculture, forestry, environment and trade can have a profound effect on the development of effective bioenergy programs (Jull et al., 2007). A recent study analysed the consequences of renewable targets of EU member states on the CO_2 sink for the EU forests and indicated a decrease in the forest sink by 4–11% (Böttchner et al. 2012).vegetable oils or animal fodder) and result in long trade disputes (Zah and Ruddy, 2009).

Therefore costs related to education and implementation of policies should be taken into account (Jakobsson et al., 2002).Certification schemes encompass all forest types but there is a concentration in temperate forests (Durst et al. 2006).

Certification schemes also support sustainable agricultural practices. Climate-friendly criteria reinforce existing certification criteria and provide additional value. However, while evaluating the role of certification schemes for biodiversity conservation, (Harvey et al., 2008) indicated some constraints that probably also apply to climate-friendly certification: weakness of compliance or enforcement of standards, transaction costs and paperwork often limit participation, and incentives are insufficient to attract high levels of participation. Biofuel certification is a specific case due to its hybrid nature as biofuels' pathways include multiple actors and several successive segments: (1) feedstock production, (2) conversion of the feedstock to biofuels, (3) wholesale trade, (4) retail, and (5) use of biofuels in engines. The length and complexity of the biofuel supply chains make the sustainability issue very challenging (Kaphengst et al., 2009); see also Annex I.

11.11 Gaps in knowledge and data

Data and knowledge gaps include:

- A global data base of the area of land use change and the further fate of affected ecosystems
- A global, high resolution data base of typical land management practices
- A better characterization of global grazing areas, in terms of their quality, the intensity of use, management, including the GHG effects of changes in management
- Better data on agricultural management practices employed globally including crop rotations, variety selection, fertilization practices (amount, type and timing) and tillage practices
- A global georeferenced database of freshwater fisheries and aquaculture, including their subsistence components
- More accurate data on C stocks in biomass for grasslands, croplands and wetlands, and C stocks in pools of dead organic matter and soils for different types of ecosystems around the world, including forests
- A global data base of fires, including forest fires (in particular large-scale and open forest fires), peatfires, fires on the grasslands and croplands with data on the amount of biomass burned
- Better data on GHG fluxes from managed and native wetlands, dams and aquaculture ponds and their mitigation potential
- Better data on and understanding of subsistence agriculture, in particular (but not only) for livestock rearing (herders) as well as shifting cultivation (large amounts of biomass burned in human-induced fires)
- Globally standardized and homogenized data on soil degradation and a better understanding of the effects of soil degradation on carbon balances and the productivity of vegetation

- Better data on forest degradation, in particular selective logging, collection of fuelwood and non-timber forest products and production of charcoal, grazing, sub-canopy fires, and shifting cultivation
- A better understanding of climate-change feedbacks on agricultural yields under real-world conditions, i.e. under nutrient limitation etc. At present, DGVMs provide limited understanding of feedbacks such as CO_2 fertilization and plant growth on croplands under different assumptions on fertilizer application
- A better understanding of the effect of current changes in climate parameters and rising CO_2 concentrations on productivity of different types of ecosystems around the world
- A better understanding of the role of mangrove forests in mitigation of climate change
- A global data set on the use of bioenergy and better understanding of its mitigation potential
- Potential changes of C stocks in different types of ecosystems around the world under various scenarios of climate change
- A better understanding of effects of different mitigation options on social and economic conditions of poor people, in particular on those living largely in subsistence conditions
- Prognosis of future global food security under various scenarios of climate change

Annex Bioenergy: Climate effects, mitigation options, potential and sustainability implications

11.A.1 General features

Bioenergy is a versatile form of energy, which can be deployed as solid, liquid and gaseous fuels to provide transport, electricity, and heat for a wide range of uses, including cooking. Bioenergy systems can have either positive or negative GHG mitigation implications. Advanced technologies and sustainable management practices, together with relevant governance (e.g. legal regulation, cascade use, coordinated land use planning, sustainability standards and certification systems), could help reduce negative effects and deliver climate change mitigation and other environmental and social benefits. If these conditions are not met, net global warming and /or detrimental effects for local environments and livelihoods can result. This crosscut Annex provides an overview of biomass resource potential for bioenergy, conversion technologies, transformation pathways, mitigation potential and sustainable development implications of bioenergy mitigation options. Much ground has been covered on these topics in the IPCC Special Report on Renewable Energy Resources and Climate Change Mitigation (SRREN) (Chum, Faaij, Moreira, Berndes, Dhamija, Dong, et al., 2011) and the Global Energy Assessment (2012); we therefore concentrate on new developments and summarize recent findings.

11.A.2 Biomass resource potential for bioenergy

Biomass resources from different sources for energy for different regions are presented in Table 11.A.1 and conversion processes in Figure 11.A.1. Biomass resource availability for energy is determined by the opportunity cost of the resource and the implications for biodiversity, soil quality and ecosystem health and socio-economic implications. Biomass sources include forest residues, unutilized forest growth, agricultural residues, dedicated biomass plantations and organic wastes. Biomass from dedicated cropping systems and plantations is often assessed as the most important resource base. Dedicated biomass plantations are estimated to have the largest potential, but there is a wide range of 26-675 EJ/yr. The total global and regional bioenergy resource supply potential, obtained by summing the average potential for the different categories and then rounding to the nearest ten leads to an estimate of 500 EJ/yr (Table 11 A.1).

SRREN (Chum et al., 2011) estimated potential deployment levels of biomass for energy by 2050 to be in the range of 100 to 300 EJ yr^{-1}, and concluded that the biomass resource potential from different sources have a wide range, as they depend on many biophysical, technical, and socio-economic factors that cannot be projected with high confidence (e.g. climate change effects, biotechnology, soil degradation, and land use regulations). Important determinants reported in SREEN include population, economic, and technology development and how these translate into fibre, fodder and food demand (especially share and type of animal food products in diets). These will have implications on demand for land, water and other resources, depending on performance in the food and forestry sectors (e.g., yields, water use efficiency, livestock feeding efficiency) and consumer behaviour (e.g., food waste, material recycling) and related regulations. Trade patterns and logistics linking supply and demand, development and innovation in feedstock production (e.g., higher yields and adaptation to specific growing conditions – influenced by climate change), and conversion (notably to allow biofuels production based on lignocellulosic resources) can significantly influence net energy potential.

SRREN concluded that investment in agricultural research, development and deployment could improve robustness of plant varieties for all applications and can result in a considerable increase in land and water productivity including bioenergy (Rost et al. 2009; Herrero et al. 2010; Lotze-Campen et al., 2010;Reynolds and Borlaug 2006; Ahrens et al. 2010). Integrated and multi-functional land use systems could provide multiple ecosystem services (IAASTD, 2009) Folke et al. 2004, 2009) (see section 11.4); the integration of bioenergy systems into agricultural landscapes could contribute to multiple environmental and socioeconomic objectives, including the development of farming systems and landscape structures that are beneficial for the conservation of biodiversity (Berndes et al. 2008; Vandermeer and Perfecto 2006). However, the implications of such developments for future resource potentials remain uncertain. Further, existing and emerging guiding principles and governance systems could determine biomass resources availability (Stupak, I., Lattimore, B., Titus, B., Smith, C.T., 2011; (Van Dam et al., 2010a).

Table 11.A.1: Supply potentials of biomass energy resource categories year 2050. The ranges were obtained from assessing a selection of studies that quantify biomass availability for energy based on a "food/fiber first principle" and various restrictions with reference to resource limitations and environmental concerns - but without any cost consideration - to obtain "technical" potentials, as restricted by some sustainability considerations (the global ranges reported in SREEN, italic numbers in the table, are wider due to a broader set of studies, but with less restrictions). The mitigation potential of these resources is discussed in Section 11.A.4.

Biomass resource category	*Supply potential (2050) EJ/yr*	
1. Forest residues: Residues from silvicultural thinning and logging; wood processing residues such as sawdust, bark and black liquor; dead wood from natural disturbances, such as storms and insect outbreaks (irregular source). Residue removal rates need to be controlled considering local ecosystem including biodiversity, climate, topography, and soil factors. iLUC effects mostly negligible but may arise if earlier uses are displaced or if soil productivity losses require compensating production. There is a near term trade-off in that organic matter retains organic C for longer if they are left on the ground instead of being used for energy.	ASIA	3-7
	LAM	1-4
	MAF	1-3
	OECD90	7-20
	REF	2-5
	GLOBAL	17-35
2. Unutilized forest growth: The part of sustainable harvest levels (often set equal to net annual increment) in forests judged as being available for wood extraction, which is above the projected biomass demand for producing other forest products. Includes both biomass suitable for, e.g., pulp and paper production and biomass that is not traditionally used. The resource potential and mitigation benefit depend (besides fossil C displacement efficiency) on both environmental and socio-economic factors: the change in forest management and harvesting regimes due to bioenergy demand depends on forest ownership and the structure of the associated forest industry; and the forest productivity and C stock response to changes in forest management and harvesting depend on the character of the forest ecosystem, as shaped by historic forest management and events such as fires, storms and insect outbreaks.	ASIA	1
	LAM	22
	MAF	2
	OECD90	33
	REF	7
	GLOBAL	64 - 74
Forest biomass (sum of category 1 and 2)	*SREEN*	*0-110*
3. Agriculture residues: Manure (given separately in paranthesis and not included in the agriculture residue potential); harvest residues (e.g., straw); processing residues (e.g., rice husks from rice milling). Similar environmental restrictions on harvest residue removal as for forests. iLUC effects and timing of C flows also similar, although the longer term soil C trade-off may be less than previously believed. Residues have varying collection and processing costs (in both agriculture and forestry) depending on quality and how dispersed they are, with secondary residues often having the benefits of not being dispersed and having relatively constant quality. Densification and storage technologies enable cost effective collections over larger areas.	ASIA	(14) 7-30
	LAM	(8) 2-11
	MAF	(6) 3-15
	OECD90	(9) 7-13
	REF	(3) 3
	GLOBAL *SREEN:*	(40) 28-59 *(5-50) 15-70*

Biomass resource category	*Supply potential (2050) EJ/yr*	
<u>4. Dedicated biomass plantations</u>: including annual (cereals, oil- and sugar crops) and perennial plants (e.g., switchgrass, Miscanthus) and tree plantations (both coppice and single-stem plantations, e.g., willow, poplar, eucalyptus, pine). Higher end estimates presume favourable agriculture development concerning land use efficiency - especially for livestock production - releasing agriculture lands for bioenergy. Diets is a critical determinant, given the large land requirements to support livestock production (Ch. 11). Large areas presently under forests are biophysically suitable for bioenergy plantations but such lands are commonly not considered available due to GHG, biodiversity and other impacts. Grasslands and marginal/degraded lands (uncertain extent and suitability) are commonly considered as available for bioenergy, but their use requires careful planning and crop selection to avoid negative impacts on GHG balances, water availability, biodiversity, and subsistence farming and equity	ASIA	6-144
	LAM	7-120
	MAF	4-152
	OECD90	6-140
	REF	3-136
	GLOBAL SREEN:	26-675 *0-700*
<u>5. Organic wastes</u>: Waste from households and restaurants, discarded wood products such as paper and demolition wood, and wastewaters suitable for anaerobic biogas production. Organic waste may be dispersed and also heterogeneous in quality but the health and environmental gains from collection and proper management through combustion or anaerobic digestion can be significant.	ASIA	4-7
	LAM	2-3
	MAF	2-3
	OECD90	2-3
	REF	0-1
	GLOBAL *SREEN:*	10-17 *5 - >50*
<u>Total potential:</u> The total global and regional potentials are obtained by summing the average potentials for the different categories and then rounding to the nearest ten. This approach implies averaging over a wide range of contrasting assumptions made in the different studies concerning the development for critical parameters discussed in the text. This approach to derive global numbers is sensitive to selection of studies in the sense that including several studies using similar assumptions and models and reaching similar (high or low) potential estimates results in higher weight for these studies. However, the judgment is that the selection includes a representative mix of studies concerning models and modeller views on critical parameters.	ASIA	100
	LAM	100
	MAF	70
	OECD90	140
	REF	80
	GLOBAL *SREEN:*	500 *<50 - >1000*

References, resource categories:

1. (Gregg and Smith, 2010); (Haberl et al., 2010); (Smeets and Faaij, 2007); (Smeets et al., 2007b); (Rogner et al., 2012)

2. Chum et al., (2011); (Smeets and Faaij, 2007)

3. (Rogner et al., 2012); (Hakala et al., 2009); ; Haberl et al., 2010; (Haberl, Erb, et al., 2011); Chum et al., 2011; (Smeets et al., 2007b); Gregg and Smith, 2010;

4. (Haberl, Erb, et al., 2011); (Van Vuuren et al., 2009); Smeets et al., 2007; (Hoogwijk et al., 2005); (Hoogwijk et al., 2009a)

5. Haberl et al., 2010; (Gregg and Smith, 2010)

11.A.3 Bioenergy conversion technologies and management practices

Bioenergy feedstock conversion pathways that are deployed for heat and power or as transportation fuel are presented in Figure 11.A.1.

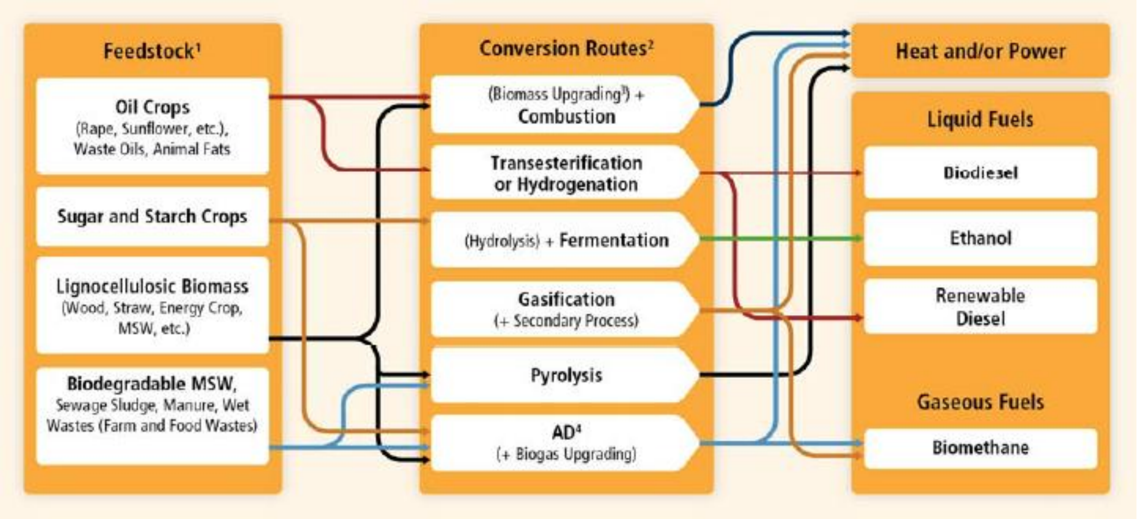


Figure 11.A.1. Bioenergy using terrestrial biomass feedstocks through current commercially available conversion pathways. Additional pathways could includebiochemical and thermochemical conversion of cellulosic sources/ agricultural and forestry residues. Source: IEA, 2009; SRREN, 2011

11.A.3.1 Production and Conversion technologies

Production technologies: Terrestrial biomass feedstocks include forest residues, agricultural residues, organic waste, and dedicated biomass plantations (Table 11.A.1). Yield improvements can possibly increase output per area by 20-50% by 2030 for many crops, with most improvement potential in sub-Saharan Africa, Latin America, Eastern Europe and Central Asia where advanced techniques are not yet fully adopted (Chum, Faaij, Moreira, Berndes, Dhamija, Dong, et al., 2011). Increasing agricultural yields may spare land for conservation purposes (Phalan et al., 2011b) and food production, needed to feed approximately 9 billion people in 2050. If yield increase is sufficiently high, this could allow for large-scale expansion of biofuel production. However, agricultural productivity can increase the profitability of production and may result in increased land conversion (Rose et al. 2013b). Yield increase is also often associated with increased GHG emissions from N_20 and from production of inputs.

Advanced management practices coupling sensors, GIS, and information technologies in planting, fertilizing, and drip irrigation have increased yields of agricultural crops in developed countries and some developing countries and could also increase in additional developing countries with appropriate adaptation of such practices and technologies to those locations (Deutsche Bank Advisers, 2009). Aquatic biomass production, i.e. microalgae potentially offers productivity levels above those of terrestrial plants and can avoid competition with agricultural lands since they can grow in arid lands and in brackish waters, or at sea. Its deployment depends on technological breakthroughs, and its market potential depends on the co-use of products for food, fodder, higher value products, and fuel markets (Chum, Faaij, Moreira, Berndes, Dhamija, Dong, et al., 2011). Similarly, lignocellulosic feedstocks produced from waste or residues, or grown on land unsupportive of food production involve less direct competition with food production. In addition, lignocellulosic feedstocks can be bred specifically for energy purposes, and can be harvested by coupling collection and pre-processing (densification and others) in depots prior to final conversion, which could enable delivery of more uniform feedstocks throughout the year (U.S. DOE 2011). Various conversion pathways are in R&D, near commercialization, or in early deployment stages in several countries (see 2.6.3 in Chum et al. 2011). Biofuels include bioethanol and biodiesel and a variety of fuels of composition similar to gasoline, diesel and jet fuels, fully compatible with the petroleum infrastructure. More productive land is economically more attractive also for cellulosic feedstock, but is then also more likely to be associated with induced land-use change emissions. Depending on feedstock, conversion process and land demand, lignocellulosic bioenergy can be associated with significant GHG emissions (e.g. excessive removal of corn stover associated with soil emissions) or low GHG emissions (e.g. Davis et al. 2012; Gramig et al., submitted).

11.A.3.2 End-uses and conversion technologies:

Traditional Bioenergy Use: Approximately 15% of total global energy use and 80% of current bioenergy use meets the cooking and heating needs of ~2.7 billion people, a number projected to increase to 2.8 billion by 2030 (Chum, Faaij, Moreira, Berndes, Dhamija, Dong, et al., 2011). Cooking is done in open fires and rudimentary stoves, with only 10-20% conversion efficiency. Changing to biogas, a clean fuel from animal and plant leafy residue, and dissemination of efficient cookstoves can potentially reduce biomass fuel consumption by 50% or more (Chum, Faaij, Moreira, Berndes, Dhamija, Dong, et al., 2011) and further lower the atmospheric radiative forcing, reducing both black carbon and CO_2 emissions by 60% (Chum, Faaij, Moreira, Berndes, Dhamija, Dong, et al., 2011; Sathaye et al., 2011). The performance of solid biomass stoves is rapidly improving including efficiency, emissions, durability, safety, and ability to provide simultaneous services (such as heating and electricity) (Annenberg et al. 2012). Worldwide, the global mitigation potential of advanced cookstoves was estimated to be between 0.6 and 2.4 Gt CO_2eq/yr (Chum, Faaij, Moreira, Berndes, Dhamija, Gabrielle, et al., 2011).

***Bioenergy for district heating, transportation and industrial applications*:** Using biomass for electricity and heat, e.g., co-firing of woody biomass with coal in the near term and large heating systems coupled with networks for district heating, and biochemical processing of waste biomass, are among the most cost-efficient and effective biomass applications for GHG emission reduction in modern pathways (Sterner and Fritsche, 2011b). IEA (2010) projects that the use of biomass and waste in industry will be three to four times higher in 2050 than in 2007. In non-OECD countries, only 12% of biomass is used in industry while OECD countries use 33% of the biomass in the industrial sector. In specific cases, powering electric cars with electricity from biomass has higher land-use efficiency and lower GWP effects than the usage of bioethanol from biofuel crops for road transport across a range of feedstocks, conversion technologies, and vehicle classes (Campbell et al., 2009; Schmidt et al., 2011), though costs are likely to remain prohibitive in the short-term (Schmidt et al., 2011). Also, biomass power is likely to substitute fossil fuel electricity, not gasoline (Lemoine et al., 2010; Geyer et al., 2013). Many pathways and feedstocks can lead to biofuels for aviation; the development of biofuel standards started and enabled commercial domestic and transatlantic flights testing of 50% biofuel in jet fuel by consortia of governments, aviation industry, associations (IEA Bioenergy 2012, REN21 2012). Advance 'drop in' fuels, such as iso-butanol or synthetic aviation kerosene, can be derived through a number of possible conversion routes such as hydro treatment of vegetable oils, isobutanol, and Fischer-Tropsch synthesis from gasification of biomass (Bacovsky et al. 2010, IEA Bioenergy, 2012). As there are no other low-carbon intensity fuel options for aviation (see Chapter 8.3) and biofuels may be the best option for GHG emissions reductions within aviation, but costs need to be reduced significantly and life-cycle emissions need to be low (Chum, Faaij, Moreira, Berndes, Dhamija, Gabrielle, et al., 2011).

Integrated bio-refineries continue to be developed; for instance, 10% of the ethanol or corresponding sugar stream goes into bio-products in Brazil (REN21, 2012). Multi product bio-refineries could produce a wider variety of co-products to enhance the economics of the overall process (IEA, 2011). Small scale decentralized biomass power generation systems based on biomass combustion and gasification and biogas production systems have the potential to meet the energy needs of rural communities in the developing countries. The biomass feedstocks for these small-scale systems could come from residues of crops and forests, wastes from livestock production and/or from small-scale energy plantations.

Negative GHG emission technologies: Carbon capture and storage (CCS) of CO_2 emissions from modern bioenergy conversion (BECCS) could produce negative emissions if CCS can be successfully deployed. Early deployment of CCS in the biofuels area is expected in ethanol production from sugar fermentation as the gas is of high purity, and already used in several markets (Chum, Faaij, Moreira, Berndes, Dhamija, Gabrielle, et al., 2011). Biopower with CCS in particular features prominently in long-run climate management energy transformation scenarios (Chapter 6). More offsets could be achieved by using crops that improve soil carbon (see section 11.3), though this carbon would need to remain undisturbed for 100 years (assuming use of 100-year GWP values) to achieve equivalence with avoided CO_2 emissions.

11.A.4 Mitigation potential of bioenergy

11.A.4.1 General issues

Bioenergy systems influence the climate through (i) GHG emissions from fossil fuels associated with the biomass production and conversion to secondary energy carriers; (ii) GHG emissions or CO_2 sequestration associated with changes in biospheric C stocks; (iii) climate forcing not related to GHG emissions including particulate and black carbon emissions from small-scale bioenergy use, aerosol emissions associated with forests, and changes in surface albedo; and (iv) effects of other changes resulting from bioenergy use, such as the degree of fossil fuel displacement, price effects on food, forest, and petroleum markets influencing consumption levels (Chum, Faaij, Moreira, Berndes, Dhamija, Gabrielle, et al., 2011). Bioenergy's contribution to climate change mitigation hinges crucially on sustainable land, water, and other resources management and rapid technological improvements, especially in biomass production and conversion (see section 11.4). However, as noted, some caution is merited regarding the implications of agricultural productivity improvements.

11.A.4.2 GHG emissions accounting and effects

The net effect of harnessing the bioenergy potential on climate change mitigation is the difference between total climate forcing of the bioenergy system and that of the energy system displaced, considering also indirect effects, such as indirect Land Use Change (iLUC). The displaced system may be based on fossil fuels or other energy sources. The mitigation benefit of bioenergy is assessed for varying temporal (near term GHG targets, longer term temperature targets) and spatial scales (project level up to global scale), with selection of methodology and indicators depending on scope and aim (Chum et al., 2011; Creutzig et al. 2012a).

SRREN Ch. 2 and Ch. 9 assessed LCA literature and reported ranges of GHG emissions for bioenergy systems compared to fossil energy systems (excluding LUC effects) and identified critical factors: (1) GHG emissions from biomass production where LUC emissions and N_2O emissions are especially important; (2) methods used for considering co-products; (3) assumptions about conversion process design, process integration and the type of process fuel used in the conversion of biomass to solid or fluid fuels; (4) the performance of end-use technology, i.e., vehicle technology or power/heat plant performance; and (5) the reference system. Consequences of LUC other than GHG (e.g. changes in the surface energy balance, including albedo) were not quantified in SRREN. The following paragraphs provide a detailed update of the recent LCA literature. Fig 11.A2 provides an overview about the relevant methods used here and their boundary conditions.

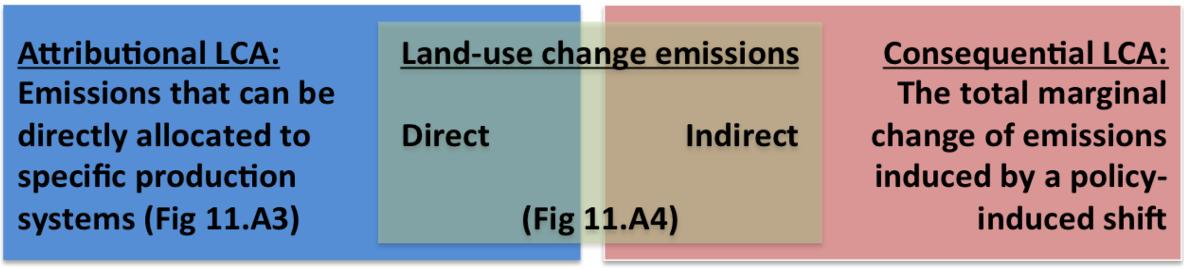


Figure 11.A.2. Overview of LCA methods and their boundary conditions. Figures 11.A.3 and 11.A.4 review estimates of GHG emissions based on attributional LCA (excluding direct land-use change emissions), and from land-use change, respectively. The more policy-relevant measure—the total emission change induced by a policy—has not been systematically studied; doing so requires estimation of market-mediated effects such as rebound effects, which introduces high structural uncertainty (Plevin et al., in review).

Beyond the climate neutrality assumption: Bioenergy systems are often assessed (e.g., in LCA studies and in integrated assessment models) under the assumption that the CO_2 released during the combustion of bioenergy is climate neutral, based on the rationale that it was earlier sequestered from the atmosphere and will be sequestered again if the bioenergy system is managed sustainably (Rabl et al. 2007; van der Voet et al. 2010, Creutzig et al., 2012a).

In recent years the climate neutrality assumption has been questioned from different perspectives related to carbon stock dynamics (Johnson, 2009; Searchinger et al., 2009a) and the temporary forcings from biogenic CO_2 fluxes (CHERUBINI et al., 2011) (Courchesne et al. 2010). Other important factors affecting the climate impact of bioenergy are non-CO_2 GHG emissions (N_2O and CH_4), non-GHG emissions (e.g., black and organic carbon, aerosols, etc.) (Tsao et al., 2012) and biogeophysical aspects related to land use (Loarie et al., 2011; Georgescu et al., 2011) (Anderson-Texeira et al., 2011).

Attributional basis – Direct forcings of CO_2 from biomass: Even if CO_2 fluxes associated with the terrestrial carbon cycle in bioenergy systems can sum up to zero at the end of each rotation period, the skewed time distribution of these fluxes lead to temporary climate forcings which are important to consider in slow growing biomass systems. These forcings can be quantified in the same manner as other GHG's, for example, by using metrics like GWP (CO_2eq). The GWPs of CO_2 emissions from biomass combustion are higher for slow re-growing biomass and lower with increasing analytical time horizons (Guest et al., 2012; Cherubini, Bright, et al., 2012). See also WGI, Chapters 6 (carbon cycle) and 8 (metrics).

Consequential perspective – Stock dynamics of increased harvest levels:
Removing biomass from forests affects the dynamics of stocks across the landscape over time (Schlamadinger and Marland, 1996; Hudiburg et al., 2011b; McKechnie et al., 2011). Many studies find that the increased outtake for bioenergy or biofuels causes a period of increased cumulative CO_2 emissions (carbon debt) for a duration in the order of a rotation cycle or longer compared to leaving the forest standing and using fossil fuels (Marland and Schlamadinger, 1997, Fargione et al., 2008, Hudiburg et al. 2011). However, landscape perspectives are important since parcels of land are managed concurrently and in anticipation of future markets, resulting in, for instance, forests being planted while others are harvested. The use of easily decomposable residues and wastes for bioenergy can produce GHG benefits even in the near term (Zanchi et al., 2011), whereas the removal of slowly decomposing residues reduces soil carbon accumulation at a site, and can result in net emissions from some residue-based bioenergy systems (Repo et al., 2011). A related problem is the "baseline error" of neglecting the alternative fate of biomass and of the land on which biomass is produced (Searchinger, 2010; Haberl et al., 2012a; Schulze et al., 2012). Such dynamics are discussed in the section on systemic effects (section 11.A.2).

Nitrous oxide (N_2O) emissions: For first-generation crop-based biofuels, as with food crops (see Chapter 11), emissions of N_2O from agricultural soils is the single largest contributor to the life cycle GHG emissions, and one of the largest contributors across many biofuel production cycles (Smeets et al., 2009; Hsu et al., 2010). Emission rates can vary by as much as 700% between different crop types for the same site, fertilization rate and measurement period (Don et al., 2012). Even for the same crop, there is a significant regional variation in N fertilizer application rates (Yang et al., 2012). Increased estimates of N_2O emissions alone can convert some biofuel systems from apparent net sinks to net sources (Crutzen et al. 2007; Smith et al. 2012). Improvements in nitrogen use efficiency and nitrogen inhibitors can substantially reduce emissions of N_2O (Robertson and Vitousek 2009)(see section 11.3). Other non first-generation bioenergy crops, such as short rotation coppice and Miscanthus, require minimal or zero N fertilization and can reduce GHG emissions relative to the former land use where they replace conventional food crops (Clair et al., 2008), though N_2O and CO_2 emissions from indirect land use change also need to be considered (see below).

Biogeophysical effects: Forest and agricultural operations also interact with the climate system through changes in surface reflectivity (i.e., albedo), surface roughness, evaporation and other factors influencing fluxes of energy and water between land and atmosphere (Marland et al. 2003; Betts et al. 2007; Bonan 2008; Jackson et al. 2008; Anderson-Teixeira et al. 2012). Changes to biogeophysical factors at the surface can lead to both direct and indirect climate forcings whose impacts can differ in spatial extent (global and/or local) (Bathiany et al., 2010) (Davin et al., 2007; Bala et al., 2007). Albedo is found to be the dominant direct biogeophysical climate mechanism linked to land use change at the global scale, especially in areas affected by seasonal snow cover (Bathiany et al., 2010; Claussen et al. 2001; Bala et al. 2007). Radiative forcing from an albedo change in some regions can be comparable and even stronger than those of CO2 fluxes associated with afforestation or deforestation (Randerson et al. 2006; Bala et al. 2007; Bonan 2008; Betts 2011,Lohila et al. 2010). Geophysical changes attributed to some bioenergy systems can lead to climate forcings that partially (Bright et al., 2011, 2012) and in some cases more than offset forcings from GHGs (Hallgren et al., under review; Loarie et al., 2011; Georgescu et al., 2011; Cherubini, Bright, et al., 2012)

Systemic effects of bioenergy systems

Direct and indirect land use change: Direct land use change (LUC) occurs when bioenergy crops displace other crops or pastures or forests, while iLUC results from the latter triggering the conversion to cropland of lands, somewhere on the globe, to replace some portion of the displaced crops (Searchinger et al. 2008; Hertel et al. 2010; Delucchi 2010). Direct LUC to establish biomass cropping systems can increase the net GHG emissions, for example if carbon rich ecosystems such as wetlands, forests or natural grasslands are brought into cultivation (Gibbs et al., 2008; UNEP, 2009; Chum et al., 2011). Biospheric C losses associated with LUC from some bioenergy schemes can be, in some cases, more than hundred times larger than the annual GHG savings from the assumed fossil fuel replacement (Gibbs et al. 2008; Chum et al. 2011). Beneficial LUC effects can also be observed, for example when perennial grasses or woody plants replace annual crops grown with high fertilizer levels, or where such plants are developed on lands with carbon-poor soils (Tilman et al., 2006), (Harper et al., 2009), (Sochacki et al., 2012) (Gibbs et al., 2008), (Sterner and Fritsche, 2011a). Further, biogeophysical perturbations from LUC can be equally important, and in some contexts, more important than perturbations to the carbon cycle (Loarie et al., 2011; Georgescu et al., 2011) (Hallgren et al. 2012; Hallgren et al. in review; Schaeffer et al., 2006).

For iLUC, as market-mediated emissions are unobservable, the magnitude of these effects must be modeled (Nassar et al., 2011) raising important questions about model validity and uncertainty (Liska and Perrin, 2009; Plevin, O'Hare, et al., 2010; Gawel and Ludwig, 2011; Khanna et al., 2011; Wicke et al., 2012). However, ignoring iLUC is equivalent to assigning the value of zero to iLUC, which is probably almost always wrong (Plevin et al., 2010). A large number of studies have examined this question in the past four years using economic models (e.g., Searchinger et al. 2008; Hertel et al.

2010; Dumortier et al. 2011; Havlík et al. 2011; Taheripour et al. 2011; Chen & Khanna 2012; Timilsina et al. 2012; Bento et al.), simpler approaches based on historical data and assumptions (Fritsche et al., 2010; Overmars et al., 2011), and statistical analyses of historical data (Arima et al., 2011; Kim and Dale, 2011; Wallington et al., 2012). Some positive induced land-use changes can also occur: co-products of bioenergy can displace additional feedstock production thus decreasing the net area needed (e.g., for corn, Wang et al. 2011; for wheat, Berndes et al. 2011), reducing the net disbenefit of iLUC. The modeling studies all find net positive emissions from iLUC, though the estimates span a wide range, and negative iLUC values are theoretically possible (Njakou Djomo and Ceulemans, 2012).

Owing to the challenges of modeling global economic behavior, the location and magnitude of iLUC, and thus the GHG emissions induced by crop-based biofuels, are highly uncertain (Plevin, O'Hare, et al., 2010; Khanna et al., 2011; Wicke et al., 2012). The estimated magnitude of iLUC emissions also varies under alternative policy scenarios and assumptions about fuel prices (Bento et al., In review; Khanna et al., 2011), and is highly sensitive to the treatment of emissions over time (Plevin, O'Hare, et al., 2010). Studies to date have mostly examined iLUC in the context of liquid biofuels, but iLUC is equally an issue for biopower and biomaterials (Weiss et al., 2012). LUC effects of residue use are mostly negligible but may arise if earlier uses (e.g. animal feeding) are displaced or if soil productivity losses occur. Thus, producing biofuels from wastes and sustainably harvested residues, and replacing first generation biofuel feedstocks with lignocellulosic crops (e.g. grasses) can reduce iLUC (Davis et al. 2012; Scown et al. 2012).

Fossil fuel displacement: Economists have criticized the assumption that each unit of energy replaces an energy-equivalent quantity of fossil energy, leaving total fuel use unaffected (Drabik and De Gorter, 2011; Rajagopal et al., 2011; Thompson, Whistance, et al., 2011). As with other energy sources, increasing energy supply through the production of bioenergy affects energy prices and demand for energy services, and these changes in consumption also affect net global GHG emissions (Hochman et al., 2010; Rajagopal et al., 2011; Chen and Khanna, 2012). The sign and magnitude of the effect of increased biofuel production on global fuel consumption is uncertain (Thompson, Whistance, et al., 2011) and depends on how the world responds in the long term to reduced petroleum demand in regions using increased quantities of biofuels, which in turn depends on OPEC's supply response and with China's and India's demand response to a given reduction in the demand for petroleum in regions promoting biofuels, and the relative prices of bio- and fossil fuels (Gehlhar et al., 2010; Hochman et al., 2010; Thompson, Whistance, et al., 2011). Notably, if the percentage difference in GHG emissions between an alternative fuel and the incumbent fossil fuel is less than the percentage rebound effect (the fraction *not* displaced, in terms of GHG emissions), a net *increase* in GHG emissions will result from promoting the alternative fuel, despite its nominally lower rating (Drabik and De Gorter, 2011). Estimates of the magnitude of the petroleum rebound effect cover a wide range and depend on modeling assumptions. Two recent modeling studies suggest that biofuels replace about 30-70% of the energy equivalent quantity of petroleum-based fuel (Drabik and De Gorter, 2011; Chen and Khanna, 2012), while others find replacement can be as low as 12-15% (Bento et al., In review; Hochman et al., 2010). Under other circumstances, the rebound can be negative, resulting in greater than 100% displacement (Bento et al., In review). The rebound effect is always subject to the policy context, and can be specifically avoided by global cap and pricing instruments.

Energy inputs in residue and forest bioenergy systems are commonly below 10% of energy in the extracted biomass and associated GHG emissions correspondingly low, but methane emissions from wood chip storage may in some situations be important (Wihersaari, 2005) (Eriksson and Gustavsson 2010)

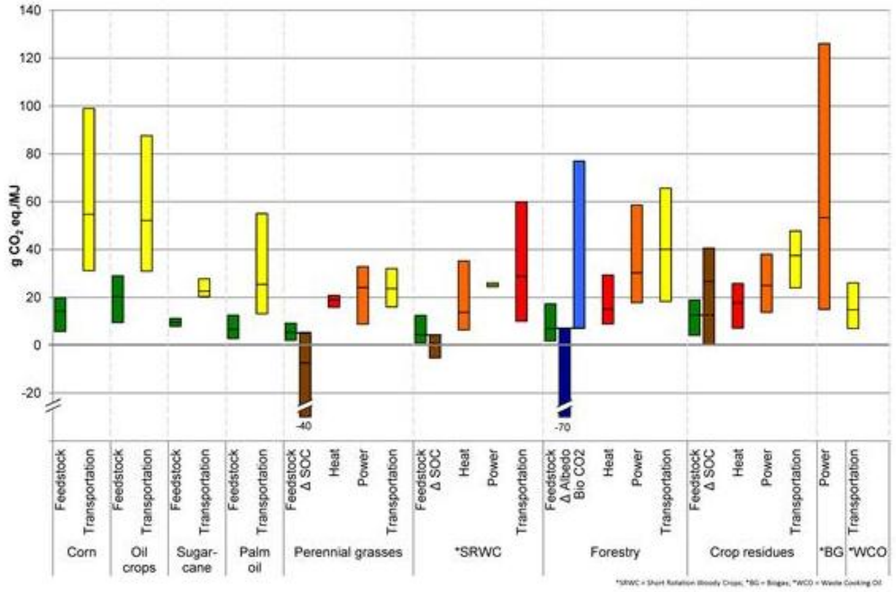


Figure 11.A.3. Ranges of life-cycle direct global climate impacts (in g CO_2 equivalents per MJ, after characterization with GWP TH=100 years) attributed to major global bioenergy products. Values represent the full range reported in peer-reviewed literature after 2010, with the arithmetic mean indicated by the black line within bars. The lower and upper bounds of the bars represents the minimum and the maximum value reported in the literature. For some options the limited literature can affect the bar width. Results are disaggregated in a manner, which shows the impacts of *Feedstock* production (in g CO_2-eq./MJ of feedstock) and the contributions from end product/conversion technology. Results from conversion into final energy products *Heat*, *Power*, and *Transportation* fuels include the contribution from *Feedstock* production and are shown in g CO_2-eq./MJ of final product combusted. For some pathways, additional site-specific climate forcing agents apply and are presented as separate values to be added or subtracted from the value indicated by the mean in the *Feedstock* bar. Final products are also affected by these factors and further energy losses in conversion, but this is not displayed here. Site-specific values were derived from specific cases in specific geographic regions with varying climates, soil properties, yields, and management regimes and are only presented to indicate the range in magnitude that can affect the bioenergy systems in question. Interpretation of this figure should consider that all values presented were obtained from studies differing in geographical locations and major assumptions about *inter alia* co-product allocation, N_2O emission factors, system boundaries, conversion efficiencies, and technological maturity. Values provide important insights but are insufficient for policy regulation.

Figure legend: Feedstock (green): Contribution from the production of 1 MJ biomass feedstock; Heat (red): Contribution from the production of 1 MJ heat; Power (orange): Contribution from the production of 1 MJ electricity; Transportation (yellow): Contribution from the production of gaseous and liquid transportation fuels; Δ Albedo (deep blue): Site-specific contribution from surface albedo changes following harvest disturbance (ranges are normalized to 1 MJ Feedstock produced); Bio CO2 (light blue): Site-specific contribution from timing of CO2 fluxes in the biomass system (ranges are normalized to 1 MJ Feedstock produced); ∆SOC (brown): Site-specific contribution from changes in soil organic carbon relative to a reference crop (ranges are normalized to 1 MJ Feedstock produced). [Work under progress].

The causes behind iLUC are multiple, complex, interlinked, and change over time and this makes quantification of iLUC effects inherently uncertain since it is sensitive to many factors that can develop in different directions, including land use productivity (e.g. agricultural technology, livestock feeding efficiency, climate impacts), diets, trade patterns, prices and elasticities, bioenergy production levels and use of by-products associated with bioenergy systems. The scale of deployment might be important. Possibly, marginal LUC-related GHG emissions increase systematically with scale of deployment (everything else kept constant) (Haberl, in review). Not least, policies and legal measures that directly or indirectly influence land use can have a strong influence on future LUC and associated emissions (Chum et al. 2011). While iLUC quantifications remain uncertain, it can be concluded that land-intensive diets, lower agricultural yields (see qualifications above) and livestock feeding efficiencies, stronger climate impacts and higher energy crop production levels can result in higher LUC-related GHG emissions and *vice versa* (Chum *et al.*, 2011).

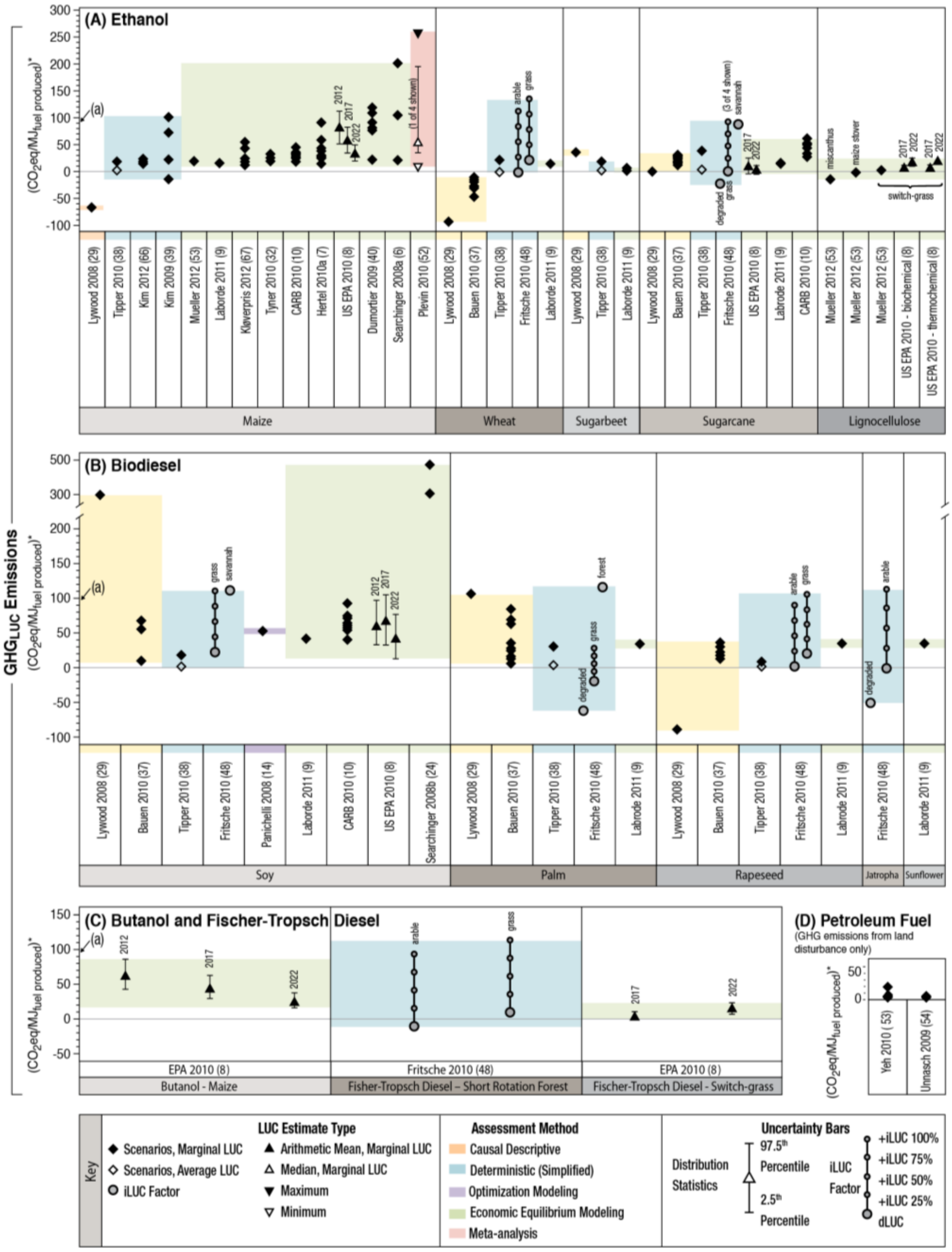


Figure 11.A.4 Estimates of GHG_{LUC} emissions - GHG emissions from biofuel production-induced LUC (as g CO_2eq/$MJ_{fuel\ produced}$) over a 30 year time horizon organized by fuel(s) (frames A-D), feedstock, and study. Assessment methods, LUC estimate types and uncertainty metrics are portrayed to demonstrate diversity in approaches and differences in results within and across any given category. Frame (D) shows available estimates of GHG emissions from local land disturbance during petroleum recovery. These estimates are not commensurable to estimates of GHG_{LUC} since the former considers only local LUC-related emissions while the latter considers global emissions. Points labeled “a” on the Y axis represent a commonly used estimate of life cycle GHG emissions associated with the direct supply chain of petroleum gasoline (frame A) and diesel frames B and C) (Argonne National

Laboratory, 2012). These emissions are not directly comparable to GHG_{LUC} because the emission sources considered are different, but are potentially of interest for scaling comparison.

Please note: These estimates of global LUC are highly uncertain, unobservable, unverifiable, and dependent on assumed policy, economic contexts, and inputs used in the modeling. All entries are not equally valid nor do they attempt to measure the same metric despite the use of similar naming conventions (e.g., indirect LUC). In addition, many different approaches to estimating GHGLUC have been used. Therefore, each paper has its own interpretation and any comparisons should be made only after careful consideration. *CO2eq includes studies both with and without CH4 and N2O accounting.

11.A.4.3 Aggregate deployment potential

Hoogwijk et al. (2009) integrated assessment modelling studies projected for specific IPCC SRES scenarios that energy crops could supply 130 to 270 EJ/yr by 2050 at production costs below $2/GJ by 2050 (see Chum et al 2011, Figure 2.17). With such projections of supplies (amounts of biomass at a cost), adding conversion costs to final energy biomass products for similar scenarios resulted in a potential range of 108 to 310 EJ/yr of liquid biomass fuels that could be derived at $12 to $20/GJ and 200–300PWh/yr under $0.10/kWh, with considerable uncertainties about overlap of resources for the two products (de Vries et al. 2007). These projected costs are coarse estimates intended to show trends and regions in which such production would be possible within the assumptions and scenarios of the study. Chum et al. (2011) section 2.2 provide additional examples from more recent regional studies with higher resolution on specific types of lands restricted by considering specific environmental and ecosystems concerns at regional level (e.g., EU) and for specific countries (county level for the U.S. see U.S. DOE 2011) and projections; sections 2.3, 2.6, and 2.7 address estimated production costs (electricity, heat, biofuels) and impacts of feedstock costs; select examples of estimated production costs for specific countries are detailed in (IPCC, 2011).

In the IPCC SRREN scenarios, bioenergy is projected to contribute 120 to 155 EJ/yr (median values) to global primary energy supply by 2050 (50 EJ in 2008). Many of these scenarios coupled bioenergy and CCS mitigation. The GEA (2012) scenarios project 80–140 EJ by 2050, including extensive use of agricultural residues and second-generation bioenergy to mitigate adverse impacts on land use and food production, and the co-processing of biomass with coal or natural gas with CCS to make low net GHG-emitting transportation fuels and or electricity. If sustainability regulations are taken into account, less than ~100 EJ occurs in areas free of sustainability concerns (Schueler et al., 2013).

Traditional biomass demand is steady or declines in most scenarios from 30EJ/yr. The transport sector increases nearly tenfold from 2008 to 18-20 EJ/yr while modern uses for heat, power, combinations, and industry increase by factors of 2-4 from 18 EJ in 2008 (Fischedick et al., 2011). The 2010 IEA model projects a contribution of 12 EJ/yr (11%) by 2035 to the transport sector, including 60 % of advanced biofuels for road and aviation. Bioenergy supplies 5% of global power generation in 2035, up from 1% in 2008. Modern heat and industry doubles their contributions from 2008 (IEA, 2010). The future potential deployment level varies at the global and national level depending on the technological developments, land availability, financial viability and mitigation policies.

Transformation pathway studies suggest that bioenergy could play a significant role within the energy system (6.3.5). For instance, Rose et al. (2012) found bioenergy contributing up to 15% of cumulative primary energy over the century during stabilization. In more recent results, from a study of 19 models, Rose et al. (in review) found modern bioenergy providing 0 to 100 EJ/yr in 2030, 15 to 225 EJ/yr in 2050 and 80 to 320 EJ/yr in 2100 in idealized participation. The scenarios project increasing deployment of bioenergy with tighter climate change targets, both in a given year as well as earlier in time (Figure 6.21). Models project increased dependence, as well as increased deployment, of modern bioenergy, with some models projecting 30% of total primary energy from bioenergy in 2050, and as much as 45% of total primary energy from modern bioenergy in 2100. Bioenergy's share of regional total electricity and liquid fuels could be significant—up to 35 percent of global regional electricity from biopower by 2050, and up to 70 percent of global regional liquid fuels from biofuels by 2050. However, the cost-effective allocation of bioenergy within the energy system varies across models.

Bioenergy with Carbon Capture and Storage (BECCS) features prominently in transformation scenarios. BECCS could be very helpful and valuable for getting to lower climate change targets (especially in later half of century), and as an overshoot response technology that even affects the degree of radiative forcing or GHG concentration overshoot. In models that include BECCS, BECCS is deployed in greater quantities and earlier in time the more stringent the climate policy. For example, Rose et al. (in review) found that in 2030, BECCS is projected to be 60-70% of modern bioenergy; in 2050, BECCS is 20% to almost 100%; and, in 2100, BECC is 40% to almost 100% (Figure 6.21). Whether BECCS is essential for climate management, or even sufficient, is unclear (6.3.5). While BECCS could reduce the cost of stabilization, it may also affect the cost-effective emissions trajectory (Rose et al., in review), and potentially the climate change outcome (Richels et al., in review). Finally, the availability of BECCS technologies could lead to *less* biomass demand globally in the first half of century and more in the second half of the century with increased bioenergy cumulatively over the entire century. Some integrated models are cost-effectively trading-off lower land carbon stocks and increased land N2O emissions for the long-run climate change management benefits of bioenergy (Rose et al., in review; Popp et al., in review).

Bioenergy deployment also involves risks. In top-down models, land-use change emissions are often excluded by assumption (Creutzig et al., 2012b). But with increasing scarcity of productive land, the growing demand for food and bioenergy may incur substantial LUC causing high GHG emissions and/or increased agricultural intensification and higher N_2O emissions unless wise integration of bioenergy into agriculture and forestry landscapes occurs (Delucchi, 2010). Consideration of LUC emissions in integrated assessment models show that valuing or protecting global terrestrial carbon stocks reduces the potential LUC-related GHG emissions of energy crop deployment, and could lower the cost of achieving climate change objectives, but could exacerbate increases in agricultural commodity prices (Havlik et al., 2011), (Popp et al., 2012), (Popp, Dietrich, et al., 2011), (Wise et al., 2009b)(Melillo et al., 2009b). However, these scenarios assuming idealized participation and implementation (Creutzig et al. 2012a). Among other things, implementing a global terrestrial carbon policy is optimistic. Analysis of staggered implementation suggests large regional leakage potential, and the possibility of accelerated deforestation (Calvin et al., 2009; Rose and Sohngen, 2011) (see also Ch. 6.3.5). Large-scale energy crop production will likely increase competition for land, water, and other inputs, potentially affecting food security, deforestation, water use and biodiversity loss (see next section). The potential to utilize biomass both sustainably, and in a commercially viable manner, at large scales might also be compromised. For example, commercial bioenergy farmers may not choose to grow bioenergy crops on degraded land, as it is likely to be relatively unprofitable (Johansson and Azar, 2007). Similarly, maintenance of biodiversity may be difficult with large-scale bioenergy deployment (Sala et al., 2009).

In summary, top-down scenarios project between 15-225 EJ/yr deployment in 2050. Sustainability and livelihood concerns might constrain beneficial deployment to lower values (see also next section).

11.A.5 Bioenergy and sustainable development

The impacts of implementing bioenergy are context, place and size specific (Creutzig et al. in review; Popp et al., 2011). The interaction between a bioenergy option, its deployment scale and the specific context is what determines the developmental impacts. Livelihoods have not yet been systematically evaluated in integrated assessments, even if human geography studies have shown that bioenergy deployment can have strong distributional impacts (Creutzig et al. in review; Creutzig et al., 2012 b). The total effects on livelihoods will be mediated by global market dynamics, including policy regulations and incentives, the production model and deployment scale, and place-specific factors such as land tenure security, labour and financial capabilities, among others (Creutzig et al. in review). It can be economically beneficial, e.g. by raising and diversifying farm incomes and increasing rural employment through the production of biofuels for domestic (Gohin, 2008) or export (Arndt et al. 2011) markets. The establishment of large-scale biofuels feedstock production can also cause smallholders, tenants and herders to lose access to productive land, while other social groups such as workers, investors, company owners, biofuels consumers, and populations who are more responsible for GHG emission reductions enjoy the benefits of this production (Van der Horst and Vermeylen, 2011). This is particularly relevant where large areas of land are still unregistered or are being claimed and under dispute by several users and ethnic groups (Dauvergne and Neville, 2010). Furthermore, increasing demand for first-generation biofuels is partly driving the expansion of crops like soy and oil palm, which in turn contribute to promote large-scale agribusinesses at the expense of family and community-based agriculture, in some cases (Wilkinson and Herrera, 2010). Biofuels deployment can also translate into reductions of time invested in on-farm subsistence and community-based activities, thus translating into lower productivity rates of subsistence crops and an increase in intra-community conflicts as a result of the uneven share of collective responsibilities (Mingorría et al., 2010). In summary, the impact of bioenergy deployment on livelihoods is ambigous; comprehensive incorporation of livelihood considerations could further limit sustainable bioenergy deployment.

Bioenergy deployment is more beneficial when it is not an additional land use activity expanding over the landscape, but rather integrates into existing land uses and influences the way farmers and forest owners use their land. Examples include adjustments in agriculture practices where farmers, for instance, change their manure treatment to produce biogas, reduce methane losses and reduce N losses; or make changes in management and harvesting regimes of forestry systems to respond to new economic opportunities. These changes in management may swing the net GHG balance of options and also have clear sustainable development implications (Davis et al, 2012).

Table 11.A.2 presents the implications of bioenergy options in the context of social, institutional, environmental, economic and technological concerns. The relationship between bioenergy and these concerns is complex and there could be negative or positive implications, depending on the type of bioenergy option, the scale of production system and the local conditions. Co-benefits and risks do not necessarily overlap, neither geographically or socially (van der Horst & Vermeyelen, 2010; Dauvergne and Neville 2010; Wilkinson and Herrera, 2010). Main potential co-benefits are related to access to energy and impacts on the economy and wellbeing, jobs creation and improvement of local resilience (Walter et al. 2008). Main risks of bioenergy for sustainable development and livelihoods include competition on arable land (Haberl et al, 2013) and consequent impact on food security, displacement of communities and economic activities, creation of a driver of deforestation, impacts on biodiversity, water and soil or increment in vulnerability to climate change, (Sala et al., 2000; Thompson, Baruah, et al., 2011);(Hall et al., 2009);(German et al 2011);(SREX, 2012).

Labelling, certification and other information-based instruments (see section 11.10) are seen as options to promote ‘sustainable’ biofuels (Janssen and Rutz, 2011). However, certification approaches alone are not sufficient and cannot substitute effective territorial policy frameworks (Hunsberger et al., 2012). Some certification approaches have been scrutinized and challenged on the basis of a lack of legitimacy in their design and a deficient on-the-ground implementation (Partzsch, 2009; Franco et al., 2010).

Table 11.A.2: Institutional, social, environmental, economic and technological implications of bioenergy options at local to global scale

Institutional		**Scale**	**References**
May contribute to energy independence (reduce dependency on fossil fuels)	+	Local to national	(Amigun et al., 2011)(Hanff et al., 2011)(Stromberg and Gasparatos, 2012) (Wu and Lin, 2009)
Impacts on land tenure for local stakeholders	+/-	Local	(Amigun et al., 2011) (German and Schoneveld, 2012)(Von Maltitz and Setzkorn, in press)
Cross-sectoral coordination (+) or conflicts (-) between forestry, agriculture, energy and/or mining	+/-	Local to national	(Amigun et al., 2011)(Diaz-Chavez, 2011)(Martinelli and Filoso, 2008)(Madlener et al., 2006a) (Steenblik, 2007)
Impacts on labor rights among the value chain	+/-	Local to national	(Amigun et al., 2011) (Awudu and Zhang, 2012)(German and Schoneveld, 2012)
Promoting of participative mechanisms for small scale producers	+	Local to national	(Duvenage et al., accepted) (Ewing and Msangi, 2009)
Social		**Scale**	**References**
Competition to food security (except for bio-energy derived from residues, wastes or by-products)	–	Local to global	(Amigun et al., 2011)(Alves Finco and Doppler, 2010b) (Haberl, Erb, et al., 2011)(Beringer et al., 2011) (Bringezu et al., 2012)(German and Schoneveld, 2012) (Koizumi, 2013)
Increasing (+) or decreasing (-) existing conflicts or social tension	+/-	Local to national	(Bringezu et al., 2012) (Duvenage et al.,accepted)(Hall et al., 2009) (Martinelli and Filoso, 2008)
Impacts on traditional practices	_	Local	(Amigun et al., 2011)
Displacement of small-scale farmers	_	Local	(Duvenage et al.)(Ewing and Msangi, 2009)(Hall et al., 2009)
Promote capacity building and new skills	+	Local	(Arndt et al., 2012) (Ewing and Msangi, 2009)
Gender impacts	+/-	Local to national	(Amigun et al., 2011) (Arndt, Benfica, et al., 2011) (Duvenage et al, accepted.)(Mwakaje, 2012) (Ewing and Msangi, 2009)
Health impacts from bioenergy production	–	Local	(Cançado et al., 2006)(Kyu et al., 2010)(Martinelli and Filoso, 2008)
Environmental		**Scale**	**References**
Biofuel plantations can promote deforestation and/or forest degradation	–	Local to global	(Alves Finco and Doppler, 2010b) (Borzoni, 2011); (Koh and Wilcove, 2008)
Increase in use of fertilizers with negative impacts on soil and water	–	Local to global	(Martinelli and Filoso, 2008)
Large scale bio-energy crops can have negative impacts on soil quality, water pollution and biodiversity	–	Local to trans-boundary	(Beringer et al., 2011) (Danielsen et al., 2009)(Martinelli and Filoso, 2008)(Selfa et al., 2011)
Displacement of activities or other land uses	–	Local to global	(Borzoni, 2011) (Martinelli and Filoso, 2008)
Creating bio-energy plantations on degraded land can have positive impacts on soil and biodiversity	+	Local	(Danielsen et al., 2009)
May or may not reduce GHG emissions when substituted for fossil fuels, depending on the specific technology and development context	-	Global	(Fargione et al., 2008), (Haberl et al., 2012b) (Searchinger et al., 2008b) (Searchinger et al., 2009b) (Smith and Searchinger, 2012)

Economic		Scale	References
Increase in economic activity and income diversification	+	Local	(Amigun et al., 2011) (Alves Finco and Doppler, 2010b)(Arndt et al., 2012)(German and Schoneveld, 2012)(Hanff et al., 2011)(Huang et al., 2012)(Mwakaje, 2012)
Increase (+) or decrease (-) market opportunities	+/-	Local to national	(Gasparatos et al., 2011)(Mwakaje, 2012)(Steenblik, 2007)
Contribute to the changes in prices of feedstock	+/-	Local to global	(Amigun et al., 2011) (Arndt et al., 2012)(Arndt, Robinson, et al., 2011)(Huang et al., 2012)
May promote concentration of income and /or increase poverty	–	Local to regional	(Amigun et al., 2011)(Gasparatos et al., 2011) (Martinelli and Filoso, 2008)
Using waste and residues may create socio-economic benefits with little environmental risks	+	Local to regional	(Amigun et al., 2011) (Fargione et al., 2008) (Tilman et al., 2009)
Uncertainty about mid- and long term revenues	-	National	(Awudu and Zhang, 2012)(Selfa et al., 2011)
Employment creation	+	Local to regional	(Arndt et al., 2012)(Duvenage et al accepted.)(Ewing and Msangi, 2009)
Technological		**Scale**	**References**
Can promote technology development and/or facilitate technology transfer	+	Local to global	(Amigun et al., 2011)(Mwakaje, 2012) (Steenblik, 2007)
Increasing infrastructure coverage (+), but reduced access to it can increase marginalization (-)	+/-	Local	(Mwakaje, 2012)(Oberling et al., 2012)(Schut et al., 2010)
Technology might reduce labour demand (-). High dependent of tech. transfer and/or acceptance	-	Local	(Awudu and Zhang, 2012) (Borzoni, 2011)(Cacciatore et al., 2012) (Van de Velde et al., 2009)(Zhang et al., 2011)

Trade Offs and synergies with Land, Water and Biodiversity

At any level of future bioenergy supply, land demand for bioenergy depends on (1) the share of bioenergy derived from wastes and residues (Rogner et al., 2012); (2) the extent to which bioenergy production can be integrated with food or fiber production, which ideally results in synergies (Garg et al., 2011; Sochacki et al., 2012) or at least mitigates land-use competition (Berndes et al., 2012); (3) the extent to which bioenergy can be grown on areas with little current or future production, taking into account growing land demand for food (Nijsen et al., 2012); and (4) the volume of dedicated energy crops and their yields (Haberl et al., 2010; Smith et al., 2012). Energy crop yields per unit area may differ by factors of >10 depending on differences in natural fertility (soils, climate), energy crop plants, previous land use, management and technology (Johnston et al., 2009; Lal, 2010; Beringer et al., 2011; Pacca and Moreira, 2011; Smith, Zhao, et al., 2012), (Erb et al., 2012). Assumptions on energy crop yields are the main reason for the large differences in estimates of future area demand of energy crops. Likewise, assumptions on future food/feed crop yields have large implications for assessments of the degree of land competition between biofuels and these land uses.

Top-down models suggest that dedicated bioenergy crops are seen as an important and cost-effective component of the energy system, especially in scenarios with ambitious climate stabilization targets (Rose et al. in review). A model comparison across three Integrated Assessment Models (Popp et al., In Review) projected that in scenarios without climate change mitigation, bioenergy cropland represents 10-18% of total cropland by 2100 and boosts cropland expansion at the expense of higher-carbon ecosystems. Under long-run climate policies, bioenergy cropland increases to 24-36% of total cropland by 2100, but pricing carbon emissions from land-use change can help to reduce forest loss, especially in Latin America, Asia and Africa. However, across models, there are very different potential landscape transformation visions in all regions (6.3.5). Overall, it is difficult to generalize on regional land cover effects of mitigation. Some models are converting significant acreage, some are not. In idealized implementation climate policy scenarios, there is expansion of energy cropland and forest land in many regions, with some models exhibiting very strong forest land expansion and others very little by 2030. Land conversion is reduced in the 450 ppm scenarios compared to the 550 ppm scenarios, a result consistent with a declining mitigation role of land-related mitigation with policy stringency. The results of these top-down studies need to be interpreted with caution, as not all GHG emissions and biogeophysical effects of bioenergy deployment are incorporated into these models (see section 4.1), as livelihoods are not considered (see the beginning of this section), and as not all relevant technologies are represented (e.g. cascade utilization).

The cultivation of conventional agricultural crops such as cereals and oil seed crops as biofuel feedstock will lead to the same water consequences as when such crops are produced for food and feed. Large-scale bioenergy production may affect water availability and quality, which are highly dependent on (1) type and quantity of local freshwater resources; (2) necessary water quality; (3) competition for multiple uses (agricultural, urban, industrial, power generation) and (4) efficiency in all sector end-uses (Gerbens-Leenes et al., 2009; Coelho, Agbenyega, Agostini, Erb, Haberl, Hoogwijk, Lal, Lucon, Masera, and Moreira, 2012). In many regions, additional irrigation of energy crops would further intensify existing pressures on water resources (Popp, J.P. Dietrich, et al., 2011). In this case, energy crops compete directly for irrigation water with other agricultural activities. Studies indicate that an exclusion of severe water scarce areas for bioenergy production (mainly to be found in the Middle East, parts of Asia and western USA) would reduce global bioenergy potentials by 17 % until 2050 (van Vuuren et al., 2009). Further, exclusion of nature conservation and high biodiversity areas may reduce area and hence energy potentials of energy crops by 9-32% in 2050 (Erb et al., 2012); (Van Vuuren et al., 2009). According to Sala *et al* (2009) and FAO (2008) increased biofuel production from dedicated crops could have negative implications on biodiversity due to (i) habitat conversion and loss; (ii) agricultural intensification; (iii) invasive species; and (iv) pollution.

11.A.6 Conclusion

The climate change mitigation value of bioenergy systems depends on myriad factors, several of which are challenging to quantify. There are a wide range of estimates of regional and global supply potentials. The average technical potential estimated here is around 500 EJ (the total range, as estimated by the SRREN and including extreme scenarios, is between <50 to >1000 EJ). The average theoretical potential estimated here is around 500 EJ. Top-down scenarios project 15-225 EJ/yr deployment in 2050. Sustainability and livelihood concerns might constrain beneficial deployment to lower values.

A large body of recent research indicates the potential for some bioenergy systems to trigger emissions and biogeophysical climate forcings from land-use change, though the magnitude of the market induced effect is highly uncertain. Whether bioenergy systems mitigate climate change is uncertain in many cases and the answer depends on whether short or long time scales are considered. However, some first generation biofuel systems almost certainly cause net increases in GHG emissions today. To deliver net climate benefits with few negative environmental or socio-economic impacts, any bioenergy systems will have to consider a range of factors that influence the level of land use change related GHG emissions and biogeophysical perturbations, displacement of other land and water uses, other livelihood aspects such as employment, land access, and social assets, and biodiversity. Other crucial factors influencing mitigation potential are the biomass feedstock and production practices, the conversion technologies used, whether CCS can be used, biogeophysical land use effects, market-mediated effects such as iLUC and fossil fuel displacement. The perceived mitigation potential also depends on exactly how the accounting is performed (e.g., definition of baseline conditions, and spatial and temporal system boundaries).

Small-scale bioenergy systems such as biogas and efficient wood stoves for cooking, small scale decentralized biomass combustion and gasification for rural electrification could not only reduce GHG emissions but also promote other dimensions of sustainable development. Land is a finite and degradable resource with multiple functions and stakeholder interests, including bioenergy production. Land resources are under increasing pressure not only from bioenergy production but also due to increased demand for food and feed, urbanisation, infrastructure development, and so on. Bioenergy deployment must therefore be considered in the context of these general characteristics and trends, and it makes it even more pertinent to raise the efficiency of land use (especially closing of the yield gap) and to develop effective and inclusive land use governance systems and processes.

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