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INVITED REVIEW

How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals?

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Abstract

Feeding 9–10 billion people by 2050 and preventing dangerous climate change are two of the greatest challenges facing humanity. Both challenges must be met while reducing the impact of land management on ecosystem services that deliver vital goods and services, and support human health and well-being. Few studies to date have considered the interactions between these challenges. In this study we briefly outline the challenges, review the supply- and demand-side climate mitigation potential available in the Agriculture, Forestry and Other Land Use AFOLU sector and options for delivering food security. We briefly outline some of the synergies and trade-offs afforded by mitigation practices, before presenting an assessment of the mitigation potential possible in the AFOLU sector under possible future scenarios in which demand-side measures codeliver to aid food security. We conclude that while supply-side mitigation measures, such as changes in land management, might either enhance or negatively impact food security, demand-side mitigation measures, such as reduced waste or demand for livestock products, should benefit both food security and greenhouse gas (GHG) mitigation. Demand-side measures offer a greater potential (1.5–15.6 Gt CO_2-eq. yr^{-1}) in meeting both challenges than do supply-side measures (1.5–4.3 Gt CO_2-eq. yr^{-1} at carbon prices between 20 and 100 US\$ tCO_2-eq. yr^{-1}), but given the enormity of challenges, all options need to be considered. Supply-side measures should be implemented immediately, focussing on those that allow the production of more agricultural product per unit of input. For demand-side measures, given the difficulties in their implementation and lag in their effectiveness, policy should be introduced quickly, and should aim to codeliver to other policy agenda, such as improving environmental quality or improving dietary health. These problems facing humanity in the 21st Century are extremely challenging, and policy that addresses multiple objectives is required now more than ever.

Keywords: AFOLU, agriculture, climate, ecosystem services, food security, forestry, GHG, mitigation

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Introduction

The earth's lands provide humanity with a multitude of goods and services (Millennium Ecosystem Assessment, 2005), and as we move towards a global population of 9–10 billion people by 2050 (Godfray *et al.*, 2010), land availability becomes an ever more critical issue (Smith *et al.*, 2010). There are competing demands for land for providing food, water, timber, energy, settlements, infrastructure, recreation and biodiversity. (Lotze-Campen *et al.*, 2010; Lambin & Meyfroidt, 2011; Coelho *et al.*, 2012; Erb *et al.*, 2012a,b). Many previous assessments of the greenhouse gas mitigation potential in the Agriculture, Forestry and Other Land Use (AFOLU) sector have failed to account explicitly for the impact on the other services provided by land, and the inter-related nature of the global issues related to land use (Wirsenius *et al.*, 2010).

Perhaps two of the greatest challenges facing humanity are (1) the need to feed a growing population and (2) trying to avoid dangerous climate change and adapting to the impacts that we cannot avoid. The solution to both challenges must be met partly by changing the way we manage our land. If this dual challenge were not daunting enough, we also need to improve the resilience of food production to future environmental change (Easterling *et al.*, 2007), protect biodiversity (FAO, 2010), protect our freshwater resource (Frenken & Kiersch, 2011), move to healthier diets (WHO, 2004, and reduce the adverse impacts of food production on the whole range of ecosystem services (Firbank *et al.*, 2011). The challenge related to providing enough food for this growing population is likely to be greater than implied by the population increase alone as standard of living is increasing in many countries with a *per capita* increase in calorific intake.

Most studies to date (with a few notable exceptions) have focussed on one challenge or another (e.g. GHG mitigation, food security, energy provision), but have not considered the complex knock-on effects that arise from the use of land. For example, in the two most recent assessment reports by the Intergovernmental Panel on Climate Change (IPCC; IPCC, 2001, 2007), greenhouse gas mitigation potential in the AFOLU sector was assessed using the SRES scenarios (Nakicenovic *et al.*, 2000), the storylines of which prescribed changes in population, wealth and dietary preference. Because of this, consumption-based measures (e.g. changes in food demand and dietary shifts) in the AFOLU sector have never been fully assessed by the IPCC. In addition, the agriculture and forestry sectors have largely been assessed separately; they were dealt with in separate chapters in the Fourth Assessment Report (IPCC, 2007). For these reasons, an integrated consideration of the land available for mitigation, and for delivering the many other goods and services it provides, has not occurred within IPCC Assessment Reports to date.

In this study, we explore how the AFOLU sector can contribute to greenhouse gas mitigation and how food supply capacity can be maintained, while using the same limited land base. Furthermore, we examine how supply-side and consumption-side measures (and the interactions between them) might be used to address the dual challenges of food security and climate change. To provide the state of the art, we focus mainly on literature published since the last IPCC Assessment Report (IPCC, 2007).

Global challenges for the AFOLU sector

The food security challenge

Feeding 9–10 billion people by 2050 will be an enormous challenge (Evans, 1998; Godfray *et al.*, 2010), and has been a topic for many decades (Pimental *et al.*, 1973). A number of options have been proposed to help address the food security challenge, including closing the yield gap (reducing the difference between the

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attainable yield and that actually realized), increasing the production potential of crops (largely through use of new technologies and investment in research), reduced waste, increasing multipurpose systems, changing diets and expanded aquaculture, which all need to be coordinated in a multifaceted and linked global strategy to ensure sustainable and equitable food security (Godfray *et al*., 2010; Tilman *et al*., 2011).

The climate change challenge

The United Nations Framework Convention on Climate Change (UNFCCC) was established to limit future climate change to a mean temperature not exceeding 2 °C above preindustrial times (UNFCCC, 2012). This is an extremely demanding target; there are various ways of meeting this target, but all require limiting increases in (or even reducing) the CO_2 concentration in the atmosphere, meaning that very significant cuts (>80%) in GHG emissions are needed over the coming decades (Meinshausen *et al*., 2009). AFOLU is estimated to be responsible for around 17–31% of anthropogenic GHG emissions (Bellarby *et al*., 2008), and there is significant potential for reducing these emissions, largely through reduced non-CO_2 emissions from agriculture, avoiding deforestation and forest degradation, net carbon sequestration in soil and vegetation (Nabuurs *et al*., 2007; Smith *et al*., 2007a) and use of land for provision of renewable, low carbon energy bioenergy (Chum *et al*., 2011; Coelho *et al*., 2012). Land use is therefore a critical component of any climate change solution.

Nonprovisioning ecosystem services

The land delivers a multitude of goods and services in addition to the provision services of food and fibre that it is usually managed for (Smith *et al*., 2012a). Of the goods and services considered by the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005), land is critical in delivering the following goods: food, fibre, energy, water, natural medicine, recreation, tourism, pollution and noise control, pest and disease control, equitable climate, erosion control and plays a role in delivering some aesthetic, inspirational and spiritual/religious cultural services (UKNEA, 2011). Underpinning these final goods and services, the land is also instrumental in delivering biodiversity, and the intermediate services of primary production, water cycling, soil formation, nutrient cycling and decomposition (UKNEA, 2011). In managing the land for either GHG mitigation, or for delivering food and fibre, the other goods and services are also potentially affected, either positively or negatively (e.g. Smith *et al*., 2012a).

Land as a limiting resource

Not all of the total land area of the planet (134 million km^2) is suitable for food production, due to climatic, soil and topographic constraints. FAO (2011) estimates that the area of current cropland production is 15.6 million km^2, with an estimated additional 27 million km^2 potentially available as prime or good land for the cultivation of conventional food and feed crops. FAO projects that the cropland area may expand by about 1.5–2.0 million km^2 up to 2050 under a business-as-usual scenario, where most of the increase in food supply will come from intensification (Fischer *et al*., 2011).

Land is used for many purposes, e.g. production of goods and services through agriculture and forestry, housing and infrastructure and absorption or deposition of wastes and emissions (Dunlap & Catton, 2002). Many of these functions limit the ability to deliver others, e.g. the area required for crops is not available for forestry or housing, leading to competition for land. In some cases land use is related to the nature of land, e.g. forestry on steep, rocky slopes; in other cases land can be used for several purposes, illustrated in particular by small farmers and indigenous groups in developing countries. Economic and population growth, changing consumption patterns and increased demand for bioenergy are expected to increase the competition for scarce land and water resources (Berndes, 2002; Smith *et al*., 2010; Woods *et al*., 2010).

Mitigation activities in agriculture and forestry can result from (1) changes in land management practices and technology (referred to here as supply-side measures), or (2) changes in the consumption of land-based resources (e.g. diets; referred to here as demand-side measures). Demand-side and supply-side measures may result in very different feedbacks, with different synergies and trade-offs. All of these feedbacks are influenced by climate change, through its impact on crucial ecophysiological drivers such as temperature, water availability and CO_2 content of the atmosphere.

Figure 1 shows why synergies and trade-offs are different for demand-side and supply-side measures. Demand-side measures save GHG emissions (1) by reducing the production emissions (e.g. CH_4 from enteric fermentation, N_2O from fertilizers or CO_2 from tractor fuels) and also GHG emissions associated with inefficiencies and management of organic waste (2) by reducing land demand, i.e. making areas available for other uses, e.g. afforestation or bioenergy, or allowing adoption of less intensive or more integrated cultivation technologies such as organic or agro-ecological agriculture (Stehfest *et al*., 2009; Popp *et al*., 2010;

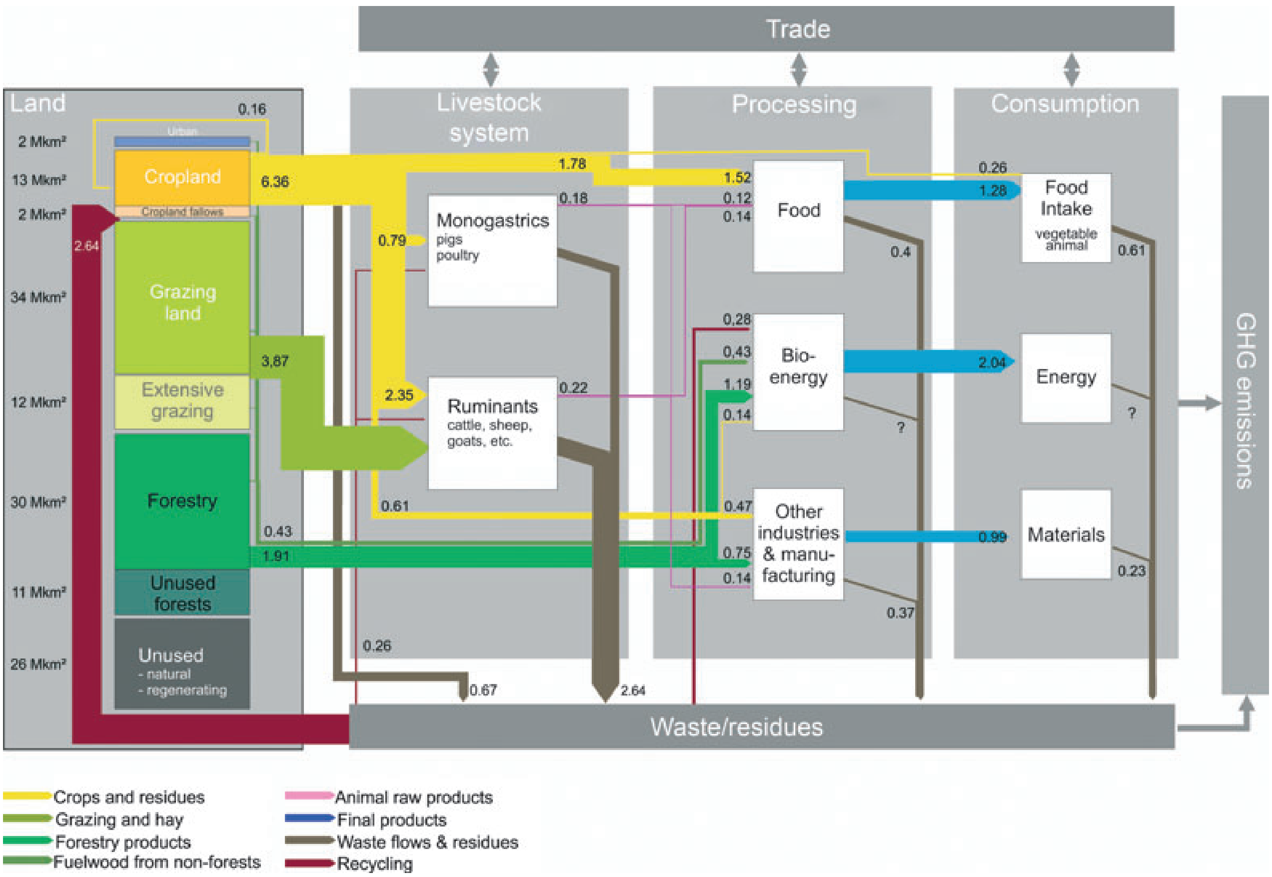

Fig. 1 Global land use and biomass flows in 2000 from the cradle to the grave. Values in Pg dm yr^{-1} (= Gt dry matter yr^{-1}) dry matter. Sources: Area estimates from Erb *et al.*, (2007); Schneider *et al.*, (2009); FAO, (2010). Data on biomass harvest on cropland and grazing land, food and feed production and animal product output taken from Krausmann *et al.*, (2008). The allocation of cropland products to material and energy use (mainly harvested crop residues) based on shares in Wirsenius, (2003). Data on forestry harvest from FAOSTAT, (2011). Data from Sims *et al.*, (2006) were used to approximate wood-fuel harvest from nonforested land and compartments not contained in FAOSTAT. Bioenergy flows to final consumption derived from Sims *et al.*, (2006). Energy units were converted into dry-matter biomass using an average energy content of 18.5 MJ kg^{-1}. Waste flows from livestock systems include manure and bedding materials, both assumed to be brought to fields or dropped during grazing. Waste flows from the livestock system comprise offal and fats from meat production; material processing generates residues from wood processing. Some of these flows are recycled in energy production. Waste flows from material consumption include recovered wood in buildings and solid wastes (derived from Sims *et al.*, 2006). Food consumption losses include food losses, human faeces and urine and were estimated based on ratios derived from Kummu *et al.*, (2012) and Wirsenius, (2000). Residues inputs in the livestock sector include, e.g. bran, oil cakes and uneaten food. Flows from processing to final use (blue) were derived by subtracting inputs and outputs for each compartment and are thus indicative only. The difference between inputs and outputs in the consumption compartment is assumed to be directly released to the atmosphere (e.g. CO_2 from respiration). Note: many of these data are uncertain; many data sources were merged. Although this was done as carefully as possible, double counting cannot be entirely ruled out. Furthermore, official statistics frequently do not take biomass flows in subsistence economies into account, which may therefore not be fully captured in this figure. Nevertheless, it is a useful indication of the scale of global biomass flows through various compartments.

Erb *et al.*, 2012a,b). The ecological feedbacks of demand-side measures are, therefore, generally beneficial, as they reduce competitive demand for land and water. Health impacts are also deemed positive, as the studies considered here generally assume a switch to healthier diets (see below). This is different to supply-side measures which may require either more land and/or more inputs (e.g. fertilizers and irrigation water) of other resources. Based on Fig. 1 one may distinguish four cases:

- *Reducing waste and optimization of biomass-flow cascades* through use of residues and by-products, recycling and energetic use of wastes and residues (Haberl & Geissler, 2000; Haberl *et al.*, 2003; WBGU, 2009). Such measures increase the efficiency of resource use, but there may be trade-offs as well. For example, using crop residues for bioenergy or roughage supply may leave less C in cropland ecosystems, and may adversely impact soil quality and the C balance of croplands (Blanco-Canqui & Lal, 2009; Ceschia *et al.*, 2010).

- *Land-sparing measures* include measures such as increases in yields in croplands (Burney *et al.*, 2010; Popp *et al.*, 2011a; Tilman *et al.*, 2011), grazing land or forestry or increases in the efficiency of biomass conversion processes such as livestock feeding (Steinfeld *et al.*, 2010; Thornton & Herrero, 2010). Such options reduce demand for land, but there may be trade-offs with other ecological, social and economic costs (IAASTD, 2009) that need to be mitigated (Tilman *et al.*, 2011). Increases in yields may also increase consumption (Lambin & Meyfroidt, 2011; Erb *et al.*, 2012a,b; Rose *et al.*, 2013), and cause local and regional land expansion, as technological improvements and productivity gains potentially also make agricultural activity more profitable and thus more attractive (Lambin & Meyfroidt, 2011; Rose *et al.*, 2013). Whether the net effect is a reduction in GHG emissions depends on the land-use change (LUC) emissions.
- *Land-demanding measures* that harness the production potential of the land for either C sequestration, maintenance of C stocks or production of dedicated energy crops. These options increase demand for land (and often water) and may have substantial social, economic and ecological effects (positive or negative) that need to be managed sustainably (UNEP, 2009; WBGU, 2009; Chum *et al.*, 2011; Coelho *et al.*, 2012). Such measures may directly or indirectly result in higher land pressure, inducing changes in land management and LUC, resulting in net C emissions or removals depending on whether changes result in larger or smaller C stocks. The common example of C stock losses is when forests are converted into croplands, which contribute to price increases in agricultural products or negatively affect livelihoods of poor people that need to be balanced against possible positive effects such as investments improving agriculture productivity, GHG reduction or job creation (Chum *et al.*, 2011; Coelho *et al.*, 2012).
- *Alternative uses of biomass* such as the use of grains for food, animal feed and as feedstock for biofuels, or the use of wood residues for chipboards, paper and bioenergy, offer opportunities for the agriculture and forestry sectors, which can find new markets for their products and also make economical use of biomass flows previously considered to be waste. But it may also result in increased land demand with the effects already described above.

An integrated energy/agriculture/land-use approach for mitigation in AFOLU is necessary to optimize synergies and mitigate negative effects (Popp *et al.*, 2011b; Creutzig *et al.*, 2012; Smith, 2012a). In the following sections we review recent literature providing estimates of the mitigation potential in the AFOLU sector, and studies proposing options for delivering food security, before analysing interactions between GHG mitigation, food security and the provision of other ecosystem services by land.

GHG mitigation in the AFOLU sector

Supply-side estimates of GHG mitigation potential in the AFOLU sector

Supply-side mitigation measures act by reducing the net GHG emissions from agriculture and forestry by changes in management. There are six main ways that supply-side mitigation activities in the AFOLU sector can reduce climate forcing, which are discussed below.

Reductions in direct N_2O or net CH_4 emissions from agriculture could result in emission reductions of around 600 Mt CO_2-eq. yr^{-1} in 2030, according to bottom-up estimates in Smith *et al.*, (2008). Estimates from top-down models range from about 270–1900 Mt CO_2-eq. yr^{-1} (Smith *et al.*, 2007a). Reductions in N_2O largely arise through better management of soils and fertilizer applications, whereas reductions in CH_4 emissions arise from managing enteric fermentation emissions from livestock, emissions from rice paddies and emissions from manure management (Smith *et al.*, 2008). More recent estimates suggest a higher mitigation potential for N_2O reduction from fertilizer use (Flynn & Smith, 2010; Reay *et al.*, 2012) than estimated in Smith *et al.*, (2007a, 2008). Additives that modify the conversion processes affecting N in soil to decrease N_2O emissions can be synthetic (e.g. nitrification inhibitors) or organic (biochar). Reductions can be measured in absolute terms, or as emissions intensity, which is a measure of GHG emissions per unit of agricultural product.

Potential reductions in GHG emissions from energy use in agriculture and forestry (Spedding & Walsingham, 1976) from direct (e.g. tractors) or indirect (e.g. production of fertilizers) uses were estimated to be 770 Mt CO_2-eq. yr^{-1} in 2030 by Smith *et al.*, (2008). Schneider & Smith, (2009) suggested that energy emissions from global agriculture could be reduced by 500 Mt CO_2-eq. yr^{-1} if countries with below-average energy efficiency in agriculture increased their efficiency to the average levels of the year 2000. Like the substitution of fossil fuels by bioenergy (see below), the emission reduction occurs in the energy, industry, transport and buildings sectors.

Reductions in carbon losses from biota and soils have the potential to reduce GHG emissions significantly through reductions in loss of large carbon stores such as those in soils (particularly, soils rich in carbon such as peatlands) and vegetation (particularly, vegetation with large carbon stocks such as forests). These large carbon stores can be protected and sustainably managed by policies such as REDD (Reduced Emissions from Deforestation and Degradation), whereby the total elimination of deforestation by 2030 could theoretically deliver a mitigation potential ~2.3–5.8 Gt CO_2-eq. yr^{-1} (Sathaye *et al.*, 2006; Blaser & Robledo, 2007; UNFCCC, 2007; Strassburg *et al.*, 2008). Peatland carbon stocks, amounting to >2000 Gt CO_2-eq. (Joosten *et al.*, 2013), could be protected by similar policies. Leakage effects may reduce the effectiveness of protection measures, which also need to be evaluated.

Enhancement of carbon sequestration in biota and soils has the potential to reduce net GHG emissions by increasing carbon stocks in soils and vegetation. The technical mitigation potential for carbon sequestration in agricultural soils (including the restoration of cultivated organic soils, which could also be considered as a reduced loss of carbon – see above) was estimated to be around 4.8 Gt CO_2-eq. y^{-1} in 2030, with economic potentials of 1.5, 2.2 and 2.6 Gt CO_2-eq. yr^{-1} at carbon prices of 0–20, 0–50 and 0–100 USD t CO_2-eq.$^{-1}$ respectively (Smith *et al.*, 2007a, 2008; Smith, 2008). The potential for net sequestration of carbon through afforestation, reforestation, forest restoration and improved forest management (but excluding reduced deforestation – see above) was estimated to be 2.3–5.7 Gt CO_2-eq. yr^{-1} [adding the global values for forestation and sustainable forest management (Nabuurs *et al.*, 2007)]. Another possibility is to intercept and stabilize carbon cycling from plant to atmosphere through pyrolysis – producing both bioenergy in the form of combustible syngas and returning carbon to soil in the form of biochar (the solid product of pyrolysis). This has an estimated technical potential to sequester 1.6 Gt CO_2 yr^{-1} into soil compared with alternative use of the material converted (Woolf *et al.*, 2010; Berndes *et al.*, 2011).

Change in albedo and evapotranspiration. LUC may also influence climate by modifying physical properties of the surface, altering for instance evapotranspiration and albedo, i.e. the extent to which the land surface reflects incoming sunlight. These impacts can be significant (Betts *et al.*, 2007; Bernier *et al.*, 2011), but as we focus on GHG emission reduction, we will not discuss them further here.

Provision of biomass with low-GHG emissions that can replace high-GHG materials and fossil fuels uses either dedicated energy crops (Havlík *et al.*, 2011) or residues from agriculture (straw, dung) or forestry (e.g. forest thinnings, slash). Like the improvement of energy efficiency (see above), the emission reduction occurs in the energy, industry, transport and buildings sectors. The estimates for the potential for GHG mitigation from bioenergy range very widely due to different assumptions about the land available (e.g. only degraded land to any land) and the fossil fuels replaced (i.e. gas vs. oil vs. coal), and assumptions about the magnitude of indirect emissions and the effectiveness to avoid them (e.g. through introduction of sustainability criteria). Estimates from global top-down energy system/economic models in IPCC AR4 estimated the GHG mitigation potential to be 0.7–1.3 Gt CO_2-eq. yr^{-1} at carbon prices up to 20 USD t CO_2-eq.$^{-1}$ and ~2.7 Gt CO_2-eq. yr^{-1} at prices above 100 USD t CO_2-eq.$^{-1}$ (Smith *et al.*, 2007a). Only few studies so far have comprehensively assessed the interaction of many terrestrial mitigation measures and their competitive interactions (Obersteiner *et al.*, 2010).

Demand-side mitigation potentials in the AFOLU sector

The character of food and fibre demand can strongly influence GHG emissions in the production chain. Given the food security issues discussed elsewhere in this article, this is a sensitive issue. Nevertheless, there are opportunities in both developing and industrialized countries today, which may become even more important for currently developing and emerging regions, if a similar consumption path to industrialized regions is followed in the future.

Two options exist to reduce GHG emissions through changes in food demand: (1) Reduction in losses and wastes of food in the supply chain as well as during final consumption (e.g. food bought and wasted during preparation or not consumed at all), and (2) changes in diet, towards less resource-intensive food, i.e. shifts to less GHG-intensive animal food products (notably from ruminant meat to pig and poultry), or to appropriate plant-based food to maintain protein supply, as well as reduction in overconsumption in regions where this is prevalent.

As regards reductions in losses in the food supply chain, globally, it has been estimated that approximately 30–40% of all food production is lost in the supply chain from harvest to final consumers (Godfray *et al.*, 2010). In developing countries, losses of up to 40% occur on farm or during distribution as an effect of poor storage, distribution and conservation technologies and procedures. In developed countries, losses of food on farm or during distribution are smaller, but up to 40% are lost in services 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 of these losses are 'avoidable' or 'potentially avoidable'. In the United Kingdom, 18% of the food waste was classified as 'unavoidable', the same amount as 'potentially avoidable' and 64% as 'avoidable' (Parfitt *et al.*, 2010). Parfitt *et al.* (2010) compared recent data for industrialized countries (Austria, Netherlands, Turkey, United Kingdom, United States) and found food waste at the household level of 150–300 kg food per household per year.

A mass-flow modelling study based on FAO commodity balances that covered the whole food supply chain, but excluded nonedible fractions, found per capita food loss values ranging from 120 to 170 kg cap^{-1} yr^{-1} in Sub-Saharan Africa, to 280–300 kg cap^{-1} yr^{-1} in Europe and North America (Gustavsson *et al.*, 2011). Despite substantial uncertainties, calculated losses ranged from 20% in Sub-Saharan Africa to >30% in the industrialized regions.

Most of these studies suggest a range of measures to reduce wastes throughout the food supply chain, including investments into harvesting, processing and storage technologies primarily in the developing countries, as well as awareness raising, taxation or retail-sector measures targeted at reduction in retail and consumer-related losses, primarily in the developed countries. However, none of the studies reviewed presents detailed, comprehensive bottom-up estimates of mitigation potentials, although the potentials are likely to be quite substantial (Reay *et al.*, 2012). Global land-use-related GHG emissions in 2050 in a 'business as usual' scenario are estimated to be approximately 11.9 Gt CO_2-eq. yr^{-1} (Stehfest *et al.*, 2009). Reay *et al.* (2012) assess that for five food types (milk, poultry, pig and sheep meat and potatoes), loss and wastage-associated emissions total more than 200 Gg N_2O-N. yr^{-1}, equal to approximately 3% of global N_2O emissions from agriculture.

For changes in diets, excluding LUC, studies show lower GHG emissions for most plant-based food than for animal products, with the exception of vegetables grown in heated greenhouses or transported via air-freight (Carlsson-Kanyama & González, 2009). This also holds for GHG emissions per unit of protein, when animal-based and plant-based protein supply is compared (González *et al.*, 2011). If land used for the production of different animal food products was instead assumed to sequester C corresponding to modelled natural vegetation growth, the resulting C sink would equate to 25–470% of the GHG emissions associated with the food production – assuming the land was not subject to any other LUC during 30–100 years (Schmidinger & Stehfest, 2012).

Modelling studies show that changes in future diets can have a significant impact on GHG emissions from food production. Using the GLOBIOM model, Havlík *et al.* (2011) suggest that GHG mitigation potentials could be close to 2 Gt CO_2-eq. yr^{-1} under different future scenarios of crop and livestock production. Using a coupled model system, comprising the land-use allocation model MAgPIE and the dynamic global vegetation model LPJmL, Popp *et al.* (2010) examined several scenarios: In a 'constant diet' scenario that considers only population growth, agricultural non-CO_2 emissions (CH_4 and N_2O) would rise from 5.3 Gt CO_2-eq. yr^{-1} in 1995 to 8.7 Gt CO_2-eq. yr^{-1} in 2055. If current dietary trends (increased consumption of animal-related food) were assumed to continue, emissions were projected to rise to 15.3 Gt CO_2-eq. yr^{-1}, whereas the GHG emissions of a 'decreased livestock product scenario' were estimated to be 4.3 Gt CO_2-eq. yr^{-1} in 2055. A combination of increased consumption of livestock products and implementation of technical mitigation measures (supply-side measures) reduced emissions compared with the scenario with increased consumption of livestock products, but emissions in 2055 were still higher than in the 'constant diet' scenario (9.8 Gt CO_2-eq. yr^{-1}), whereas the emissions could be reduced to 2.5 Gt CO_2-eq. yr^{-1} in 2055 in a 'reduced meat plus technical mitigation' scenario. Popp *et al.* (2010) concluded that the potential to reduce GHG emissions through changes in consumption (i.e. demand-side measures) was substantially higher than that offered by supply-side, technical GHG mitigation measures.

Stehfest *et al.* (2009) examined the effects of changes in diets on GHG emissions based using the IMAGE model; their study included CO_2, CH_4 and N_2O. They estimated that land-use-related GHG emissions (including C sequestration in land) will rise to 11.9 Gt CO_2-eq. yr^{-1} in the year 2050 in a scenario largely based on FAO (2006). They investigated several other diets, (1) no ruminant meat – here all ruminant meat is substituted by proteins derived from plant products, (2) no meat – all meat substituted by plant products, (3) no animal products – all animal products, including eggs and milk, substituted by plant products and (4) a 'healthy diet' based on recommendations of the Harvard Medical School – this diet implies reductions in animal product intake in countries with rich diets, but increases in countries with poor, protein-deficient diets. Their findings show a huge range of future emissions with changes in diets resulting in GHG emissions compared with business as usual ranging from 36% to 66% (see Table 1). Depending on the scenario, CO_2 contributed 44–67% to the total emission reduction, CH_4 28–47% and N_2O 6–11%. A large fraction of the

Table 1 Food supply-chain-related GHG mitigation potentials in 2050

	Global GHG reduction potential compared with 'business as usual' scenario [Gt CO_2-eq yr^{-1}]	Sources
Reduction in food supply chain losses and wastes	0.76–1.5	Extrapolation from Gustavsson *et al.* (2011) and Stehfest *et al.* (2009)
Switch to a 'no ruminant meat' diet	5.8*	Stehfest *et al.* (2009)
Switch to a 'no meat' diet	6.4*	Stehfest *et al.* (2009)
Switch to a purely plant-based diet	7.8*	Stehfest *et al.* (2009)
Switch to a 'healthy' diet (Harvard Medical School)	4.3*	Stehfest *et al.* (2009)

*Original values were given in C-eq and were converted into CO_2-eq by multiplication with 3.66667.

total GHG reduction was due to the availability of larger areas for carbon sequestration; in addition to the above-cited reductions in land-based emissions, land sparing was also assumed to allow for a higher bioenergy production, which helped to lower GHG emissions in the energy sector. Stehfest *et al.* (2009) also analysed the effects of the adoption/nonadoption of dietary change on abatement costs required to reach a predefined GHG concentration target (450 ppm CO_2-eq.). They found that a global adoption of the 'healthy diet' would reduce global GHG abatement costs by about 50% compared to the reference case because fewer costly measures in the energy sector are required if these large, and comparably cost effective, mitigation potentials in the land sector are implemented.

For demand-side options related to wood and forestry, global carbon stocks in long-lived products (i.e. carbon contained in products in use; e.g. wood or plastics in buildings, libraries or furniture, roads paved with bitumen, but not carbon in landfills) were approximately 8.4 Gt CO_2 in 1900 and increased to 37.0 Gt CO_2 in 2008. Per capita C stocks remained about constant at ~5 t CO_2 cap^{-1} with a falling share of wood products (68% in 2008) and a rising share of plastics and bitumen. The rate of C sequestered in these stocks increased from 62 Mt CO_2 yr^{-1} in 1900 to a maximum of 690 Mt CO_2 yr^{-1} in 2007. The net amount of C sequestered annually (C inflows minus C outflows of socioeconomic C stocks) in long-lived wood products in recent decades ranged from ~180 to 290 Mt CO_2 yr^{-1} (Lauk *et al.*, 2013). If inflows were to rise through increased use of long-lived wood products, C sequestration in wood-based products could be enhanced, thus contributing to GHG mitigation. Substitution of GHG-intensive construction materials (such as concrete) with wood may reduce emissions, but reuse of the wood for energy at the end of its life in buildings is critical (Böttcher *et al.*, 2012; Nässén *et al.*, 2012) as are the GHG reduction policies implemented in the energy sector.

Improving traditional biomass use, which is mostly devoted to satisfy the cooking energy needs of 2.7 billion people worldwide and involves large emissions of GHG gases and black carbon will also help mitigate climate change. Improved cookstoves (ICS) and other advanced biomass systems for cooking are cost effective for achieving large benefits in energy use reduction and climate change mitigation (Berrueta *et al.*, 2008). The global mitigation potential of advanced ICS, excluding black carbon emission reductions, was estimated to be between 0.6 and 2.4 Gt CO_2-eq. yr^{-1}. Reduction in fuel wood and charcoal through adoption of advanced ICS may help reduce pressure on land and improve aboveground biomass stocks and soil and biodiversity conservation (Chum *et al.*, 2011).

Food security

Food security is a multifaceted challenge, involving much more than just food production. Indeed, food production is just one of the challenges of providing food availability (which also relies on distribution and exchange), and food availability is just one aspect of food security which includes also food access and food utilization (see Smith & Gregory, 2013). In this review, we do not attempt to address all aspects of food security; rather we focus on those aspects of food security that interface with greenhouse gas mitigation in agriculture. Historical expansion of agriculture into forests and natural ecosystems (Bruinsma, 2003) has contributed significantly to the loss of what we now refer to as ecosystem services (Costanza *et al.*, 1997). Because many ecosystem services are lost on such conversion, it is apparent that future increases in food supply need to be met without large increases in agricultural area, i.e. to derive more agricultural products from the same area (Godfray *et al.*, 2010; Smith *et al.*, 2010; Smith, 2012b).

The main means of intensifying crop production will be through increased yields per unit area together with a smaller contribution from an increased number of crops grown in a seasonal cycle. As cereal production (wheat, maize and rice) has increased from 877 Mt in 1961 to 2342 Mt in 2007, the world average cereal yield has increased from 1.35 t ha^{-1} in 1961 to 3.35 t ha^{-1} in 2007, and is projected to be about 4.8 t ha^{-1} in 2040. Simultaneously, per capita arable land area has decreased from 0.415 ha in 1961 to 0.214 ha in 2007 (Smith *et al.*, 2010). Put another way, had the increases in yield of the last 60–70 years not been achieved, almost three times more land would have been required to produce crops to sustain the present population; land that does not exist except by using some that is unsuitable for cropping. So some form of sustainable intensification of food production will be required (Garnett & Godfray, 2012).

Smith (2012b) and Smith & Gregory (2013) recently reviewed the literature exploring options for sustainable intensification, which are outlined below. Tilman *et al.* (2011) conclude that securing high yields on existing croplands of nations where yields are suboptimal is very important if global crop demand is to be met with minimal environmental impact. At the high-tech end are options such as the genetic modification in living organisms and the use of cloned livestock and nanotechnology (IAASTD, 2009; Godfray *et al.*, 2010; Foresight, 2011), whereas at the low-tech end are options such as the closure of yield gaps, e.g. by the redistribution of inputs such as nitrogen fertilizer from regions which overfertilize (such as China) to regions were nitrogen supply is limiting (such as much of sub-Saharan Africa; Foley *et al.*, 2011; Mueller *et al.*, 2012; Porter *et al.*, 2010; Tilman *et al.*, 2011).

Godfray *et al.* (2010) examined the possibility of increasing crop production limits, as not all crop yields are similar, with some plant species being far more productive. They argue that modern genome sequencing techniques will allow a range of food crops to be developed more quickly than has been possible in the past, and without the reliance on increased water and fertilizer input that characterized the Green Revolution. Whereas current genetically modified crops rely on single gene manipulations, Godfray *et al.* (2010) suggest that by 2050, it will be possible to manipulate traits controlled by many genes and confer desirable traits (such as improved nitrogen and water-use efficiency). Cloned animals with innate resistance could also reduce losses from disease. Genetic manipulation, then, could play a role in future sustainable intensification, although in some regions (such as Europe) public opposition to genetic modification currently prevents its use.

Foley *et al.* (2011) and Mueller *et al.* (2012) examined the closure of the yield gap as a mechanism of sustainable intensification (in some regions) by rebalancing the distribution of inputs to optimize production. Cassman *et al.* (2002) noted that many regions of the globe are overfertilized, whereas others are underfertilized. Foley *et al.* (2011) also showed that benefits and impacts of irrigation are not evenly distributed and that water needed for crop production varies greatly across the globe. They suggest that redistributing these imbalances could largely close the yield gap, and show that bringing yields to within 95% of their potential for 16 important food and feed crops could add 2.3 billion tonnes (5×10^{15} kilocalories = 21×10^{15} kJ = 21 EJ) of new production, which represents a 58% increase (Foley *et al.*, 2011). Closing the yield gap of the same crops to 75% of their potential would give a global production increase of 1.1 billion tonnes (2.8×10^{15} kilocalories = 11.7×10^{15} kJ = 11.7 EJ), which is a 28% increase. Mueller *et al.* (2012) updated this work by examining nutrient redistribution and improved water management in more detail.

Other agronomic mechanisms for increasing crop productivity include better matching of nutrient supply to crop need (e.g. improved fertilizer management, precision farming), better recycling of nutrients, improved soil management (to reduce erosion, maintain fertility and improve nutrient status) and better matching of crops with the bioclimatic regions where they thrive. All of these efficiency improvements are possible now, but their impact on closing the yield gap remains largely unquantified. Another parameter that needs to be considered is water management. Availability of water and competition for different water uses can have an important impact on agricultural productivity as well as a number of social impacts (Rockström *et al.*, 2010).

As described in the paragraphs above, considerable attention has been paid to prospects for increasing food availability, and limiting agricultural expansion, through higher yields on cropland. In contrast, prospects for efficiency improvements in the entire food-chain and dietary changes towards less land-demanding food have not been explored as extensively (Wirsenius *et al.*, 2010). Given that conversion efficiency of plant to animal matter conversion is in the region of 10%, and that about a third of the world's cereal production is fed to animals, a reduction in the livestock product consumption could greatly reduce the need for more food. On average, the production of beef protein requires several times the amount of land and water than the production of vegetable proteins, such as cereals. Whereas meat currently represents only 15% of the total global human diet, approximately 80% of the agricultural land is used for animal grazing or the production of feed and fodder for animals.

Much of the increasing demand for livestock products to 2050 is projected to occur in developing countries (FAO, 2006). Changes towards diets that include less livestock products reduce food demand, increase food supply potential and dramatically decrease the demand for land (Smith & Gregory, 2013). In a reference scenario of Wirsenius *et al.* (2010) – developed to represent FAO projections – global agricultural area expands from the current 5.1 billion ha to 5.4 billion ha in 2030. In the faster-yet-feasible livestock productivity growth scenario, global agricultural land use decreases to 4.8 billion ha. In a third scenario, combining the higher productivity growth with a substitution of pork and/or poultry for 20% of ruminant meat, agricultural land use drops further, to 4.4 billion ha. In a fourth scenario, applied mainly to high-income regions that assumes a minor transition towards vegetarian food (25% decrease in meat consumption) and a somewhat lower food wastage rate, agricultural land use in these regions decreases further, by about 15% (Wirsenius *et al.*, 2010).

Synergies and trade-offs of mitigation in the AFOLU sector with other environmental outcomes

The implementation of the AFOLU mitigation measures (Section 2) will result in a range of other outcomes, some being beneficial (synergies) and others detrimental (trade-offs; Smith *et al.*, 2007b). Apart from considering activities in terms of net GHG mitigation benefit, other outcomes that can be considered including profitability (Sandor *et al.*, 2002), energy use, biodiversity (Koziell & Swingland, 2002; Venter *et al.*, 2009), aspects of social amenity and social cost. Some of these factors can be easily measured, whereas metrics for others are less clear. Modelling frameworks are being developed which allow an integrated assessment of multiple outcomes at project to national scales.

Synergies

In several cases, the implementation of AFOLU mitigation measures may result in an improvement in land management. There are many examples where existing land management is suboptimal, resulting in various forms of desertification or degradation including wind and water erosion, sedimentation of rivers, rising groundwater levels, groundwater contamination, eutrophication of rivers and groundwater or loss of biodiversity. Management of these impacts is implicit in the United Nations Convention to Combat Desertification (UNCCD, 2011) and Convention on Biological Diversity (CBD), and thus mitigation action may contribute to a broader global sustainability agenda.

Major potential synergies include:

- *Increases in food and fibre production*: including increases in food yields and timber production, such as within agroforestry systems, or the conversion of agriculture to forestry.
- *Increases in water yield and quality*. Water yield and quality is often affected by land management and surface cover, in particular (Calder, 2005). Reducing deforestation and shifting from annual crops to perennial plants can reduce water quality impacts such as eutrophication, turbidity and salinity (Maes *et al.*, 2009; Dimitriou *et al.*, 2011). Plantations can be managed as buffer strips for capturing the nutrients in passing run-off water (Börjesson & Berndes, 2006; Dimitriou & Rosenqvist, 2011). Watershed restoration by reforestation can result in an array of benefits including improvements in water quality (Townsend *et al.*, 2012), biodiversity (Swingland *et al.*, 2002), shading to reduce water temperatures (Deal *et al.*, 2012) or improvements in amenity.
- *Improvements in biodiversity conservation*: Biodiversity conservation can be improved both by reducing deforestation, and by using reforestation/afforestation to restore biodiverse communities on previously developed farmland (Koziell & Swingland, 2002; Swingland *et al.*, 2002; Harper *et al.*, 2007). Integration of perennial grasses and woody plants into monocultural landscapes can similarly improve species diversity (Dimitriou *et al.*, 2011). Reforestation may also provide a mechanism to fund translocation of biodiverse communities in response to climate change;
- *Improvements in sustainable agriculture*: 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 as can biomass plantations.
- *Restoration of degraded land:* Reforestation or bioenergy systems can be used to restore or stabilize degraded land (Wicke *et al.*, 2011; Sochacki *et al.*, 2012). In many cases, there is no economic incentive to restore such lands, and carbon mitigation may not only provide the capital to allow this to occur but also allow it to occur at watershed or catchment scales (Harper *et al.*, 2007).
- *Increase in economic activity*: Economic activity can increase through an increase in the overall capital available in particular systems and thus intensification. Examples include the capital costs of mitigation systems that involve the reforestation or revegetation of agricultural land, and the

consequent increase in demand for labour and other inputs. In some situations, several synergies can be sold (e.g. timber, water), thus providing additional cash flow for landholders.

Several of these synergies may result in additional payment streams – and thus impact on the net cost of mitigation. Examples include reforestation schemes that also produce timber. Other synergies may not be easily valued.

Trade-offs

In some situations mitigation activities may result in negative consequences. Examples of trade-offs include:

- *Competition with food availability ('food vs. fuel')*. Mitigation measures may result in a decrease in the amount of land available for food production (e.g. reforestation of farmland to sequester carbon or produce bioenergy), decrease yields (e.g. competition between trees and crops, reduced yields with reduced fertilizer inputs) or directly compete for food materials as a bioenergy feedstock (e.g. conversion of sugar or maize into ethanol). Also, strategies targeting land that is judged as not needed or unsuitable for food crops can impact food production by claiming other resources (labour, capital) that otherwise might have been used for food production.
- *Impacts on water availability*: 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. LUC such as reforestation and establishment of high-yielding biomass plantations on lands with sparse vegetation (e.g. degraded pastures) can salinize or acidify some soils and reduce downstream water availability by using irrigation water or redirecting precipitation from run-off and groundwater recharge to evapotranspiration (Jackson *et al.*, 2005; Zomer *et al.*, 2006; Berndes, 2008). The net effect on the state of water depends on the character of land use and water management associated with the new land use compared with the previous situation (e.g. Garg *et al.*, 2011).
- *Impacts on biodiversity* where the mitigation project involves land-use change. An example of this is palm oil development following deforestation.
- *Precluding other land-use options*. Agricultural profitability often relies on landholders being able to switch between crops. Mitigation projects may have rules that require the mitigation activity to be in place for 70–100 years; this can reduce future flexibility in land use. Similarly, landholders have to consider the marginal spread of carbon prices between when they sell and wish to repurchase carbon credits.

Assessing the overall costs and benefits

A range of synergies and trade-offs are summarized here; this analysis is qualitative. More sophisticated, quantitative analyses are being developed and will involve consideration of multiple interacting factors.

Ecosystem markets. In some jurisdictions ecosystem markets are developing (Costanza *et al.*, 1997; Millennium Ecosystem Assessment, 2005; Engel *et al.*, 2008; Deal & White, 2012; Wünscher & Engel, 2012) and these allow valuation of various components of land-use changes, in addition to carbon mitigation (Mayrand & Paquin, 2004; Barbier, 2007). Different approaches are used; in some cases the individual components (both synergies and trade-offs) are considered singly (bundled), in other situations they are considered *in toto* (stacked). Ecosystem market approaches provide a framework to value the overall merits of mitigation actions at both project, regional and national scales (Farley & Costanza, 2010). The ecosystem market approach also provides specific methodologies for valuing the individual components (e.g. water quality response to reforestation, timber yield), however, for some types of ecosystem services (e.g. biodiversity, social amenity) these methodologies are less well developed.

Scale of impacts. It is also important to consider the scale of any impacts. The synergies and trade-offs from mitigation measures will be largely scale dependent – thus if the uptake of mitigation is poor, then the synergies and trade-offs will be likewise 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 synergies and trade-offs.

Getting a balance between mitigation options and other societal goals – including food security and preservation of ecosystem services – requires understanding the dynamics of land governance. It is necessary to assess the role of different social actors under different land management options as well as the potential impacts of various incentives mechanisms, financing schemes, technology access and land tenure agreements. Ideally, such an assessment, combined with a good understanding of the climate mitigation potential, would form the basis for international agreements as well as national legislations aimed at maximizing societal and environmental benefits of land management (Ostrom, 2010).

Analysis of the mitigation potential in the AFOLU sector while delivering food security and minimizing environmental impact

GHG mitigation options are seldom implemented in isolation. Working towards ambitious climate mitigation targets, e.g. limiting global warming to 2 °C, requires portfolios of measures being implemented at the same time. In some cases, individual measures can be effective independently of others. However, in many cases, implementation of one measure influences the GHG reduction potentials, and perhaps also the costs, of other measures. Such interactions are the rule rather than the exception in complex supply chains such as the food supply chain.

For example, Popp *et al.* (2010) showed that a change in diets towards a smaller fraction of animal products and a larger fraction of vegetables or staples reduces the amount of meat, milk and eggs produced, and with that the GHG emissions from enteric fermentation, manure management and soil emissions due to animal feed cropping. But at the same time, the emission reduction potential of food additives or other technical mitigation options such as precision farming also declines, and reduced emissions from livestock production are to some extent counteracted by increases in N_2O soil emissions from food cropping, and CH_4 emissions from rice production resulting from the increased direct use of plants for human consumption. Figure 2 provides a conceptual basis for analysing such interactions.

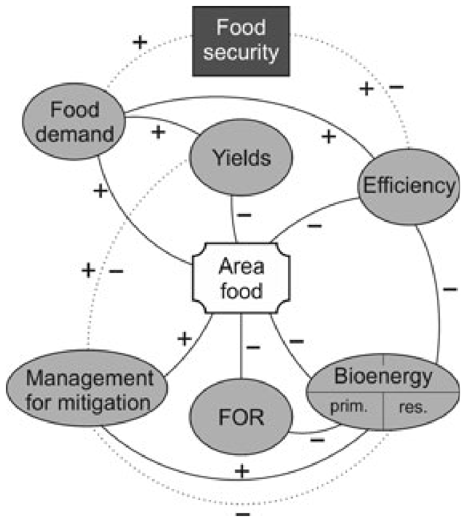

Fig. 2 Interrelationships between different bundles of GHG mitigation options (grey shaded boxes) and food security. Area for food production (food area) is a central link of the system. Option bundles refer to changing food demand, increasing yields in agriculture, increasing efficiency in the food supply chain, including livestock feeding efficiency, mitigation options related to cropland management (e.g. no-tillage agriculture), reduced deforestation, peatland conversion or afforestation (forest area) and bioenergy production, either from primary or secondary biomass sources (e.g. residues). '+' and '−' indicate the direction of the interrelationship: '+' indicates that growth of one factor drives up another; note that mitigation options related to food demand would reduce losses or resource-intensive food (e.g. animal products) which would also reduce food area, but might have feedbacks on yields and efficiency. Dotted lines indicate ambiguous or loose interrelationships.

Figure 2 depicts the interrelations between different mitigation options related to land. Mitigation options in the AFOLU sector are strongly linked via their effect on land demand for food production ('food area'). Options aimed at influencing diets ('food demand'), e.g. either by changing average per capita consumption (contract and converge scenarios between industrial and developing countries) or by reducing food wastes or the share of livestock products in affluent regions, result in reduced land demand for food production (positive relationship; i.e. higher food demand results in increased land demand). Although the production of enough food is not a sufficient condition for food security (Smith & Gregory, 2013), food supply is generally thought to be positively associated with food security. Food area demand is negatively related to input–output efficiency of the food supply chain and yield levels in agriculture; increasing efficiency or yields will decrease area demand, except in the case of stimulated agricultural activity, see below. Efficiency improvement measures also include intensification strategies in the livestock sector that reduce the amount of feed input per unit of product output (Haberl *et al.*, 2012), e.g. the switch to feed concentrate or improved feedstuff, as well as changes in herd management to optimize product output. Such efficiency gains are often beneficial for food security because of their positive effect on food production, but they can, in certain instances, have negative effects on food security, e.g. when the ratio of edible protein input per edible protein output of the livestock system deteriorates in intensive livestock systems (Steinfeld *et al.*, 2010; FAO, 2011; Erb *et al.*, 2012b).

The area required for food production is a key factor influencing the mitigation potentials of primary bioenergy and carbon sequestration in forests (avoided deforestation or afforestation) and peatlands ('forestry'); increased area demand for food production would decrease these potentials (negative relationship). Energy crops and C sequestration may also compete for land, and hence are negatively related with each other. In contrast, management options on cropland, e.g. optimization of organic residue addition or drainage in rice cultivation, increase with the area of food production, as there is a larger area on which to practice these activities (Smith *et al.*, 2008); conversely, reduced food demand would also reduce the potential of such options. If management options reduce yields, however, agricultural activity is displaced to other areas, thereby increasing the demand for land for food production (Haberl *et al.*, 2011).

Although yield increases thus generally increase areas available, and therefore potentials for bioenergy production and C sequestration, yield increases that rely on increased inputs can result in larger GHG emissions per unit of output during the agricultural production process, e.g. by increased N_2O emissions (Reay *et al.*, 2012); only yield increases driven by improved efficiency (e.g. better timing and placement of fertilizer to maximize plant uptake) would be expected to reduce GHG emissions per unit of output (Smith *et al.*, 2008; Popp *et al.*, 2011b; Reay *et al.*, 2012). Options for reducing GHG emissions from agriculture, e.g. the use of organic agricultural methods which sequesters more carbon in soils than conventional farming (Gattinger *et al.*, 2012), might reduce GHG emissions per unit of output, but could increase demand for agricultural land area if they reduce average yields, as organic agriculture often does (Seufert *et al.*, 2012) or as zero tillage agriculture may do (Ogle *et al.*, 2012).

Another mitigation option concerns the use of cropland residues for soil carbon sequestration (mulching), which also improves soil quality ('management for mitigation'). The use of this mitigation measure negatively affects the potential of bioenergy generation from residues, as the residues are not then available for use in generating energy (Lal, 2005). Likewise, improved efficiency in the food supply chain will reduce the quantity of waste flows, which will negatively affect the mitigation potential of bioenergy from residues and waste (Haberl *et al.*, 2011).

Thus, mitigation options in the AFOLU sector are highly interdependent. Direct interrelationships are relatively straightforward to quantify (e.g. the comparison of the mitigation potential in afforestation vs. fossil fuel substitution through bioenergy). Indirect interrelationships, mediated *via* area demand for food production, which in turn impacts upon the area available for other purposes, are much less straightforward to quantify and require systematic approaches. These complex relationships are often mediated by socioeconomic feedbacks, e.g. those related to price changes. For example, switching from one production technology to another (e.g. from conventional to organic agriculture) may influence prices and hence demand. Also, increases in yields may affect demand through supply–demand rebound effects, i.e. increases in consumption often cause the implementation of more efficient, and hence often more cost-effective ways of production (Lambin & Meyfroidt, 2011; Erb *et al.*, 2012a,b), although higher yield and profitability tend to attract migrants and hence, can increase deforestation rates (Angelsen & Kaimowitz, 1999).

Table 2 demonstrates the possible magnitude of such feedbacks in the land system in 2050. It first shows the effect of single mitigation measures compared with a reference case, and then shows the combined effect of the individual measures, using model results discussed in Erb *et al.*, (2009, 2012a,b) and Haberl *et al.*, (2011). The biomass-balance model underlying these results consistently describes land use and biomass flows between production (i.e. agricultural land use) and consumption of biomass (i.e. nutrition and other uses) for 11 world regions, with trade balancing mismatches of supply and demand between regions. Based on this model, we assess in a consistent way the areas freed or consumed by changing yields, diets and livestock efficiencies, which potentially can be used for bioenergy or carbon sequestration. The 'reference' case is similar to the projections of the FAO, (2006) for 2050 in terms of changes in diets and cropland yields, as implemented in the TREND scenario in Erb *et al.*, (2012a). The 'diet change' case assumes a switch to a low animal product diet ('fair and frugal' diet; see Erb *et al.*, 2012a) and a contract and converge model of global food demand to the global average in the year 2000 (i.e. 2800 kcal cap^{-1} d^{-1}, compared to the global mean of 3100 kcal cap^{-1} d^{-1} in the reference case). The 'yield growth' case assumes 9% higher yields than those forecast by FAO (2006), based on the 'Global Orchestration' scenario in the Millennium Ecosystem Assessment, (2005). The livestock 'feeding efficiency' gain case assumes improved livestock feeding efficiencies according to the 'intensive' livestock feeding efficiencies as described in Erb *et al.*, (2012a); under this assumption, input–output ratios of livestock are on average 17% better than in the reference case. The 'waste reduction' case assumes a reduction in the losses in the food supply chain by 6% (see section 2.2.), which was evaluated by assuming that demand reduction would linearly reduce all flows. As Table 2 shows, the combination of all measures results in a substantial reduction in cropland and grazing areas, even though the individual measures cannot be added up due to the interactions between the individual compartments shown in Fig. 1, and regional disparities considered in the biomass-balance model (Erb *et al.*, 2012a,b).

In all cases, former agricultural land (i.e. cropland plus grazing land area) would become available for nonfood purposes (afforestation or bioenergy crops) if

Table 2 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

Cases	Food crop area [Gha]	Livestock grazing area	C sink on farmland* Gt CO_2eq. yr^{-1}	Afforestation of spare land†′‡	Bioenergy on spare land†′§	Total mitigation potential	Difference in mitigation from reference case
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) and Erb *et al.* (2012a).

‡Assuming 11.8 tCO_2. eq ha^{-1} yr^{-1} (Smith *et al.*, 2000).

§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^{-1} yr^{-1} (Smith *et al.*, 2012b). Low bioenergy value: ethanol from maize replaces gasoline and reduces GHG by 45%, energy yield 75 GJ ha^{-1} yr^{-1} (Chum *et al.*, 2011).

stocking densities on grazing land were increased to higher, but still sustainable, levels; the latter were derived from spatially explicit data on the productivity of grazing areas (see Erb *et al.*, 2009, 2012a,b; Haberl *et al.*, 2011). Table 2 shows the GHG reductions that could be achieved in 2050 by using the spare land for afforestation, assuming a CO_2 sequestration of 11.8 t CO_2eq ha^{-1} yr^{-1} (based on Smith *et al.*, 2000). GHG reduction resulting from bioenergy was calculated using two different assumptions: a high value was calculated assuming that biomass produced in short-rotation coppice or energy grass plantations would replace fossil fuels, thereby saving 18.3 tCO_2-eq. ha^{-1} yr^{-1} based on an EROI of 1 : 30, and an average yield of 10 t dry matter ha^{-1} yr^{-1} (Matthews, 2001; Smith *et al.*, 2012b; but see Johnston *et al.*, 2009). A low value was derived by assuming that maize would be grown to produce bioethanol to replace gasoline. The CO_2 reduction in replacing gasoline with bioethanol was assumed to be 45% with an average ethanol yield of 75 GJ ha^{-1} yr^{-1}, according to Chum *et al.* (2011). C sequestration on cropland and grazing land was calculated using a mean sequestration rate of 0.60–0.62 tCO_2-eq. ha^{-1} yr^{-1}, calculated as mean global figures from the values in Smith *et al.* (2008).

When interpreting Table 2 it is essential to keep in mind that these are indicative values derived using assumptions described above. They are useful to estimate the magnitude of feedback effects, but they should only be interpreted as an indication, not as exact quantification. Important feedbacks such as increased GHG emissions from additional inputs (e.g. tractors, fertilizer use) required in intensification (e.g. the yield growth case) are not included.

Table 2 shows that demand-side measures can have substantial beneficial effects, in particular through their ability to create 'spare land' that can be used for either bioenergy or C sequestration through afforestation. This effect is strong and nonlinear, and cancels out reduced C sequestration potentials on agricultural land. Demand-side potentials are substantial when compared with supply-based mitigation measures (see also section 2). Uncertainties related to the possible GHG savings from bioenergy are large and strongly depend on the assumptions regarding energy plants, utilization pathway (e.g. substitution for coal used in power plants vs. liquid biofuels, use of carbon capture and storage), energy crop yields (see Erb *et al.*, 2012a) and effectiveness of sustainability criteria. It should also be noted that the mitigation potentials for bioenergy refer to the case that one additional unit of bioenergy supplied reduces the according fuels by the same amount. However, a recent empirical study by York, (2012) found significantly lower replacement effects, which would reduce the mitigation potential accordingly.

Implications for climate mitigation and food security policy

Supply-side mitigation measures have a mixed impact on food security. Some supply-side mitigation measures could also enhance agricultural production, thereby helping to address food security issues.

Improved timing of fertilization and nitrification inhibitors, e.g. can increase crop production as can measures to improve carbon sequestration (Pan *et al.*, 2009). Other supply-side measures could potentially reduce production, e.g. where the mitigation measure decreases crop yield (e.g. reduced fertilizer inputs). Demand-side measures, on the other hand, should benefit both food security and GHG mitigation. Our analysis lends further support to the findings of Stehfest *et al.* (2009) and Popp *et al.* (2011a), which suggest that consumption-based measures offer a greater potential for GHG mitigation than do supply-side measures. This finding highlights the need for further research into demand-side measures, which have received far less attention than have supply-side measures.

Most technical supply-side measures considered in previous assessments of mitigation potential in the AFOLU sector (Nabuurs *et al.*, 2007; Smith *et al.*, 2008; Smith, 2012b) are close to current practice and can be implemented by a relatively small number of land managers who can be incentivized to implement the measures. Demand-side measures, though, will require behaviour change relative to projected dietary shifts, and require action from many more actors (all consumers globally). Effecting such behaviour change is one of the most challenging aspects of any large-scale policy shift, be that addressing our addiction to fossil fuels, changing personal travel behaviour or changing our diet (e.g. Hardeman *et al.*, 2002). Effecting behaviour change remains one of the greatest challenges to implementing demand-side measures.

If the enormous joint challenges of delivering food security and reducing climate forcing by 2050 are to be met, all available options will need to be considered. Given the challenges of implementing demand-side measures, supply-side measures should be implemented immediately, focussing on those that improve agricultural efficiency and allow the production of more agricultural product per unit of (energy, chemical, etc.) input, so that both GHG mitigation and food security benefit from the change in practice. Given the difficulties in implementing demand-side measures and the time taken for behaviour change to occur, policy should be introduced quickly, and should aim to codeliver to other policy agendas, such as improving environmental quality (Smith *et al.*, 2012a) or improving dietary health (Macdiarmid *et al.*, 2011). Neither challenge will be easy to address, and joined up policy is required more now than ever before.

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